A Cellular Automata-based Model for Simulating Vehicle Platooning Operations in Heterogeneous Traffic Flow

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Abstract

Vehicle platooning possesses enormous potential for improving road capacity and traffic throughput. Traditional analytical approaches for assessing the impact of platooning strategy are often based on well-prepared assumptions and insufficiently consider the effects of actual platooning maneuvers. This study develops a modeling framework for simulating dynamic platooning operations in mixed traffic flow to investigate potential factors affecting the performance of connected and autonomous vehicles (CAVs) through platooning. The main focus of this work is to analyze how platooning settings affect the macroscopic characteristics of mixed traffic flow. The developed model captures the essential characteristics of vehicle platooning operations, including platoon formation, platoon maintenance, lane-changing, and platoon split. Simulation experiments are performed on several potentially influencing factors, including traffic demand levels, maximum platoon size, and CAV penetration rate in mixed traffic flow. The results show that platooning operations in mixed traffic flow are affected by traffic demand levels, CAV penetration rates, and platooning-related configurations. The proportion of CAVs in mixed traffic flow significantly impacts road capacity; the higher the percentage of CAVs, the greater the capacity of the mixed flow system. Maximum platoon size affects road capacity, especially when the proportion of CAVs in the mixed traffic flow exceeds 50%. Intra-platoon spacing has relatively little effect on road capacity. At 75% CAV penetration, road capacity increased by more than 63%, and CAV penetration contributed more than 57% and 87% to the increase in road capacity compared to maximum platoon size and intra-platoon spacing.

Keywords: Vehicle platooning, Mixed traffic flow model, Hybrid automaton, Road capacity

1. Introduction

Vehicle platooning is an emerging application of cooperative connected technology in the field of Intelligent Transportation Systems (ITS) [1-5]. It is widely expected that planning will be applied in conjunction with the deployment of Connected and Autonomous Vehicles (CAVs) in future transportation systems. Platooning refers to the driving strategy of enabling multiple vehicles to drive in close proximity to each other by forming a platoon. Depending on the setup, a platoon leader may control the driving parameters and coordinates the movements of all following vehicles in the platoon through vehicle-to-vehicle (V2V) communication [6] [7]. One of the first major demonstration of platooning was the PATH platoon demonstration at the National Automated Highway Systems Consortium Technical Feasibility Demonstration held in San Diego from August 7-10, 1997 [8] [9]. Since then, vehicle platooning has received extensive attention from the automotive industry and the transportation sector.

Much research has been done on the potential benefits of vehicle platooning for road transportation systems. These benefits include increased traffic throughput and alleviation of traffic congestion [10-12], enhanced traffic safety [13], improved fuel efficiency, and reduced emissions [14] [15], as vehicle platoons employ tighter space gap between vehicles, which not only improves the road capacity but also reduces the air resistance during the car-following process [16]. The advantages of vehicle platooning have been shown to be largely determined by the percentage of platooning vehicles in mixed traffic flow. It should also be noted that there is growing concern about the formation process of CAV platoons and the potential impact of platooning-related configurations, as these factors play important roles in the performance of platooning in mixed traffic flow [17-22].

Previous studies that have focused on the impacts of vehicle platooning can be principally divided into the following three categories: simulation studies, analytical methods, and experimental approaches. Harwood and Reed studied the effect of platooning on motorway capacity using VISSIM; in their study, vehicle platoons were modeled as single and long vehicles. Results showed that vehicle platooning has the potential to significantly increase road capacity and alleviate traffic congestion [12]. Wang et al. investigated the effect of platoon formation on the operation of autonomous mobility-on-demand systems using an agent-based model, where vehicles are not allowed to join or leave the platoon after the platoon departs; their research shows that, to form a preassembled platoon, the hold-on time of the leading vehicle may affect the average time delay of vehicles in the platoon [23]. Zhu et al. proposed a cellular automata-based traffic flow model for the traffic mixed by platoons and regular vehicles; they investigated the effect of platoon penetration rate and platoon size on traffic flow and concluded that, under a specific traffic environment, there exists an optimal platoon penetration rate and platoon size that maximizes road capacity [24]. Sala and Soriguera proposed a generalized macroscopic model to estimate the average CAV platoon length under various scenarios; they concluded that the estimated platoon length was the main factor contributing to the increase in highway capacity [25]. In these studies, vehicle platoons are modeled focusing primarily on longitudinal car following process, without considering actual platooning maneuvers such as platoon formation and split.

