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Setting the Intermittent Bus Approach of Intersections: A Novel Lane Multiplexing-Based Method with an Intersection Signal Coordination Model

Chenxin Zhao ^{1,2} , Hongzhao Dong ², Kai Wang ^{1,3}, Jianwen Shao ^{1,4} and Cunbin Zhao ^{1,*}

¹ Research Division of Metrology in Transportation and Acoustics, Zhejiang Institute of Metrology, Hangzhou 310018, China; zcx_2009@foxmail.com (C.Z.)

² Joint Institute of Intelligent Transportation System, Zhejiang University of Technology, Hangzhou 310023, China

³ Key Laboratory of Acoustics and Vibration Precision Measuring Technology for State Market Regulation, Hangzhou 310018, China

⁴ Key Laboratory of Acoustics and Vibration Precision Measuring Technology of Zhejiang Province, Hangzhou 310018, China

* Correspondence: zhaocunbin@126.com

Abstract: Intermittent bus lanes (IBLs) can alleviate the contradiction between bus priority and the urgent demand of general vehicles for road resources. However, existing IBL strategies seldom pay attention to the setting method of the dynamic bus lanes at intersections, which leads to the still serious delay of buses at intersections in the traffic congestion environment. To tackle this issue, this research explores a novel method of setting the intermittent bus approach (IBA) of intersections for lane sharing and bus priority at intersections. In particular, a time slice division strategy with an intersection signal coordination model is developed to fully and reasonably allocate the idle time of bus lanes at intersections. Besides, considering the lane-changing demands of general vehicles at intersections, the parameters of the IBA lane system are modeled and optimized. For testing and verifying the feasibility of the proposed method, comparative experiments are conducted through microscopic traffic simulation. Results show that the proposed IBA setting method can effectively solve the problem of bus priority failure at intersections. It can maintain the continuity of vehicle running on intersection sections, which better exerts the operational benefits of dynamic bus lanes.

Keywords: intermittent bus approach; lane multiplexing; bus priority; time slice division; dynamic lane control; traffic modeling



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1. Introduction

The development of public transport systems and the guarantee of bus priority are effective ways of alleviating urban traffic congestion, as buses have greater carrying capacity than private transport (such as cars), which can occupy less road resources and improve road utilization. The right-of-way priority of buses is an important guarantee to improve the speed of bus operation, shorten the travel time of passengers, and increase the attractiveness of public transport. As one of the most popular bus priority strategies, conventional dedicated bus lanes (DBLs), which require at least one entire lane, have achieved remarkable results in realizing the right-of-way priority of buses [1]. However, it is inevitable that the setting of DBLs occupies the road resources originally belonging to general traffic in urban roads to a certain extent [2]. With the increasing shortage of urban road resources, the waste of lane resources caused by the intermittent idling of DBLs has brought side effects to the urban transportation system, which leads to increasingly severe conflicts in the right-of-way competition between buses and general vehicles and hinders the promotion of the concept of bus priority. As transit networks cover huge areas of cities, it is very difficult to reconcile the need to maximize the level of bus service and yet minimize the

delays to general vehicles when considering an increase in DBLs [3]. Thus, how to fully develop and utilize the limited road resources of existing lanes while guaranteeing bus priority has become the focus of common concern of many cities and traffic management departments. To alleviate the contradiction between bus priority and the urgent demand of general vehicles for road resources, the intermittent bus lane (i.e., dynamic bus lane) system came into being.

The concept of intermittent bus lane (IBL) was first proposed by Viegas and Lu [4] in 1996. They set up temporary bus lanes for incoming buses by means of signal prompts and restored to general lanes after the buses passed. It is notable that their system only restricts general vehicles from changing into the bus lane ahead of the bus but does not request those vehicles already there to leave the lane, so the system needs to cooperate with transit signal priority (TSP) to flush the queues at traffic signals and clear the way for the bus. Subsequently, Viegas and Lu [5–8] further developed their own theories and methods, studied the vehicle operation rules, traffic control systems, and intersection signal settings in the IBL strategy, which laid a solid theoretical foundation for the development of dynamic bus lanes in the future. Although this method can minimize the impact on general vehicle driving, the IBL strategy does not force general vehicles to leave the bus lane and, thus, TSP may not be able to clear the downstream lane in time in a high-flow traffic environment, resulting in the failure of bus priority.

In view of this, Eichler [9] proposed the bus lanes with intermittent priority (BLIP) strategy, which is essentially a variant of the IBL concept. This method uses variable message signs (VMSs) to control the access of general vehicles to and from the bus lane, and does not require changing the intersection signal setting. Therefore, it would not cause significant perturbations to the regional traffic flow. Subsequently, Eichler and Daganzo [10] conducted a macroscopic traffic flow analysis of the BLIP strategy based on the kinematic wave theory, and evaluated and analyzed the traffic capacity and operation effect of the BLIP road section. The results show that when the traffic flow approaches or exceeds the capacity of the non-bus lanes, the traffic delay of the road section increases, so the strategy is only suitable for the non-saturated traffic road section. To some extent, the BLIP strategy compensates for the limitations of the original IBL strategy. However, it is inevitable that in the vicinity of the BLIP setup signal (i.e., the VMS setup area), the mandatory lane-changing behavior of vehicles caused by intermittent opening/closing of lanes will cause serious right-of-way conflict with traffic in adjacent lanes. Implementing the BLIP strategy in high-traffic environments can actually have negative effects on road traffic. In addition, the BLIP strategy does not involve the calculation of the length of reserved clearance lanes. The lane clearance distance in front of the bus is relatively fixed (usually set to a one block), which cannot be adaptively changed according to the current traffic conditions of the road section. This may lead to insufficient utilization of lane resources or the failure of bus priority.

In recent years, numerous scholars have proposed many IBL conceptual variants [11–15]. Guler and Cassidy [11] developed a similar strategy to share bottleneck capacity among buses and cars by inserting cars into a shared lane without delaying buses. Luo et al. [12] developed a dynamic bus lane with moving block in a connected-vehicle environment, where the length of the moving block can be adjusted with the bus speed in real time. Inspired by the principle of time-division multiplexing in communications, the authors of this paper first proposed a novel intermittent bus lane with time-division multiplexing (BLTDM) in 2011 [16]. By giving vehicles different priorities, the time and space domains of multiplexing links are controlled for lane sharing and bus priority. Subsequently, the authors further improved their methodology system, and conducted research and demonstration on the system architecture, control strategy and operation evaluation of BLTDM [17–20]. These studies suggest that the BLTDM strategy compensates for the limitations of existing IBL strategies to a certain extent, which provides new insights into the construction and management of bus lanes.

As an innovative and promising bus priority strategy, the usefulness and feasibility of IBLs have been proved by many theoretical studies [21–23]. However, due to this mode setting rely on the hardware technology foundation of Cooperative Vehicle Infrastructure

System (CVIS), there are few relevant practical applications (only experimental applications have been carried out in Europe and Australia) [24–27]. Among them, Viegas [25] conducted a field survey of the IBL system in Lisbon, and the results showed that during the lane operation, the bus speed on the line increased by an average of about 20%. However, the operation effect of the system fluctuates greatly due to the influence of traffic conditions, and the system will fail when the road is seriously congested. Currie and Lai [26] conducted a field survey of Melbourne’s IBL operations. The survey found that the system had limited operational benefits compared to the Lisbon trial, which could be attributed to its highly congested and complex traffic environment. Chiabaut and Barcet [27] conducted a case study and evaluation of the BLIP test road section in Lyon. The results show that only enabling the BLIP strategy does not lead to bus travel time savings compared to the classic TSP strategy because setting the BLIP signal creates additional delays for upstream traffic. Therefore, this strategy is not suitable for deployment on short road sections. Only in the implementation environment of longer road sections and more signalized intersections can the operational benefits of the strategy gradually become apparent.

Thus far, research associated with the IBL strategy has focused on system components, traffic operation, and intersection signal setting, but has seldom paid attention to the setting method of the dynamic bus lanes at intersections. This may be one of the main reasons why IBL does not play the expected benefits in the above practical applications. Signalized intersections are bottlenecks of urban traffic, which often represent a major source of bus delays in urban environments. Existing IBL systems are usually combined with TSP schemes to achieve priority passage of buses at the intersection approach [28–31]. Unfortunately, TSP loses effectiveness with heavy traffic because the signals have to accommodate, not just the bus, but also the traffic in which it is embedded [10]. In high-flow traffic environments, TSP still forces buses to mix with cars, which can result in significant bus delays at the intersection [32,33]. In addition, the traffic scene at intersections is more complex, where general vehicles will have the behavior of mandatory lane changing (or merging into lanes) near the intersection due to the journey route. Meeting the lane-changing demands of general vehicles at intersections while reducing the disturbance to bus running is an important factor to be considered in the setting of IBLs at intersections. In view of this, how to minimize the negative impacts imparted to vehicles (including general vehicles and buses) while maintaining the continuity of dynamic bus lanes at intersections, is a problem worthy of study in the current IBL system, which is the focus of the current paper.

