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Research Article

Modelling Method on Dynamic Optimal Setting and Associated Control for Intermittent Bus Lane

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A new type of dynamic bus lane not only ensures the strategy of bus priority but also significantly improves the spatiotemporal utilization of road resources and reduces the conflicting demands of buses and social vehicles on road resources. Firstly, the heterogeneity of bus arrival time is analysed according to the process of aggregation and dissipation of vehicle queues at intersections. Considering the correlation between the operating states of social vehicles and buses, a dynamic control strategy for bus lane based on the insertable interval of social vehicles is established. Secondly, combining the setting conditions of the intermittent bus lane control area with the correlation scenario of signal control at intersections and then according to the HCM 2010 vehicle delay equation and the BPR function, the associated optimized control model with the minimum total travel time consumption of the road section as the objective function is constructed. The global optimal control of the intermittent bus lane is realized through the computational experiment. Finally, the setting conditions and benefits of three lane organization schemes (including intersect (i.e., no bus priority), parallel, and intermittent bus lanes) are compared and analysed through case study. The results indicate that the intermittent priority bus lanes have opening hours, which can not only ensure bus priority but also expand the right way for social vehicles and make full use of road space resources, thus improving the overall traffic efficiency.

1. Introduction

With the increasing shortage of urban road resources and the imbalance of traffic supply and demand, the exclusive bus lanes are used as a common method of bus priority control. However, their periodical idleness will cause a waste of lane level space resources, which hinders the promotion of bus priority concept. As a result, the concept of intermittent bus lane (IBL) has emerged with the times, which can effectively balance the interaction between the operational efficiency of social vehicles on buses and lane resources, thus improving the bus service level.

In recent years, the setting of exclusive bus lanes is of great significance to improve the operational efficiency of public transport. However, the setting of exclusive bus lanes has not achieved the expected effect. In order to improve the efficiency of bus priority and the utilization of road resources, Viegas and Lu presented the concept of an intermittent bus lane (IBL) in the traffic control system, with the goal of providing public transport with access equivalent to permanent bus lanes, but the system only adjusts the signal timing to satisfy bus priority, buses and social vehicles must still mix. This will not only have an impact on the development of public transport concept but also lead to a shortening of the green time in the nonpriority phases while giving the priority signal phases to public transport. The expected social benefits may not be achieved when the nonpriority phase has a high volume of social flow [1]. IBL has been widely applied in many cities. IBL has attracted extensive attention and also achieved fruitful results, mainly including traditional and intermittent bus lanes.

For traditional bus lane control, bus priority (BP) methods, as one of the most widely used public transport priority (PTP) strategies, are commonly recognized as effective in lowering traffic congestion and reducing bus travel times [2]. For the setting and implementation of bus lanes, Xie et al. put forward a control system of intermittent bus-only approach and its control method to get traffic flow conditions [3]. Christoffel et al. provided an analysis on the equity impacts of operational bus rapid transit (BRT) systems [4]. Chiabaut and Barcet proposed a general traffic lane that can be intermittently converted to an exclusive bus lane to evaluate the impacts on the bus system performance [5]. Basso et al. proposed a dynamic congestion approach that endogenously models queuing both on the road and at BRT stations [6]. Dong et al. established a three-lane cellular automaton vehicle lane-changing model by optimizing car-following rules and lane-changing rules for DBL and IBL [7]. Huang et al. proposed a multistage stochastic programming model based on the uncertainty of passenger demand [8]. Zheng and Zhang established an intermittent bus lane control model based on cellular automata to prevent blocking of right-turning vehicles [9]. Sun et al. optimized a bus at an intersection with a left-turn special phase by “tandem design” [10]. Kampouri et al. modelled various scenarios to determine the level of traffic volumes and bus service frequencies for which such bus lane concept would be effective [11]. In terms of economic efficiency, Basso et al. analysed three strategies for reducing traffic congestion from an economic perspective; it was found that bus lanes are a better standalone policy than transit subsidization or congestion pricing [12]. Liang et al. established a bus delay model based on the shockwave theory by analysis of the interaction influence between bus stop and traffic flow [13]. Wu et al. proposed an evaluation index that reflects the performance of bus lane and the passengers’ interests. Finally, the impact of the length of road-side bus lane on bus operation reliability was analysed [14]. Zhao et al. examined the various factors on the utilization rate of park and ride (PnR) lots with bus [15]. Wu et al. established a biobjective integer linear programming model to solve a complex combinatorial optimization problem with bus line planning and lane reservation [16].

In summary, many studies have made great progress in the physical conditions of IBLs. However, the interaction between bus operating characteristics (including arrival distribution patterns, queuing aggregation and dissipation, bus flow, density, and speed and bus entering/leaving intersection differential variations) during different time periods within a cycle and different traffic states (including undersaturation, near saturated state, and oversaturated state) is not taken into account when delineating the control areas. And there is still a lack of research on optimal control methods for IBLs based on parallel system.

As a novel and promising bus priority strategy, the intermittent bus lane is still in the primary stage of development. In terms of signal correlation control, Chang et al. analysed the general traffic delay at intersection quantitatively after performing the optimized system [17]. Ilgin Guler et al. explores a novel method to provide priority to buses at signalized intersections with single-lane approaches that (nearly) eliminates bus delays while minimizing the negative impacts imparted to cars [18]. Yang et al. presented a predetective signal priority strategy for BRT with coordination between primary and secondary intersections [19]. Wu put forward the capacity reduction mechanism of intermittent priority bus lanes through vehicle collisions [20]. Zhao and Zhou presented a dynamic exclusive bus lane (DBL) design, in which the exclusive bus lane at the exit can be dynamically used for the left turn buses and the opposing through buses during the various periods of a signal cycle [21]. Zhao et al. developed a mathematical model for exclusive bus lane network design with operational dynamics at intersections explicitly captured [22]. Ma et al. provided the control strategies of the BRT lane spatially and temporally [23]. Song et al. proposed the determination method of dynamic lane clear distance and lane control flow based on the dissipation process of queue at intersection [24]. Rocha et al. integrated a novel metric for measuring clustering quality to the omit-one-variable-out-at-a-time selection procedure [25]. Mathew et al. presented travel time reliability-based approach to assess the effect of the light rail transit (LRT) system on the road network within its vicinity [26]. Dong et al. proposed a dynamic time slice policy for the time division multiplexing (TDM) method to share dedicated bus lanes [27]. Bayrak et al. proposed a bilevel optimization algorithm to determine dedicated bus lane locations on a network to reduce the total travel time of all network users while considering traffic dynamics [28]. Dong et al. presented a new improved management strategy for tram lanes with intermittent priority (TLIP) based on the clear distance and no-entrance distance metrics [29]. Lin et al. proposed a method to determine the capability of IBL permitted for regular vehicles [30]. Xu et al. proposed a novel max-pressure signal control that considers transit signal priority of bus rapid transit systems to achieve both maximum stability for private vehicles and reliable transit service [31]. Yang et al. proposed a new deep learning model named TmS-GCN to predict region-level traffic information, which is composed of graph convolutional network (GCN) and gated recurrent unit (GRU) [32]. In terms of IBL simulation, Wu et al. developed a mandatory IBL lane-changing rule to analyse special asymmetric lane-changing behaviors based on a three-lane CA model under opening boundary condition [33]. Wu et al. investigated some critical operating parameters for implementing bus lane with intermittent and dynamic priority system [33]. Wang et al. proposed resilient observer-based nonlinear control based on the triple-step approach [34]. Liu et al. formulated a system-optimal dynamic traffic assignment (SO-DTA) problem with car-exclusive lane segments [35]. Othman et al. enabled a new priority strategy by vehicle connectivity and provided bus priority while allowing the general traffic to access the bus lane when buses are not present [36]. Wu et al. developed a two-lane cellular automation (CA) model to simulate bus lanes with intermittent priority [37]. Ou et al. proposed a mixed-integer linear programming model to optimize the scheduling of bus arrivals and the bus-berth matching at a curbside stop [38].

In summary, IBLs are not universally applicable and can only be effective within a certain setting range, so how to determine the quantified interval is a problem that needs to be solved. The key to analyse the lane setting conditions is to determine the critical traffic conditions for setting and then obtain the quantified interval for setting. However, there are few studies on the setting conditions and critical traffic conditions for intermittent bus lanes.

As an innovative lane management mode, the practicality and feasibility of dynamic bus lanes have been proven in many studies and will become an important approach to lane management. However, with the development in the construction and operation of bus lanes, there is growing concern about the under-utilisation of road resources in bus lanes, and some of the current research is addressing the above issues using traffic flow simulation models. There are several deficiencies in the existing studies as follows:

(1) As a novel and promising bus priority strategy, IBLs are still in the preliminary stage of development. Trial applications have been carried out in Lisbon (Portugal), Melbourne (Australia), and Lyon (France), among others [5, 39, 40]. The results show that the system performs very differently on different road sections and in traffic situations. Complex systems are complex because of the inability to perform reductive and experimental analyses. The inability to perform reductive analysis is the essential difficulty faced by complex systems, while the inability to perform experimental analysis is the means difficulty or instrumental difficulty faced by them. Public transport system is an open and complex giant system with randomness, dynamics, fuzziness, and self-adaptability, including vehicles, roads, and traffic environment. Research in the field of public transport systems such as IBL control also faces the abovementioned difficulties that exist in complex systems. The concept of "computational experiment" provides a new and effective approach to overcome these difficulties. There are few studies on establishing a computational experiment execution mode for IBL in parallel systems and evaluating and interpreting the results of computational experiments.

(2) The study of clearing distance is mainly based on continuous input of updated traffic states and road conditions. The physical setting conditions are analysed by simulation output effects with the average vehicle delay as the index, which lacks the necessary theoretical basis. As the bus departure interval and arrival time at the intersection change, the queue length at the downstream intersection also changes, resulting in different clearing distances. Therefore, the analysis of clearing distance by simulation method has a certain deviation from the actual situation.

(3) Most research studies rarely consider the dynamic control of bus lanes where social vehicles can be inserted under the background of the actual traffic flow. Due to the different operating characteristics of buses, it is easy to form mutual influence between buses and social vehicles. While ensuring bus priority and providing resource utilization of lane level, there are few studies on reducing the related impact of social vehicles on the operational efficiency of buses.

In order to overcome the abovementioned problems, different from the previous studies, the contribution of this paper lies in proposing a modelling method for dynamic optimal setting and associated control for intermittent bus lanes. The heterogeneity of bus arrival time is analysed based on the process of aggregation and dissipation of vehicle queues at intersections. A dynamic control strategy for bus lanes based on the insertable interval of social vehicles is established. Then, a correlated optimal control model with the minimum total travel time consumption of the road section as the objective function is constructed according to the HCM 2010 vehicle delay equation and the BPR function. Finally, in order to analyse and evaluate the operating characteristics and control results under the proposed method, the computational experiments can solve the optimal control model of intermittent bus lanes.

The rest of this study is organized as follows: Section 2 presents the dynamic control strategy of bus lane based on social vehicle insertable interval. In Section 3, the dynamic associated control model of intermittent bus lane is presented. Section 4 shows the model solving algorithm based on computational experiment. Section 5 presents a case study. In Section 6, the conclusions are given at the end of the paper.

2. The Dynamic Control Strategy of Bus Lane Based on Social Vehicle Insertable Interval

The intermittent bus lane is a means of dynamically allocating road resources. The main idea is that when there are no buses in the bus lane, the bus lane is open to social vehicles, which can use the bus lane. When the bus reaches the control area, the road section in front of the bus is closed to social vehicles to achieve bus priority. The road section behind the bus is closed to social vehicles because it does not cause delay and interference to the bus. Social vehicles can still use the bus lane.

As shown in Figure 1, in a scenario where the intermittent bus lane control area is associated with the intersection signal, the time when the bus enters the control area and the signal timing state when the vehicle arrives at the intersection can be obtained. At this time, the road section ahead of the bus does not need to be completely closed to social vehicles, but to ensure that the entering social vehicles can pass through the intersection in time without affecting the bus operation. This adjustment allows the use of road resources to be further allocated to improve the overall utilization of the road.

The main concept of the intermittent bus lane is that when there are no buses in the bus lane, the bus lane is open to social vehicles. When a bus arrives, the road section in front of the bus is closed to social vehicles to give priority to

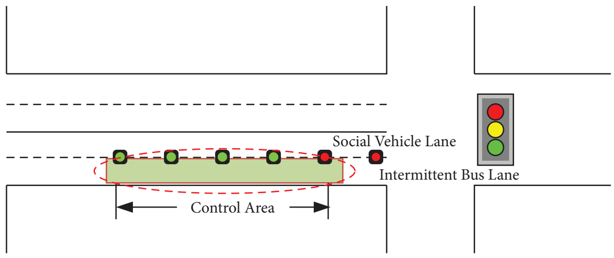


FIGURE 1: The schematic diagram of intermittent bus lane control scenario.

the bus. The road section behind the bus allows social vehicles to continue using the bus lane as they do not cause delays to the bus. Intermittent bus lane is mainly through the inter-road amber flashing lights, variable message signs (VMS), and clearing distance settings to ensure the rapid passage of buses. The structure of its facilities is shown in Figure 2, where D and F are the vehicle detectors near the intersection and E is the end of the clearing distance.

The length of the clearing distance has a significant impact on the utilization of dynamic bus lanes. Whether or not social vehicles entering the bus lane interfere with bus operations depends primarily on the queue length of the social vehicle, i.e., the interval at which social vehicles can be inserted. If the queue length is too short, the unused space on the carriageway is greater. When the bus lane is open to social vehicles for a shorter time, the overall utilization of the lane is not high. If the queue length is too long, the arrival time of the buses at the intersection is less than the dissipation time of the queue of social vehicles ahead, causing delays to the buses and preventing bus priority from being achieved. The symbols of the variables are described in Table 1.

Basic relationships are calculated as follows:

$$\begin{aligned}
\ell_1 &= \frac{Q_1}{v_1},\\
\ell_2 &= \kappa \cdot \ell_1,\\
Q_2 &= \xi \cdot t,\\
\omega_2^1 &= \frac{0 - Q_2}{\ell_j - \ell_2},\\
\omega_2^2 &= \frac{Q_m - 0}{\ell_m - \ell_j},\\
l_x &= \frac{l_1 \cdot Q_2}{Q_1},\\
v_2 &= \frac{Q_2}{\ell_2} = \frac{\xi \cdot t}{\kappa \cdot \ell_1}.
\end{aligned} \tag{1}$$

The red light for the direction of bus operation at the intersection is set to start at time zero, at which point the lane indicator turns green to allow social vehicles to enter the bus lane. The aggregation and dissipation of social vehicles in the direction of bus operation are shown in Figure 3.

