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Impacts of bus holding strategy on the performance and pollutant emissions of a two-lane mixed traffic system

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This paper investigates the impacts of a bus holding strategy on the mutual interference between buses and passenger cars in a non-dedicated bus route, as well as the impacts on the characteristics of pollutant emissions of passenger cars. The dynamic behaviors of these two types of vehicles are described using cellular automata (CA) models under open boundary conditions. Numerical simulations are carried out to obtain the phase diagrams of the bus system and the trajectories of buses and passenger cars before and after the implementation of the bus holding strategy under different probabilities of passenger cars entering a two-lane mixed traffic system. Then, we analyze the flow rate, satisfaction rate, and pollutant emission rates of passenger cars together with the performance of a mixed traffic system. The results show that the bus holding strategy can effectively alleviate bus bunching, whereas it has no significant impact on the flow rate and pollutant emission rates of passenger cars; the flow rate, satisfaction rate, and pollutant emission rates of passenger cars for either the traffic system or for each lane are influenced by the bus departure interval and the number of passengers arriving at bus stops.

Keywords: mixed traffic flow, bus holding strategy, cellular automata, traffic emissions

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1. Introduction

Buses play a crucial role in mitigating traffic congestion and reducing environmental pollution in urban areas as an integral part of the public transportation system. However, buses can be affected by stochastic factors in actual operations, such as time-varying traffic demands at bus stops, uneven traffic demands between bus stops, traffic lights, etc., which ultimately leads to bus bunching. Then, bus bunching will lead to longer waiting time and higher travel costs for bus passengers.

To more accurately understand the mechanism of bus operations, researchers have devoted themselves to considerable studies on bus route systems and proposed various models, such as car-following models,[1,2] the time headway models,[3] and cellular automata (CA) models.[4,5] In these models, when a bus experiences a delay caused by various disruptions, it results in a gradual reduction of the time interval between the current bus and the subsequent bus, ultimately leading to bus bunching. Among the aforementioned models, the CA model is extensively utilized in traffic flow simulation owing to its efficient and rapid performance. The traffic flow CA model was initially proposed by Nagel and Schreckenberg[6] to reproduce the stop-and-go waves observed in real traffic.[7] Since then, numerous improved traffic flow CA models have been proposed,[8–10] including the Kerner–Klenoy–Wolf (KKW) model,[9] the brake light model,[10] and so on. The first CA model of a bus route system, developed by O'Loan *et al.*,[11] discovered that as bus density rises, traffic flow state transitions from a clustered state to a homogeneous state. Luo *et al.*[12] simulated a bus route using a single-lane CA model and obtained four phases of bus operations. Qiang *et al.*[13] analyzed the interaction between buses and passenger cars in a two-lane mixed traffic flow system. Zhou *et al.*[14] used a CA model to investigate the effects of bus bays on heterogeneous traffic flow. In addition, to mitigate the problem of bus bunching, the real-time control methods for buses have also become a focus of the public transportation research over the past decades. Klumpenhouwer *et al.*[15] adopted the Markov chain to model the stochastic nature of bus operations and proposed a bus holding strategy to mitigate bus bunching. Liang *et al.*[16] developed a self-adaptive control scheme to equalize the headway between buses, which can reduce the travel time of buses by about 12%. Apart from the bus holding strategy,[15,16] the stop-skipping[17,18] and coordinated control[19–21] strategies were also commonly used for bus control.

Recently, traffic emissions (i.e., vehicle emissions or vehicle pollutant emissions) have become a non-negligible constraint on the sustainable development of a society. Kaza *et al.*[22] discovered that the emissions of greenhouse gases from transportation were roughly equivalent to those of the electricity sector in America. The research conducted by Stafoggia *et al.*[23] revealed that atmospheric particulate matter posed a se-

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rious hazard to human cardiovascular and respiratory systems. In the pursuit of reducing traffic pollution, researchers have undertaken numerous studies focusing on traffic emissions from both simulated and experimental perspectives.[24–26] Panis *et al.*[24] developed a vehicle exhaust emission model that correlated traffic emissions with vehicles' instantaneous velocity and acceleration using the measured data from vehicle tailpipes. Zheng *et al.*[26] discussed the effects of traffic and meteorology on particle concentrations in varied temporal scales using real measurements.

Combining different traffic flow models and traffic emission models to investigate traffic pollution has been widely discussed.[27–36] Tang *et al.*[27,28] explored the relationship among fuel consumption, emissions, and the cost of travel without delays in the equilibrium state and studied the impacts of traffic signals on fuel consumption and emissions using a car-following model. Zhu *et al.*[29,30] unveiled the effects of traffic signals on carbon dioxide (CO_2) emissions of traffic flow and put a delay-feedback control strategy to mitigate traffic emissions. Lakouari *et al.*[32] used a CA model to study CO_2 emissions in a roundabout. Qiao *et al.*[34] investigated particulate matter (PM) emissions of two typical traffic flow CA models with a slow-to-start rule. Wang *et al.*[37] coupled a traffic flow CA model with a traffic emission model to reveal the emissions of pollutants such as CO_2, nitrogen oxides (NO_x), volatile organic compounds (VOC), and PM in a single-lane mixed traffic flow.

In previous studies, there are sparse researches on the control strategies for non-dedicated bus routes from a microscopic perspective. Furthermore, it is rare to study the traffic emissions in non-dedicated bus routes using CA models. Given this, in a two-lane mixed traffic system with a non-dedicated bus route, we investigate a traffic flow CA model under open boundary conditions to study the effects of a bus holding strategy on the flow rate, satisfaction rate and pollutant emission rates of passenger cars together with the performance of a mixed traffic system.

The rest of the paper is organized as follows. Section 2 presents the mixed traffic flow model and the bus holding strategy in a two-lane mixed traffic system with a non-dedicated bus route. Section 3 introduces the empirical traffic emission model. Section 4 fulfills the numerical simulations and the result analyses. Section 5 gives some conclusions.

2. Mixed traffic flow model

In this section, a two-lane CA model which considers buses and passenger cars is introduced. Subsection 2.1 describes a two-lane mixed traffic system with a bus route. Subsection 2.2 presents the traffic flow CA model for buses and passenger cars (collectively called as vehicles). Subsection 2.3 gives the optimal dwell time of a bus at a bus stop.

Notations of model parameters and variables are listed in Table 1.

Table 1. Notations of model parameters and variables.

Notion	Description
N_S	number of bus stops
l_B	length of a bus
l_C	length of a passenger car
l	distance between two adjacent bus stops
T_D	bus departure interval
α	probability of passenger cars entering the traffic system
T	desired time gap
s_n^E	effective spacing
x_S	position of the bus stop
$v_n(t)$	velocity of vehicle n at time step t
$v_n^{PV}(t)$	desired velocity of the preceding vehicle at time step t
$x_n(t)$	position of vehicle n at time step t
$b_n(t)$	brake light state of vehicle n at time step t
$t_n^S(t)$	spacing between vehicle n and its preceding vehicle at time step t
$s_n(t)$	spacing between vehicle n and its preceding vehicle at time step t
$s_n^{PV}(t)$	spacing between passenger car n and the preceding vehicle on the target lane at time step t
$s_n^{LV}(t)$	spacing between passenger car n and the lagging vehicle on the target lane at time step t
$\hat{d}$	ability of vehicle to randomly slow down
p	randomization probability
T_n^D	dwell time of bus n
T_n^S	time for passengers getting on and off a bus
T_n^H	holding time
$T_{n,s}^O$	optimal dwell time of bus n at bus stop s
N_A	number of passengers arriving at a bus stop per minute
M	passenger capacity of a bus
$N_s^P(t)$	number of passengers waiting for a bus at bus stop s at time step t
$N_{n,s}^B(t)$	number of passengers on bus n when it arrives at bus stop s at time step t
$N_{n,s}^O(t)$	number of passengers getting off a bus at bus stop s
$N_{n,s}^I(t)$	number of passengers allowed to get on a bus at bus stop s

2.1. Bus route description

The schematic diagram in Fig. 1 illustrates a two-lane mixed traffic system with a bus route. In the system, both buses and passenger cars are encompassed. The length of a bus, that of a passenger car and that of a vehicle are denoted by l_B, l_C, and $L_V \in \{L_B, L_C\}$, respectively. The lane without bus stops and that with bus stops are denoted by lane 1 and lane 2, respectively. Each lane can be regarded as a lattice consisting of L cells. Along lane 2, there are N_S bus stops without bus bays. These bus stops are numbered as 1, 2, 3, ..., N_S sequentially from left to right.