To this end, this research explores a novel method of setting the intermittent bus approach (IBA) of intersections based on lane multiplexing, aiming to alleviate the contradiction between lane utilization rate and bus priority at intersections. On the one hand, it can maintain the continuity of vehicle running between the lane and the intersection approach in the road section, where the operational benefits of the overall bus lane in the road section can be better brought into play. On the other hand, the traffic pressure of the general traffic at intersections can be shared through the bus approach, so that the road resource utilization of intersection approaches will be more balanced. The IBA setting method that we propose operates differently than traditional IBL-TSP in several ways: (1) it does not involve the signal control of downstream intersections in order to minimize the interference to the original traffic system, and can be used for each intersection independently without coordinating with the setting of IBLs in road sections, which has more flexibility; (2) it controls the opening/closing of the intermittent bus approach of intersections by setting VMS in order to realize the complete right-of-way priority of buses, and avoid the buses being delayed by the general vehicle queuing at intersections; (3) it considers the lane-changing demands of general vehicles at intersections, where general vehicles can effectively pass through the intersection by using the bus approach without interfering with the bus running.

The goals of the current paper are twofold: (1) to define this new IBA lane operation strategy and (2) to verify its feasibility and evaluate its potential impacts, including both the benefits to buses and the corresponding impacts to general vehicles.

The rest of this paper is organized as follows. In the next section, the lane multiplexing-based method for IBA setting is outlined. Following that, the details of the IBA operating strategy are described, including its parameter optimization. Subsequently, microscopic traffic simulation experiments are conducted to verify the feasibility of the IBA operating strategy, and the experimental results are discussed in detail. The final section concludes this research and proposes further research topics.

2. Outline of the Lane Multiplexing-Based Method for IBA Setting

In this section, we will first elaborate the time-division multiplexing control strategy of bus lanes based on vehicle right-of-way priority and explain the operating mechanism of the BLTDM. On this basis, a typical physical environment of IBA based on lane multiplexing is presented, and the key issues of lane control are described.

2.1. Operation Mechanism of the Bus Lane with Time-Division Multiplexing

The concept of time-division multiplexing was first proposed in the field of communication [34]. The principle of time-division multiplexing is to transmit different signals at different time intervals by way of the same physical connection to improve the utilization of the channel. In the BLTDM strategy, bus lanes are analogous to “public channels” for information transmission, whereas vehicles are analogous to “transmitted signals”, meaning that various types of vehicles can travel without interference in their respective time and space domains.

To describe the time scale and space scale of bus lanes allowed by various types of vehicles, the concepts of time slice and space slice are introduced. The time quantum (time window) during which vehicles are allowed to use bus lanes is defined as “time slice.” The space area segment where vehicles are allowed to use bus lanes is defined as “space slice”. We hope that by giving different types of vehicles corresponding priority (e.g., the priority level of general vehicles is given to 1, that of ordinary buses is given to 2, that of bus rapid transit (BRT) is given to 3, etc.), the time slices in the lane multiplexing period are allocated from high-to-low according to the priority of vehicle types, to realize that bus lanes are logically dedicated by buses, but practically allow other types of vehicles to use them by way of dynamic sharing at particular times and spaces.

Figure 1 shows the ideal operation effect of BLTDM. When there are no high-priority vehicles in the bus lane, the low-priority vehicles are allowed to enter the bus lane. This process is called lane-borrowing. When high-priority vehicles approach the bus lane, the low-priority vehicles change lanes to the adjacent lanes, emptying the bus lane. This process is called lane-returning. When the high-priority vehicles leave the bus lane, the low-priority vehicles can again enter the lane. The aforementioned vehicle lane-changing behaviors constitute the operation process of BLTDM, and this process ensures high-traffic efficiency for high-priority vehicles and improves the overall utilization of road resources.

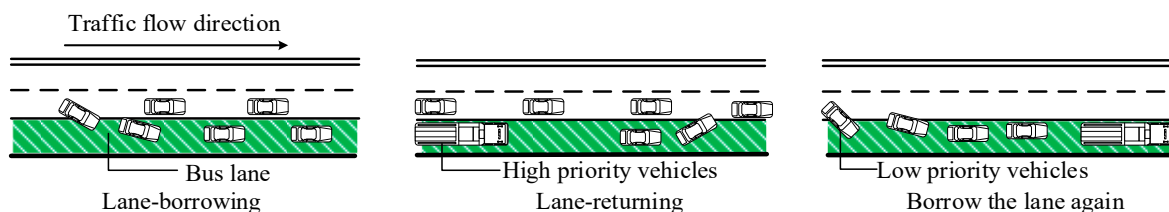


Figure 1. Ideal operation effect of BLTDM.

Figure 2 presents the layout of BLTDM in a road section (the upstream and downstream intersection are used as road section division nodes), which involves two types of space slices: general space slice and intersection space slice. The general space slice is defined as the space domain of the middle area of the road section, excluding the intersection area (such as the general space slices *a* and *b* in Figure 2), and the intersection space slice is defined as the space domain of the road section close to the downstream intersection

(including the intersection approach). Compared with general space slices, the lane control of the BLTDM in intersection space slices needs to consider the influence of downstream intersection signals in addition to the traffic status of the lanes in the space slice.

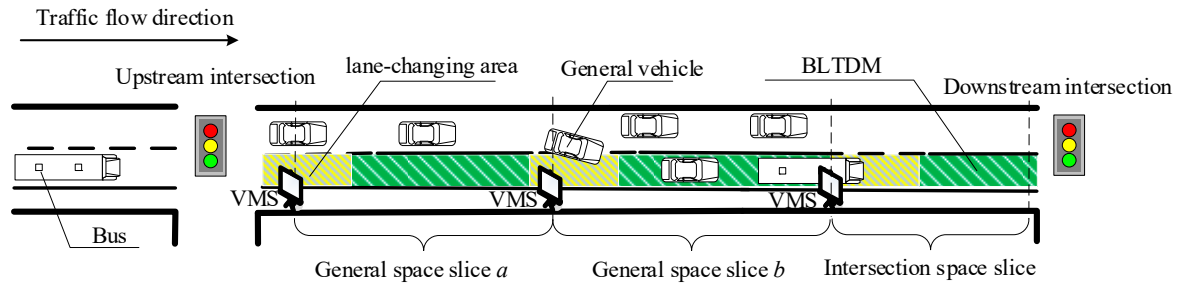


Figure 2. Layout of BLTDM in a road section.

As shown in Figure 2, a long road section can be divided into several general space slices and an intersection space slice. The lane state of the BLTDM of each space slice is controlled independently, and the number of space slices depends on the length of the road section. When the road section is short, there may be only one intersection space slice or no space slice (i.e., the time-division multiplexing control of bus lanes is not carried out in this road section). The length of each general space slice should be set evenly to facilitate the coordinated control of regional lane state signals. Note that a longer or shorter space slice will have a negative impact on the operating performance of the lanes. The recommended length range for general spatial slices is 206–580 m, and the exploration of its applicable length is left in the authors' other work [35]. The details of the length design of intersection space slices are described in Section 3.3.

To control the lane state of each space slice, a lane-changing area (the yellow area in the lane in Figure 2) and a VMS are set at the beginning of each space slice. The lane control signal of the current space slice is displayed and switched through the VMS, and the vehicles can perform lane-borrowing or lane-returning operations in the lane-changing area according to the instructions of the VMS. Figure 3 gives an example of the lane control signals displayed by a VMS, but this is not the best design. In actual traffic implementation, gantry (or cantilever) type, high-resolution VMS panels, or more concise and visual signals can be used to better serve road users. Each lane-changing area is actually the entrance of each corresponding space slice, and vehicles are only allowed to perform lane changing in the lane-changing area. In this way, the VMS at the entrance can easily control the entry of vehicles, ensuring the enforceability of the lane operation strategy. In practice, when a low-priority vehicle violates the signal order to continue to use the bus lane, it will attract a fine from the traffic control department with the evidence from video surveillance equipment.

Translation:

Allow ordinary buses to enter the bus lane

Prohibit general vehicles from entering the bus lane



Figure 3. Lane control signals displayed by a VMS.

“When” and “where” open the bus lane to general vehicles under the premise of ensuring bus priority is the key to the operation of BLTDM. Based on this, the operation mechanism of BLTDM can be summarized as follows. First, on the basis of considering the spatial operation information of buses and the traffic status of the road section, the time slices of various types of vehicles are divided and allocated; second, the VMS system is used to dynamically control the lane state of the corresponding space slice according to the time slice division result. Therefore, various types of vehicles can “borrow” and “return” the bus lane in an orderly manner without interfering with each other according to the instructions of the VMS.

2.2. Issue Description of the IBA Based on Lane Multiplexing

The IBA based on lane multiplexing is actually the BLTDM in aforementioned intersection space slices. The details of the time slice division and lane control strategy of general space slices are described in the references [19,20]. This paper focuses on the IBA lane setting of intersection space slices. We consider here a typical physical environment of intersection space slices for the IBA based on lane multiplexing, as illustrated in Figure 4, where the VMS is installed at the upstream position of the weaving section at the intersection. The lane section from the VMS to the weaving section is defined as the merging section. The drivers can choose whether to travel in the bus lane of this space slice by observing the lane status information displayed on the VMS.