For analytical studies, Kamali et al. conducted verification of automotive platooning, where requirements for platooning are first analyzed, and further extended to the system level; their research provides insight into the characteristics of actual autonomous platooning systems from an operational perspective [26]. Jin et al. proposed a fluid queuing model and studied the macro impact of platooning operations on traffic congestion and throughput while considering the interaction between CAV platoons and non-CAVs and the impact of key platooning-related parameters; their analysis revealed the possible trade-off between platoon-induced congestion and efficiency gains through tighter intra-platoon spacing [17] [18]. Mena-Oreja et al. studied the impact of the configuration of platooning maneuvers under mixed traffic scenarios using the simulator of PERMIT and found that parameters of vehicle platooning have a significant impact on traffic flow [19-21]. Zhou and Zhu analyzed the impact of maximum platoon size of CAVs on capacity and flow stability and found that a larger maximum platoon size contributed to higher capacity; meanwhile, this marginal effect decreases with further increase in the maximum platoon size [22]. These studies have provided insights into the relationship between platooning configurations and system performance, such as larger maximum platoon size and tighter intra-platoon spacing generally contributing to improved road capacity. However, the properties of such hybrid systems are yet to be fully investigated due to their complex nature.

In addition to analytical studies and simulation models, several field experiments have been performed on the platooning strategy. Vehicle platooning demonstrations have been conducted around the world over the past decade, most well-known including the vehicle platooning demonstration under the EU-funded SARTRE project, the California Partnership for Advanced Transportation Technology (PATH) truck platooning demonstration, and FHWA's truck platooning demonstration. These demonstrations provide ample evidence for the reliability of platooning technology. More recently, Knoop et al. conducted an experiment with seven SAE level-2 vehicles, driven in platooning mode on public roads for nearly 500km; they found that intentionally creating platoons on public roads is difficult under heavy traffic conditions [27]. Calvert and Arem reported field operation testing of cooperative adaptive cruise control (CACC) enabled vehicles on an arterial corridor as 3-vehicle or 7-vehicle platoons; they analyzed the performance of platooning strategy using indicators such as platooning time and number of platoon disengagements and found that platooning on the arterial road was affected by multiple factors, and frequent recoupling of platoons seemed inevitable [28]. Cerutti et al. investigated the aerodynamic drag reduction effect in platoons of 2,3,4 light commercial vehicles; they found that smaller inter-vehicle distances can reduce the aerodynamic drag effect by up to 35%, suggesting that platooning-related configuration plays an important role in the performance of the platooning strategy [29]. Although field experiments provide the most reliable results for platooning operations under current transportation systems, due to their resource-intensive nature, such field experiments are rather limited in scale and cannot provide a systematic understanding of the impact of platooning at the system level.

Previous studies have mainly used preassembled platoons to simulate vehicle platooning in several specific traffic scenarios, without the necessity to form platoons in operation. The proportion of preassembled platoons in the mixed traffic flow was widely used as a key variable for assessing the impact of platooning strategy on the traffic system. However, the probability of CAVs forming or joining platoons differs at different levels of traffic demand. At the same time, the penetration rate of CAVs in mixed traffic flow also plays a decisive role in this process. In most recent literature, these factors have not been explicitly considered and likely lead to an overestimation of the performance of the platooning strategy. Although some researchers have recently investigated the impact of different platooning-related configurations on traffic flow performance and found that larger maximum platoon size and tighter intra-platoon spacing is beneficial to road capacity [17-22], their studies are very limited to a few fixed-density scenarios and fail to provide a systematic and comprehensive understanding of the problem.