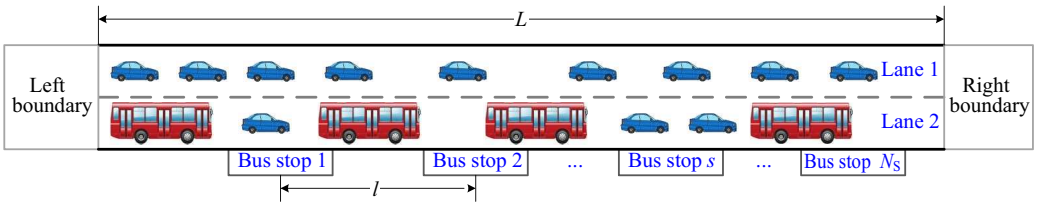


Fig. 1. Schematic diagram of a two-lane mixed traffic system.

To focus on the impacts of the bus holding strategy on the performance and pollutant emissions of traffic flow, the following assumptions are made in this paper.

(i) Bus stops are uniformly arranged along lane 2,[12,13] and the distance between two adjacent bus stops is l cells, thus a total road length is $L=(N_{\rm S}+1)l$ cells.

(ii) The length of a bus stop is equivalent to that of a bus.[12]

(iii) Buses are restricted to run on lane 2 without overtaking, while passenger cars can run on lane 1 or lane 2.[4,13]

(iv) Passengers always board the first-arriving bus unless that bus is full.

(v) All passengers are homogeneous, meaning that factors such as route selection and transfers are not considered.

2.2. Updating rules of vehicle movement with open boundary

During the operations of a bus, it begins along its route from the origin bus stop, passes through multiple intermediate bus stops, and ultimately arrives at the destination bus stop. To depict this progression, open boundary conditions are employed in the process of model formulation.

Each bus enters the traffic system from the left boundary of lane 2, then passes through $N_{\rm S}$ bus stops in sequence, and exits from the right boundary of lane 2 at last. At each bus departure interval $T_{\rm D}$, if the first $l_{\rm B}$ cells of lane 2 are free, a new bus without passengers will enter lane 2; otherwise, no new bus will be generated. After each bus updates its position, if the position of the leading bus $x_{\rm L}$ is greater than L, this leading bus will be removed and its follower will replace it to become a new leader; otherwise, the leading bus will continue to run on lane 2.

Each passenger car enters the traffic system from the left boundary of lane 1 or that of lane 2 with a probability α; it selects lane 1 with a probability P, while selecting lane 2 with a probability $1-P$. At each time step t, if the first $l_{\rm C}$ cells of lane 1 or those of lane 2 are unoccupied, a new passenger car will enter lane 1 with a probability αP or lane 2 with a probability $\alpha(1-P)$; otherwise, no passenger car will be generated. Similarly, after each passenger car updates its position, the leading passenger car will be removed when its position $x_{\rm L}$ is greater than L; otherwise, it continues to run.

The updating rules for each vehicle consist of two subprocesses, i.e., longitudinal and lateral movement rules.

2.2.1. Longitudinal movement rules

In the longitudinal direction, the velocity and position updating are considered for each vehicle. The desired time gap brake light (DTGBL) model[38] is adopted to depict the longitudinal movement of each vehicle in each lane. $v_n(t)$ and $x_n(t)$ represent the velocity and position (i.e., position of the front) of vehicle n at time step t, respectively; here n belongs to $\{1,2,3,\ldots,N\}$, and N is the number of vehicles in a single lane. In the two-lane traffic, a car is relabeled after changing a lane. At each evolutionary time step $t\to t+1$, the parallel updating rules of the DTGBL model are as follows.

Step 1 Acceleration

If a vehicle accelerates, its velocity updating rule is

$$v_n(t+1)=\begin{cases}\min[v_n(t)+a_{\rm Q},v_{\rm M}], & [b_n(t)=0||t_n(t)\geq t_n^{\rm S}(t)]\ \ \&\ \ v_n(t)>0,\\ \min[v_n(t)+a_{\rm S},v_{\rm M}], & !\{[b_n(t)=0||t_n(t)\geq t_n^{\rm S}(t)]\ \ \&\ \ v_n(t)>0\},\end{cases}$$
$$t_n(t)=\frac{x_{n+1}(t)-x_n(t)-L_{\rm V}}{v_n(t)},\quad t_n^{\rm S}(t)=\min\left[v_n(t),h\right], \tag{1}$$

where $a_{\rm Q}$ and $a_{\rm S}$ are the values of acceleration taken by a vehicle in the relatively quick and slow states, respectively; $v_{\rm M}$ is the maximum velocity of a vehicle; $b_n(t)$ is the brake light state of vehicle n at time step t, $b_n(t)=1$ means the brake light on, $b_n(t)=0$ means the brake light off; $t_n(t)$ and $t_n^{\rm S}(t)$ are the time gap and safety time gap that vehicle n reaches the position of the rear of its preceding vehicle at time step t, respectively; h is the interaction range of the brake light; &, ||, and ! are logical operators representing 'and', 'or', and 'not', respectively; min means minimize.

Step 2 Deceleration

If a vehicle decelerates, its velocity updating rule is

$$v_n(t+1)=\min\left[v_n(t+1),\left\lceil\frac{1}{T}s_n^{\rm E}(t)\right\rceil\right],$$

$$v_n(t+1) < v_n(t), \quad b_n(t+1) = 1, \tag{2}$$

where $\lceil x \rceil$ is the minimal integer which is greater than or equals to x; T is the desired time gap; $s_n^{\mathrm{E}}(t)$ is the effective spacing.

When vehicle n slows down, it will switch on its brake light. Thus, $s_n^{\mathrm{E}}(t)$ can be expressed as

$$\begin{aligned} s_n^{\mathrm{E}}(t) &= s_n(t) + \max\left[\left(v_n^{\mathrm{PV}}(t) - g\right), 0\right], \\ s_n(t) &= x_{n+1}(t) - x_n(t) - l_{\mathrm{V}}, \\ v_n^{\mathrm{PV}}(t) &= \min\left[s_{n+1}(t), v_{n+1}(t)\right], \end{aligned} \tag{3}$$

where $s_n(t)$ is the spacing between vehicle n and its preceding vehicle at time step t, $l_{\mathrm{V}} = l_{\mathrm{C}}$ if the preceding vehicle is a passenger car, otherwise, $l_{\mathrm{V}} = l_{\mathrm{B}}$; $v_n^{\mathrm{PV}}(t)$ is the desired velocity of the preceding vehicle of vehicle n at time step t; g is a parameter to guarantee safety for the subject vehicle and its preceding vehicle; max means maximize.

When vehicle n is a bus and needs to stop, the spacing is determined not only by the empty cells between the bus and the preceding vehicle, but also by the spacing between the bus and the next bus stop. In this case, $s_n(t)$ needs to be rewritten as

$$s_n(t) = \min\left[x_{n+1}(t) - x_n(t) - l_{\mathrm{V}}, x_{\mathrm{S}} - x_n(t)\right], \tag{4}$$

where x_{S} is the position of the bus stop which is the closest to vehicle n.

Step 3 Randomization with probability p

If a vehicle randomly slows down, its velocity updating rule is

$$\begin{aligned} &v_n(t+1) = \max\left[v_n(t+1) - \hat{d}, 0\right], && \mathrm{rand}() < p, \\ &p = p_{\mathrm{B}}, && \mathrm{rand}() < p, b_n(t+1) = 1, \end{aligned} \tag{5}$$

where $\hat{d}$ is the ability of a vehicle to randomly slow down; rand() is a random number within [0,1]; p is the randomization probability; p_{B} is the braking probability when a vehicle switches on its brake light.

Here, the randomization probability satisfies the following conditions:

$$p = \begin{cases} p_{\mathrm{B}}, & b_{n+1}(t) = 1 \ \ \& \ \ t_n(t) < t_n^{\mathrm{S}}(t), \\ p_0, & v_n(t) = 0, \\ p_{\mathrm{D}}, & !\left[\left(b_{n+1}(t) = 1 \ \ \& \ \ t_n(t) < t_n^{\mathrm{S}}(t)\right) | v_n(t) = 0\right], \end{cases} \tag{6}$$

where p_{B}, p_0, and p_{D} are different randomization probabilities.

Step 4 Motion

After the velocity of a vehicle is updated, its position updating rule is

$$x_{n+1}(t) = x_n(t) + v_{n+1}(t). \tag{7}$$

2.2.2. Lateral movement rules

Lane-changing behavior is an important component of the CA model for multi-lane traffic flow. Because buses do not change lanes, so the lane-changing rules[13] are used to guide the lane-changing decisions for passenger cars. The lane-changing is permitted if the following conditions are satisfied.