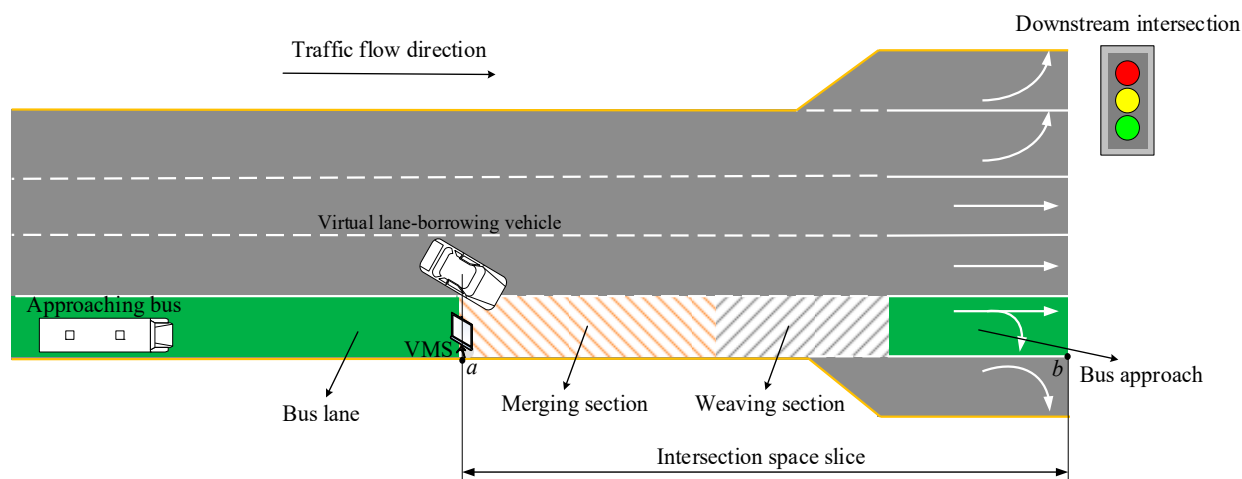


Figure 4. Typical physical environment of the IBA based on lane multiplexing.

In the intersection space slice, the virtual lane-borrowing vehicles can enter the bus approach from the merging section and the weaving section according to the IBA lane state of the space slice and then pass through the downstream intersection, where the IBA lane state is related to the signal cycle, current signal phase and queue length of the intersection. It should be noted that since the signal of urban intersection involves the coordinated control of traffic in the trunk line and region, the lane control strategy of IBA in this paper does not involve the signal control of intersection, so as to minimize the interference to the original traffic system.

In this paper, we hope to provide a clear time allocation scheme for various types of vehicles using bus lanes and avoid the conflict of the right-of-way between different types of vehicles when using the lanes, where buses cannot be delayed by the general vehicle queuing at the intersection, whereas the general vehicles can effectively use the IBA lane to pass through the intersection without interfering with the bus running. In view of this, when considering the time-division multiplexing control of the IBA lane in intersection space slices, the following three key issues need to be addressed:

1. Does each type of vehicle have the right to use the bus lane in this space slice at the current time?

2. For these vehicles that are entitled to use, how long are they allowed to be used?
3. What is the appropriate length for the setting of the intersection space slice? In this way, it can satisfy the orderly and smooth lane changing of the virtual lane-borrowing vehicles in the relatively congested near-intersection area.

3. Strategy and Model

The time slice division of various types of vehicles for using bus lanes is the core content of the BLTDM strategy. It is also the key to controlling the lane state in the operation process of BLTDM. Existing control strategies of IBLs are mostly based on simple trigger control logic, lacking reliable theoretical models as the basis for lane control, which may easily lead to insufficient utilization of resources in bus lanes or failure of bus priority [35]. How to fully and reasonably allocate the idle time of bus lanes at intersections on the premise of ensuring bus priority is the key problem to be discussed in this section.

For simplicity of exposition, two types of vehicles are involved in this paper: buses and cars; buses have high priority and cars have low priority. Different from general space slices, the time slice allocation of intersection space slices needs to consider the signal state of the downstream intersection, so as to realize the coordinated change of the space slice lane control signal (i.e., VMS) and the intersection signal. Thus, the time slice division strategy for intersection space slices can be divided into the following two steps.

1. Judge whether the cars have the right to use the bus lane in the space slice without the influence of intersection signals at the current moment.
2. If yes, further analyze the impact of intersection signal status on bus priority, judge whether the cars are allowed to enter the bus approach at the current moment, and then coordinate and allocate of the time slice of the cars according to the current intersection signal status.

The operational details of the above two steps are explained in Sections 3.1 and 3.2, respectively.

3.1. Basic Time Slice Division Strategy

Before dividing the time slices for space slices, it is first necessary to determine whether the cars (virtual lane-borrowing vehicles) have the right to use the bus lane at the current moment, where the key is to compare the travel time between the virtual lane-borrowing vehicles and the approaching bus to the end of the space slice at the current moment.

The right-of-way priority of the virtual lane-borrowing vehicles is defined as p and assume that they are located at the beginning position of the space slice (the position of point a in Figure 4) and try to drive on the bus lane. The right-of-way priority of the approaching bus is defined as q ($q > p$) and its position determines whether the virtual lane-borrowing vehicles can use the bus lane of this space slice, where the approaching bus can be identified by floating vehicle data. If the virtual lane-borrowing vehicles can pass through the space slice before the approaching bus reaches the end position of the space slice (the position of point b in Figure 4), the virtual lane-borrowing vehicles are allowed to use (or borrow) the bus lane of this space slice, i.e., the lane-borrowing assumption is tenable under the assumption that there is no influence of the intersection signal; otherwise, the virtual lane-borrowing vehicles are forbidden to travel in the bus lane. This relationship can be formulated as follows:

$$\left\{ \begin{array}{l} \text{Vehicles with priority } p \text{ are allowed to borrow the bus lane,} \\ \text{Vehicles with priority } p \text{ are forbidden to borrow the bus lane,} \end{array} \right. \begin{array}{l} \text{when } T_{\text{travel}}^q > T_{\text{travel}}^p + T_{\text{min}} + h_t \\ \text{when } T_{\text{travel}}^q \leq T_{\text{travel}}^p + T_{\text{min}} + h_t \end{array} \quad (1)$$

where T_{travel}^q and T_{travel}^p are the predicted travel time of the approaching bus and the virtual lane-borrowing vehicles traveling to the end position of the space slice at the current moment, respectively, including the vehicle lane travel time, lane-changing time, delay time at bus stops, and intersections, etc. A segmented travel time prediction method can be used here, which is described in [19], and the specific details are no longer detailed. T_{min} is

the minimum time slice, which is equivalent to the minimum green time of intersection signals. The purpose of setting is to prevent the fragmentation of the lane control signal of the space slice caused by too small time slice division. The parameter design details of the minimum time slice are described in the reference [35], which is set to 11 s here. h_t is the minimum safe headway when vehicles change lanes, which is set to 2 s according to the relevant literature [36].

It is obvious that the prediction accuracy of vehicle travel time is related to the accuracy of lane system control. Generally, a longer space slice will increase the fluctuation range of the vehicle travel time in the space slice, which will lead to a larger prediction error of the vehicle travel time and a decrease in the effectiveness of lane utilization. Therefore, an appropriate space slice length should be set within the acceptable range of prediction error, which is discussed in Section 3.3.

The division method of dynamic time slices (i.e., the duration of time allowed to enter the bus lane) for vehicles with priority p is as follows.

1. Identify the position of the high-priority vehicle (i.e., the approaching bus) in the upstream area at the current moment that is closest to the beginning position of the space slice.
2. Predict the travel time of the approaching bus and the virtual lane-borrowing vehicles traveling to the end position of the space slice at the current moment and substitute the prediction result into Equation (1) to determine whether the virtual lane-borrowing have the right to use the bus lane of the space slice at the current moment.
3. According to the result of the lane-borrowing judgement, the dynamic time slice of vehicles with priority p is calculated as follows:

$$T_{\text{basic}}^p = \begin{cases} T_{\text{travel}}^q - (T_{\text{travel}}^p + h_t), & \text{If vehicles are allowed to borrow the bus lane} \\ 0, & \text{If vehicles are forbidden to borrow the bus lane} \end{cases} \quad (2)$$

where T_{basic}^p is the basic time slice of vehicles with priority p allowed to use the bus lane at the current moment, i.e., the duration that the virtual lane-borrowing vehicles are allowed to use the bus lane in this space slice at the current moment under the assumption that there is no influence of the intersection signal.

3.2. Intersection Signal Coordination Model Based on Time Slice Division

For the intersection space slice, the prerequisite for allowing the virtual lane-borrowing vehicles to use the bus lane is $T_{\text{basic}}^p > 0$:

$$T_{\text{basic}}^p = T_{\text{travel}}^q - (T_{\text{travel}}^p + h_t) > 0 \quad (3)$$

When $T_{\text{basic}}^p > 0$, the virtual lane-borrowing vehicles in the space slice will not interfere with the normal running of the approaching bus, and the bus approach of the intersection space slice has the possibility to be open to the virtual lane-borrowing vehicles.