This work presents a framework for modeling vehicle platooning operations in heterogeneous traffic flow. The objective of this study is to investigate the potential impact of vehicle platooning on road capacity and the relationship between platooning-related configurations (i.e. maximum platoon size, intra-platoon spacing, etc.) and mixed traffic flow performance. In this study a state-of-the-art microscopic cellular automata model is applied to model conventional traffic flow [30]. Vehicle platooning is incorporated through a novel hybrid automaton approach which has been developed in this study: three operating modes are defined for the CAV, including normal driving mode, platoon formation mode, and platooning mode. The corresponding evolution rules for each mode are established and integrated into the mixed flow model. Platooning operations are modeled by switching the corresponding operating mode. This study does not consider the optimal control problem or string stability of the formed vehicle platoons [31] [32]. The main focus of this work is to analyze how platooning settings affect the macroscopic characteristics of mixed traffic flow. Our model captures the essential characteristics of vehicle platooning operations, including platoon formation, platoon maintenance, lane-changing, and platoon split. A key feature of the proposed model is that CAV platoons are formed spontaneously in mixed traffic flow. This study aims to gain insight into the optimal design and operation of future vehicle platooning systems.

The rest of the article is organized as follows. Section 2 presents the methodology of the proposed mixed flow model, introducing the corresponding rules for simulating background traffic and the rules for modeling platooning operations, respectively. Section 3 describes the simulation setup. Section 4 presents the simulation results of a single experiment to facilitate the understanding of the proposed mixed flow model. Simulation results, including platooning ratio, platoon formation time, average platoon size, and platoon size distribution, are obtained to evaluate the performance and efficiency of platooning operations in mixed traffic flow. Sensitivity analyses of platooning-related configurations are discussed, including intra-platoon spacing, maximum platoon size, and the ratio of CAVs in mixed traffic flow. In Section 5, the main findings of this work are briefly summarized.

2. Methodology

The cellular automata (CA) model is a rule-based model that is discrete in both space and time, and has been widely used in the field of microscopic traffic flow modeling. In this section, a modeling framework for vehicle platooning operations in mixed traffic flows is presented. The established cellular automata-based flow model consists of the following two parts: a background flow model for simulating conventional vehicles and a hybrid automaton model for simulating CAV platooning in mixed traffic flow. Vehicles are divided into the following two types: conventional vehicles and CAVs. CAVs are defined as vehicles with corresponding platooning functions, which will choose to drive in platooning mode as long as the necessary conditions for platooning are met. Following the typical setting of CA model, each time step in the model is equal to 1 second, and the units of velocity and acceleration rate are m/s and m/s^2, respectively. Distances are measured in meters. This setup makes speed and distance quantitatively comparable at each time step. The following rules are defined for each vehicle per 1 second.

2.1 The Two-lane TSM for simulating background traffic.

To model conventional vehicles, the same rules as the Two-State Safe-Speed Model (TSM) are applied. The TSM model was first proposed by Tian et al. (2016), which can reproduce complex traffic flow characteristics of conventional traffic flow, including the metastable state, traffic oscillation, phase transition, etc. [30]. This study further extends this model to a two-lane model by applying a classical lane-changing model to reproduce background traffic. This model is a Cellular Automata (CA) model with a refined cell length (equal to 0.5 m) than the classical CA model (cell length is 7.5 m). CA models are widely used to reveal the effects of microscopic vehicular behavior changes on macroscopic traffic flow characteristics. The refined cell length makes it possible to capture more detailed interactions in the traffic flow, as the velocity is discrete in steps of 0.5 m/s instead of 7.5 m/s in the classical CA model. The model makes use of the following updating procedure:

(1) Deterministic speed update:

$$v'_{\mathrm{det}} = \min(v + a, v_{\max}, d_{\mathrm{anti}}, v_{\mathrm{safe}}) \tag{1}$$

In this step, the speed of the target vehicle at the next time step is determined as the minimum of the speed under acceleration, the maximum speed, the anticipated space gap, and the safe speed.

(2) Stochastic deceleration:

$$v' = \begin{cases} \max(v'_{\mathrm{det}} - b_{\mathrm{rand}}, 0) & \text{with probability } p \\ v'_{\mathrm{det}} & \text{otherwise} \end{cases} \tag{2}$$

The stochastic deceleration step means that the target vehicle may experience speed deceleration due to random factors during driving.

(3) Position update:

$$x' = x + v' \tag{3}$$

The position update indicates that the target vehicle will move forward by the distance of the updated speed within 1 second of the next time step.