(i) Incentive condition

When a passenger car driver finds that the driving conditions on the target lane (the lane that the passenger car driver intends to enter) are superior to those on the current lane, the passenger car driver will have the motivation to change a lane. This condition can be expressed as

$$s_n^{\mathrm{PV}}(t) > s_n(t), \tag{8}$$

where $s_n^{\mathrm{PV}}(t)$ is the spacing between passenger car n and the preceding vehicle on the target lane at time step t.

(ii) Safety condition

The act of a passenger car changing a lane to the target lane should not disrupt the normal movement of the lagging vehicle on the target lane, this condition can be expressed as

$$s_n^{\mathrm{LV}}(t) > v_{\max}, \tag{9}$$

where $s_n^{\mathrm{LV}}(t)$ is the spacing between passenger car n and the lagging vehicle on the target lane at time step t; $v_{\max}$ is the maximum desired velocity of a vehicle.

2.3. Optimal dwell time for buses

When bus n arrives at bus stop s, its estimated dwell time T_n^{D} needs to be calculated, which is determined by two factors: the service time T_n^{S} for passengers getting on and off a bus, and the holding time T_n^{H} calculated using the bus holding strategy. The estimated dwell time can be expressed as

$$T_n^{\mathrm{D}} = \max(T_n^{\mathrm{S}}, T_n^{\mathrm{H}}). \tag{10}$$

2.3.1. Service time

It is assumed that a passenger arrives at each bus stop at each time step with a probability $P_{\mathrm{A}} = N_{\mathrm{A}}/60$, where N_{A} represents the average number of passengers arriving at a bus stop per minute. Also, the number of passengers waiting for a bus at bus stop s at time step t is denoted by $N_s^{\mathrm{P}}(t)$.[12] When a passenger arrives at bus stop s at time step t, the updating rule of the number of passengers waiting for a bus at bus stop s at each evolutionary time step $t \to t+1$ is

$$N_s^{\mathrm{P}}(t+1) = \begin{cases} N_s^{\mathrm{P}}(t) + 1, & \mathrm{rand}() \le P_{\mathrm{A}}, \\ N_s^{\mathrm{P}}(t), & \mathrm{rand}() > P_{\mathrm{A}}, \end{cases} \tag{11}$$

where s belongs to $\{1, 2, 3, \ldots, N_{\mathrm{S}} - 1\}$ since there is no passenger to board a bus at the last bus stop.

When bus n arrives at bus stop s at time step t, it is required to serve for a period to allow passengers to get on and off a bus. Let $N_{n,s}^{\mathrm{B}}(t)$ represent the number of passengers on

bus n when it arrives at bus stop s at time step t. Then, the number of passengers getting off at bus stop s, denoted by $N^{\mathrm{O}}_{n,s}(t)$, can be given by

$$N^{\mathrm{O}}_{n,s}(t)=\begin{cases}0, & s=1,\\ \mu\cdot N^{\mathrm{B}}_{n,s}(t), & s\in\{2,3,4,\cdots,N_{\mathrm{S}}-1\},\\ N^{\mathrm{B}}_{n,s}(t), & s=N_{\mathrm{S}},\end{cases}\tag{12}$$

where μ is the percentage of passengers getting off a bus, and no passenger gets off a bus at the initial bus stop, and all the passengers get off a bus at the last bus stop.

Let M be the passenger capacity of a bus, thus the number of passengers allowed to get on a bus at bus stop s, denoted by $N^{\mathrm{I}}_{n,s}(t)$, can be expressed as

$$N^{\mathrm{I}}_{n,s}(t)=\min\left[N^{\mathrm{P}}_{s}(t+1),M-N^{\mathrm{B}}_{n,s}(t)+N^{\mathrm{O}}_{n,s}(t)\right].\tag{13}$$

Then, the number of passengers on bus n at the next bus stop is computed as

$$N^{\mathrm{B}}_{n,s+1}(t)=N^{\mathrm{B}}_{n,s}(t)-N^{\mathrm{O}}_{n,s}(t)+N^{\mathrm{I}}_{n,s}(t).\tag{14}$$

Next, the number of passengers waiting for the next bus at bus stop s at the next time step is calculated as

$$N^{\mathrm{P}}_{s}(t+1)=N^{\mathrm{P}}_{s}(t)-N^{\mathrm{I}}_{n,s}(t).\tag{15}$$

Correspondingly, the service time for bus n at bus stop s, denoted by $T^{\mathrm{D}}_{n,s}$, is

$$T^{\mathrm{D}}_{n,s}=\max\left(\beta_{\mathrm{I}}N^{\mathrm{I}}_{n,s}(t),\beta_{\mathrm{O}}N^{\mathrm{O}}_{n,s}(t)\right)+\kappa,\tag{16}$$

where β_{I} and β_{O} are the average time of getting on a bus and that of getting off a bus for one passenger, respectively, and β_{I} is greater than β_{O} since getting on a bus takes longer time than getting off a bus; κ is a parameter to represent the time required to open and close the doors of a bus at a bus stop.

2.3.2. Holding time

It is assumed that the bus holding strategy[16] is applicable to each bus except the leading bus at all the bus stops. If bus n is not the leading bus, the bus holding strategy implemented by bus n at bus stop s is as follows.

When bus n arrives at bus stop s at time step t, the time gap between bus n and the preceding bus and that between it and the lagging bus are denoted by $t^{+}_{n}(t)$ and $t^{-}_{n}(t)$, respectively. To avoid bus bunching, the holding time for bus n at bus stop s, denoted by $T^{\mathrm{H}}_{n,s}$, is given by

$$T^{\mathrm{H}}_{n,s}=\begin{cases}\lambda\left[t^{-}_{n}(t)-t^{+}_{n}(t)\right], & t^{-}_{n}(t)>t^{+}_{n}(t),\\ 0, & t^{-}_{n}(t)\le t^{+}_{n}(t),\end{cases}\tag{17}$$

where $\lambda\in(0,1)$ is a parameter and set to 0.5 to ensure the convergence rate.[10]

Then, $t^{+}_{n}(t)$ and $t^{-}_{n}(t)$ are expressed as

$$t^{+}_{n}(t)=t^{\mathrm{A}}_{n,s}-t^{\mathrm{D}}_{n+1,s},$$

$$t^{-}_{n}(t)=\frac{x_s-x_{n-1}}{\bar{v}},\tag{18}$$

where $t^{\mathrm{A}}_{n,s}$ is the time that bus n arrives at bus stop s; $t^{\mathrm{D}}_{n+1,s}$ is the time that bus $n+1$ leaves bus stop s; x_s is the position of bus stop s; x_{n-1} is the position of bus $n-1$; $\bar{v}$ is the average velocity of a bus towards a bus stop.

When the dwell time of bus n at bus stop s is greater than zero, it means that bus n needs to serve passengers or implement the bus holding strategy. In this case, if there is still space left on bus n and there are new passengers arriving at bus stop s, bus n must prolong its service time at bus stop s. Let $T^{\mathrm{P}}_{n,s}$ represent the prolong time of bus n at bus stop s, thus the optimal dwell time of bus n at bus stop s, denote by $T^{\mathrm{O}}_{n,s}$, is expressed as

$$T^{\mathrm{O}}_{n,s}=\max\left(T^{\mathrm{D}}_{n,s}+T^{\mathrm{P}}_{n,s},T^{\mathrm{H}}_{n,s}\right).\tag{19}$$

3. Traffic emission model

Panis *et al.*[24] developed an empirical model to estimate traffic emissions using the nonlinear multiple regression technique and the measured data. This model considers the instantaneous velocity and acceleration of each vehicle. At 95% confidence level, CO_2 emissions produced by vehicles can be exactly predicted. The Panis emission model only considers exhaust pollutant emissions emitted by the engine through the tailpipe,[39] and allows researchers to estimate traffic emissions in real-time during traffic simulation (online traffic emissions estimation), which implies that the effects of traffic lights, pedestrian crossings, etc. on traffic flow can be reflected by the pollutant emissions immediately captured by the Panis emission model. The Panis emission model is widely utilized by the scientific community, where recent studies employ it as an online traffic emission estimator.[31,36,40,41] The researchers integrated the Panis emission model with traffic modeling approaches based on CA model, car-following, or fluid dynamics to examine the effects of different situations on traffic emissions. Woodward *et al.*[42] utilized the Panis emission model to investigate the dispersion of pollutants on an intersection modeled as a fluid dynamics problem. Wang *et al.*[43] followed a CA approach to analyze the impacts of the follower stopper control strategy on traffic efficiency, pollutant emissions, etc. under different penetration rates of connected and automated vehicles.