Basic constraints are described as follows:

$$\begin{aligned}
t &< P_1,\\
l_x &< d,\\
d + l &= S,\\
l_x &= \omega_2^2 \cdot T_R = \omega_2^1 \cdot t.
\end{aligned} \tag{2}$$

Combining the abovementioned equations gives

$$\begin{aligned}
t &< \min\left(\frac{S-l}{\omega_2^1}, r\right),\\
l_x &< S - l.
\end{aligned} \tag{3}$$

The queue length depends on duration of green light on lane indicator and average number of vehicles able to change lanes per unit time. Thus, the core relationship is calculated as follows:

$$l_x = \frac{l_1 \cdot \xi \cdot t}{Q_1}. \tag{4}$$

Therefore, the analysis of the insertion intervals of social vehicles translates into the problem of determining the duration of the green light for social vehicle indicators. In order to simplify the calculation, let $\xi = 1$. According to the intervals between buses' arrivals in the control area can be divided into single bus arrivals and multiple bus arrivals.

2.1. Single Bus Arrival

2.1. Single Bus Arrival. When only a single bus enters the control area, there are no other vehicles in front of or behind the bus. Social vehicles can be allowed to enter the bus lane. The time when the bus enters the control area is defined as t_n. When the bus enters the control area, there is t_e time before the current green light ends. Then, t is calculated by the following equation:

$$t = \begin{cases} 0, & t_n \in \left(t_{i,1}, t_{i,2}\right), t_e - g > t_s \\ t_r + t_e, & t_n \in \left(t_{i,1}, t_{i,2}\right), t_e - g \le t_s \\ t_s + t_e, & t_n \in \left(t_{i,2}, t_{i,2} + g\right), \end{cases} \tag{5}$$

where t_r determined taking into account the constraints of vehicle aggregation and dissipation conditions and spatial queue length, as calculated by the following equation:

$$s.t. \begin{cases} w_2 \cdot t_1 + \dfrac{s}{t_s} \cdot \left[t_1 + t_s - \left(t_e - g\right)\right] = s, \\ w_2 \cdot t_1 = t_r, \end{cases} \tag{6}$$

where w_2 is the dissipated wave speed of the vehicle.

2.2. Multiple Bus Arrival. Two consecutive buses A and B are taken as an example. Let bus A enter the control area S during the red light of cycle i. The time at which bus A enters the control area is t_A. The time at which bus A enters the control area S is t_a before the end of the green light of cycle i. The time at which bus B enters the control zone is t_B. The time at which bus B enters the control area S is t_b before the

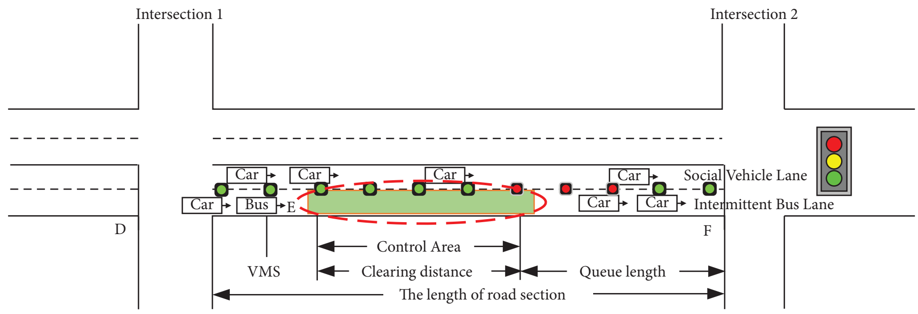


Figure 2: The intermittent bus lane structure diagram.

Table 1: The symbols of the variables.

Symbols	Description
d	Maximum length of bus lane where social vehicles can enter
t	Duration of green light on lane indicator
v_1	Speed of social vehicles in social lane
v_2	Speed of social vehicles after lane change in bus lane
l	The average headway of vehicles
l_1	Queue length for social vehicles in social lane
Q_1	Flow of social vehicles in a social lane
ℓ_1	Density of social vehicles on social lanes
ℓ_2	Density of social vehicles in bus lanes
κ	Density proportionality factor
ω_2^1	Aggregated wave speed of social vehicles in a bus lane
ω_2^2	Dissipated wave speed of social vehicles in a bus lane
ξ	Number of vehicles able to change lane per unit time
Q_2	Flow of social vehicles in a bus lane
ℓ_j	Density of jam traffic flow in a bus lane
Q_m	Average saturation flow in a bus lane
ℓ_m	Average density of saturated flow in a bus lane
l_x	Queue length of social vehicles in bus lanes
S	The length of control area
r	The red-light time at the intersection
g	The green-light time at the intersection
$t_{i,1}$	The start time of the red light for cycle i
$t_{i,2}$	The end time of the red light for cycle i
t_s	The time for the bus to pass through the control area

end of the green light of cycle i. The time difference between the two buses AB entering the control area S is t_c.

When buses A and B are travelling at normal speed on the road section, the operation of bus B is not affected by the vehicles in front of it. The queuing of vehicles only occurs when bus A or the social vehicles following it encounter a red light at the downstream intersection. Therefore, in order to ensure that bus B is not affected by the state of the vehicle in front of it during its operation on the road section, it is necessary to ensure that the clearing road section in front of bus B can accommodate the queuing impact of bus A. On this basis, the opening time of lane indicator light is analysed as follows:

Step 1: determine the combination situations of front and rear vehicle states.

The AB buses are analysed to determine whether it is possible to pass through the intersection without stopping. Six combinations of the states of two buses could be identified, as shown in Table 2.

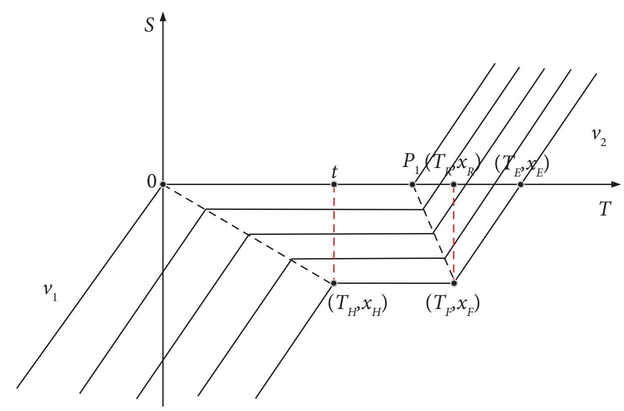


Figure 3: The aggregation and dissipation of social vehicles in the direction of bus operation.

Step 2: determine the green light opening time of the lane indicator for each combination.

According to the combination situations, the operating state of AB buses is analysed to determine the green light opening time of the lane indicator; there are several steps as follows:

Step 2.1: AB buses arrive at the intersection successively during the green light period in cycle i without stopping to pass.

$$\begin{aligned} t &= t_{k1} + t_{k2} + t_b t_A \in \left(t_{i,1}, t_{i,2}\right), t_a - g \leq t_s \\ t_A&, t_B \in \left(t_{i,2}, t_{i,2} + g\right), \end{aligned} \quad (7)$$

where t_{k1} is the green light time of the lane indicator that can be opened in front of bus A. t_{k2} is the green light time of the lane indicator that can be opened between AB buses. T_{k1} and t_{k2} are determined by equations (8) and (9), respectively.

$$f^1(t) = \begin{cases} w_2 \cdot t_1 + \dfrac{s}{t_s} \cdot \left[t_1 + t_s - \left(t_a - g\right)\right] = s, \\ w_2 \cdot t_1 = t_{k1}, \end{cases} \quad (8)$$

$$t_{k2} = \begin{cases} 0, & t_c \leq l, \\ t_c, & t_c > l. \end{cases} \quad (9)$$

Table 2: Bus arrival at the intersection.

Combination situations	Bus A (front)	Bus B (rear)	Whether passing the intersection in the same cycle
1	Pass through the intersection without stopping	Pass through the intersection without stopping	Yes
2	Pass through the intersection without stopping	Pass through the intersection without stopping	No
3	Pass through the intersection without stopping	Waiting in queue	No
4	Wait in queue	Pass through the intersection without stopping	Yes
5	Wait in queue	Pass through the intersection without stopping	No
6	Wait in queue	Wait in queue	Yes

Step 2.2: AB buses arrive at the intersection during the green light period of two consecutive cycles i and i+1 and pass through without stopping.

$$t = t_{k1} + t_a + t_{k3}, \quad t_A \in \left(t_{i,1}, t_{i,2}\right), t_a - g \le t_s, \tag{10}$$

where t_{k3} is the opening time of the lane indicator after the end of green light during cycle i, which is determined by the following equation:

$$t_{k3} = \begin{cases} t_{k4} + t_b, & t_B \in \left(t_{i+1,2}, t_{i+1,2} + g\right), \\ t_b, & t_B \in \left(t_{i+1,1}, t_{i+1,2}\right), t_b - g \ge t_s, \\ t_{k5} + t_b, & t_B \in \left(t_{i+1,1}, t_{i+1,2}\right), t_b - g \ge t_s, \end{cases} \tag{11}$$

where t_{k4} and t_{k5} are the green light time of lane indicator that can be opened before cycle $i+1$ for bus B, which are determined by equations (12) and (13), respectively.

$$f^2(t) = \begin{cases} w_2 \cdot t_2 + \dfrac{s}{t_s} \cdot \left(t_2 + g - t_b\right) = s, \\ w_2 \cdot t_2 = t_{k4}, \end{cases} \tag{12}$$

$$f^3(t) = \begin{cases} w_2 \cdot t_3 + \dfrac{s}{t_s} \cdot \left[t_3 + t_s - \left(t_b - g\right)\right] = s, \\ w_2 \cdot t_3 = t_{k5}. \end{cases} \tag{13}$$

Step 2.3: bus A arrives at the intersection within the green light period of cycle i and passes through without stopping. Bus B stops and waits for the green light of cycle $i+1$ turns on and then passes.

$$t = \begin{cases} t_{k1} + t_c + g, & t_A \in \left(t_{i+1,1}, t_{i+1,2}\right), t_a \ge t_c, \\ t_{k1} + t_a + g, & t_A \in \left(t_{i+1,1}, t_{i+1,2}\right), t_a < t_c. \end{cases} \tag{14}$$

Step 2.4: bus A stops and waits for the green light of cycle i turns on and then passes the intersection. Bus B arrives at the intersection during the green light period in cycle i and passes without stopping.

$$t = g - \left(t_b - t_s\right), \quad t_a \ge t_c. \tag{15}$$

Step 2.5: bus A stops and waits until the green light of cycle i turns on and then passes through the intersection. Bus B arrives at the intersection during the green light period in cycle i + 1 and passes through without stopping.

$$t = \begin{cases} g + t_{k4} + t, & t_B \in \left(t_{i+1,2}, t_{i+1,2} + g\right), \\ g + t_b, & t_B \in \left(t_{i+1,1}, t_{i+1,2}\right). \end{cases} \tag{16}$$

Step 2.6: AB buses stop and wait for green light of cycle i turns on and then passes through the intersection.

$$t = g, \quad t_a \ge t_c. \tag{17}$$

3. Dynamic Associated Control Model of Intermittent Bus Lane

3.1. Calculation of Total Travel Time Consumption under Dynamic Setting Conditions of Intermittent Bus Lane. In the case of dynamic intermittent bus setting, the bus delay is minimized by the bus lane dynamic control strategy based on the insertable interval of the social vehicle, thus ensuring that the buses will not be delayed. Therefore, the total travel time consumption (including travel time and intersection delay) is a direct basic parameter that reflects the traffic efficiency of a road section. Considering the impact of social vehicles on the operating state buses, the travel time and intersection delay of a road section are calculated based on HCM2010 delay equation and BPR function [24].

$$t_0 = T_0\left[e^0 + \alpha\beta e^{\left(\frac{\Delta q_{\text{bus}}}{c}\right)}\right], \tag{18}$$

$$\begin{aligned} t_{\text{delay}} = {} & \frac{C(1-\lambda)^2}{2[1 - \min(1,x)\lambda]} \\ & + 900t\left[(x-1) + \sqrt{\frac{(x-1)^2 + 8k \cdot Ix}{c_{\text{lane}} \cdot t}}\right], \end{aligned} \tag{19}$$

where t_0 represents the travel time of free flow through the road section. α and β represent the road resistance coefficient, which is calibrated from the measured traffic flow data of the road section. Δq_{bus} is the variation of bus flow in the road section. c refers to road capacity. T_0 represents the travel time of the free flow through the road section for that type of vehicle. T_{delay} refers to the average signal control delay per vehicle. C is the cycle length. λ indicates the calculated green signal ratio of the lane at which it is located. x is the lane saturation. c_{lane} refers to the traffic capacity of the lane. t represents the duration of the analysis setting method. k refers to incremental delay of signal control. I is the correction factor for incremental delays such as vehicle lane change and signal regulation.

In order to obtain the critical value for the dynamic setting of intermittent bus lanes, an intermittent bus associated optimization control model is established with the objective function of minimising the total travel time consumption of the road section, taking into account traffic efficiency and constraints under different combinations of setting methods such as intersect (i.e., no bus priority), parallel, and intermittent bus lanes.

Step 1: The bus lane intersects (i.e., no bus priority) setting condition.