Here, v (v') and x (x') denote the speed and position at the current and subsequent time steps, respectively. a and $v_{\max}$ are the acceleration rate and maximum velocity of the vehicle, respectively. b_{rand} denotes the randomization-deceleration rate. d_{anti} denotes the anticipated space gap, v_{safe} denotes the safe speed defined in the Gipps model [33]. d_{anti} and v_{safe} are defined as follows.

$$d_{\mathrm{anti}} = d + \max(v_{\mathrm{anti}} - g_{\mathrm{safety}}, 0) \tag{4}$$

$$v_{\mathrm{safe}} = [-b_{\max} + \sqrt{b_{\max}^2 + v_l^2 + 2b_{\max}d}] \tag{5}$$

These equations assume (i) a reaction time of 1 s (which is presumably the time step of the CA model), and (ii) no acceleration at the present time-step.

$d = x_l - x - L_{\mathrm{veh}}$ is the real space gap. L_{veh} is the length of the vehicle.

v_{anti} denotes the expected velocity of the preceding vehicle.

$$v_{\mathrm{anti}} = \min(d_l, v_l + a, v_{\max}) \tag{6}$$

x_l, d_l, and v_l denote the position, real space gap, and speed of the preceding vehicle, respectively. g_{safety} is a safety parameter that helps avoid accidents considering the limitation of human perception, with the constraint $g_{\mathrm{safety}} \geq b_{\mathrm{rand}}$. $b_{\max}$ is the maximum deceleration rate. The round function $[x]$ helps return the integer nearest to x.

The randomization deceleration b_{rand} and stochastic deceleration probability p are specifically defined as follows:

$$b_{\mathrm{rand}} = \begin{cases} a & \text{if } v < b_{\mathrm{defense}} + \lfloor d_{\mathrm{anti}}/T \rfloor \\ b_{\mathrm{defense}} & \text{otherwise} \end{cases} \tag{7}$$

$$p = \begin{cases} p_{\mathrm{b}} & \text{if } v = 0 \\ p_{\mathrm{c}} & \text{else if } v \leq d_{\mathrm{anti}}/T \\ p_{\mathrm{defense}} & \text{otherwise} \end{cases} \tag{8}$$

where $p_{\mathrm{defense}} = p_{\mathrm{c}} + \frac{p_{\mathrm{a}}}{1+e^{\alpha(v_{\mathrm{c}}-v)}}$ is a logistic function used to define the randomization probability p_{defense}. In the function b_{rand}, two different randomization-deceleration values are employed to describe the difference in the driving behaviors under two different states, i.e., the defensive and normal states. $\lfloor x \rfloor$ is the floor function used to return the maximum integer no greater than x. b_{defense} is the randomization-deceleration rate under the defensive state. T is the effective safe time gap. The defensive state is activated if $v>d_{anti}/T$. Under the normal state, the randomization-deceleration rate equals a.

(4) Symmetry lane-changing:

Incentive criteria: $d(i, t) < \min\{v + a, v_{max}\}$ and $d(i, t)_{other} > \min\{v + a, v_{max}\}$

Safety criteria: $d(i, t)_{back} > v_{max}$

The incentive criteria indicate that space ahead of the object vehicle i is not enough for traveling with a higher velocity, and the driving condition on the target lane is better than that in the current lane. The safety criteria indicate that, when changing lanes, the vehicle immediately behind the object vehicle moving on the target lane will not crash into the object vehicle after changing lanes. When the two conditions are fulfilled simultaneously, the object vehicle will move onto the target lane with a lane-changing probability P_{lc}.

2.2 Modeling vehicle platooning in heterogeneous traffic flow

Platooning operations are modeled in a hybrid automaton approach. A hybrid automaton is a system that contains both continuous dynamic and discrete switching logic [34]. In modeling platooning operations, the continuous dynamic represents the car-following rules under each operation mode, which is a continuous process. The discrete switching logic instructs platooning vehicles to switch between several operation modes according to the corresponding jump conditions during platooning operations. This section was originally proposed in this study to simulate dynamic platooning operations and constitutes part of the proposed mixed flow model.

Three different modes are defined for CAVs: normal driving mode, platoon-formation mode, and platooning mode. Each mode corresponds to a different stage in the platoon formation process. By switching between the above modes, CAVs can form or join platoons in mixed traffic flow. Rules for platoon merging and split are also established and integrated into the model. For simplicity, this study assumes that CAVs maintain a constant distance from each other in the platoon, referring to the intra-platoon spacing d_{intra}. The maximum platoon size L_{max} represents the maximum number of vehicles in a platoon. The physical length of a platoon is determined by the number of vehicles in the platoon and the intra-platoon spacing. Figure 1 shows the structure of the established hybrid automaton model.