The Panis emission model incorporates a lower limit of pollutant emissions (E_0 in units of g/s). The pollutant emissions have severe negative impacts on human beings. In this study, it is assumed that buses are new-energy vehicles and do not produce pollutant emissions, and CO_2, NO_x, VOC, PM emissions of petrol passenger cars are considered. Then, the pollutant emissions of passenger car n at time step t, denoted

by $E_n(t)$, can be given by

$$E_n(t) = \max\left[E_0, f_1 + f_2 v_n(t) + f_3 v_n(t)^2 + f_4 a_n(t) + f_5 a_n(t)^2 + f_6 v_n(t) a_n(t)\right], \quad (20)$$

where $a_n(t)$ is the acceleration of passenger car n at time step t; f_1, f_2, f_3, f_4, f_5, f_6 are all the parameters to estimate the pollutant emissions and determined using nonlinear regression techniques.

Table 2 lists the calibrated values of the parameters in Eq. (20) for CO_2, NO_x, VOC, PM emissions of petrol passenger cars.

The emissions of traffic flow, denoted by $\bar{E}$, can be reflected by the average emissions of passenger cars and defined as

$$\bar{E} = \frac{1}{T'}\frac{1}{N}\sum_{t=t_0+1}^{t_0+T'}\sum_{n=1}^{N} E_n(t), \quad (21)$$

where t_0 and T' are the start time and the duration of an analysis period, respectively; N is the number of passenger cars during the analysis period.

Table 2. Calibrated values of the parameters in Eq. (20).

Pollutant	Parameter						
	E_0	f_1	f_2	f_3	f_4	f_5	f_6
CO_2	0	5.53×10^{-1}	1.61×10^{-1}	-2.89×10^{-3}	2.66×10^{-1}	5.11×10^{-1}	1.83×10^{-1}
NO_x	0	6.19×10^{-4}	8.00×10^{-5}	-4.03×10^{-6}	-4.13×10^{-4}	3.80×10^{-4}	1.77×10^{-4}
VOC	0	4.47×10^{-3}	7.32×10^{-7}	-2.87×10^{-8}	-3.41×10^{-6}	4.94×10^{-6}	1.66×10^{-6}
PM	0	0	1.57×10^{-5}	-9.21×10^{-7}	0	3.75×10^{-5}	1.89×10^{-5}

Table 3. Parameter settings during traffic simulation.

Parameter	N_S	l	P	h	T	p_B	p_0	p_D	g	M	μ	β_I	β_O	κ
Value	30	500	0.3	6	1.8	0.94	0.5	0.1	7	100	0.25	1.4	0.8	6
Unit	–	cells	–	s	s	–	–	–	cells	persons	–	s	s	s

During traffic simulation, each cell corresponds to 1.5 m on a real road, and one time step represents 1 s in reality. According to the related references,[12,13] each passenger car takes up 5 cells and can reach a maximum velocity of 12 cells per time step; each bus takes up 8 cells and can reach a maximum velocity of 8 cells per time step. Besides, the values of other parameters are shown in Table 3.[13,38] Traffic simulation is performed with 30 independent runs. Each run lasts for 2×10^4 s and the data of the first 1.2×10^4 s of each run are discarded in measuring traffic emissions.

4. Results and discussion

4.1. Operational states of buses

The operational states of buses can be classified into four different categories: homogeneous, bunching, with sufficient capacity, and with insufficient capacity. If the actual time gap between two successive buses arriving at a bus stop is not less than a half of the scheduled time gap, the operational state of buses is in a homogeneous state; otherwise, it is in a bunching state.[13,44] If the first-arriving bus has an enough capacity to pick up all the passengers waiting for a bus at a bus stop, thus the operational state of buses is in a state with sufficient capability. If the first-arriving bus cannot accommodate all the passengers waiting for a bus at a bus stop, thus a part of the passengers must wait for the next bus at the bus stop. At this case, the operational state of buses is in a state with insufficient capacity.

Figure 2 depicts the typical trajectories of buses under the homogeneous and bunching states, which are obtained before and after implementing the bus holding strategy. In this figure, T_D, α, and N_A are set to 2.5 min, 0, and 4 persons/min, respectively.

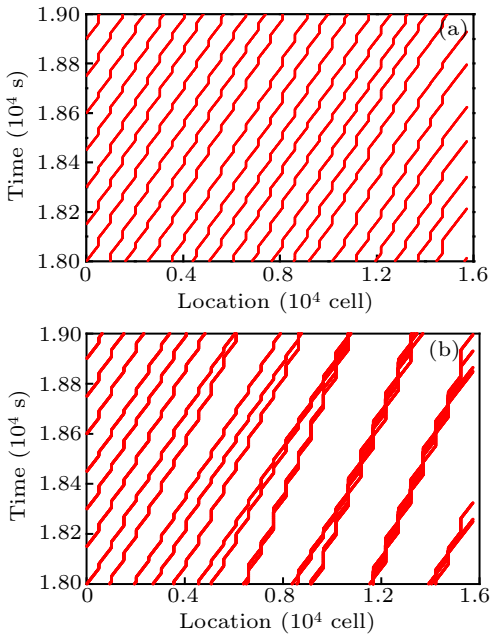


Fig. 2. Typical trajectories of buses: (a) homogeneous state, (b) bunching state.

Figure 3 illustrates the evolution of the number of passengers waiting for a bus at the selected bus stop corresponding to the states with insufficient and sufficient capacities, which are obtained before and after implementing the bus holding

strategy. Here, T_{D}, α, and N_{A} are set to 1 min, 0, and 6 persons/min, respectively.

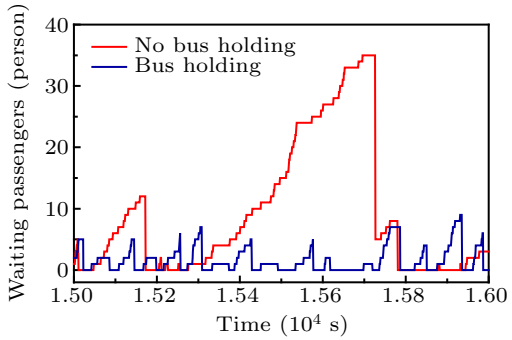


Fig. 3. Evolution of the number of passengers waiting for a bus at bus stop 25.

4.2. Phase diagrams of bus system

By combining the four operational states of buses described in Subsection 4.1, the bus system can be divided into the following four possible phases:

Region I: Homogeneous & sufficient capability;

Region II: Homogeneous & insufficient capability;

Region III: Bunching & sufficient capability;

Region IV: Bunching & insufficient capability.

Figure 4 shows the phase diagrams with the four phases described above in the (T_{D}, N_{A}) space under different probabilities of passenger cars entering the traffic system. Here, figures 4(a), 4(c), 4(e), and 4(g) represent the phase diagram without the bus holding strategy, whereas figures 4(b), 4(d), 4(f), and 4(h) represent the phase diagram with the bus holding strategy. In addition, figures 4(a) and 4(b) consider a special scenario in which passenger cars do not enter the bus system, that is, buses run in the dedicated bus lane. Figures 4(c), 4(d), 4(e), 4(f), 4(g), and 4(h) all consider mixed traffic flow consisting of buses and passenger cars.

Based on Fig. 4, it is evident that the area of bus bunching regions decreases even without implementing the bus holding strategy as the probability of passenger cars entering the traffic system increases. This phenomenon indicates that when T_{D} and N_A remain constant, different probabilities of passenger cars entering the traffic system may result in distinct bus operating conditions. Comparing the phase diagram obtained by no bus holding strategy with that obtained by bus holding strategy under the unchanged probability of passenger cars entering the traffic system, the noticeable difference occurs. The overall range of regions I and II obtained by no bus holding strategy is significantly smaller than that obtained by bus holding strategy, which implies that the bus holding strategy can effectively alleviate the bus bunching. Additionally, the overall range of regions II and IV obtained by no bus holding strategy is significantly larger than that obtained by bus holding strategy, which indicates that the bus holding strategy can effectively improve the bus capability.