On the premise that the above prerequisite is met, when a virtual lane-borrowing vehicle reaches the intersection, if the signal phase of the intersection is green, or the signal phase of the intersection is red and the virtual lane-borrowing vehicle can pass through the intersection before the approaching bus reaches the intersection, it is allowed to use the bus lane (bus approach) of the intersection space slice; otherwise, it is forbidden to travel in the bus lane.

According to the above logic analysis, on the basis of obtaining the phase, phase remaining time and cycle of the intersection signal at the current moment, the dynamic time slice divisions of the intersection space slice are modeled for different intersection signal states.

When the current signal phase is red,

$$\text{mod}(T_{\text{travel}}^p - T_{\text{remain}}^{\text{red}}, T_{\text{cycle}}) < T_{\text{green}}? \tag{4}$$

where $\text{mod}()$ is the remainder function; T_{cycle} is the cycle of the intersection signal; $T_{\text{remain}}^{\text{red}}$ is the remaining time of the current red phase; T_{green} is the green period duration of the intersection signal.

If $\text{mod}(T_{\text{travel}}^p - T_{\text{remain}}^{\text{red}}, T_{\text{cycle}}) < T_{\text{green}}$, the signal phase of the intersection is green when the virtual lane-borrowing vehicles reach the intersection; thus, virtual lane-borrowing vehicles are allowed to enter the bus approach of the intersection space slice. The time slice of vehicles with priority p allowed to enter the bus approach at the current moment T_{allow}^p is calculated as follows:

$$T_{\text{allow}}^p = \min\{T_{\text{basic}}^p, T_{\text{green}} - \text{mod}(T_{\text{travel}}^p - T_{\text{remain}}^{\text{red}}, T_{\text{cycle}})\} \tag{5}$$

If $\text{mod}(T_{\text{travel}}^p - T_{\text{remain}}^{\text{red}}, T_{\text{cycle}}) \geq T_{\text{green}}$, the signal phase of the intersection is red when the virtual lane-borrowing vehicles reach the intersection.

$$T_{\text{travel}}^q - T_{\text{travel}}^p > T_{\text{cycle}} - \text{mod}(T_{\text{travel}}^p - T_{\text{remain}}^{\text{red}}, T_{\text{cycle}}) + T_{\text{queue}}? \tag{6}$$

where T_{queue} is the queue dissipation time of the intersection approach during the red signal phase, which can be estimated as follows [29]:

$$T_{\text{queue}} = \psi * T_{\text{red}} / (s - \psi) \tag{7}$$

where ψ is the arrival rate of vehicles in the traffic flow direction of the intersection approach; s is the saturated flow rate of all approaches in this traffic flow direction; T_{red} is the red period duration of the intersection signal, $T_{\text{red}} = T_{\text{cycle}} - T_{\text{green}}$.

If $T_{\text{travel}}^q - T_{\text{travel}}^p > T_{\text{cycle}} - \text{mod}(T_{\text{travel}}^p - T_{\text{remain}}^{\text{red}}, T_{\text{cycle}}) + T_{\text{queue}}$, the virtual lane-borrowing vehicles can pass through the intersection before the approaching bus reaches the intersection. Therefore, the virtual lane-borrowing vehicles are allowed to enter the bus approach of the intersection space slice, where T_{allow}^p is calculated as follows:

$$T_{\text{allow}}^p = \min\{T_{\text{basic}}^p, T_{\text{travel}}^q - T_{\text{travel}}^p - T_{\text{cycle}} + \text{mod}(T_{\text{travel}}^p - T_{\text{remain}}^{\text{red}}, T_{\text{cycle}}) - T_{\text{queue}}\} \tag{8}$$

If $T_{\text{travel}}^q - T_{\text{travel}}^p \leq T_{\text{cycle}} - \text{mod}(T_{\text{travel}}^p - T_{\text{remain}}^{\text{red}}, T_{\text{cycle}}) + T_{\text{queue}}$, the virtual lane-borrowing vehicles cannot pass through the intersection before the approaching bus reaches the intersection. Therefore, the virtual lane-borrowing vehicles are forbidden to enter the bus approach of the intersection space slice, i.e., $T_{\text{allow}}^p = 0$.

When the current signal phase is green (i.e., non-red phase; note that the yellow phase is also classified as green phase here) then

$$\text{mod}(T_{\text{travel}}^p - T_{\text{remain}}^{\text{green}}, T_{\text{cycle}}) > T_{\text{red}}? \tag{9}$$

where $T_{\text{remain}}^{\text{green}}$ is the remaining time of the current green phase.

If $\text{mod}(T_{\text{travel}}^p - T_{\text{remain}}^{\text{green}}, T_{\text{cycle}}) > T_{\text{red}}$, the signal phase of the intersection is green when the virtual lane-borrowing vehicles reach the intersection. Therefore, the virtual lane-borrowing vehicles are allowed to enter the bus approach of the intersection space slice, where T_{allow}^p is calculated as follows:

$$T_{\text{allow}}^p = \min\{T_{\text{basic}}^p, T_{\text{cycle}} - \text{mod}(T_{\text{travel}}^p - T_{\text{remain}}^{\text{green}}, T_{\text{cycle}})\} \tag{10}$$

If $\text{mod}(T_{\text{travel}}^p - T_{\text{remain}}^{\text{green}}, T_{\text{cycle}}) \leq T_{\text{red}}$, the signal phase of the intersection is red when the virtual lane-borrowing vehicles reach the intersection.

$$T_{\text{travel}}^q - T_{\text{travel}}^p > T_{\text{red}} - \text{mod}(T_{\text{travel}}^p - T_{\text{remain}}^{\text{green}}, T_{\text{cycle}}) + T_{\text{queue}}? \quad (11)$$

If $T_{\text{travel}}^q - T_{\text{travel}}^p > T_{\text{red}} - \text{mod}(T_{\text{travel}}^p - T_{\text{remain}}^{\text{green}}, T_{\text{cycle}}) + T_{\text{queue}}$, the virtual lane-borrowing vehicles can pass through the intersection before the approaching bus reaches the intersection. Therefore, the virtual lane-borrowing vehicles are allowed to enter the bus approach of the intersection space slice, where T_{allow}^p is calculated as follows:

$$T_{\text{allow}}^p = \min\{T_{\text{basic}}^p, T_{\text{travel}}^q - T_{\text{travel}}^p - T_{\text{red}} + \text{mod}(T_{\text{travel}}^p - T_{\text{remain}}^{\text{green}}, T_{\text{cycle}}) - T_{\text{queue}}\} \quad (12)$$

If $T_{\text{travel}}^q - T_{\text{travel}}^p \leq T_{\text{red}} - \text{mod}(T_{\text{travel}}^p - T_{\text{remain}}^{\text{green}}, T_{\text{cycle}}) + T_{\text{queue}}$, the virtual lane-borrowing vehicles cannot pass through the intersection before the approaching bus reaches the intersection. Therefore, the virtual lane-borrowing vehicles are forbidden to enter the bus approach of the intersection space slice, i.e., $T_{\text{allow}}^p = 0$.

After dividing the time slice of the intersection space slice, detect and judge whether the current signal phase ends or whether T_{allow}^p decreases to 0. If yes, the time slice division of the next cycle is performed.

Figure 5 presents the logic control flow of the above time slice division strategy.

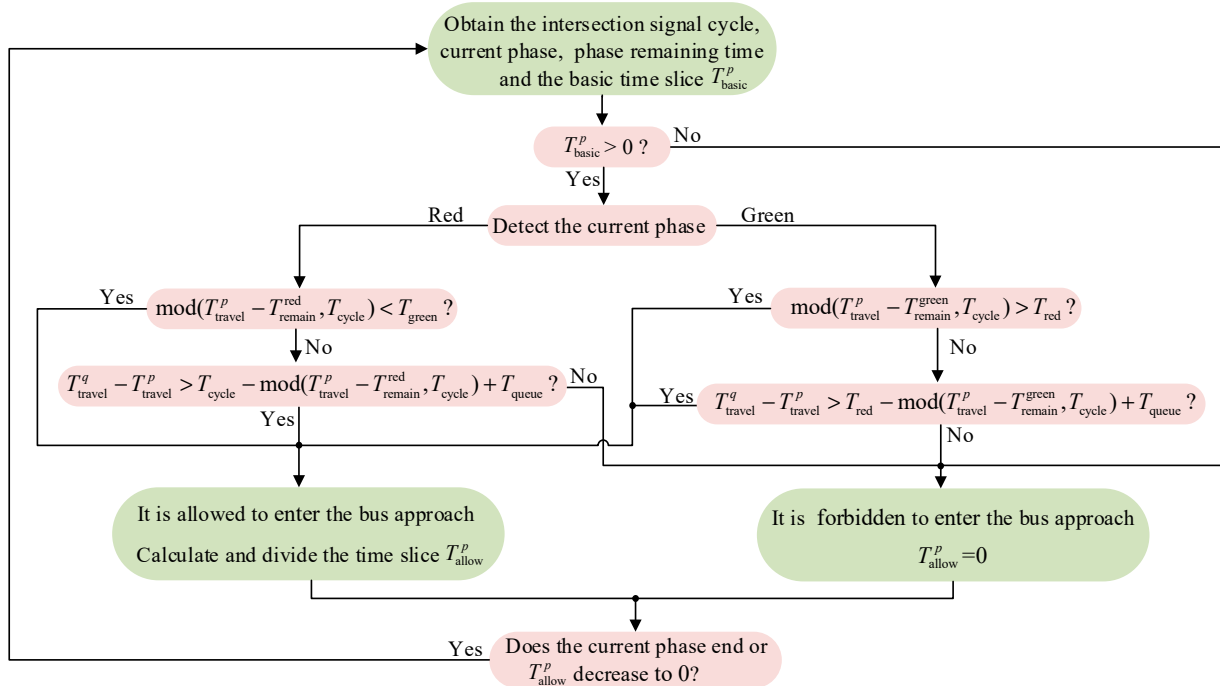


Figure 5. Logic control flow of dynamic time slice division strategy of intersection space slices.