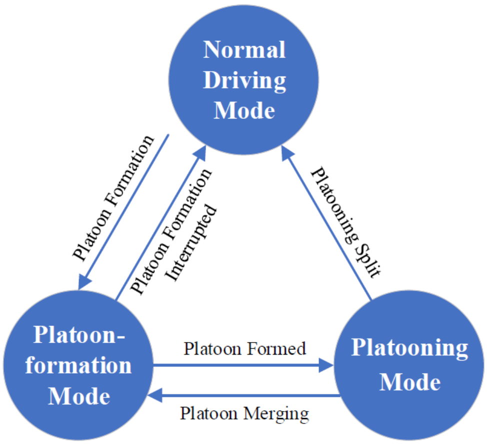


Fig.1. Schematic diagram of the hybrid automaton model.

Corresponding rules and jump conditions are established in each operation mode. The details are as follows:

(1) Normal driving mode

In normal driving mode, the speed update rules are the same as for conventional vehicles described in the previous section. The difference is the lane-changing rules are:

Incentive criteria: i. $d(i, t) < \min\{v + \mathrm{a}, v_{\max}\}$ and $d(i, t)_{\mathrm{other}} > \min\{v + \mathrm{a}, v_{\max}\}$

ii. If the preceding vehicle on the current lane is a conventional vehicle and the preceding vehicle on the target lane is a CAV.

Safety criteria: $d(i, t)_{\mathrm{back}} > v_{\max}$

Compared with the lane-changing rules for the background traffic, a second incentive criterion was added, which takes into account the vehicle's intention of driving in a platoon. The lane-changing rate for the first incentive criterion is the same as the lane-changing probability P_{lc} used in background traffic. In contrast, the lane-changing rate of the second incentive criterion equals 1. As we assumed, CAVs are sufficiently willing to operate in the platooning mode. This setting allows CAVs in different lanes to form platoons through the lane-changing process.

(2) Platoon-formation mode

The platoon-formation mode refers to the process of two successive vehicles forming a platoon or a new vehicle joining an existing platoon. During this process, the speed difference between the target vehicle and its target partner is required to reduce the distance between the two vehicles to facilitate the platoon-formation process. The speed difference can be realized through the catch-up strategy of the following CAV or the slow-down strategy of the preceding CAV. For simplicity, only the catch-up strategy is implemented in this work. That is, the CAV will accelerate to catch up with the preceding

CAV or platoon in front of it. The conditions for the CAV to switch from normal driving mode to platoon-formation mode are as follows:

i. If its preceding vehicle is a CAV.

ii. If its preceding vehicle is already running in an existing platoon and the size of the leading platoon is less than the maximum platoon size $L_{\max}$.

Once either of the above two conditions are met, a platoon formation event will be trigged and the vehicle will switch to the platoon-formation mode and update its speed according to the following rules:

$$v' = \min(v + a_p',\ v_{\max}',\ d - d_{\text{intra}}) \tag{9}$$

Where a_p' is the acceleration rate during the platoon formation process. $v_{\max}'$ represents the maximum speed of the vehicle in platoon-formation mode. d_{intra} stands for intra-platoon spacing, which is a predefined fixed variable in the simulation settings.

For vehicles in the platoon-formation mode, the lane-changing probability is zero, as priority is given to catching up with the target CAV or platoon in front of it. The platoon-formation process will be interrupted if either a vehicle appears in the gap between the target CAV in front of it, or if neither of the above two conditions are met. The CAV will switch back to normal driving mode.

(3) Platooning mode

Platooning mode means that following CAVs apply the same driving parameters as their platoon leader and maintain constant intra-platoon spacing.

If a_p'=0 and d=d_{intra}, the vehicle will switch from platoon-formation mode to platooning mode. During the deterministic speed update step, the following vehicles in the platoon will be updated with the same speed as the platoon leader $v_{\text{det}}^{\text{leader}}$:

$$v' = v_{\text{det}}^{\text{leader}} \tag{10}$$

For the platoon leader, the same deterministic speed update applies as for conventional vehicles, skipping the stochastic deceleration step.