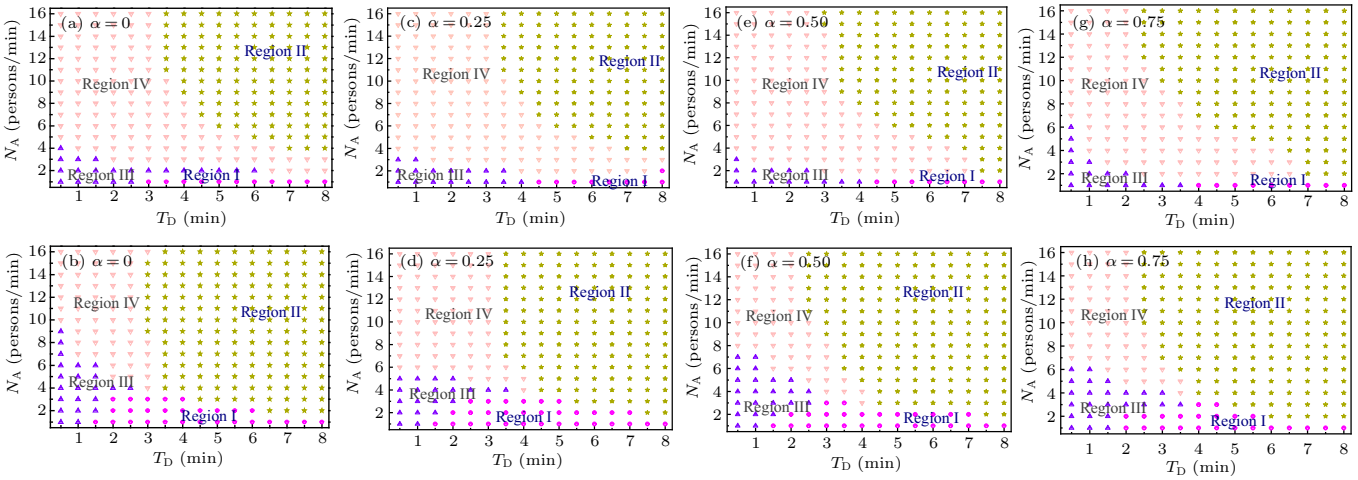


Fig. 4. Phase diagrams of the bus system: (a), (c), (e), and (g) no bus holding; (b), (d), (f), and (h) bus holding.

To validate the conclusion that different probabilities of passenger cars entering the traffic system may result in distinct bus operating conditions when T_{D} and N_{A} remain constant, the spatiotemporal patterns of buses on lane 2 under different probabilities of passenger cars entering the traffic system without the bus holding strategy are investigated. Specifically, we set $T_{\mathrm{D}} = 3$ min and $N_{\mathrm{A}} = 10$ persons/min per minute (simplified as (3,10)). The analysis is conducted for two cases: $\alpha = 0$ representing that no passenger cars enter the traffic system, and $\alpha = 0.75$ representing that 75% passenger cars enter the traffic system.

Figure 5 illustrates the spatiotemporal diagrams of buses under the parameter set (3,10), without implementing the bus holding strategy. Figure 5(a) depicts the scenario under which no passenger cars enter the traffic system, it can be seen that noticeable congestion in the bus trajectories is revealed, as highlighted by the purple elliptical regions. In contrast, figure 5(b) shows the bus trajectories when passenger cars enter

the traffic system with a probability of $\alpha = 0.75$, it can be seen that, unlike Fig. 5(a), there is no pronounced bus bunching.

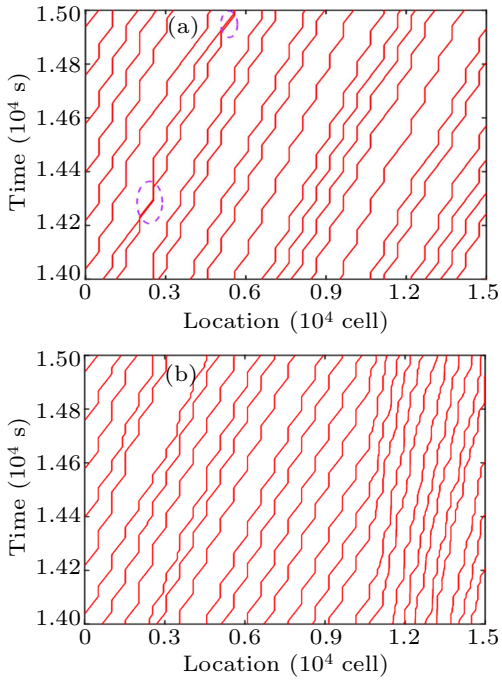


Fig. 5. Spatiotemporal diagrams of buses without implementing the bus holding strategy: (a) $\alpha = 0$, (b) $\alpha = 0.75$.

Figure 6 examines the intensity of buses under different probabilities of passenger cars entering the traffic system under the cases of (3,1) and (3,10). Here, the number of the bus holding actions is used to reflect the intensity of buses. As depicted in Fig. 6, the number of the bus holding actions first rises and then declines as the probability of passenger cars entering the traffic system increases. Further, the comparison of the bus holding actions reveals that the higher passenger demand is more likely to trigger the bus holding strategy when the probability of passenger cars entering the traffic system keeps unchanged.

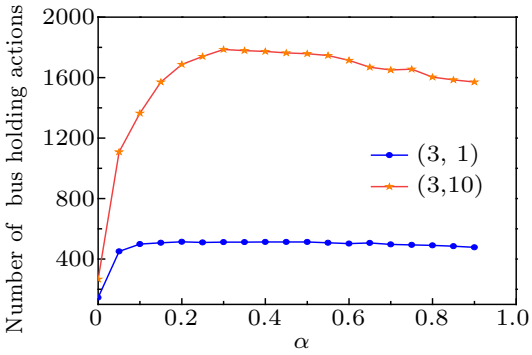


Fig. 6. Number of the bus holding actions in two cases.

Figure 7 illustrates the spatiotemporal diagram of buses and passenger cars on lane 2 under different probabilities of passenger cars entering the traffic system. In this figure, the corresponding parameters are set to (2,6), and the blue and red dots represent the trajectories of buses and passenger cars, respectively. Also, figures 7(a), 7(c), 7(e), and 7(g) display the spatiotemporal diagrams obtained without the bus holding strategy, whereas figures 7(b), 7(d), 7(f), and 7(h) show the spatiotemporal diagrams obtained by implementing the bus holding strategy.

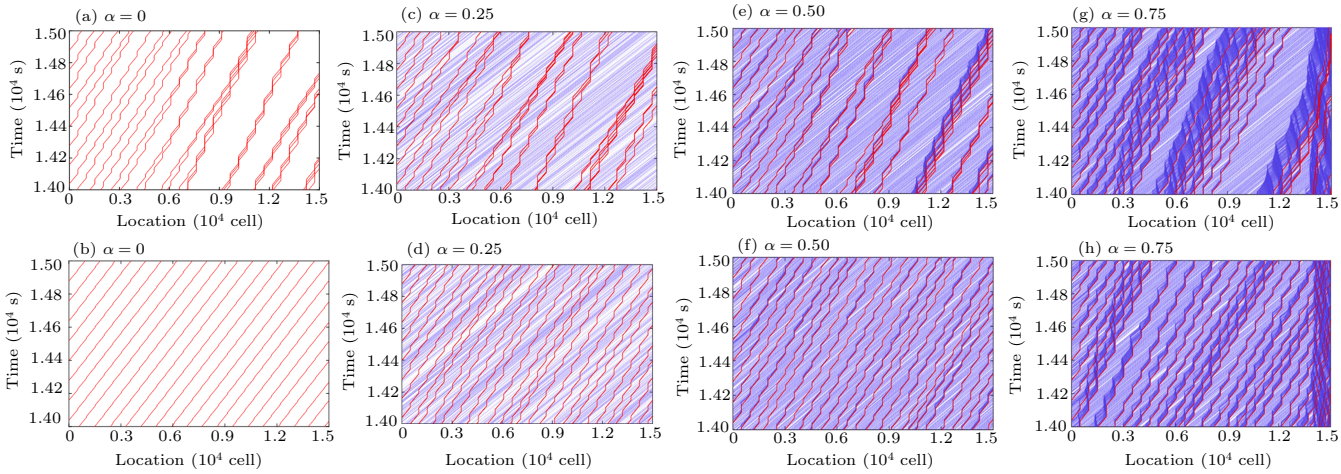


Fig. 7. Spatiotemporal diagrams of buses and passenger cars on lane 2: (a), (c), and (e) no bus holding; (b), (d), and (f) bus holding.

From Fig. 7, it can be seen that: (i) when the probability of passenger cars entering the traffic system remains unchanged, the bus holding strategy significantly alleviates the problem of bus bunching; (ii) when the probability of passenger cars entering the traffic system is relatively low, buses have an insignificant impact on passenger cars (see Fig. 7(c)); which is because the volume of traffic flow is relatively small, in this case, passenger cars following buses have sufficient opportunities to change lanes; (iii) as the number of passenger cars entering the traffic system rises, the chances of passenger cars changing lanes become more scarce; (iv) when buses stop at bus stops to provide service, more and more passenger cars gather behind them, which will lead to traffic jam; at this case, traffic jam gradually spreads upstream (see Figs. 7(g) and

7(h)).

4.3. Traffic flow characteristics and pollutant emissions

Whether implementing the bus holding strategy has effects on traffic flow characteristics (e.g., flow rate, satisfaction rate) and traffic emissions (i.e., pollutant emissions from petrol passenger cars). The parameter values of ($T_{\rm D}$, $N_{\rm A}$) are set to (5,1), (5,10), (2,1), and (2,10), each set of parameter values represents different phases of the bus system. Traffic simulation is conducted for these four scenarios, and the corresponding results are obtained.