3.3. Parameter Optimization

The control strategy of the IBA setting method based on lane multiplexing has been elaborated in the previous subsections, which addresses the key issues (a) and (b) in Section 2.2. However, there is a key parameter in its lane system that has not yet been determined, which is the length of the intersection space slice.

The length of the intersection space slice actually corresponds to the set distance between the VMS and the downstream intersection in the lane system, and its size will affect the operation effect of the lane system. When the length of the intersection space slice is set too small, cars will not be able to change lanes in time in the relatively congested near-intersection area, resulting in the formation of queues in the lane-changing area, which

may interfere with the normal running of the rear buses, and increase the suffering of cars added by the IBA strategy. On the other hand, if the intersection space slice is too long, the prediction error of the vehicle travel time of the space slice will become larger, resulting in the decline of the control accuracy of lane system, which will reduce the lane utilization rate, and even the bus priority cannot be guaranteed. Thus, how to set the optimal length of the intersection space slice under the premise of ensuring that the cars can smoothly merge into the intersection space slice and taking into account the control accuracy of the lane system, is the key issue to be addressed in this subsection.

As shown in Figure 4, the intersection space slice is composed of three parts: the merging section, the weaving section, and the bus approach. Among them, the weaving section and the bus approach are the original intersection road infrastructure, and their length depends on the road traffic characteristics of the intersection, which belongs to the traditional intersection planning and design. The IBA based on lane multiplexing does not involve changes to the existing road infrastructure, so here we only optimize the design for the length of the merging section in the intersection space slice.

The merging section is set to allow the cars to have enough space and time to merge into the bus lane, and its length is defined as l . By analyzing the lane-changing behavior of the IBA lane system, an optimal model of the length of the merging section for the intersection space slice is established by using the gap acceptance theory and the differential method.

Whether the headway of adjacent lanes is greater than the acceptable gap of lane-changing is the key factor when determining the smooth lane change of merging vehicles. Therefore, the successful merging of vehicles depends on the headway of adjacent lanes. Common headway distribution functions are shown in Table 1.

Table 1. Common headway distribution functions.

Headway Distribution Function	Scope of Application
Negative exponential distribution	Less than 250 veh/h
Shifted negative exponential distribution	250~750 veh/h
Erlang Distribution	250~750 veh/h
M3 distribution	More than 750 veh/h and the phenomenon of vehicle queuing is obvious

In view of the traffic scene in which the lanes near the intersection of urban roads are crowded and have obvious vehicle queuing, the M3 distribution function is used to describe the headway distribution of vehicles in the merging area [37], as shown in the following formula:

$$F(h) = \begin{cases} 1 - \alpha e^{-\lambda(h-\tau)} & h > \tau \\ 1 - \alpha & h = \tau \\ 0 & h < \tau \end{cases} \quad (13)$$

where $F(h)$ is the probability distribution of vehicle headway h ; α is the proportion of free-flow vehicles in adjacent lanes; λ is the attenuation constant; τ is the minimum headway.

The M3 distribution assumes that the vehicle travels in two states: the vehicle queuing state and the free-flow state.

1. Vehicle queuing status: vehicles are queuing up to keep the minimum headway.
2. Free-flow state: the headway of vehicles is randomly distributed and greater than the minimum headway.

As the vehicle approaches the end of the merging section, the critical gap of lane-changing will decrease due to the driver’s anxiety about not being able to change lanes smoothly. It is assumed that there is a linear relationship between the two as follows:

$$t_d = t_0 - \frac{d}{l}(t_0 - \tau) \quad (14)$$

where t_d is the acceptable gap when the vehicle travels to distance d ; d is the distance traveled by the vehicle in the merging section; l is the length of the merging section; t_0 is the initial critical gap of lane-changing.

$P(d)$ is defined as the successful merging probability of the vehicle traveling from $x = 0$ to $x = d$ in the merging section. Considering that the headway in adjacent lanes obeys the M3 distribution, the probability $P(h \geq t_d)$ that the headway of adjacent lanes is greater than the critical gap of lane-changing at the merging section d can be calculated as follows:

$$P(h \geq t_d) = 1 - F(t_d) = \alpha e^{-\lambda(t_d - \tau)} \tag{15}$$

Whether the headway of adjacent lanes is greater than the critical gap of lane-changing at the merging section, d is related to the waiting time of the merging vehicle there. Thus, the probability distribution function of the vehicle merging into the merging section at d can be equivalent to the geometric distribution of the waiting time of the merging vehicle at d . Based on this, the differential method is applied to solve d and $P(d)$.

Assuming that $d + \Delta d$ ($\Delta d \rightarrow 0$) is the position where the vehicle successfully merges, the merging probability can be decomposed into the sum of the probability of merging at $(0, d)$ and the probability of not merging at $(0, d)$ but merging at $(d, d + \Delta d)$:

$$P(d + \Delta d) = P(d) + (1 - P(d)) * \Delta t * P(h \geq t_d) \tag{16}$$

where Δt is the travel time of Δd for the merging vehicle.

Considering $\Delta d \rightarrow 0$, the acceptable gap of lane-changing for the merging vehicle at $d + \Delta d$ is the same as that at d , i.e., t_d . The driving velocity of the merging vehicle within Δd is also the same as at d , denoted as $v(d)$, and is described as follows:

$$\Delta t = \frac{\Delta d}{v(d)} \tag{17}$$

Substitute Equation (17) into Equation (16):

$$\frac{P(d + \Delta d) - P(d)}{\Delta d} = (1 - P(d)) * \frac{P(h \geq t_d)}{v(d)} \tag{18}$$

Let $\Delta d \rightarrow 0$ and find the limit on the left side of the above formula, as follows:

$$P'(d) = (1 - P(d)) * \frac{P(h \geq t_d)}{v(d)} \tag{19}$$

Solve the differential equation and get the general solution as follows:

$$P(d) = e^{-\frac{P(h \geq t_d) * d}{v(d)}} (e^{\frac{P(h \geq t_d) * d}{v(d)}} + C) \tag{20}$$

Solve the constant C in combination with physical meaning: if $d \rightarrow 0$, $P(d) \rightarrow 0$. Take the limit $d = 0$ and $P(d) = 0$ on both sides of the above formula and get $C = -1$.

Then, the equation results in the following:

$$P(d) = 1 - \exp\left[-\frac{P(h \geq t_d) * d}{v(d)}\right] = 1 - \exp\left[\frac{-\alpha d}{v(d)} \cdot e^{-\lambda(t_0 + \frac{d}{v}(\tau - t_0) - \tau)}\right] \tag{21}$$

It can be found from the above equation that the greater the distance d traveled by the merging vehicle, the greater the probability of successful merging. When $d = l$ and $P(d)$ is close to 1, it can be considered that the merging vehicle can change lanes smoothly in the merging section of the intersection space slice, so that the optimal length l of the merging section for the intersection space slice can be deduced.

To ensure that the merging vehicle can change lanes smoothly in the merging section of the intersection space slice, the length of the merging section should be calculated in a

conservative way. Let $P(d) = 0.9$, $\alpha = 0.5$, and $l = d$; $v(d)$ takes 70% of the urban road speed limit of 60 km/h, i.e., 11.7 m/s, and the calculation is as follows:

$$\begin{aligned} 0.9 &= 1 - e^{-\frac{0.5 \times d}{11.7}} \\ l = d &\approx 53.9 \text{ m} \end{aligned} \tag{22}$$

Under this traffic condition, when the length of the merging section of the intersection space slice is set to 53.9 m, it can ensure that 90% of the merging vehicles can smoothly merge into the bus lane. It should be noted that it is impossible to achieve a 100% probability that the merging vehicle can change lanes smoothly in theory. Here, it is just set to 90% to close to 100%. Taking into account the control accuracy of the lane system and the smooth lane change of merging vehicles, the optimal setting length of the merging section of the intersection space slice is 53.9 m.

4. Results and Discussion

In this section, we conduct microscopic traffic simulation experiments to verify the feasibility of the IBA setting method base on lane multiplexing. As a powerful tool for studying traffic flow in a microenvironment [38], cellular automaton (CA) is adopted to build microscopic traffic models to help us evaluate the operation effect of lane operation strategies.