(4) Platoon merging

Platoon merging also follows the catch-up strategy in this model. For the platoon leader, if the size of the target platoon is smaller than the maximum platoon size $L_{\max}$, the platoon leader has the ability to leave the current platoon with the merging probability of P_m, and switch to the platoon-formation mode to join the front platoon. In this case, if the size of the current platoon is greater than 2, the following vehicle immediately behind it will become the new platoon leader. Otherwise, the platoon will be dispersed. The following vehicle will switch to normal driving mode. Multiple vehicle platoons may be formed through orderly platoon-formation processes between consecutive vehicles or through a platoon merging process. The merging of two different platoons involves several separate steps through the platoon-merging process in a vehicle-by-vehicle process.

(5) Platoon split

Platoon splits are modeled by lane-changing rules set specifically for vehicles in platooning mode. P_d represents the probability that a platooning vehicle will leave the current platoon, which may be due to deviating from the current platoon's route or intending to get off the highway when approaching an interchange. This parameter corresponds to the possible recoupling of platoons in the simulated system. The process of separating from the platoon is similar to the lane-changing process, which is affected by surrounding traffic, especially in congested conditions.

Incentive criteria: $P_{rand} < P_d$

Safety criteria: $d(i, t)_{back} > v_{max}$

$P_{rand} \in (0, 1)$ is a randomly generated number. If the conditions are met, the vehicle will disperse from the platoon and leave its current lane. If the vehicle is the platoon leader and the number of following vehicles in the platoon is greater than 2, the following vehicle immediately behind it will become the new platoon leader; otherwise, the following vehicle will switch to the normal driving mode, the original platoon will be completely dispersed; if the vehicle is a following vehicle, depending on its position in the platoon, the platoon may be regrouped into two sub-platoons, or part of the original platoon may be completely dispersed.

According to the characteristics of each stage in platooning operations, the corresponding modeling method in mixed traffic flow was established. This modeling approach covers the entire process of platooning operations, including platoon formation, maintenance, merging, and splitting. The developed model is a two-lane model in which symmetrical lane-changing rules are applied for all vehicles. For CAV platoons, there is no preference for which lane of the simulated two-lane highway to use. Lane-changing behavior of CAV platoons was not considered in this study. The model is built on the following basic assumptions:

(1) CAVs are assumed to have a similar driving performance to conventional vehicles; the only difference is reduced randomness during driving. This study mainly focuses on platooning strategy in mixed traffic flow; Differences in driving performance between CAVs and conventional vehicles are beyond the scope of this study.

(2) It is assumed that under perfect communication conditions, platooning vehicles always maintain a constant spacing in the platoons. Control issues and stability within the CAV platoons are also beyond the scope of this study.

The proposed model provides a foundation for comprehensively evaluating the performance of the CAV platooning strategy in mixed traffic flow.

3. Simulation setup

In the CA model, road segments are divided into cells, and time is divided into time steps. The length of each cell is equal to 0.5 meters, and each time step corresponds to 1 second. Each cell has only two states at each time step and is either occupied by a vehicle or empty. Each vehicle occupies a row of 15 consecutive cells (with a physical length of 7.5 m), which includes the physical length of the vehicle and the minimum clearance in stationary queueing conditions. Simulations were performed on a 10-kilometer two-lane road segment with periodic boundary conditions. The periodic boundary condition indicates that every time a vehicle leaves the road segment through the endpoint, a vehicle with the same driving parameters is injected at the start point of the road segment, which means that the vehicle density on the road segment remains constant.

The initial state involves two types of vehicles randomly distributed over the road segment. Each simulation lasts 12000 time-steps. The platooning operation starts after 5000 time-steps. The results of the first 10000 time-steps are disregarded to eliminate transition effects. Four scenarios are included in the simulation. Each scenario is injected with different proportions of CAVs P_{av}, 0%, 25%, 50%, and 75%, respectively. Simulations are performed at various levels of traffic demand covering the full density regions. For the simulation results for specific traffic demand levels, three density values of 30 vehicles/km, 60 vehicles/km, and 90 vehicles/km are used to represent free flow, moderate traffic demand level, and congested flow.

Table 1 and Table 2 list the parameters of the TSM and those used to model vehicle platooning operations, respectively.