Under these conditions, the operating states of the vehicles are influenced by the overall traffic flow on the road. Different from social vehicles, the delay time of the bus is calculated by taking into account delays at bus stops, so that social vehicle and bus travel times are calculated according to equations (20) and (21), respectively.

$$t_{\text{vehicle}}^{1} = t_{0}^{\text{vehicle}}\left[e^{0} + \alpha_{\text{vehicle}}\beta_{\text{vehicle}}e^{\left(\frac{\Delta q_{\text{vehicle}} + \mu\Delta q_{\text{bus}}}{c}\right)}\right], \tag{20}$$

$$t_{\text{bus}}^{1} = t_{0}^{\text{bus}}\left[e^{0} + \alpha_{\text{bus}}\beta_{\text{bus}}e^{\left(\frac{\Delta q_{\text{vehicle}} + \mu\Delta q_{\text{bus}}}{c}\right)}\right], \tag{21}$$

where t_{vehicle}^{1} and t_{bus}^{1} represent the travel times of social vehicles and buses under the setting method of intermittent bus lane intersect, respectively. t_{0}^{vehicle} and t_{0}^{bus} represent the free flow time of social vehicles and buses, respectively. $\Delta q_{\text{vehicle}}$ indicates the variation of social traffic flow on the road section. μ represents the conversion coefficient of bus and social vehicles, which refer to the Traffic Engineering Handbook for passenger car equivalent on road section taken as 1.5 [41]. α_{vehicle}, β_{vehicle}, α_{bus}, and β_{bus}, respectively, represent the calibration coefficients for the operation of social vehicles and buses in the road section are to be calibrated by the measured traffic data of the road section.

The intersection delay time is calculated as follows:

Set

$$a_{1} = \min\left(1, x_{\text{vehicle}}, x_{\text{bus}}\right), \tag{22}$$

$$a_{2} = \max\left(x_{\text{vehicle}}, x_{\text{bus}}\right). \tag{23}$$

Substituting equations (22) and (23) into (19), the result is obtained as follows:

$$t_{\text{de lay}}^{1} = \frac{C(1-\lambda)^{2}}{2\left[1 - a_{1}\lambda\right]} + 900t\left\{\left[a_{2} - 1\right] + \sqrt{\frac{a_{2}^{2} + 8k\cdot I\cdot a_{2}}{c_{\text{lane}}\cdot t}}\right\}. \tag{24}$$

Step 2: The bus lane parallel setting condition.

In bus lane environment, social vehicles and buses travel in their own lanes, with each other's lanes functioning independently. The travel times for social vehicles and buses are calculated as follows:

$$\begin{aligned} t_{\text{vehicle}}^{2} &= t_{0}^{\text{vehicle}}\left[e^{0} + \alpha_{\text{vehicle}}\beta_{\text{vehicle}}e^{\left(\frac{\Delta q_{\text{vehicle}}}{c_{n_a}^{\text{vehicle}}}\right)}\right],\\ t_{\text{bus}}^{2} &= t_{0}^{\text{bus}}\left[e^{0} + \alpha_{\text{bus}}\beta_{\text{bus}}e^{\left(\frac{\mu\Delta q_{\text{bus}}}{c_{n_b}^{\text{bus}}}\right)}\right], \end{aligned} \tag{25}$$

where t_{vehicle}^{2} and t_{bus}^{2} represent the travel time for social vehicles and buses in the parallel setting condition, respectively. $c_{n_a}^{\text{vehicle}}$ and $c_{n_b}^{\text{bus}}$ represent the capacity of ordinary lane ($n_a \geq 1$) and bus lane ($n_b \geq 1$) in the road section, respectively. n_a and n_b represent the number of ordinary lane and bus lane in the road section, respectively.

The intersection delay time is calculated as follows:

$$t_{\text{de lay}}^{2} = \frac{C(1-\lambda)^{2}}{2\left[1 - \min\left(1, x_{\text{bus}}\right)\lambda\right]} + 900t\left[\left(x_{\text{bus}} - 1\right) + \sqrt{\frac{\left(x_{\text{bus}} - 1\right)^{2} + 8k\cdot Ix_{\text{bus}}}{c_{\text{lane}}\cdot t}}\right]. \tag{26}$$

Step 3: The intermittent bus lane setting condition.

The intermittent bus lane proposed in this paper not only ensures that buses have exclusive right of way but also allows social vehicles to occupy the bus lane for mixed traffic under the dynamic setting condition. For buses, there is no delay as social vehicles are guaranteed based on the dynamic setting of the bus lane state without affecting the normal operation of the bus. For social vehicles, they occupy part of the bus lane resources in addition to the original normal lane. Therefore, the resource occupancy factor R is defined as the proportion of space resources occupied by social vehicles in the bus lane per unit of time. And then, the travel times of social vehicles and buses are calculated as follows:

$$\begin{aligned} t_{\text{vehicle}}^{3} &= t_{0}^{\text{vehicle}}\left[e^{0} + \alpha_{\text{vehicle}}\beta_{\text{vehicle}}e^{\left(\Delta q_{\text{vehicle}}/c_{n_a}^{\text{vehicle}} + \delta\cdot R\cdot c_{n_b}^{\text{bus}}\right)}\right],\\ t_{\text{bus}}^{3} = t_{\text{bus}}^{2} &= t_{0}^{\text{bus}}\left[e^{0} + \alpha_{\text{bus}}\beta_{\text{bus}}e^{\left(\mu\Delta q_{\text{bus}}/c_{n_b}^{\text{bus}}\right)}\right], \end{aligned} \tag{27}$$

where t_{vehicle}^{3} and t_{bus}^{3} represent the travel time of social vehicles and buses, respectively, under the setting condition of the intermittent bus lane. δ refers to the attenuation coefficient of lane capacity resources during the switching of the open state of the intermittent bus lane.

The travel times and intersection delays of social vehicles under the dynamic setting factor of the intermittent bus lane, including the saturation of social lanes (defined as $x_{vehicle}$) and intermittent bus lanes (defined as x_{bus}), are calculated as follows:

$$\begin{aligned} x_{\text{vehicle}} &= \frac{\Delta q_{\text{vehicle}} - \Delta q_{\text{vehicle}}\cdot t_{s}^{\text{catt}}/n_{\text{vehicle}}/n_{\text{vehicle}} + n_{\text{bus}}\cdot t^{\text{patt}}}{n_{\text{lane}}\cdot c_{\text{lane}}},\\ x_{\text{bus}} &= \frac{\Delta q_{\text{bus}} + \Delta q_{\text{bus}}\cdot t_{s}^{\text{catt}}/n_{\text{vehicle}}/n_{\text{vehicle}} + n_{\text{bus}}\cdot t^{\text{patt}}}{n_{\text{lane}}\cdot c_{\text{lane}}}, \end{aligned} \tag{28}$$

where x_{vehicle} represents the road saturation of the social lanes. x_{bus} represents the road saturation of intermittent bus lanes. s represents the dynamic lane functional attribute, $s \in$ bus or vehicle. $t_{\text{vehicle}}^{\text{catt}}$ indicates the average travel time of social vehicles in social lanes. t_{bus}^{catt} indicates the average travel time of social vehicles in bus lanes. $n_{vehicle}$ refers to the average number of social vehicles in social lanes. n_{bus} is the average number of buses in bus lanes. n_{lane} is the number of dynamic lanes.

The average delay of social vehicles in the social lane (defined as $t_{vehicle}^{cad}$) and the average delay of social vehicles in the bus lane (defined as t_{bus}^{cad}) are obtained by substituting $x_{vehicle}$ and x_{bus} into (19). Then, the average delay of all vehicles (defined as $t_{de\,lay}^{3}$) is calculated by equation (30).

Set

$$a_3 = \frac{\Delta q_{\text{vehicle}} \cdot t_s^{catt}}{n_{\text{vehicle}}/n_{\text{vehicle}} + n_{\text{bus}} \cdot t^{patt}}, \quad (29)$$

t_{delay}^{3} is obtained by substituting equation (29) into (30) as follows:

$$t_{delay}^{3} = \frac{\left[(\Delta q_{\text{vehicle}} - a_3)t_{\text{vehicle}}^{cad} + a_3 t_{\text{bus}}^{cad} + \Delta q_{\text{bus}} t_{\text{bus\_delay}}\right]}{n_a \Delta q_{\text{vehicle}} + n_b \Delta q_{\text{bus}}}, \quad (30)$$

where t_{bus_delay} is the average signal control delay of each bus.

3.2. Constraints of Intermittent Bus Lane Dynamic Setting. The following constraints are considered for the dynamic setting of intermittent bus lanes: green light opening time constraint of lane indicators in various combinations, social vehicle insertable interval, green light time constraint, bus flow constraint, social vehicle flow constraint and the traffic efficiency constraint, and so on.

Step 1. Green light opening time constraint of lane indicators in various combinations:It has been elaborated in detail in Section 2 and will not be repeated here.

Step 2. Social vehicle insertable interval: Intermittent bus lane control is only activated during the control area, when incoming social vehicles can pass the intersection in time and without interfering with bus operations. In this case, the social vehicles insertable interval should satisfy the constraints: $0 < l_x \leq S$.

Step 3. Green light time constraint

Step 3.1. Minimum green time: The minimum green time not only ensures that the last vehicle in the queue at a red phase can successfully pass the intersection but also that pedestrians approaching the intersection can cross safely. Therefore, the minimum green time consists of a minimum green time for vehicles (defined as $g_{\min_1}$) and a minimum green time for pedestrians crossing the road (defined as $g_{\min_2}$).

In an undersaturated state, $g_{\min_1}$ can be calculated by the dissipation time of the vehicle queue (defined as t_{w_2}).

$$g_{\min_1} = t_{w_2} = \frac{l_x}{q_s - q_{\text{arrive}}}, \quad (31)$$

where l_x is the queue length of social vehicles. q_s is the saturation flow rate of intersection entrance. q_{arrive} refers to the arrival rate of intersection entrance.

Similarly, $g_{\min_2}$ is obtained according to the HCM2010.

$$g_{\min_2} = 7 + \frac{L_p}{v_p} - I, \quad (32)$$

where L_p is the distance from the road surface to safe traffic infrastructure, such as pedestrian safety islands, traffic islands, and the nearest road surface. v_p is pedestrian speed. I is the intergreen time.

The minimum green time (defined as $G_{\min}$) can be expressed as $G_{\min} = \min(g_{\min_1}, g_{\min_2})$.

Step 3.2. Extended green time: The extension of unit green time is designed to reduce the green light loss time under the condition of ensuring traffic safety and improving the operational efficiency of the control system. The calculation equation is shown as follows:

$$G_{\text{extime}} = \frac{3.6L}{\sum_{n=1}^{n_{\text{vehicle}}} v/n_{\text{vehicle}}}, \quad (33)$$

where L represents the distance between the detector and the stop line. $\overline{v} = \sum_{n=1}^{n_{\text{vehicle}}} v/n_{\text{vehicle}}$ is the average speed of the vehicle.

Step 3.3. Maximum green time: When the maximum green time is reached in the signal transition phase, the green light is forced to end its operation and switch to the next phase. Therefore, the maximum green time should be greater than or equal to the sum of the green time extension and the minimum green time, i.e.,

$$G_{\max} \geq G_{\text{extime}} + G_{\min}. \quad (34)$$

Step 4. Bus flow constraint: The purpose of the intermittent bus lane is to ensure that buses are given priority when the traffic light turns green. This paper dynamically determines the time when the intermittent bus lane is open to social vehicles, so that the utilization rate of space resources by social vehicles is greatly improved. The constraint relationship between bus flow and social traffic flow is calculated by equation (35) as follows:

$$\frac{\mu\Delta q_{\text{bus}}}{n_b} < \frac{\Delta q_{\text{vehicle}}}{n_a + Rn_b}. \tag{35}$$

As the number of buses in the lane continues to rise, the utilization rate of space resources occupied by buses also gradually increases. In order to ensure that buses operate in the dedicated lane without system delays caused by random moderation of social vehicles in the lane, it is necessary to set a reserved storage interval to ensure the bus priority control. According to the road experiments described in [27], during peak periods, the intermittent bus lane efficiency will immediately fail when the space resource occupancy of the bus lane is greater than 0.7. Therefore, it is set that the intermittent bus lane is activated when $R > 0.295$.

Step 5. Social vehicle flow constraint: When the social traffic flow on the road section is in an undersaturated state, social vehicles are travelling at the desired speed in the original lane. There is no need to open the intermittent bus lane. When the road service level drops to level B based on HCM2000 [41], the road section begins to be congested, i.e., the traffic saturation is greater than 0.7. The intermittent bus lanes are set up. The social vehicle flow should satisfy the following constraints:

$$\frac{\Delta q_{\text{vehicle}}}{c_{n_a}^{\text{vehicle}}} > 0.7. \tag{36}$$

Step 6. The traffic efficiency constraint: After setting up the intermittent bus lane, the total travel time consumption of the road section cannot be greater than that before setting up, which indicates that the overall traffic efficiency of the road section is reduced. This is contrary to the purpose of setting the intermittent bus lane. Therefore, the traffic efficiency constraints are described as follows:

Set

$$a_4 = \Delta q_{\text{vehicle}} Q_{\text{vehicle}}, \tag{37}$$

$$a_5 = \Delta q_{\text{bus}} Q_{\text{bus}}. \tag{38}$$

Substitute equations (37)–(38) into equations (39)–(40)

$$t_{\text{vehicle}}^3 a_4 + t_{\text{bus}}^3 a_5 + \left(n_a \Delta q_{\text{vehicle}} + n_b \Delta q_{\text{bus}}\right)\left(a_4 + a_5\right) t_{\text{delay}}^3 < t_{\text{vehicle}}^2 a_4 + t_{\text{bus}}^2 a_5 + a_5 t_{\text{delay}}^2, \tag{39}$$

$$t_{\text{vehicle}}^3 a_4 + t_{\text{bus}}^3 a_5 + \left(n_a \Delta q_{\text{vehicle}} + n_b \Delta q_{\text{bus}}\right)\left(a_4 + a_5\right) t_{\text{delay}}^3 < t_{\text{vehicle}}^1 a_4 + t_{\text{bus}}^1 a_5 + \left(a_4 + a_5\right) t_{\text{delay}}^1, \tag{40}$$

where Q_{vehicle} refers to the average passenger capacity of social vehicles on the road section. Q_{bus} indicates the average passenger capacity of the bus on the road section.