As shown in Figure 6, a two-lane traffic simulation scene is constructed with CA. Lane 1 is a general lane and lane 2 is a bus lane. In our modeling, there are two types of vehicles on the road: cars and buses. When adopting open boundary rules, vehicles are created at the left boundary of lanes and exits from the right boundary. Specifically, lane 1 creates cars, where the input car flow can be controlled by adjusting the entry probability of cars; lane 2 creates buses at each bus departure interval, and similarly, the bus volume can be controlled by setting the bus departure interval. The signal phase of the downstream intersection can be controlled by adjusting the exit probability of the right boundary (e.g., the exit probability of vehicles is 1 in the green phase of the intersection signal and 0 in the non-green phase). The vehicle movement rule follows the NaSch model [39] and the vehicle lane-changing rule follows the STCA model [40]. The key parameters in the CA traffic model are summarized in Table 2. The details of the CA traffic modeling process are described in [20], which is no longer detailed in this paper.

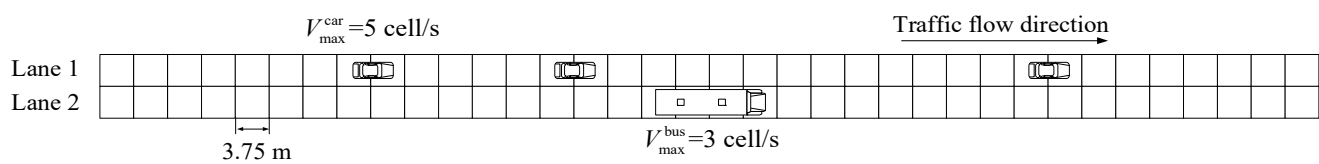


Figure 6. Two-lane traffic simulation scene.

Table 2. Key parameters in the CA traffic model.

Parameter	Value
Cell length	3.75 m
Lane length	300 cells
Car dimensions	2 cells
Maximum velocity of cars V_{\max}^{car}	5 cell/s (67.5 km/h)
Bus dimensions	4 cells
Maximum velocity of buses V_{\max}^{bus}	3 cell/s (40.5 km/h)
Randomization probability in the NaSch model	0.35
one time step	1 s

The basic variables are defined as follows:

$$\rho_i(t) = \frac{2 * N_{i,car}(t)}{L} + \frac{4 * N_{i,bus}(t)}{L} \quad (23)$$

$$v_k(i, t) = \frac{\sum_{j=1}^{N_{i,k}(t)} v_{i,j(j \in k)}(t)}{N_{i,k}(t)} \quad (24)$$

where $\rho_i(t)$ represents the traffic density in lane i at time t (pcu/2site); $v_k(i, t)$ refers to the average velocity of type k vehicles in lane i at time t , $i \in (1, 2)$, $k \in (\text{car}, \text{bus})$; L is the lane length (cells); $N_{i,k}(t)$ is the number of type k vehicles in lane i at time t ; and $v_{i,j(j \in k)}(t)$ refers to the velocity of vehicle j (type k) in lane i at time t . j is the label of the vehicle of type k in lane i at time t , $j = 1, 2, \dots, N_{i,k}(t)$.

In our simulations, the proposed IBA lane operation strategy is applied to the CA traffic modeling, and three cases of CA two-lane traffic model under different lane operation strategies are designed for comparison experiments, as follows:

Case A: conventional two-lane road section with no bus priority (i.e., road section with mixed traffic flow of buses and cars). In this road section, cars are free to change lanes except in the area of the intersection approach.

Case B: BLTDM road section with conventional intersection approach setting.

Case C: BLTDM road section with IBA setting.

The lane operation strategies are transformed into the evolution rules in CA to construct the two-lane traffic models of the above three cases. The experimental parameters of the simulation environment are presented in Table 3. The number of the evolutionary time steps in simulations is set to 10,000 steps, and each time step corresponds to a physical time of 1 s. Since the transient phenomenon occurs in the initial stage of the simulation, the first 8000-time steps are discarded to reduce the negative effect of the transient time. As such, the experimental results are obtained from 8001- to 10,000-time steps.

Table 3. Experimental simulation parameters.

Parameter	Value
Signal cycle of the downstream intersection	100 s
Green phase timing of the intersection signal	25 s
Length of the intersection approach	52.5 m
Length of the merging and weaving section	67.5 m
Input car flow	0~1800 veh/h
Bus volume	{30, 60, 90, 120} veh/h
Simulation time	10,000 steps

As bus stops are often installed close to intersections to utilize the red time to board and debus passengers [41], it can be argued that the bus stop is not a primary influential factor on traffic flow in the comparison between the three cases [21]. This paper focuses on how these strategies affect traffic flow on road sections and does not take the bus stops into account.

The experimental results of microscopic traffic simulation are obtained by performing numerical simulation in MATLAB. The analysis of experimental results focuses on the impact of each lane operation strategy on the traffic density, travel time, and traffic capacity of the experimental link to evaluate the operation effect of each strategy.

4.1. Traffic Density

The lane multiplexing strategy is developed to improve the traffic situation of road sections by utilizing the idle road resource in bus lanes. The traffic density is one of the indicators for evaluating the traffic situation of road sections. Figure 7 presents the traffic

density distribution on the experimental link in each case at different bus volume, and it is clear that the traffic density of experimental link increases as input car flow rises.

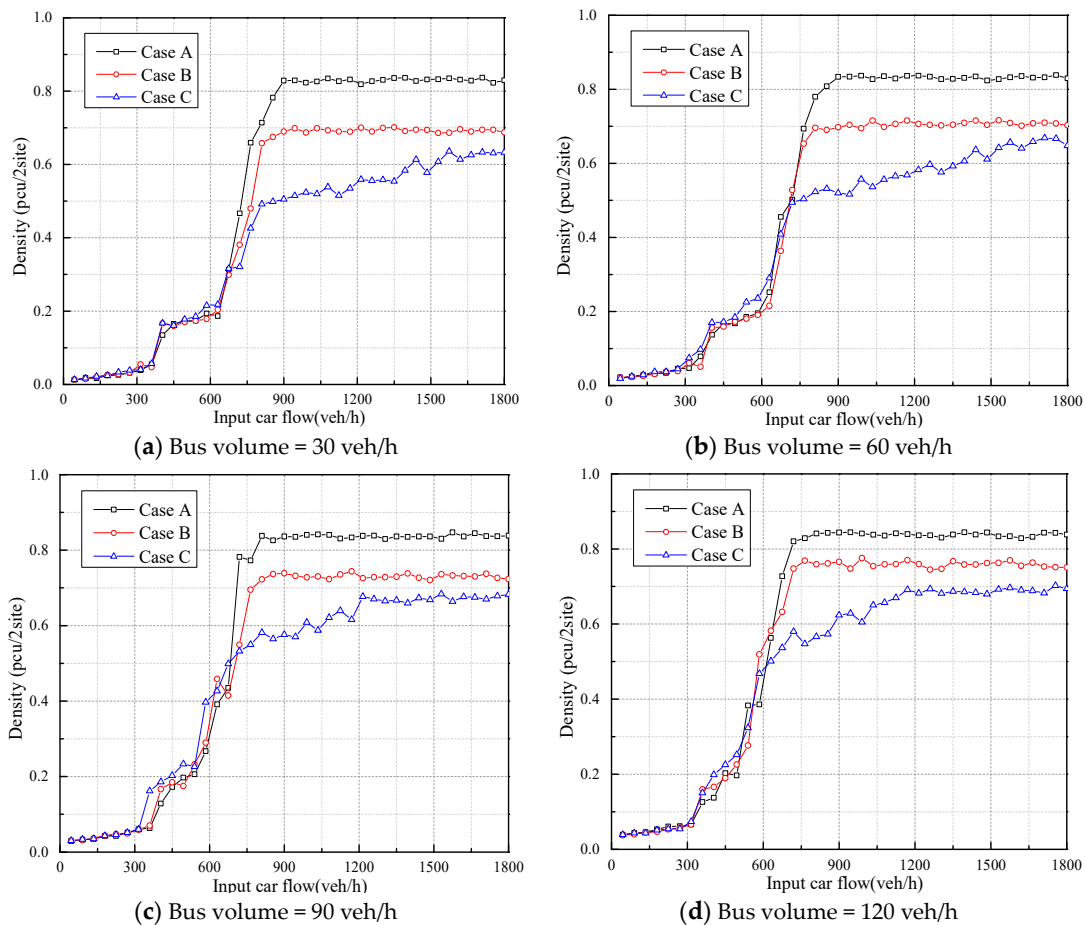


Figure 7. Traffic density distribution on the experimental link in each case.

When the input car flow is less than 600 veh/h, the traffic density changes almost the same in the three cases, which indicates that the lane multiplexing strategy has almost no impact on the traffic situation of the experimental link in the low-flow traffic environment. In fact, when the experimental link is in a low-flow traffic environment, the cars could achieve the desired velocity in free traffic flow, so there is no need to implement the lane multiplexing strategy to optimize traffic in this situation.