Table 1 Parameters of two-lane TSM model

Parameters	L_{cell}	L_{veh}	v_{max}	T	a	b_{max}	$b_{defense}$	P_a	P_b	P_c	g_{safety}	v_c	α	P_{lc}
Units	m	L_{cell}	m/s	s	m/s^2	m/s^2	m/s^2	-	-	-	L_{cell}	L_{cell}/s	s/L_{cell}	-
Values	0.5	15	25	1.8	1	−3	1	0.85	0.52	0.1	20	30	10	0.2

Table 2 Parameters for modeling vehicle platooning

Parameters	v'_{max}	a'_p	d_{intra}	P_d	P_m	L_{max}
Units	m/s	m/s^2	m	-	-	veh
Values	27	1	1	0.2	0.2	3

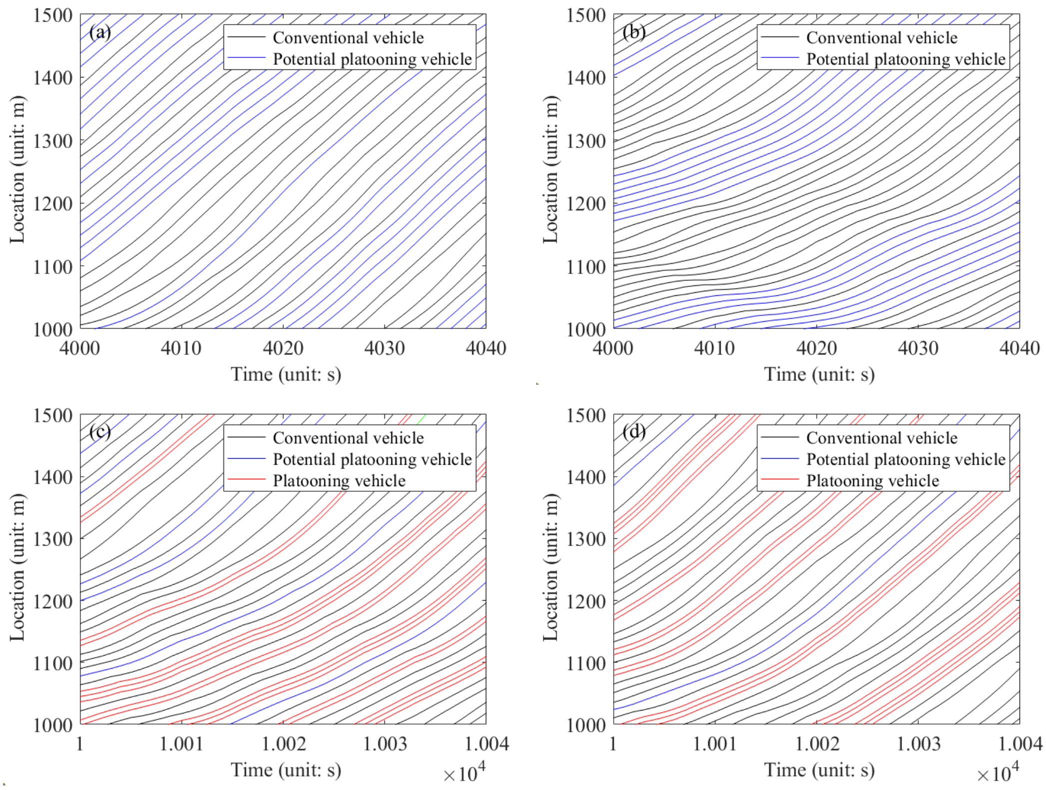
L_{cell} represents the length of each cell of the road segment, which is 0.5 m in this study. L_{veh} indicates the length of each vehicle and is equal to 7.5 m. The maximum speed v_{max} is equal to 25 m/s, and the maximum speed of CAVs in platoon-formation mode is 27 m/s, which is slightly larger than the maximum speed of the rest of the vehicles. This setting enables platoon-formation in free-flow traffic when all vehicles can travel at maximum speed. L_{max} represents the maximum platoon size. d_{intra} represents the intra-platoon spacing. The other parameters involved in the two-lane TSM model follow the same settings originally proposed in Tian's work [24].