Figure 8 represents the flow rate of passenger cars in the traffic system. It can be found that the flow rate of passenger cars in the traffic system is influenced by the bus departure interval and the number of passengers arriving at a bus stop. The longer the bus departure interval is, the fewer the number of passengers arriving at a bus stop is, and the higher the flow rate of passenger cars in the traffic system is.

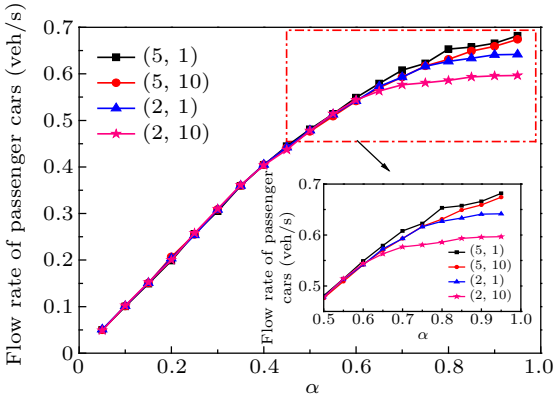


Fig. 8. Flow rate of passenger cars in the traffic system.

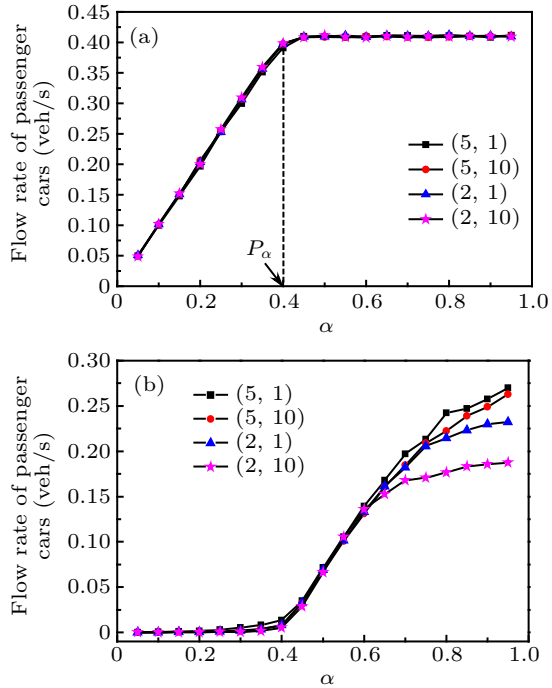


Fig. 9. Flow rate of passenger cars on each lane: (a) lane 1 and (b) lane 2.

Further, figure 9 illustrates the flow rate of passenger cars on lane 1 and that on lane 2 for the above-mentioned four scenarios. It can be found that the bus departure interval and the number of passengers arriving at a bus stop both affect the flow rate of passenger cars on lane 1 and that on lane 2, and these two factors particularly affect the latter; such effects on lane 2 show a similar trend with those on the traffic system, whereas those on lane 1 demonstrate an opposite trend with those on the traffic system.

Furthermore, we utilize the satisfaction rate to quantify whether passenger cars are traveling at the maximum desired velocity ($v_{\rm max}$) or whether they are being impeded by other vehicles while traveling. The satisfaction rate η is calculated by

$$\eta = \frac{1}{T'}\frac{1}{N}\sum_{t=t_0+1}^{t_0+T'}\sum_{n=1}^{N}\frac{v_n(t)}{v_{\rm max}}. \tag{22}$$

When η equals 1, it signifies ideal traffic flow, where all passenger cars are traveling at the maximum desired velocity. The smaller the value of η is, the lower the traffic volume of passenger cars in the traffic system is. In this case, passenger cars have to travel at slower velocities. Hence, η can be used to quantify the traffic state.

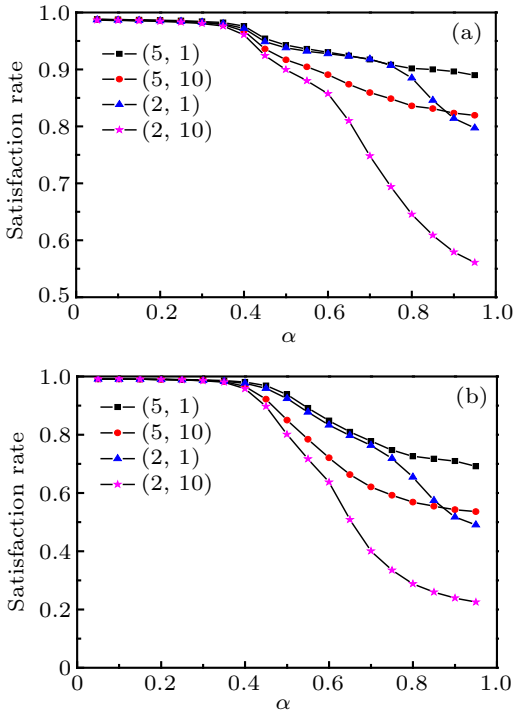


Fig. 10. Satisfaction rate of passenger cars on each lane: (a) lane 1, (b) lane 2.

As depicted in Fig. 10, both the bus departure interval and the number of passengers arriving at a bus stop similarly influence the satisfaction rate of passenger cars on lane 1 and that on lane 2. When the probability of passenger cars entering the traffic system is below 0.4, the satisfaction rate of passenger

cars on lane 1 and that on lane 2 remain nearly constant. However, if it exceeds 0.4, the satisfaction rate of passenger cars decreases as the bus departure interval shortens and the number of passengers arriving at the bus stop increases. It is noteworthy that the satisfaction rate of passenger cars on lane 2 is significantly lower than that on lane 1 for certain values of α, T_{D} and N_{A}. This discrepancy originates from shorter bus departure intervals and more passengers arriving at a bus stop both resulting in more frequent service stops, consequently causing a large number of passenger cars trailing behind a bus to substantially decelerate. In addition, passenger cars on lane 2 opt to switch lanes to lane 1 in pursuit of better driving conditions, thereby affecting the satisfaction rate of passenger cars on lane 1.

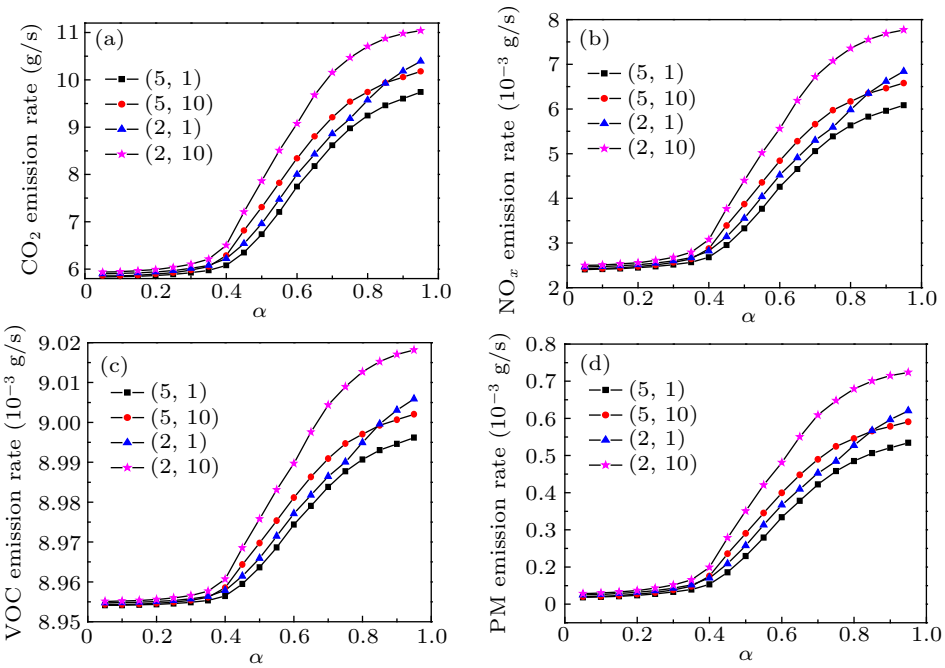


Fig. 11. Pollutant emission rates of passenger cars in the traffic system: (a) CO_2 emissions, (b) NO_x emissions, (c) VOC emissions, (d) PM emissions.