When the input car flow is greater than 600 veh/h, the traffic density in the three cases shows different trends. The traffic density of Case A is the highest and that of Case C is the lowest, which indicates that the lane multiplexing strategy can improve the traffic situation of the experimental link (i.e., reduce the traffic density of the road section with mixed traffic flow). This should be ascribed to the fact that frequent vehicle lane changes will occur on the mixed road section in the high-flow traffic environment, and this would slow down the traffic and increase the traffic density [42]. The lane multiplexing strategy can effectively control the lane changing of cars by setting the lane-changing area, which can reduce the negative effect of frequent vehicle lane changes on the traffic flow of the experimental link. Analogously, the traffic density that of Case C is lower than that of Case B in the high-flow traffic environment, which indicates that the IBA can further improve the traffic situation of the BLTDM road section by controlling the lane-changing of cars in the downstream intersection area.

As the bus volume increases, it is found that the traffic density of Case B and Case C tends to increase in high-flow traffic environment, which can be ascribed to the fact that

the lane multiplexing strategy will reduce the resource proportion of cars using bus lanes to ensure bus priority. It can be expected that with the further increase in bus volume, their traffic density will gradually approach the traffic density of Case A. When the bus volume is large enough, the bus lane in the BLTDM road section will become a bus-only lane (i.e., DBL).

Note that in our simulations, buses flow through the road section evenly and on time, and the bunching issue is not considered. Based on the operation mechanism of the lane multiplexing strategy, the bunching issue actually weakens the influence of the strategy on the traffic flow of the road section [21]. For example, if there is a bunch of three buses passing through the road section, the dynamic bus lane system provides bus priority as if there is only one bus. The time-space for prioritizing each bus has almost overlapped, which is actually an excellent circumstance because cars do not suffer as much as the even bus flow. The situation in our study represents the extreme case for verifying the influence of the lane multiplexing strategy upon traffic flow.

4.2. Travel Time

Bus priority is the primary condition for the operation of lane multiplexing strategy. It is meaningless to set up dynamic bus lanes when bus priority cannot be guaranteed. The travel time of the buses of the experimental link is the most intuitive index to measure whether bus priority is guaranteed, and the travel time of vehicles is an important indicator for evaluating the traffic efficiency of a road section. Figure 8 presents the travel time of cars and buses of the experimental link in each case.

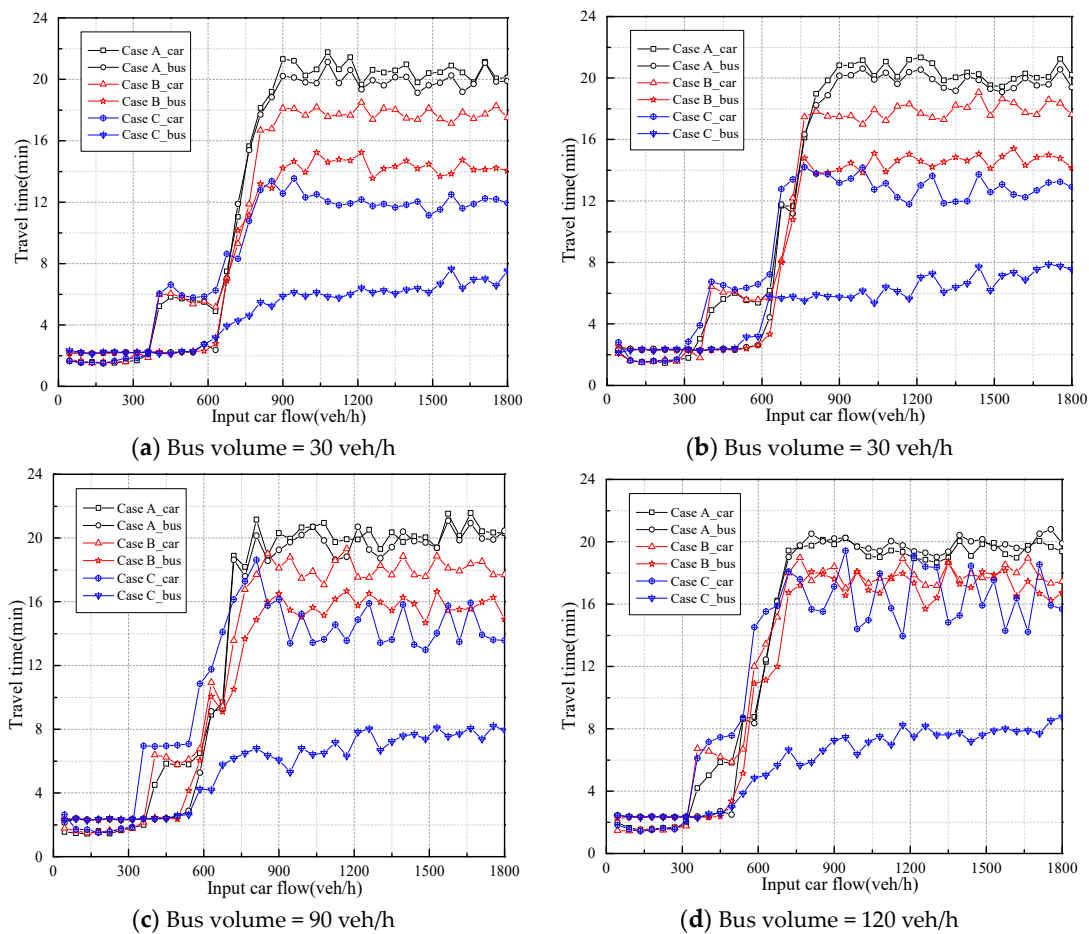


Figure 8. Travel time of cars and buses of the experimental link in each case.

As shown in Figure 8, it can be observed that the car travel time and bus travel time in Case A are not much different in the high-flow traffic environment due to the mixed traffic flow. Meanwhile, the travel times of the cars and buses in Case B and Case C are both lower than those in Case A, which indicates that the lane multiplexing strategy can reduce the travel time of vehicles (including cars and buses) of the experimental link and improve the operating efficiency of the lanes. Compared with Case B, the decrease in vehicle travel time in Case C is more significant, which confirms that the setting of IBA can further improve the traffic situation of the BLTDM road section in the high-flow traffic environment and improve the traffic efficiency. Interestingly, however, when the input car flow is between 300 and 600 veh/h, the travel time of cars in Case C is slightly higher than that in the other two cases, which indicates that setting IBA in a low-flow traffic environment cannot improve the traffic efficiency of the experimental link. This should be ascribed to the fact that the IBA's on-off control of the bus approach will lead to more forced lane-changing behavior of cars near the intersection, which will increase the disturbance to car running in the low-flow traffic environment. Thus, it can be considered that the IBA is not suitable for urban intersections with low traffic flow.

In addition, it is clear that the travel time of buses in Case B and Case C is less than that of cars in the high-flow traffic environment, except for the Case B in Figure 8d, which suggests that the lane multiplexing strategy can provide bus priority in the experimental link. Especially in Case C, compared with the other two cases, the travel time of buses is significantly lower than that of cars. This should be ascribed to the fact that the IBA can give bus priority at intersections to maintain the continuity of bus running between the lane and the intersection approach in the road section, where the operational benefits of the overall bus lane in the road section can be better brought into play. It is worth noting that in Case B of Figure 8d, the travel time of buses is not significantly reduced compared with that of cars in the high-flow traffic environment, which indicates that the lane multiplexing strategy is invalid and cannot provide bus priority in this case. This should be ascribed to the fact that conventional intersection approaches cannot provide bus priority at intersections. When the traffic flow of both buses and cars is high, buses will inevitably be disturbed by cars at the intersection, resulting in large delays, which will offset the travel time benefit that the buses get from running in the bus lane. In contrast, the travel time of buses in Case C is still greatly improved. It indicates that the IBA can effectively reduce the delay of buses at intersections and improve the operating speed of buses on the entire road section, which further confirms the feasibility and necessity of IBA setting.

As the bus volume increases, it can be found that the travel time of buses in Case C is stable in the high-flow traffic environment, whereas the travel time of cars shows an upward trend. It indicates that the bus running is not disturbed by cars on the BLTDM road section with IBA setting, where the buses can get a good driving environment on the bus lane. On the other hand, it is inevitable that due to the increase of bus volume, the dynamic bus lane will reduce the proportion of open time for cars to ensure bus priority, which leads to the increase of the car travel time in the high-flow traffic environment (i.e., traffic congestion environment). Furthermore, it can also be found that with the increase of bus volume, the fluctuation of the car travel time in Case C becomes more and more significant in the high-flow traffic environment. This should be ascribed to the fact that the increase of bus volume will lead to the aggravation of dynamic lane opening and closing frequency, as well as the increase in the frequency of vehicle lane changes (especially mandatory lane changing), which will lead to the instability of road traffic flow. The frequent opening and closing of dynamic lanes increases the suffering of car drivers, which may bring additional negative effects on the traffic situation of the road section. Thus, when the bus volume is high, it is an appropriate method to adopt the DBL strategy to ensure bus priority.