3.3. Intermittent Bus Lane Dynamic Associated Control Modelling. According to the detailed analysis in Sections 3.1 and 3.2, an associated optimization control model for intermittent bus is constructed based on taking the minimum total travel time consumption of the road section as the objective function. The control objective function is calculated by the following equation:

$$Y = \min\left[t^{3}_{\text{vehicle}}a_4 + t^{3}_{\text{bus}}a_5 + \left(n_a q_{\text{vehicle}} + n_b q_{\text{bus}}\right)\left(a_4 + a_5\right)t^{3}_{\text{de lay}}\right]$$

$$s.t.\begin{cases} \text{The opening time } t \text{ should satisfy Section 2 of various combinations,} \\ 0 < l_x \le S, \\ G_{\min} = \min\left(g_{\min_1}, g_{\min_2}\right), \\ G_{\max} \ge G_{\text{extime}} + G_{\min}, \\ G_{\min} \le T_{\text{green}} \le G_{\max}, \\ \dfrac{\mu q_{\text{bus}}}{n_b} < \dfrac{q_{\text{vehicle}}}{n_a + R n_b}, \\ R > 0.295, \\ t^{3}_{\text{vehicle}}a_4 + t^{3}_{\text{bus}}a_5 + \left(n_a q_{\text{vehicle}} + n_b q_{\text{bus}}\right)\left(a_4 + a_5\right)t^{3}_{\text{delay}} < t^{2}_{\text{vehicle}}a_4 + t^{2}_{\text{bus}}a_5 + a_5 t^{2}_{\text{delay}}, \\ t^{3}_{\text{vehicle}}a_4 + t^{3}_{\text{bus}}a_5 + \left(n_a q_{\text{vehicle}} + n_b q_{\text{bus}}\right)\left(a_4 + a_5\right)t^{3}_{\text{delay}} < t^{1}_{\text{vehicle}}a_4 + t^{1}_{\text{bus}}a_5 + \left(a_4 + a_5\right)t^{1}_{\text{delay}}, \\ \dfrac{q_{\text{vehicle}}}{c^{\text{vehicle}}_{n_a}} > 0.7, \\ 0 \le q_{\text{vehicle}} \le c^{\text{vehicle}}_{n_a}, \\ 0 \le q_{\text{bus}} \le c^{\text{bus}}_{n_b}, \end{cases} \tag{41}$$

where T_{green} is the green light time of the current phase.

4. The Model Solving Algorithm Based on Computational Experiment

Public transport systems are complex giant systems. Intermittent bus lane control is one of the aspects of public transport system research that is also affected by various factors of complex giant systems. Computational experiment is a new active simulation method based on artificial objects to address these influences and difficulties. Like research methods of artificial life and artificial society, they include computational experiment of intermittent bus lane control based on social vehicle insertable interval, dynamic optimization of model, and experimental analysis and evaluation.

The operation sequence of the intermittent bus lane control model is described: the calculation of the combination for social vehicle insertable interval and the adjacent front and rear bus operating state of the green light opening time for lane indicator under is the premise and foundation of the modelling. The dynamic optimization of this model can be further realized by using the computational experiment of the artificial system. The abovementioned parts complement each other and are indispensable, forming a closed-loop feedback parallel system structure. The main steps are shown as follows.

Step 1. Computational experiment of green light opening time of lane indicators for different combinations of insertable intervals of social vehicles and the operating states of adjacent front and rear buses: According to the experimental framework of parallel system computation, as shown in Figure 4, multiple indicator sets J such as the detected bus entry time into the control area in the mth road section, the signal timing state when the vehicle arrives at the intersection, and the bus operating state are input. The abovementioned indicator sets are initialized. When the model is operated, the multiple indicator results are fed back to the artificial system to output the social vehicle insertable interval (defined as l) and the opening time of lane indicator (defined as t). In addition, the artificial system module includes a road static model, a traffic flow model, and a traffic rule model. Among them, the characteristic attributes of the road model include the associated road section topology, the lane functional classification, physical channelization, and the speed limit of the road section. The traffic flow model includes the traffic state (undersaturation, critical saturation, and oversaturation) and the distribution characteristics of traffic flow and the traffic rules such as bus lane and bus priority. The main purpose of the artificial system is to achieve an accurate reproduction of the real public transport system and to conduct computational experiments on the interval at which social vehicles can be inserted and the opening time of lane indicators, in order to provide data support for model control.

Step 1.1. After initialisation of the experiment, the queue length of the control area is calculated based on the green light opening time of the lane indicator and the average number of vehicles that can change lanes per unit time.

Step 1.2. In the artificial scenario of a single bus, considering the vehicle distributed wave state and queue length constraint, the green light opening time of the lane indicator is calculated.

Step 1.3. In the artificial scenario with multiple buses, the combination state situations of the front and rear vehicles are determined. And then, the green light opening time of the lane indicator is analysed based on each combination.

Step 2. Model a dynamic control artificial system of intermittent bus lane. In the ideology of adaptive feedback control of the parallel system, under combinations of different bus operating states of the social vehicle insertable interval and the green light opening time of lane indicator, the model controller corresponding to it in the artificial system is selected to improve the parallel control accuracy of the intermittent bus lane. According to the feedback index, the indicators interact with the model controller to form a closed-loop control structure.

Step 2.1. Create the model constraint set: The initial model constraint set is to consider multiple combinations of situations, such as green light opening time constraint of lane indicator, bus flow constraint, social vehicle flow constraint, and traffic efficiency constraint, established by the a priori knowledge of the computational experiments of the artificial system and its results. The data calibration in the actual system is further used to determine the variation range of the constraint set. The multiple groups of initial model parameters and constraint knowledge bases based on offline design are used to construct the initial model. The purpose is to allow social vehicles to pass through the intersection in time without affecting the bus operation, thus improving the initial response speed and model control accuracy of the artificial system. Therefore, the establishment of an initial model that satisfies the actual system is a prerequisite guarantee for ensuring accurate control of intermittent bus lanes.

According to the impact of social vehicles on the bus operating state, all travel times and intersection delays of artificial system operation are aggregated to construct the initial model parameter knowledge base. The characteristic vectors of model parameters are set based on the statistical results of the artificial system operation. The initial model parameter knowledge base is divided into corresponding benchmark submodel parameter sets by combining different setting conditions of the bus lane (including intersect (i.e., no bus priority), parallel, and intermittent bus lanes). Considering multiple initial constraint knowledge bases, the initial model (defined as Y) is constructed with the objective function of minimizing the total travel time consumption of road section.

Step 2.2. Model adaptive artificial controller:The model-adaptive artificial controller for the parallel system designed in this paper is shown in . The artificial controller is selected based on the submodel stage of the system in Step 2.1. The artificial system obtains the corresponding submodels for different setting methods and the corresponding model control parameters by a large number of multicombination hybrid computational experiments. Furthermore, the artificial system assigns the submodel data and control parameters to the artificial model selector and the corresponding adaptive artificial controller, which solves the model and outputs Y based on the adaptive artificial controller. Meanwhile, the evaluation index is calculated to evaluate model control effect. The basic idea of the indicator evaluator is to introduce the idea of feedback into the control process. On the one hand, the accuracy of the model is evaluated by judging the control accuracy. On the other hand, the judgment indicators are fed back to the input of the artificial system. According to the input parameters, it is judged whether the index needs to be recalculated for experimentation.

The evaluation index is constructed by the following equation:

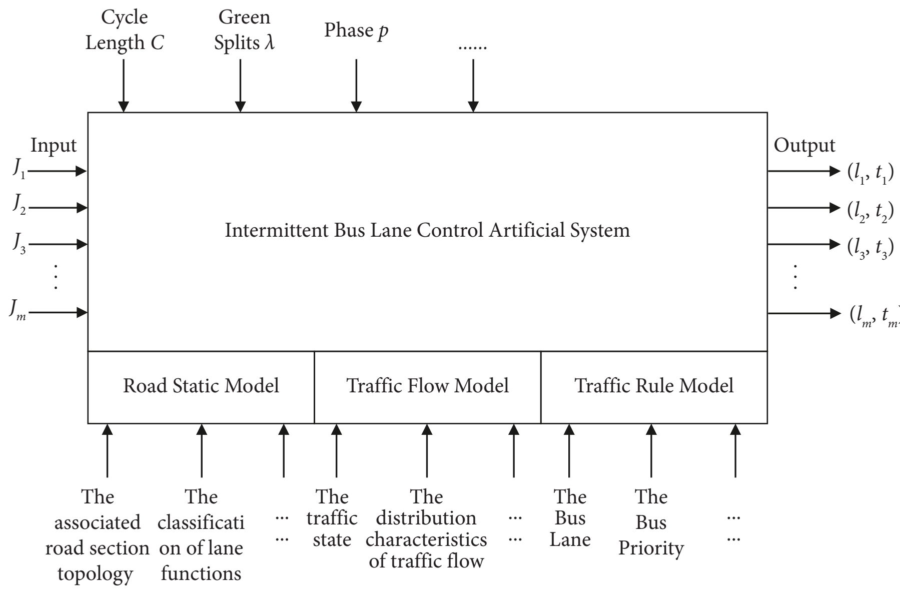


Figure 4: The schematic diagram of intermittent bus lane control artificial system.

$$\dot{J}\left(t_{\text{step}}\right) = \varpi E_i^{\exp\left[-\frac{1}{2}\left(\frac{X_P - M_P}{\sigma_P}\right)\right]} + \varepsilon \int_0^{t_{step}} E^{-\theta\left(t_{step}-\tau\right)} E_i^{\exp\left[-\frac{1}{2}\left(\frac{X_P - M_P}{\sigma_P}\right)\right]}(\tau)\mathrm{d}\tau,$$

$$s.t.\begin{cases} \overline{M}_P = \begin{cases} \exp\left[-\dfrac{1}{2}\left(\dfrac{X_P - M_1}{\sigma_P}\right)^2\right], & X \le M_1, \\ 1, & M_1 < X \le M_2, \\ \exp\left[-\dfrac{1}{2}\left(\dfrac{X_P - M_2}{\sigma_P}\right)^2\right], & X > M_2, \end{cases} \\ \underline{M}_P = \begin{cases} \exp\left[-\dfrac{1}{2}\left(\dfrac{X_P - M_1}{\sigma_P}\right)^2\right], & X \le \dfrac{M_1 + M_2}{2}, \\ \exp\left[-\dfrac{1}{2}\left(\dfrac{X_P - M_2}{\sigma_P}\right)^2\right], & X > \dfrac{M_1 + M_2}{2}, \end{cases} \end{cases} \tag{42}$$

where ϖ represents the weight of the current computational error in the performance index. ε is the weight of the historical cumulative computational error in the performance index. $\varpi \ge 0$, $\varepsilon > 0$, and $\theta > 0$ represent the forgetting gate factor (i.e., the memory length size of the performance index). $E_i = E(t_{\text{step}}) - \hat{E}(t_{\text{step}})$ represents the adaptive discrimination error of computational experiment. X_P is the set of submodel data and control parameters. $\overline{M}_P$ and $\underline{M}_P$ represent the upper and lower limit membership functions, respectively. σ is a fixed value. The observation interval of the artificial system is $T_P = [T_{\text{step}_1}, T_{\text{step}_2}]$, where peak_{P_i} is the peak value in X_P within T_P. Let $M_1 = \min(\text{peak}_{P_i})$ and $M_2 = \max(\text{peak}_{P_i})$. The abovementioned M_1 and M_2 are substituted into the submembership degree of M, that is, $f_M(M_i, M_{i+1}) = \kappa f(M_i, M_{i+1})/f(M_1, M_2)$, where $f(M_i, M_{i+1})$ refers to the frequency of peak value ($\text{peak}_{P_i}' \in [M_i, M_{i+1}]$) in actual data of the actual system. κ is the secondary membership weight.

Step 2.3. Model adaptive switching control strategy: The artificial system judges whether the operating state under the current setting method is consistent with the current submodel. If not, it will autonomously find the submodel that is consistent with the existing state or satisfies the similar conditions from all submodels based on the hysteresis

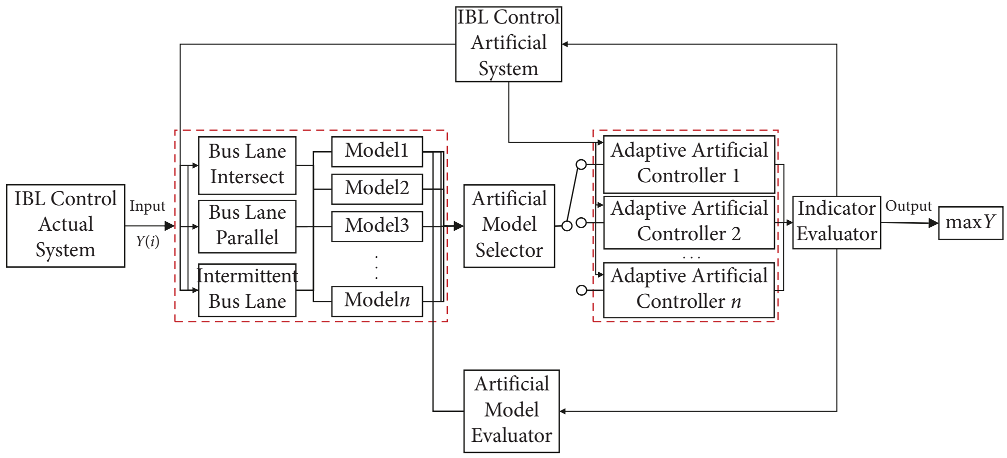


Figure 5: The schematic diagram of model adaptive artificial controller in parallel system.

switching strategy [42, 43], so as to prevent the switching control strategy from bringing instability and feature distortion to the artificial system.

Step 2.3.1. Determine whether the actual operating state is consistent with the submodel under the multicombination setting method. If consistent, the selected control model will not be changed. Otherwise, go to Step 2.3.2.

Step 2.3.2. Calculate the performance index and then preselect the minimum value of the index (i.e., $\min[\dot{J}(t_{\text{step}})]$). Go to Step 2.3.3.

Step 2.3.3. Determine whether the artificial system is switched and adopt the corresponding operation strategy. The specific strategy is shown as follows:

$$\begin{cases} \dot{J}\left(t_{\text{step}}\right) \leq \min\left[\dot{J}\left(t_{\text{step}}\right)\right] + \omega & \text{Do not execute switching strategy,} \\ \dot{J}\left(t_{\text{step}}\right) > \min\left[\dot{J}\left(t_{\text{step}}\right)\right] + \omega & \text{Execute switching strategy.} \end{cases} \tag{43}$$

where ω is the lag factor and $\omega > 0$.