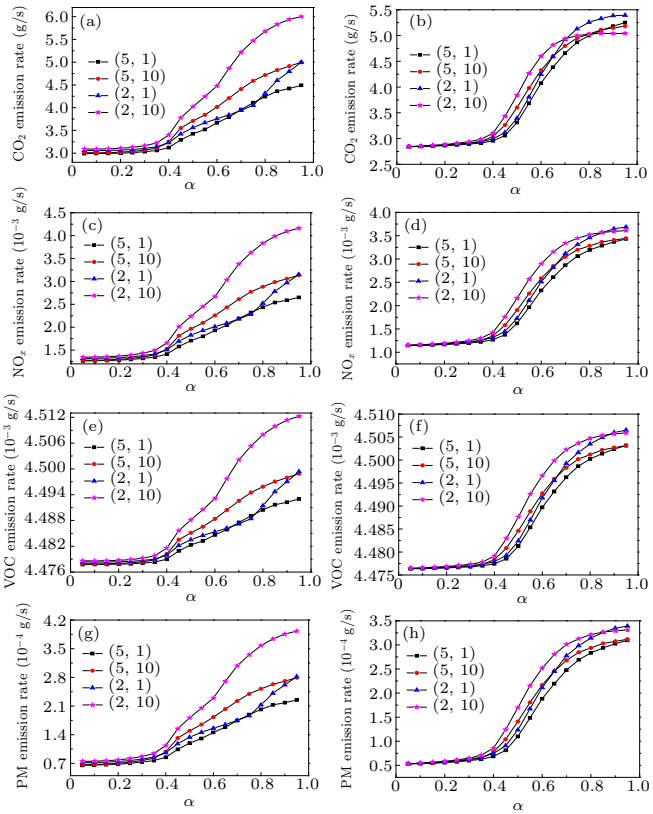


Fig. 12. Pollutant emission rates of passenger cars on each lane: (a), (c), (e), and (g) lane 1; (b), (d), (f), and (h) lane 2.

Figure 11 illustrates the CO_2, NO_x, VOC, and PM emission rates of passenger cars in the traffic system. It can be revealed that: (i) the change trends of CO_2, NO_x, VOC, and PM emission rates are roughly the same with the change of α; (ii) when the bus departure interval remains constant, as the number of passengers arriving at a bus stop increases, the pollution emission rates of passenger cars increase; (iii) when the number of passengers arriving at a bus stop remains constant, the shorter the bus departure interval is, the higher the pollution emission rates of passenger cars are. The phenomena originate from the reduction of the bus departure interval or the surge of passengers arriving at bus stops, leading to more buses in the traffic system and the stop time of a bus prolonged at bus stops. Consequently, the passenger cars trailing behind the buses must constantly adjust their velocities, ultimately resulting in more pollutant emissions.

Figure 12 depicts the CO_2, NO_x, VOC, and PM emission rates of passenger cars on lane 1 and those on lane 2. From Figs. 12(a), 12(c), 12(e), and 12(g), it is evident that the pollution emission rates of passenger cars on lane 1 in the case of (5,10) are greater than those in the case of (2,1), which suggests that the number of passengers arriving at a bus stop has the most significant impacts on the pollution emission rates of

passenger cars on lane 1. From Figs. 12(b), 12(d), 12(f), and 12(h), the greater the number of buses is, the higher the pollution emission rates of passenger cars are; which indicates that the bus departure interval has a more important effect on the pollution emission rates of passenger cars on lane 2.

To further explore the impacts of the bus holding strategy on passenger cars, the flow rate, satisfaction rate and pollution emission rate of passenger cars are shown before and after the implementation of the bus holding strategy, as depicted in Figs. 13–15.

When the parameters are set to (2,10), figure 13 depicts the flow rates of passenger cars with the change of α. It can be seen that the bus holding strategy has no significant impact on the flow rates of passenger cars either for the traffic system or for each lane.

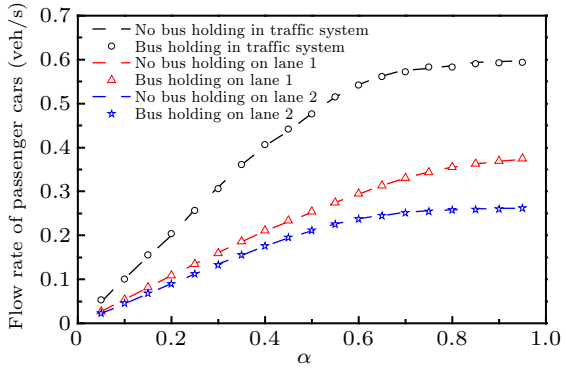


Fig. 13. Impacts of bus holding strategy on the flow rates of passenger cars.

Figure 14 illustrates the impacts of the bus holding strategy on the satisfaction rate of passenger cars on each lane. The results reveal that compared with no bus holding strategy, the bus holding strategy makes the satisfaction rate of passenger cars on lane 1 and that on lane 2 slightly decrease.

Since the changes of the CO_2, NO_x, VOC, and PM emissions of passenger cars are similar with the change of α, figure 15 only depicts the CO_2 emissions of passenger cars before and after the implementation of the bus holding strategy at different phases. It is evident that the bus holding strategy has rare impact on the CO_2 emissions of passenger cars either for the traffic system or for each lane.

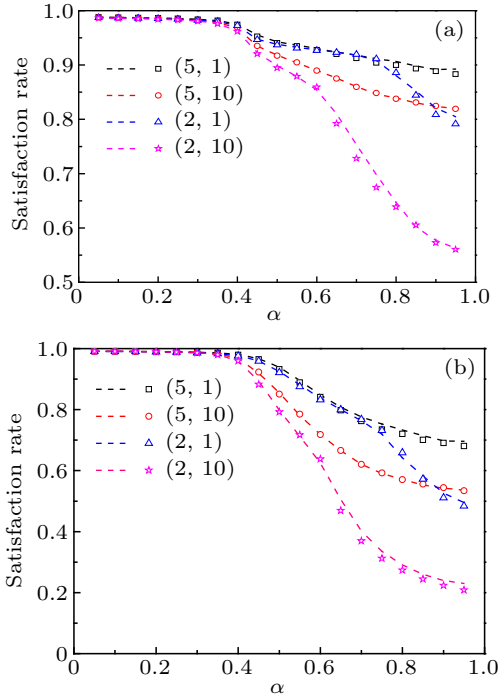


Fig. 14. Impacts of bus holding strategy on the satisfaction rate of passenger cars on each lane: (a) lane 1 and (b) lane 2.

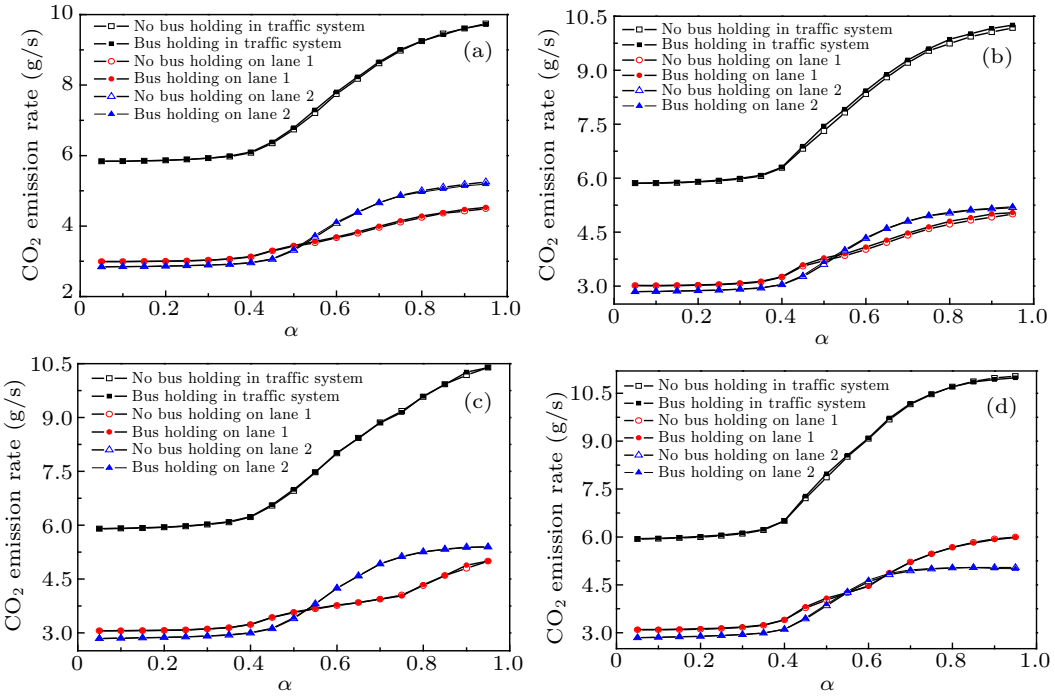


Fig. 15. Impacts of bus holding strategy on CO_2 emission rate of passenger cars: (a) parameters adopt (5, 1), (b) parameters adopt (5, 10), (c) parameters adopt (2, 1), (d) parameters adopt (2, 10).