4.3. Traffic Capacity

Buses are generally seen as slow-moving bottlenecks in traffic flow [21]. For the special traffic scenario under the lane multiplexing strategy, it is difficult to calculate the traffic

capacity by theoretical methods because of the dynamic disturbance of the moving buses, whereas it is a better method to use CA simulation to evaluate the traffic capacity of the road section. Figure 9 presents the car traffic flow of the experimental link in each case. The maximum car traffic flow in each case can be regarded as the traffic capacity of the road section under each lane operation strategy. It is obvious that the lane operation strategy in Case C can effectively improve the traffic capacity of the road section compared with the other cases.

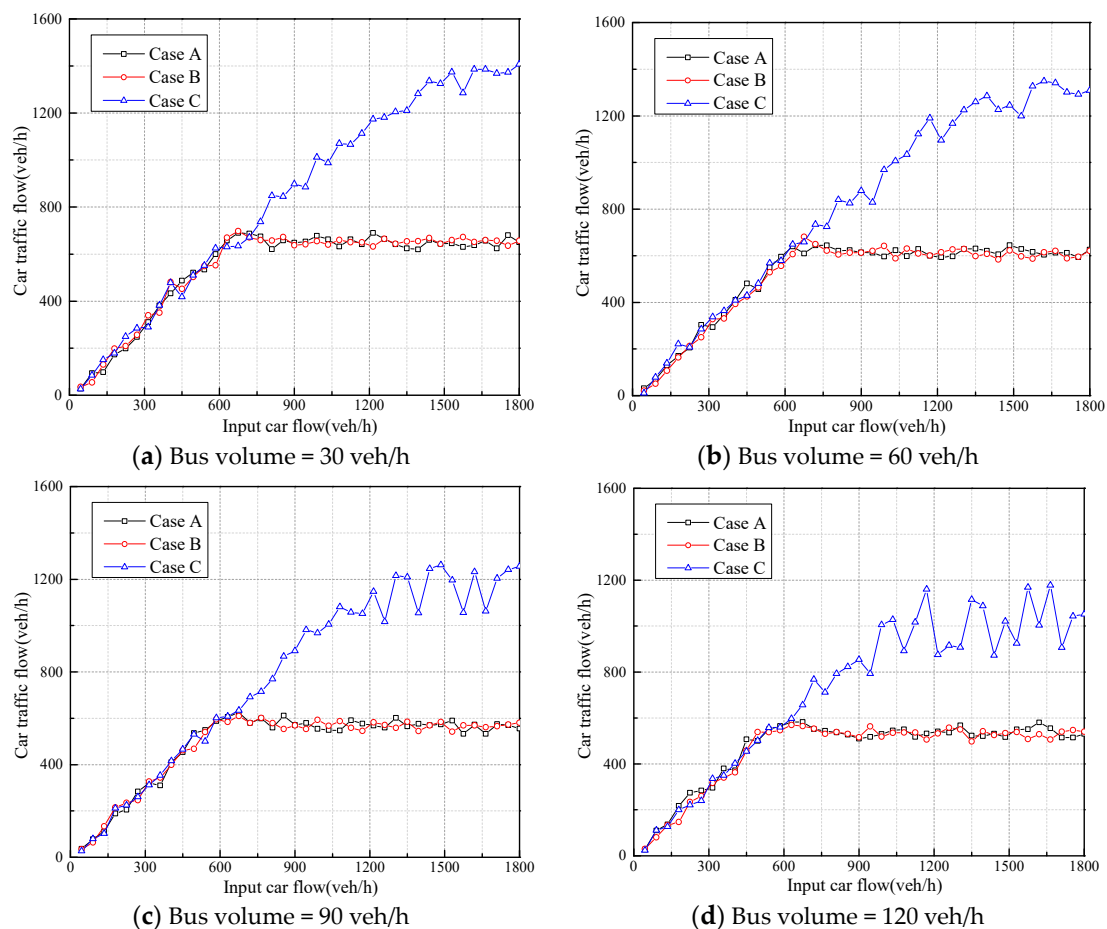


Figure 9. Car traffic flow of the experimental link in each case.

When the input car flow is less than 600 veh/h, the change trend of traffic flow in the three cases is almost the same, and the car traffic flow increases steadily with the increase of the input car flow. When the input car flow reaches 600 veh/h, the traffic flow of the experimental link in Case A and Case B reaches the peak, and as the input car flow continues to increase, it remains at a stable value, which means that the traffic flow of the experimental link in Case A and Case B is saturated at this time. It can be found that the magnitude of the saturated traffic flow in Case A and Case B is almost the same, which can be ascribed to the fact that the traffic capacity of the experimental link in this simulation environment mainly depends on the traffic capacity of the downstream intersection approach. Due to the setting of the conventional intersection approach in Case B, the traffic capacity of the experimental link in Case B is not improved compared with Case A. In contrast, the saturated traffic flow in Case C is significantly increased, which indicates that the setting of IBA can effectively improve the traffic efficiency of the intersection, and then improve the traffic capacity of the road section. Table 4 summarizes the traffic capacity of the experimental link in each case at different bus volume, and it is clear that the traffic capacity of the experimental link in Case C is the highest. In addition,

as the bus volume increases, it is found that the traffic capacity of the experimental link in each case shows a decreasing trend, which can be ascribed to the slow-moving bottleneck effect of buses.

Table 4. Traffic capacity of the experimental link in each case at different bus volume (veh/h).

	Bus Volume = 30 veh/h	Bus Volume = 60 veh/h	Bus Volume = 90 veh/h	Bus Volume = 120 veh/h
Case A	689.4	645.0	625.2	582.6
Case B	697.8	681.0	609.0	568.8
Case C	1407.0	1348.8	1261.8	1177.8

Similarly, as the bus volume increases, it can also be observed that the fluctuation of the car traffic flow in Case C becomes more and more significant in the high-flow traffic environment. This can be ascribed to the frequent opening and closing of dynamic lanes, which will lead to the instability of road traffic flow. It is actually an unsatisfactory traffic state and needs to be avoided, which also confirms that when the bus volume is high, the DBL strategy is a better lane operation scheme.

In conclusion, there is no doubt that the lane multiplexing strategy can provide bus priority while improving the traffic situation of the experimental link under certain circumstances. However, when the traffic flow of both buses and cars is high, the vehicle delays caused by the conventional intersection approach will lead to the failure of the bus priority strategy. The aforementioned limitation can be effectively compensated by adopting the proposed IBA setting method. It can maintain the continuity of vehicle running between the lane and the intersection approach in the road section, and better exert the overall operational benefits of dynamic bus lanes. Note that our work in the current paper concentrates on studying the lane operation strategies on a two-lane road section. Based on the work by Muñoz and Daganzo [43], the effect of a single-lane restriction is less noticeable in wider roadways, so it can be considered that the benefits of the lane multiplexing strategy would be more remarkable when there are three or more lanes in the road section.

5. Conclusions

IBLs can effectively develop the relatively surplus road resources in DBLs under bus priority. However, existing IBL strategies mainly focus on the traffic operation of the bus lane and the intersection signal setting in the road section, neglecting the connection between the approach of the downstream intersection and the bus lane in the road section, which leads to the still serious delay of buses at intersections in traffic congestion environments. To this end, the authors proposed a novel method of setting IBAs based on lane multiplexing for alleviating the contradiction between lane utilization rate and bus priority at intersections. Based on the operation mechanism of the bus lane with time-division multiplexing, a time slice division strategy for the intersection space slice of the BLTDM road section has been developed, and an intersection signal cooperation model based on time slice division has been established. To ensure that cars can smoothly merge into the bus lane, the optimal modeling of the length of the merging section in the IBA lane system is carried out. The CA is used to build microscopic traffic simulation environments. Specifically, three cases of CA two-lane traffic model under different lane operation strategies were designed for comparison experiments. By comparing the traffic flow characteristics in the three cases, the operation effects of lane operation strategies were evaluated. The following findings were made.

- (a) There is no need to implement the IBA strategy at urban intersections with low traffic flow because the cars in the road section could achieve the desired velocity in free traffic flow. For a traffic environment with high bus operation frequency, the DBL strategy is a recommended choice to ensure bus priority at intersections.

- (b) The IBA can give bus priority at intersections to maintain the continuity of bus running between the lane and the intersection approach in the road section, where the operational benefits of the overall bus lane in the road section can be better brought into play.
- (c) The setting of IBA can alleviate the contradiction between lane utilization rate and bus priority at intersections, effectively improve the traffic efficiency of intersections, and then improve the traffic capacity of the road section.

There is still much work to be done before real implementation of the IBA begins. For example, the influence of bus stops has not been considered in our simulations, which is still possible to be analyzed using our method if the models are slightly improved. More extensive simulation numerical experiments need to be conducted to assess the effectiveness of the proposed strategy under different patterns of bus stops, passenger volumes, and a probability of private drivers who obey lane operating indications. The quantitative range of applicable traffic conditions for IBA is also worth exploring. As a hot research topic on bus priority and lane management, this study provides a new insight into the setting of dynamic bus lanes at intersections, which has important implications for promoting public transportation as a viable option to alleviate urban traffic congestion. In the near future, we would like to further investigate the operation of the IBA strategy in a connected-vehicle (CV) environment, and to explore the sensitivity of bus delay and traffic capacity to CV penetration. Additionally, we are planning to conduct a field trial of the IBA lane system to better understand its feasibility in a real-world setting.

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