Step 3. Computational experiment strategy based on the dynamic optimization execution mode: The corresponding submodel data and control parameters in the observation interval are modified through collecting the real-time bus data in the actual system. The obtained results are tested in the artificial system, in which the submodel data and control parameters need to construct a dynamic optimisation strategy to ensure that they are as close as possible to the actual system. The performance index results in Step 2.2 are fed back to the computational experiment of the artificial system based on the mechanism of model adaptive parameter adjustment. Determine whether it is necessary to implement the existing scheme through the performance evaluation index and the operating state of actual system to achieve dynamic updating and feedback optimization of the model .

After the submodel data and knowledge base of control parameter are established, there is a certain error between the Y obtained from the computational experiment and the actual system output due to the initialised benchmark submodel parameter set being more ideal. If there is a large error between the Y obtained from computational experiment and the actual system output, it is necessary to replace the initial value in Step 2.2~2.3. The update strategy of computational experiment is described as follows:

$$\begin{aligned} \dot{J}_{m,T_P} &= E_{m,T_P}^{\exp\left[-1/2\left(X_P - M_P/\sigma_P\right)\right]}, \\ E_{m,T_P} &= S_{m,T_P} - R_{m,T_P}, \end{aligned} \tag{44}$$

where S_{m,T_P} represents the operating value of the actual system in the observation interval T_P corresponding to the mth road section. R_{m,T_P} refers to the computational experiment result in the observation interval T_P corresponding to the mth road section.

Considering that there are some random disturbances, abnormal traffic states and other unexpected situations in the model, if $\dot{J}_{m,T_P} < \mathfrak{R}$, there is no need to update the computational experiment strategy, where $\mathfrak{R}$ is the error threshold. The corresponding number of computational experiments is $cs'_{m,j} = cs_{m,j} + 1$. Otherwise, if $\dot{J}_{m,T_P} \geq \mathfrak{R}$, there is a need to update the computational experiment strategy.

Step 4. Experimental analysis and evaluation based on parallel credibility

Step 4.1. Converge the computational experiment results through the expert knowledge system, and record the value of each expert's evaluation of the results (defined as ζ_{zj_i}), where $i = 1, 2, \ldots, n$.

Step 4.2. Fuse each expert's estimation of performance indicator to obtain the fusion result $Z(i)$, $i = 1, 2, \ldots, n$.

*Step 4.3.*Carry out multidimensional combination of the fusion results for each index, that is, in the evaluation system, there is an expert evaluation set $\{Z_{J1}, Z_{J2}, \ldots, Z_{Jn}\}$ so that the set of weights of each expert evaluation in the process of evaluating performance indicator is ϑ. The set of evaluation index is $\{\text{value}_1, \text{value}_2, \cdots, \text{value}_n\}$.

The evaluation value of each expert's contribution to the overall operational functional credibility of the artificial system is calculated based on each performance indicator, as shown in equation (45).

$$Z(i) = \sum_{i=1}^{n} \zeta_{zj_i} \times \vartheta(ZJ_i). \tag{45}$$

Combined with the weights of each performance indicator, the verification value of the credibility of the overall operational function in the artificial system is calculated through the following equation:

$$\psi = \sum_{i=1}^{n} \vartheta(\text{value}_i) Z(i). \tag{46}$$

Step 4.4. Use equation (47) to evaluate the accuracy and credibility of the artificial system in the multi-combination hybrid computational experiment.

$$\text{MAE}_{T_P} = \psi \frac{\sum_{P=1}^{N} \left| \overline{e}_P^N - e_P^N \right| / e_P^N}{N}, \tag{47}$$

where $\overline{e}_P^N$ refers to the computational experimental data of the Pth observation interval in the Nth test. e_P^N represents the median value of the Pth observation interval in the Nth test. N is the total number of tests.

5. Case Study

5.1. Scenario Description. The 384.96 m long Ralph McGill Blvd in Atlanta, United States, is selected as the research object. The road includes two-way bus lanes and four social lanes in one direction in Figure 6. The bus lanes are located on the innermost and outermost sides of the road and no left turns. The intersections of Piedmont Ave. NE and Central Park PI. NE are both secondary roads and do not have bus lanes. The distance between upstream intersection 1 and intersection A is 188.97 m. Similarly, according to the actual data, the distance between downstream intersection 2 and intersection B is 210.31 m. The lane width is 3.5 m. The free-flow speed for social vehicles is 50 km/h, and the free-flow speed for buses is 40 km/h. The intersections are operated on a fixed four-phase cycle with a cycle length of 120 s in Figure 7.

5.2. Numerical Simulation. The actual data of this area from 00:01 to 23:59 on 12 March, 2018 is selected for numerical simulation. After processing, the corresponding relationship between traffic flow for lane level and time interval per 10 min during a day is obtained, as shown in Figure 8. The abovementioned data are used to calibrate the coefficients of the BPR model by logarithmic regression [44]. We obtain $\alpha_{\text{vehicle}} = 0.1851$, $\beta_{\text{vehicle}} = 3.8201$, $\alpha_{\text{bus}} = 0.1529$, and $\beta_{\text{bus}} = 3.6410$. The calibration model is evaluated by using the root mean square error (RMSE) and the coefficient of determination (goodness of fit) of the fitting curve. The results of the evaluation are shown in Table 3. It can be seen that the calibrated model has a good fitting effect on different types of vehicles, which can accurately reflect the functional relationship presented by the actual traffic.

According to the abovementioned three conditions, the input parameters include social vehicle flow and bus flow. Since the intermittent bus lane is suitable for the situation where the social vehicle flow should not be too large, the control rules of social vehicle flow and bus flow are set as follows: the threshold value of the social vehicle flow is set as $q_{\text{vehicle}} = (0.45c, 2.55c)$, where $c = 1080$ pcu/h. The threshold value of the bus flow is set as $qbus = (75, 430)$.

The boxplot has the advantage of making it easier to compare multiple datasets. Therefore, boxplot is chosen in this paper to provide a comprehensive analysis of the three setting scenarios. As shown in Figure 9, in terms of the average travel times, the average travel time is greater than in the case of no bus lanes because the bus lanes in scheme 2 have a greater impact on social vehicles. However, the intermittent bus lanes are effective in reducing the average travel time of vehicles because they are open to social vehicles part of the time.

As shown in Figure 9, the median of the intermittent bus lane is 49.8996 s. The median of the proposed method is lower than the other two schemes. The results show that in more than half of the cases, the bus lane parallel setting condition can reduce the travel time, in which the intermittent bus lane has a greater reduction. For the overall analysis, the travel time of scheme 2 fluctuates greatly, which shows that the conventional bus lanes are not applicable in some cases. In contrast, the intermittent bus lane has a smaller range of variation and a better effect.

In order to comprehensively analyse the advantages and disadvantages of the three setting schemes, the three setting schemes are compared under low, medium, and high flow conditions. The applicability and stability of the three schemes are analysed. Among them, the low flow is set as $0.450c{\sim}0.975c$. The medium flow is set as $0.975c{\sim}1.500c$. The high flow is set as $1.500c{\sim}2.100c$.

5.2.1. Comparative Analysis of Travel Time under Low Flow Condition. As shown in Figure 10, the average travel time of scheme 1 is the lowest when the flow of social vehicle is greater than 982 pcu/h and the flow of bus is less than

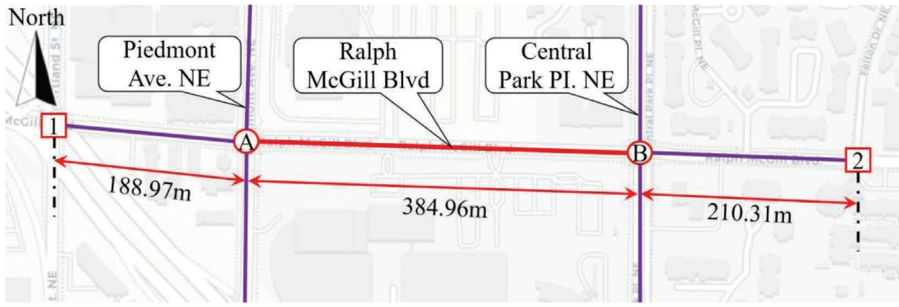


Figure 6: The study area.

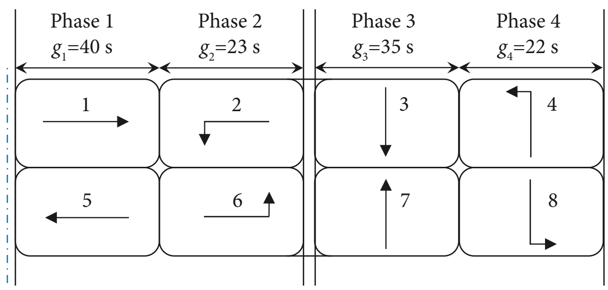


Figure 7: Original signal timing.

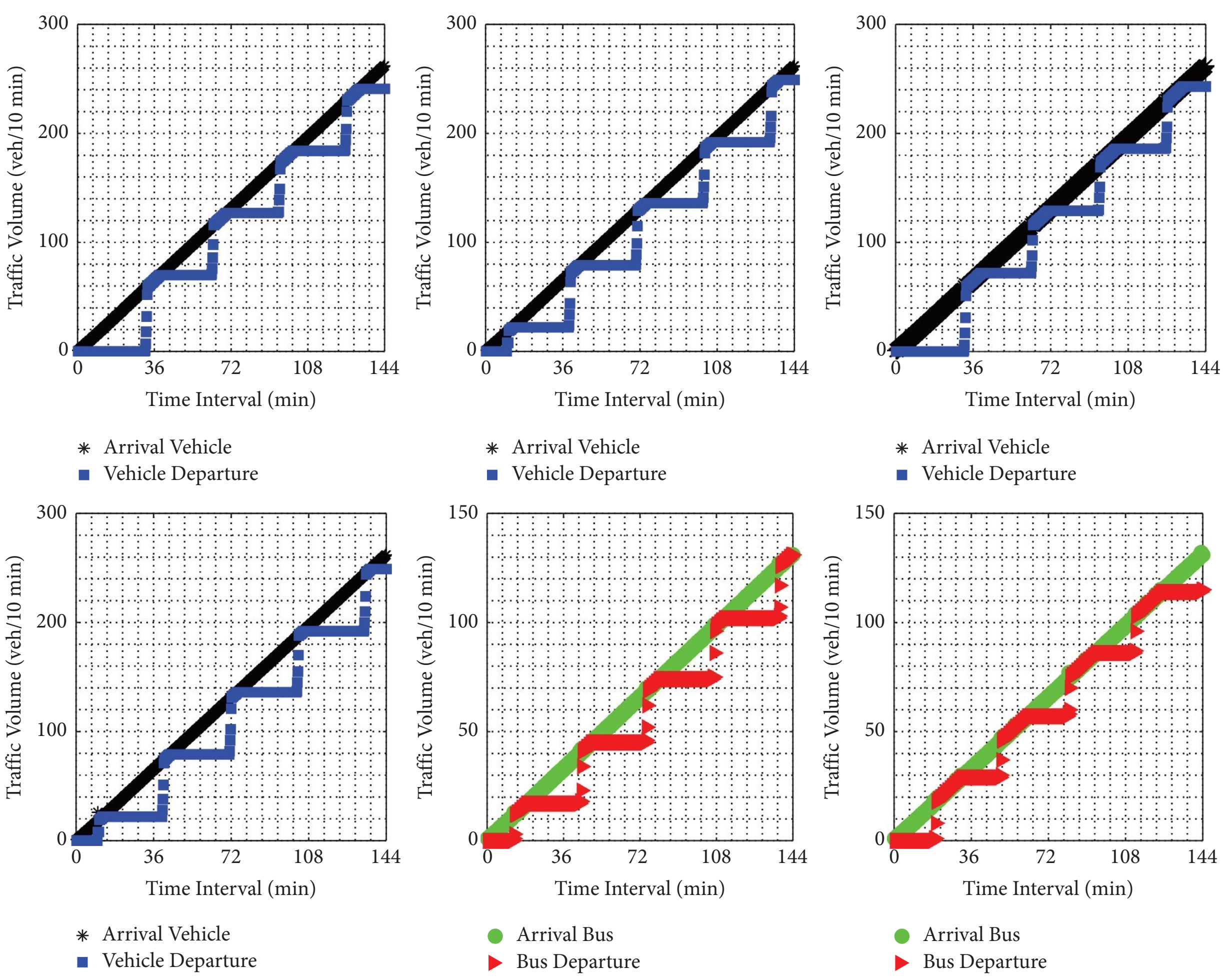


Figure 8: The relationship between traffic flow for lane level and time interval.

Table 3: Evaluation of BPR model calibration results.

Vehicle types	95% confidence interval of fitting value α	95% confidence interval of fitting value β	RMSE	Goodness of fit
Social vehicles	(0.172, 0.195)	(3.705, 3.911)	8.0046	0.9107
Buses	(0.148, 0.159)	(3.5914, 3.703)	7.7631	0.9243

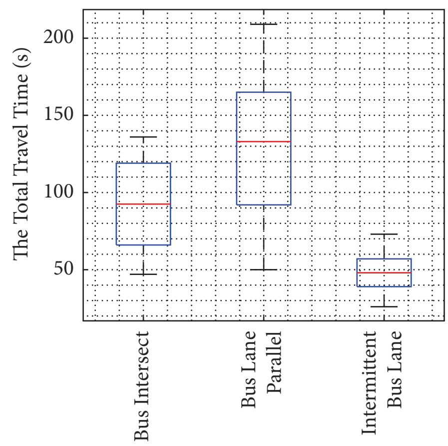


Figure 9: The comparison diagram of total travel time under different settings.

185 pcu/h. For other road conditions, the average travel time of scheme 3 (intermittent bus lane) is the lowest. The results show that the intermittent bus lane is the better scheme for low flow conditions.