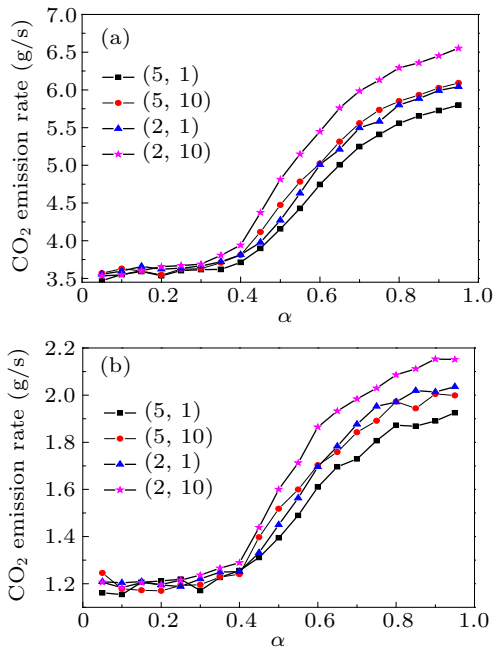


Fig. 16. CO_2 emission rate when the new energy passenger cars entering the traffic system occupy (a) 0.4 and (b) 0.8.

To investigate the impacts of new energy passenger cars on pollutant emissions, the CO_2 emissions of passenger cars have been illustrated in Fig. 16. Since the trends of different pollutant emissions are similar, the analysis only focuses on CO_2 emissions of passenger cars. The results indicate that the trend in CO_2 emissions of passenger cars is close to that observed in Fig. 11(a). Moreover, a comparison between Figs. 16(a) and 16(b) reveals that, with constant values of T_D and N_A, the CO_2 emissions of passenger cars decrease progressively as the proportion of new energy passenger cars increases.

5. Conclusions

In this paper, an integrated CA model is applied to a two-lane mixed traffic system consisting of buses and passenger cars under open boundary conditions. The phase diagrams of the bus system before and after implementing the bus holding strategy are obtained by numerical simulations under different probabilities of passenger cars entering the traffic system. Subsequently, the vehicle trajectories on lane 2, the flow rate, satisfaction rate and pollutant emission rates of passenger cars are discussed before and after implementing the bus holding strategy. The main findings are as follows.

(i) The bus holding strategy in non-dedicated bus lanes can effectively enhance the operational efficiency of buses. Furthermore, when the bus departure interval and the average number of passengers arriving at a bus stop per minute remain constant, different probabilities of passenger cars entering the traffic system may result in distinct bus operating conditions.

(ii) The flow rate, satisfaction rate and pollutant emission rates of passenger cars either for the traffic system or for each lane are influenced by the bus departure interval and the number of passengers arriving at bus stops.

(iii) When the number of passengers arriving at the bus stop is fixed, the bus holding strategy has no significant impacts on either the flow rate of passenger cars or the pollutant emission rates of passenger cars.

The primary purpose of this work is to validate the effectiveness of the bus holding strategy and to assess the impacts of buses as moving bottlenecks on passenger cars and pollutant emissions under open boundary conditions. However, the lane-changing behavior of buses is considered together with the car-following behaviors of passenger cars and buses. In the future work, it needs to be further investigated that the impacts of the lane-changing behavior of buses and the overtaking behavior of passenger cars and buses on bus bunching in non-dedicated bus routes. Additionally, the impacts of uneven bus stops and traffic lights on bus bunching need to be analyzed. More advanced techniques will also be applied to explore the complicated and combined impacts of two or more factors on bus bunching.

Acknowledgements

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References

[1] Tang T Q, Shi Y F, Wang Y P and Yu G Z 2012 *Nonlinear Dyn.* **70** 209
[2] Huijberts H J C 2002 *Physica A* **308** 489
[3] Nagatani T 2001 *Phys. Rev. E* **63** 036115
[4] Huang Q X, Jia B, Qiang S J, Jiang R, Liu F and Gao Z Y 2020 *IEEE Intel. Transp. sy.* **13** 179
[5] Qiang S J and Huang Q X 2023 *Physica A* **611** 128455
[6] Nagel K and Schreckenberg M 1992 *Journal de Physique I* **2** 2221
[7] Chowdhury D, Ludger S and Andreas S 2000 *Phys. Rep.* **329** 199
[8] Du G L and Ye F F 2022 *Chin. Phys. B* **31** 086401
[9] Kerner B S, Klenov S L and Wolf D E 2002 *J. Phys. A* **35** 9971
[10] Knospe W, Santen L, Schadschneider A and Schreckenberg M 2000 *J. Phys. A* **33** L477
[11] O'loan M R E and Cates M E 1998 *Phys. Rev. E* **58** 1404
[12] Luo Y J, Jia B, Li X G, Wang C and Gao Z Y 2012 *Transport. Res. C* **25** 202
[13] Qiang S J and Huang Q X 2021 *Physica A* **570** 125839
[14] Zhou W, Liu M, Liu T and Wang Y 2023 *IEEE Access* **11** 89455
[15] Klumpenhouwer W and Wirasinghe S C 2018 *Transport. Res. B* **117** 209
[16] Liang S D, Zhao S Z, Lu C X and Ma M G 2016 *Transport. Res. B* **87** 33
[17] Tang C Y, Shi H D and Liu T 2023 *Transport. Res. D* **117** 103652
[18] Gkiotsalitis K 2021 *Transportmetrica A* **17** 492
[19] Liang S D, Ma M, He S X, Zhang H and Yuan P C 2019 *Transportmetrica B* **7** 1175
[20] Rodriguez J, Koutsopoulos H N, Wang S H and Zhao J H 2023 *Transport. Res. C* **155** 104308
[21] Khan Z S and Mónica M 2023 *Transport. Res. A* **177** 103825
[22] Kaza N 2020 *Energ. Policy* **136** 111049
[23] Stafoggia M, Faustini A, Rognoni M, Tessari R, Cadum E, Pacelli B, Pandolfi P, Miglio R, Mallone S, Vigotti M A and Serinelli M 2009 *Epidemiol. Prev.* **33** 65

[24] Panis L I, Broekx S and Liu R H 2006 *Sci. Total Environ.* **371** 270

[25] Ahn K, Rakha H, Trani A and Van Aerde M 2002 *J Transp. Eng.* **128** 182

[26] Zheng T, Wang H W, Li X B and He H D 2021 *Atmos. Environ.* **253** 118354

[27] Tang T Q, Wang T, Chen L and Shang HY 2017 *Physica A* **479** 341

[28] Tang T Q, Yi Z Y and Lin Q F 2017 *Physica A* **469** 200

[29] Zhang L D and Zhu W X 2015 *Physica A* **428** 481

[30] Zhu W X and Zhang J Y 2017 *Physica A* **467** 107

[31] Bibeka A, Songchitruksa P and Zhang Y L 2021 *J. Intell. Transport S* **25** 281

[32] Lakouari N, Oubram O and Bassam A 2019 *J. Comput. Sci.* **40** 101072

[33] Xue Y, Wang X, Cen B L, Zhang P and He H D 2020 *Nonlinear Dyn.* **102** 393

[34] Qiao Y F, Xue Y, Wang X, Cen B L, Wang Y, Pan W and Zhang Y X 2021 *Physica A* **574** 125996

[35] Pérez-Sansalvador J C, Lakouari N, Garcia-Diaz J and Pomares Hernandez S E 2020 *Appl. Sci.* **10** 1592

[36] Qiao Y F, Xue Y, Cen B L, Zhang K, Chen D and Pan W 2024 *Physica A* **633** 129392

[37] Wang X, Xue Y, Cen B L and Zhang P 2020 *Physica A* **537** 122686

[38] Tian J F, Jia B, Ma SF, Zhu C Q, Jiang R and Ding Y X 2017 *Transport. Sci.* **51** 807

[39] Grigoratos T and Giorgio M 2015 *Environ. Sci. Pollut. R* **22** 2491

[40] Nyhan M, Sobolevsky S, Kang C, Robinson P, Corti A, Szell M, Streets D, Lu Z F, Britter R, Barrett S R and Ratti C 2016 *Atmos. Environ.* **140** 352

[41] Astarita V, Giofrè V P, Guido G and Vitale A 2019 *Energies* **12** 409

[42] Woodward H, Stettler M, Pavlidis D, Aristodemou E, ApSimon H and Pain 2019 *Atmos. Environ.* **215** 116891

[43] Wang Y, Jiang Y S, Wu Y and Yao Z H 2024 *Expert Syst. Appl.* **235** 121275

[44] Nguyen P, Diab E and Shalaby A 2019 *Public Transport* **11** 299