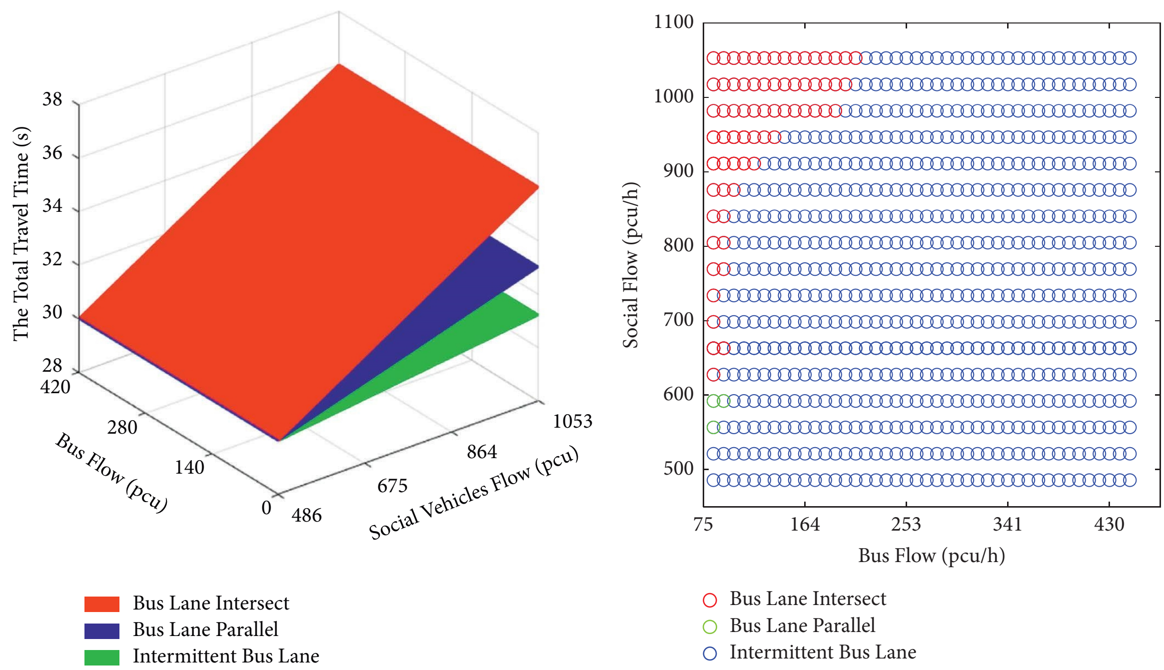
5.2.2. Comparative Analysis of Travel Time under Medium Flow Condition. As shown in Figure 11, the average travel time of scheme 3 (intermittent bus lane) is the lowest when the flow of the social vehicle does not exceed 1407 pcu/h and the flow of bus exceeds 253 pcu/h. For other road conditions, the average vehicle delay of scheme 1 is the lowest. Therefore, if the average vehicle travel time is used as the evaluation index, it is better not to install bus lanes in the medium flow condition. On the other hand, if the average per capita travel time is taken as the evaluation index, the intermittent bus lane is the better scheme.

5.2.3. Comparative Analysis of Travel Time under High Flow Condition. As shown in Figure 12, the average travel time of scheme 1 is the shortest. The average travel time of scheme 2 is the longest. For the average per capita travel time, if the flow of the social vehicle is greater than 2066 pcu/h, the per capita travel time of scheme 1 is the smallest. In this case, it is better not to have a bus lane. If the flow of social vehicle is less than 2066 pcu/h, it is better to set up an intermittent bus lane at this time. Since the intermittent bus lane is an improvement of the bus lane, the implementation effect of the intermittent bus lane is good.

5.2.4. Computational Experiment Analysis. Considering that the actual system is time-varying, complex, and uncertain, although the actual system generally shows a certain trend, the output of the actual system fluctuates. The actual data are simply used to process its average value, median and other data will cause data distortion and partially obscure the whole. Therefore, it is necessary to find a method that can effectively reflect the various states and dynamic characteristics of the actual system. The combination of computational experiment and prediction model satisfy this requirement. The prediction model predicts the future development state of the actual system through the long-term historical data. Moreover, compared with a single value curve, fuzzifying the result into an interval can better reflect the essence of the actual system.

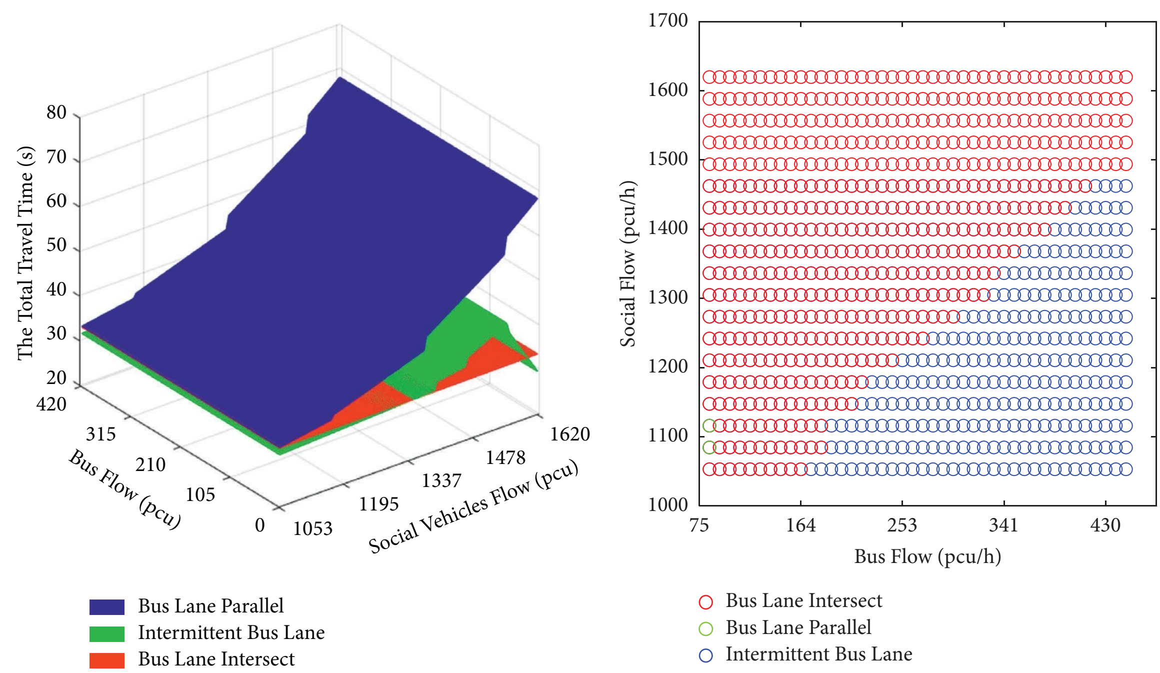
The development laws and dynamic characteristics of the actual system are obtained by the prediction model. Combined with the computational experiment, we can obtain the characteristics of the artificial system. In this way, the credibility of the parallel system can be calculated by comparing the two systems. Thus, the implementation of the algorithm is still carried out by comparing between the prediction model and computational experiment.

As shown in Figure 13, the errors of the actual system and the artificial system fluctuate slightly under the three settings. Especially, the computational experiment of the intermittent bus lane is better than that of the two situations. As shown in Figure 14, in the case of no bus priority, when the loss function converges, the value of epochs is 42. In the case of bus lane parallel setting condition, when the loss function converges, the value of epochs is 31. Similarly, in the case of intermittent bus lane, when the loss function converges, the value of epochs is 20. The results show that the prediction results of the intermittent bus setting are better than the other two cases.



(a) (b)

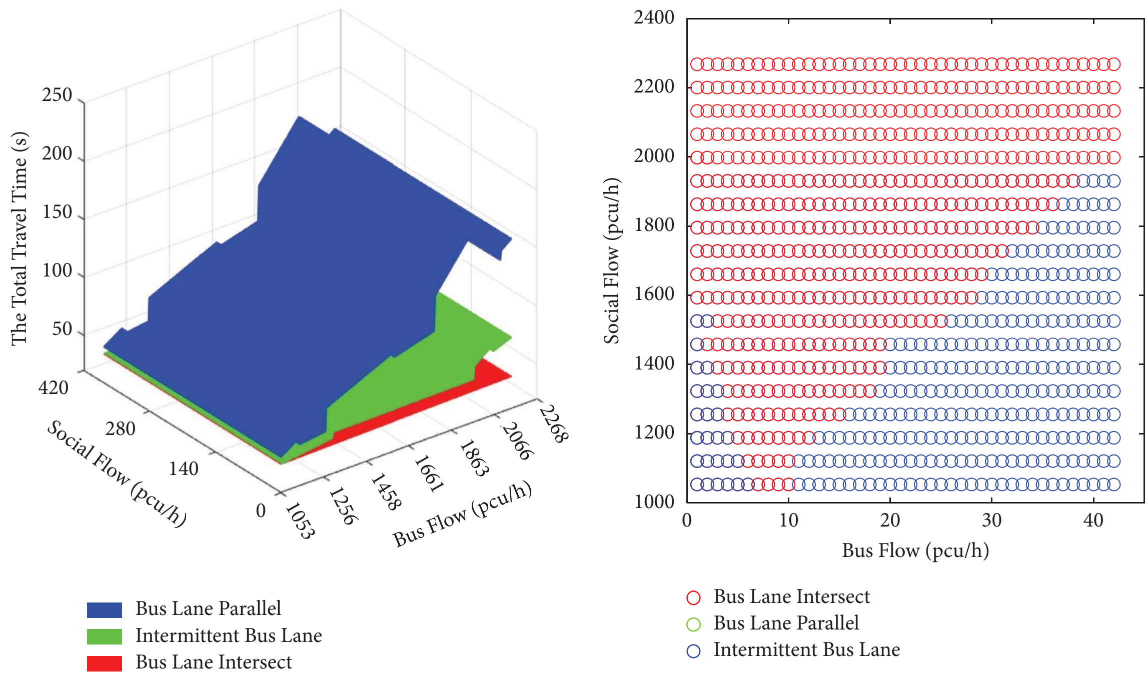
Figure 10: Comparison of travel time of each program under low flow condition: (a) the average travel time under low flow condition and (b) the scatter diagram of average travel time under low flow condition.



(a) (b)

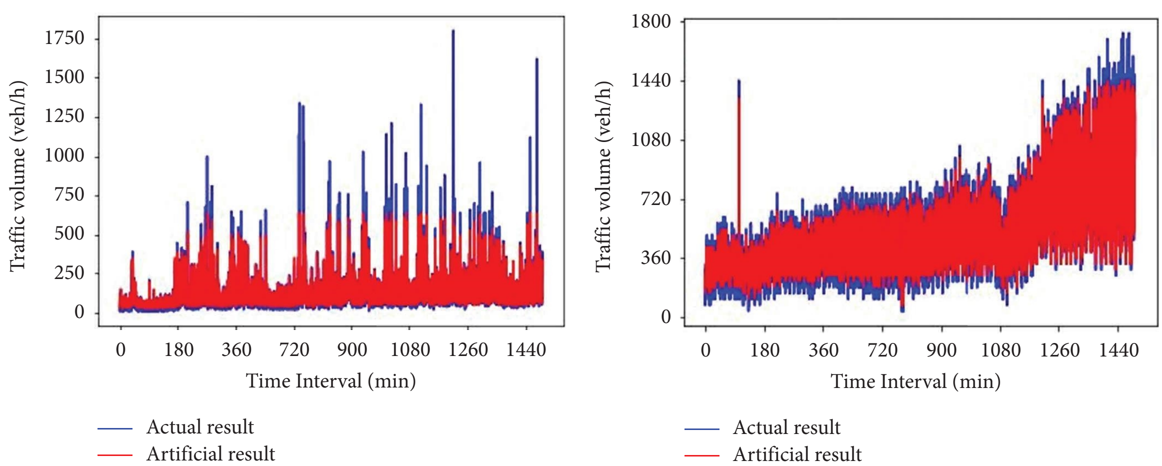
Figure 11: Comparison of travel time of each program under medium flow condition: (a) the average travel time under medium flow condition and (b) the scatter diagram of average travel time under medium flow condition.

As shown in Figure 15, the introduction of bus lanes reduces the road resources available to social vehicles. The total travel time consumption of social vehicles is significantly increased. Therefore, the total travel time under the bus intersect setting condition is longer than that of the parallel setting method. On the contrary, the intermittent bus lane has opening times that can not only ensure bus priority but also extend the right of way for social vehicles



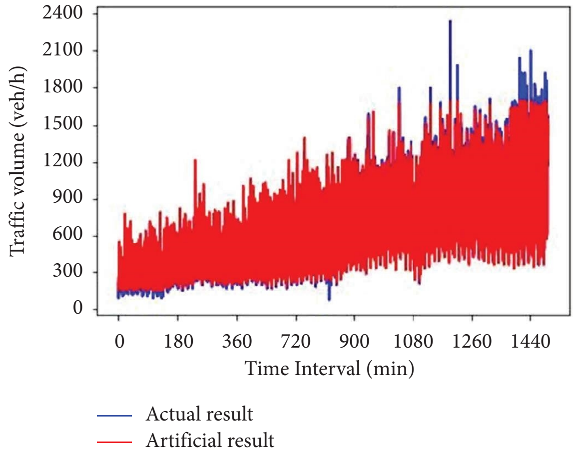
(a) (b)

FIGURE 12: Comparison of travel time of each program under high flow condition: (a) the average travel time under high flow condition and (b) the scatter diagram of average travel time under high flow condition.



(a) (b)

FIGURE 13: Continued.



(c)

Figure 13: The comparison results in computational experiment between the actual system and artificial system under three setting conditions: (a) the comparison results in bus lane intersect, (b) the comparison results in bus lane parallel, and (c) the comparison results in intermittent bus lane.

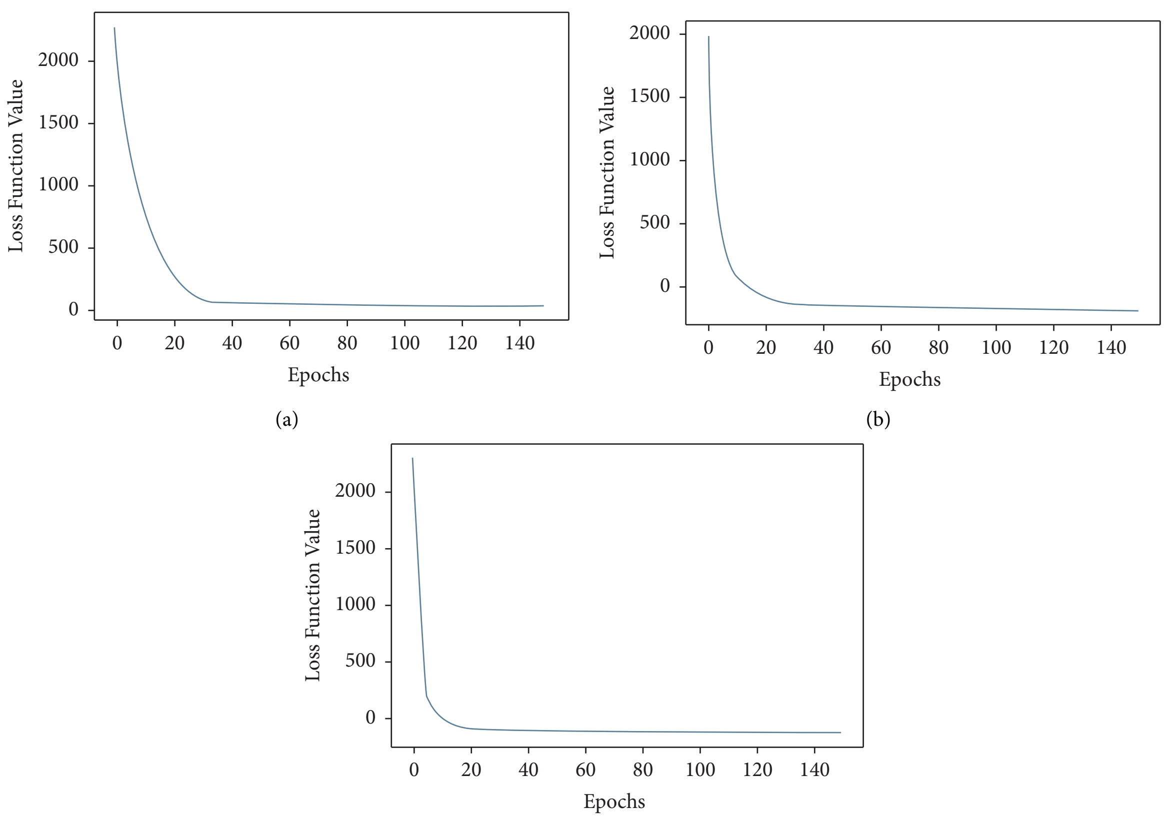


Figure 14: The comparison results loss function in prediction model between the actual system and artificial system under three setting conditions: (a) the predicted results in bus lane intersect, (b) the predicted results in bus lane parallel, and (c) the predicted results in intermittent bus lane.

and maximize the use of road space resources. Therefore, the intermittent bus lane method has great advantages.

Figure 15 shows that the average MAE values under three setting conditions based on the multicombination hybrid computational experiment are 0.272, 0.299, and 0.207, respectively. The average MAE values of the intermittent bus lane are the smallest among the above-mentioned two values, indicating that the accuracy and reliability of the model control under the intermittent bus lane are better than the other two conditions.

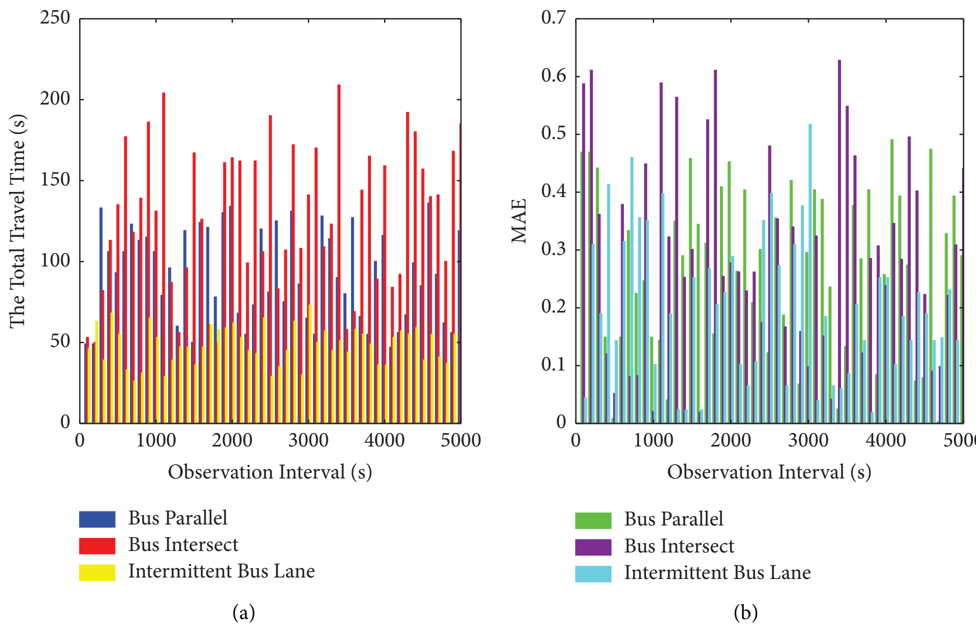


Figure 15: The comparison results loss function in prediction model between the actual system and artificial system under three setting conditions: (a) the distribution of total travel time and (b) computational experiment evaluation results.

5.3. Result Analysis. This section analyses the impact of different schemes on the total travel time consumption under different bus flows. As shown in Figure 16(a), the results show that the number of roads available for social vehicles is reduced due to bus lanes and the total travel time consumption of social vehicles is significantly increased. In Figure 16(b), the average delay of the bus flow is significantly reduced. Therefore, the total travel time consumption in scheme 2 is much longer than that in scheme 1, while the intermittent bus lane can be opened for bus lanes in some time. Therefore, it can effectively reduce the total travel time. Intermittent bus lane can not only ensure bus priority but also extend the right of way of social vehicles, which have obvious advantages and can significantly reduce the average vehicle travel time.

Three setting conditions are selected respectively to compare and evaluate the operating effect of before and after the abovementioned setting conditions. The average speed on the road section is one of the important indicators for evaluating the effect of lane operation. Tables 4 and 5 show the average speed of buses and social vehicles on the road section under different setting methods.

Combined with Tables 4 and 5, the establishment of bus lanes can significantly improve the speed of buses and reduce the average speed of social vehicles in the road section. Compared with setting bus lanes, intermittent bus lane can improve the average speed of social vehicles in the road section without interfering with bus travel, which shows that the operation efficiency of bus lanes is greatly improved. It optimizes the allocation of road resources more reasonably and alleviates the allocation contradiction of road resources between public transport and social traffic.

In order to verify the benefits of three setting conditions, the queuing vehicle number (QVN) and throughput flow rate (TFR) are selected as the evaluation indicators. As shown in Figure 17, 1~8 in the radar map represent the phase corresponding to the research intersections.

As shown in Figure 17, the values of QVN and TFR are the largest in phases 1 and 5 of the associated intersections, especially the setting method of bus parallel and intermittent bus lane, indicating that setting the abovementioned two bus lane modes in the direction of the arterial road with small traffic flow can improve the overall traffic capacity of the road section. On the contrary, if the traffic flow of the associated road sections (including upstream and downstream intersections) is too large, the bus parallel and intermittent bus lane modes will not be set up, which is conducive to the rational allocation of road resources and the alleviation of traffic congestion.

5.4. Sensitivity Analysis. In order to analyse the performance of the three setting conditions, the sensitivity analysis is done with the variations of different traffic factors, including different clearing distances, different saturations, and different speeds of social vehicles and buses.

5.4.1. The Sensitivity Analysis of Average Delay under Different Clearing Distances and Saturations. In the average delay analysis, the proposed method selects the different traffic factors such as saturation 0.1 to 0.9 and the clearing distance set to 100~300 m for evaluation. As shown in Figure 18, the results show that the average delay of intermittent bus lane decreases with increasing clearing

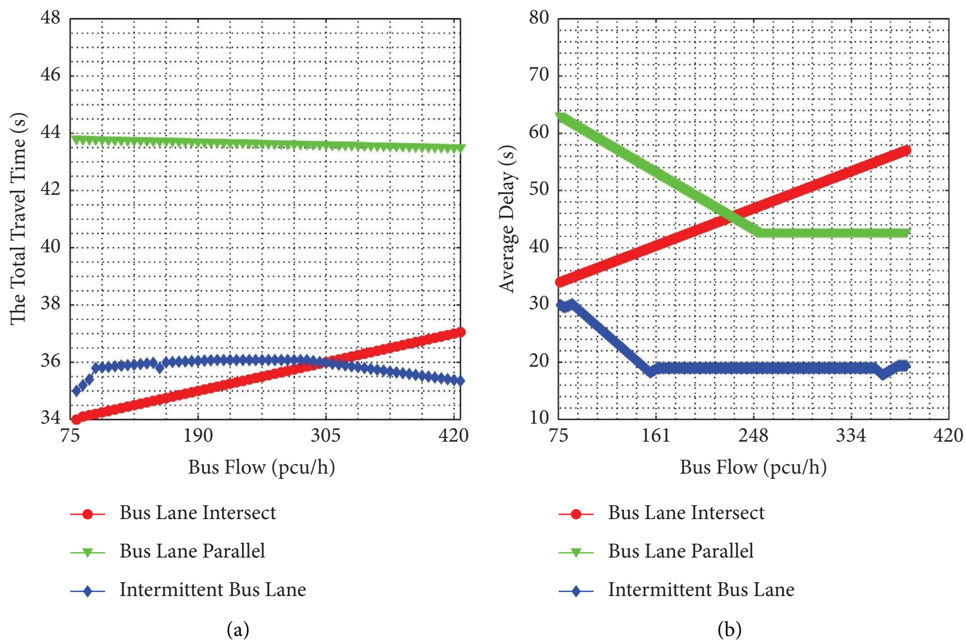


FIGURE 16: Influence of bus flow on different evaluating indicators: (a) total travel time and (b) average delay.

TABLE 4: Average speed of buses in each setting mode.

	Bus lane intersect	Bus lane parallel	Intermittent bus lane
v_{bus} in low flow condition	21.32	31.11	35.43
v_{bus} in medium flow condition	27.65	31.11	33.02
v_{bus} in high flow condition	24.87	31.11	31.11

TABLE 5: Average speed of social vehicles in each setting mode.

	Bus lane intersect	Bus lane parallel	Intermittent bus lane
$v_{\text{social-vehicle}}$ in low flow condition	26.61	23.27	25.10
$v_{\text{social-vehicle}}$ in medium flow condition	34.25	32.04	33.47
$v_{\text{social-vehicle}}$ in high flow condition	31.72	28.93	30.09

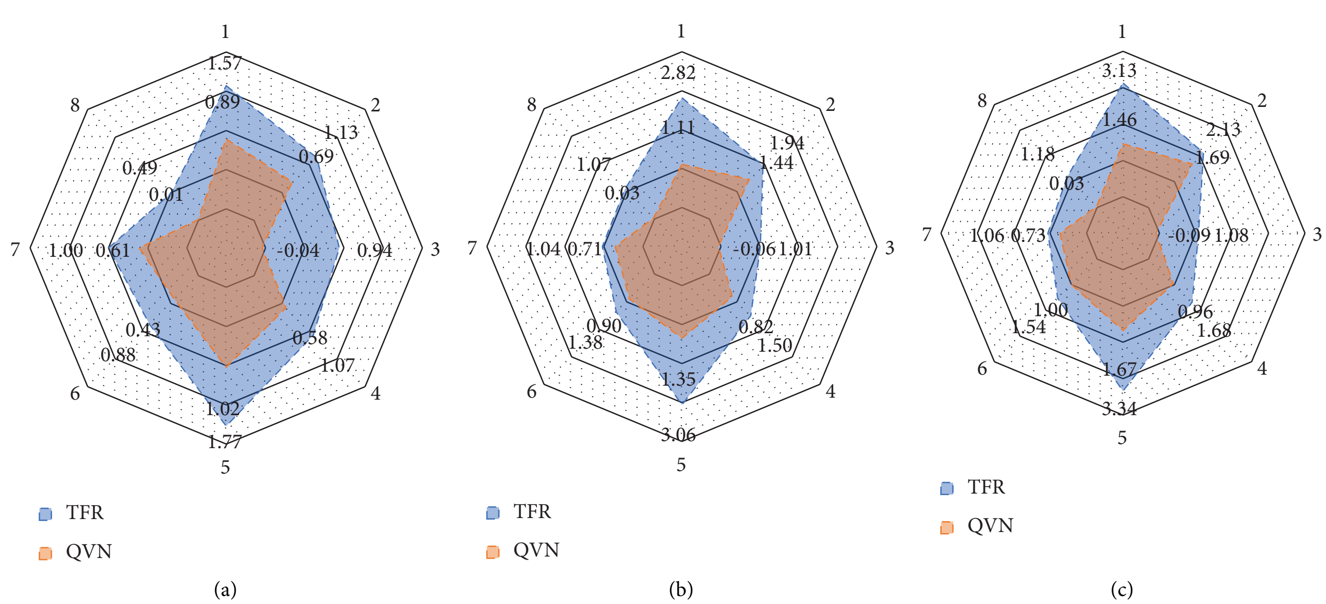


FIGURE 17: Benefits of QVN and TFR in different setting conditions: (a) bus intersect condition, (b) bus parallel condition, and (c) intermittent bus lane condition.

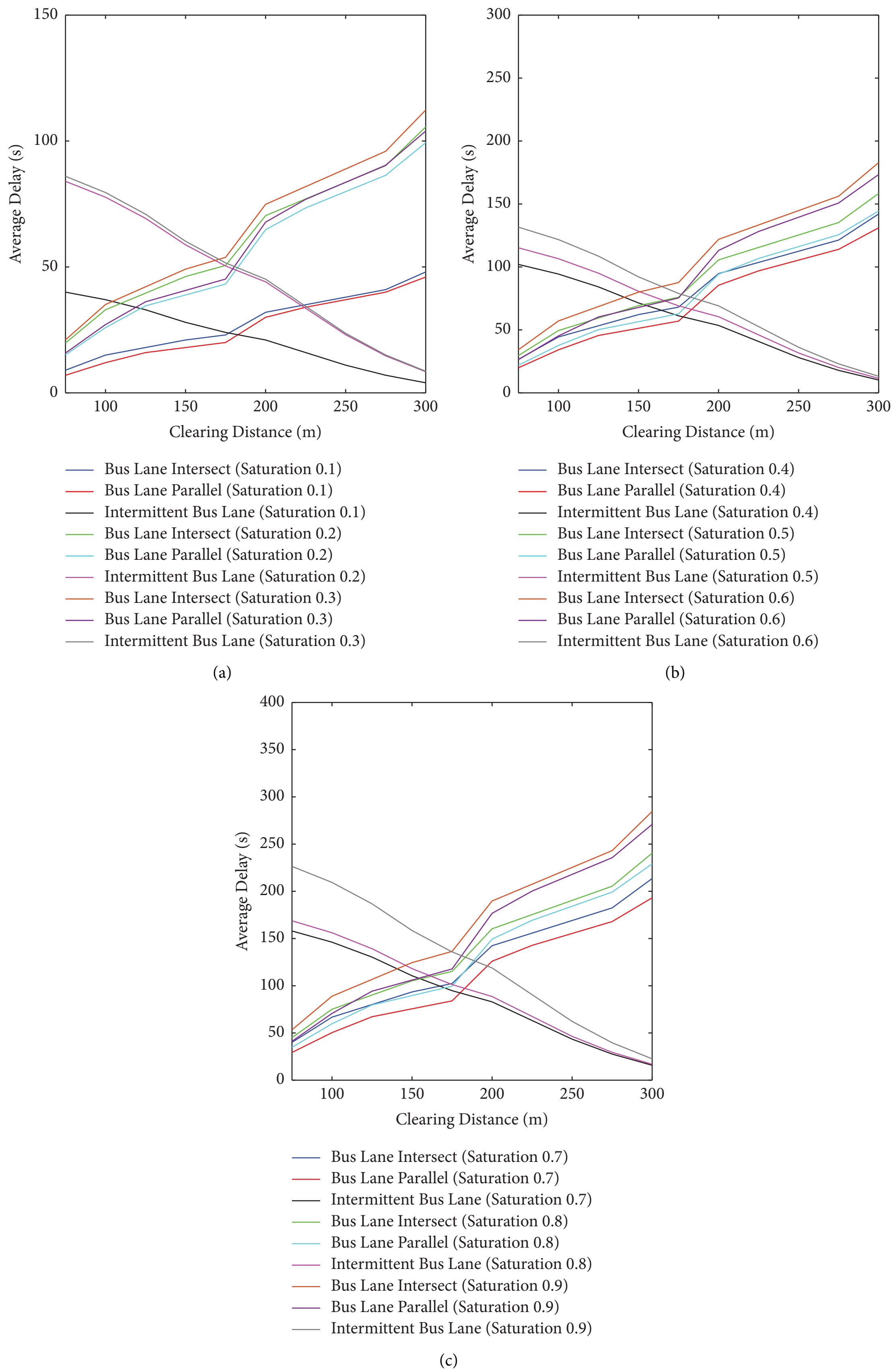


Figure 18: The sensitivity analysis of average delay under different clearing distances and saturations: (a) 0.1~0.3, (b) 0.4~0.6, and (c) 0.7~0.9.

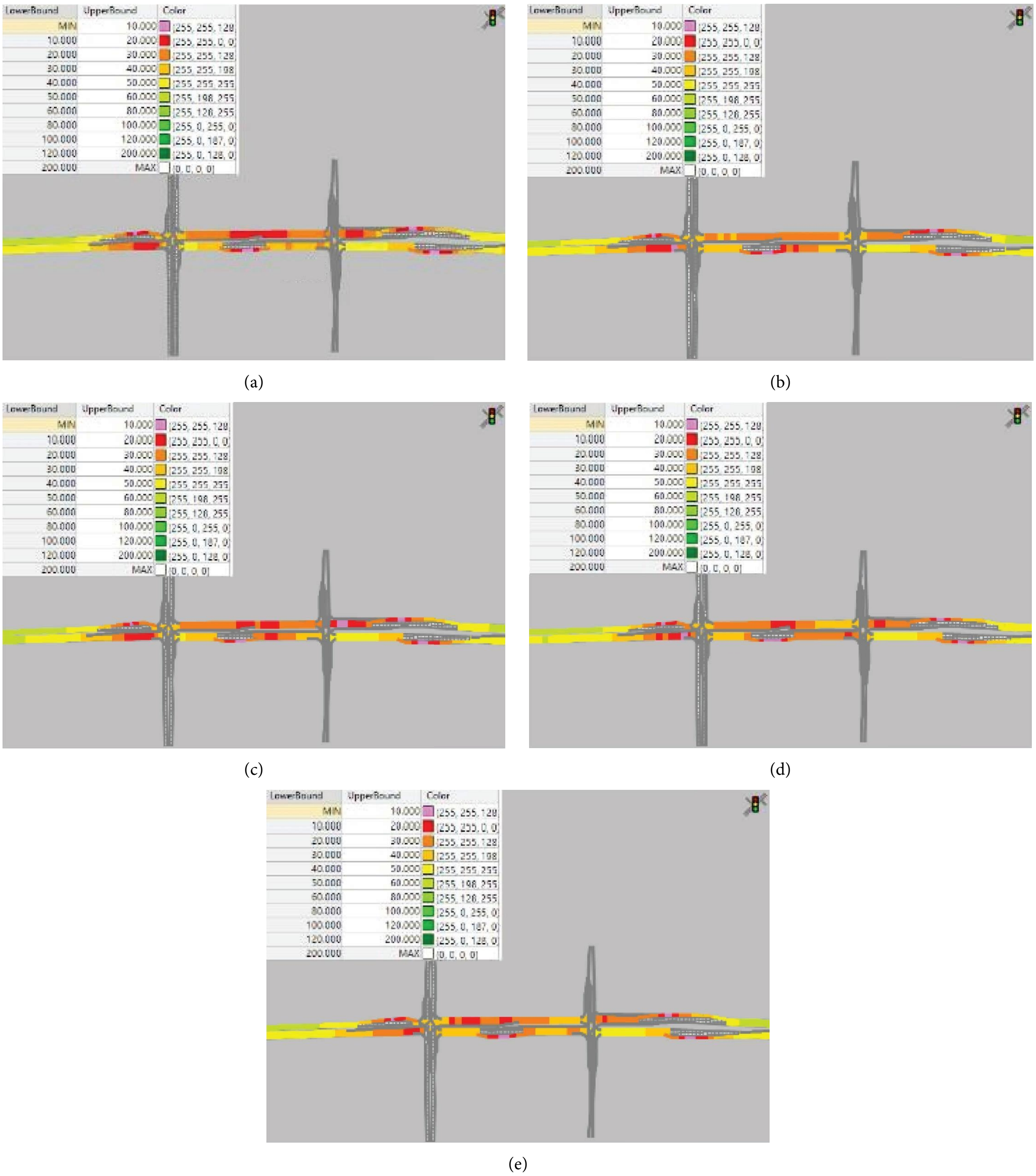


Figure 19: The speed distribution of bus under different saturations: (a) 0.1~0.2, (b) 0.3~0.4, (c) 0.5~0.6, (d) 0.7~0.8, and (e) 0.9~1.0.

distance at each level of saturation. On the other hand, the average delay of bus lane parallel and bus lane intersect increases with increasing clearing distance at each level of saturation. When the saturation is greater than 0.8 and the clearing distance is set to 150~200 m, it can satisfy the clear rule for social vehicles, thus reducing the average delay of social vehicles without affecting intermittent buses and improving the overall utilisation rate of road resources.

5.4.2. The Sensitivity Analysis of the Speeds of Social Vehicles and Buses under Different Saturations. The speed distribution of bus is shown in Figure 19. From Figure 19(a), it can be seen that a certain bus priority effect can be achieved even when the saturation is only 0.1~0.2. For example, on Ralph McGill Blvd in the east-to-west direction, there is about a 100 m long section where the average speed of bus increases from 30~40 km/h to 50~60 km/h.

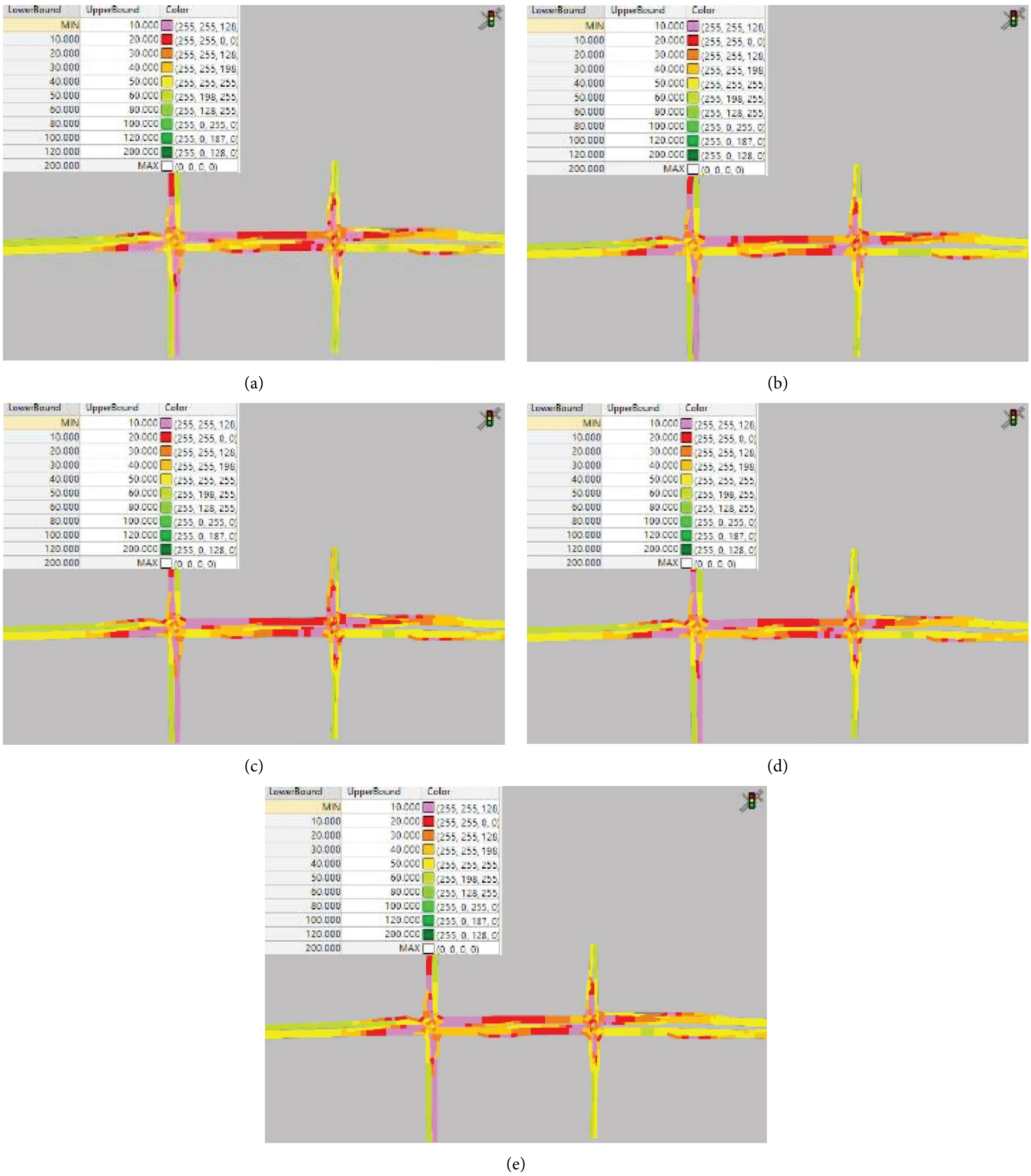


Figure 20: The speed distribution of social vehicle under different saturations: (a) 0.1~0.2, (b) 0.3~0.4, (c) 0.5~0.6, (d) 0.7~0.8, and (e) 0.9~1.0.

When saturation 0.3 is gradually increased to 0.4 (as shown in Figure 19(b)), an increase in average bus speed is also observed at some intersection entrances and road sections, but the increase is limited. This result shows that there may be some disruption as the number of social vehicles increases. Therefore, the effect of bus priority is limited. After the saturation level is gradually increased to 0.6 and 0.8 (as shown in Figures 19(c) and 19(d)), the average speed of buses also increases slightly at some intersections and road sections. Overall, the average speed of buses increases with the increase of social vehicles and there is a better guarantee effect of bus priority.

The speed distribution of social vehicle is shown in Figure 20. The results show that as the saturation of social vehicles increases, there is no significant change in the average speed of the overall traffic flow between the related road sections. This indicates that the average speed of traffic flow between related road sections is not very sensitive to saturation.

6. Conclusions

In view of the current low utilization rate of exclusive bus lane capacity and the lack of flexibility in the setting form, this paper presents a dynamic optimal setting and associated control for intermittent bus lane modelling method. Firstly, the heterogeneity of bus arrival time is analysed based on the process of vehicle queue aggregation and dissipation at intersections. Considering the correlation between social vehicles and bus operating state, a bus lane dynamic control strategy based on social vehicle insertable interval is established, then, combined with the setting conditions of the IBL control area and the intersection signal correlation scene. According to the HCM 2010 vehicle delay equation and the BPR function, the associated optimization control model is constructed with the minimum total travel time consumption of the road section as the objective function to realize the optimal control of the intermittent bus lane. We also design a bus lane dynamic control strategy based on social vehicle insertable interval and the corresponding model solving algorithm based on computational experiment. Combined with the actual case, design related experiments, and carried out experimental evaluation of the proposed method, the simulation results show that, intermittent bus lane is more suitable for low, medium, and relatively large flow conditions. Meanwhile, the total travel time consumption of intermittent bus lane has a high reduction rate. Through the sensitivity analysis of the model, the proposed method is applied to the traffic factors such as saturation is low 1.0 and clearing distance between 150 and 200 m. The results show that within a reasonable clearance distance, intermittent bus lanes can increase the average speed of buses, reduce the average delay, and further improve the effectiveness of bus priority. Similarly, the proposed model also has some limitations, such as what in conditions can be satisfied to give priority to buses in oversaturated traffic conditions. The model is constructed at a macrolevel and does not take into account the flow of bus passengers at different time periods and the dwell time at bus stop effect on lane settings.

There are still many areas of research for future studies, some of which are discussed below. For instance, the model can be more refined and dynamic to adapt to the complex and changeable road traffic environment, so that the lane setting scheme can be output more accurately and efficiently. In addition, if there is a high volume of social traffic on the same phase as the bus, consideration can also be given to integrate the combining this system with intersection bus signal prioritization to better achieve spatial and temporal bus prioritization.

Data Availability

The data presented in this study are available on request from the corresponding author.

Conflicts of Interest

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

Acknowledgments

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