For some of the parameters listed above, exact values for the simulation cannot be determined, such as the values of lane-changing, platoon merging/split probability. These parameters are determined based on the simulation performance to ensure that CAVs perform the corresponding operation smoothly and do not significantly affect the final result. The final result is an average of 3 simulation results to minimize random effects on the initial spatial distribution of the two types of vehicles.

4. Simulation results

Simulations are performed at different levels of traffic demand. In subsection 4.1, trajectories of a specific scenario with fixed density and P_{av} are first presented to facilitate a better understanding of the modeling process. Specifically, the scenario with density equal to 60 veh/km and P_{av} equal to 50% is chosen as demonstration, as these settings are favorable for illustrating platooning operations in mixed traffic flow. Subsections 4.2 to 4.5 present platooning operations performance indicators at different levels of traffic demand, including platooning ratio, average formation time, average platoon size, and platoon size distribution. For this part, the reference case of 0% CAV penetration is not applicable. Subsections 4.6 to 4.8 present sensitivity analyses of flow-density diagrams for different platooning-related configurations, including intra-platoon spacing, maximum platoon size, and CAV penetration rates. In subsection 4.9, the main findings of the simulation results are summarized and followed by discussions.

4.1 Microscopic characteristics of the mixed flow model



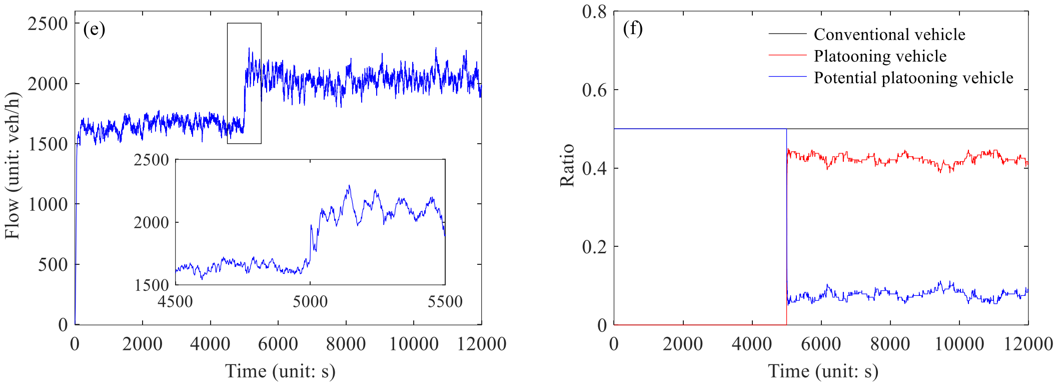


Fig.2. Simulation results for a specific scenario with density of 60 veh/km and P_{av} of 50%.

Fig. 2 (a, b) and 2 (c, d) show the trajectories of the proposed mixed flow model on each lane of a specific simulation scenario before and after deploying the platooning strategy, respectively. The trajectories of conventional vehicles are marked in black; the trajectories of platooning vehicles are marked in red, and the trajectories of CAVs are marked in blue. The maximum platoon size is 3 vehicles, and the intra-platoon gap is 1 meter. As shown in Fig. 2(a, b), before deploying the platooning strategy, conventional vehicles and CAVs are randomly distributed in the mixed traffic flow. Fig. 2(c, d) shows that vehicle platoons (consisting of 2 or 3 vehicles) are randomly distributed in the mixed traffic flow. In a platoon, the CAVs share the same driving parameters with the corresponding platoon leader. A small fraction of CAVs cannot join any platoons, either due to maximum platoon size limitation or because their position in the mixed traffic flow is not favorable to joining or forming a platoon. Compared to Fig. 2(a, b), platooning CAVs maintain relatively closer gaps within their platoons than other vehicles. Fig. 2(e) shows the flow-time relationship in the simulation. The flow rate increases significantly at 5000 time-steps when CAVs started to form platoons and operate in platooning mode. Fig. 2(f) shows the vehicle composition during the simulation. Before platooning operations start at 5000-time steps, conventional vehicles and CAVs evenly constitute the mixed traffic flow, equal to 50%. After platooning operation begins, the proportion of platooning CAVs in mixed traffic flow increases, and the proportion of rest CAVs decreases accordingly. During the simulation, the proportion of platooning CAVs fluctuated continuously, indicating that platooning operation is a dynamic process in the mixed traffic flow.

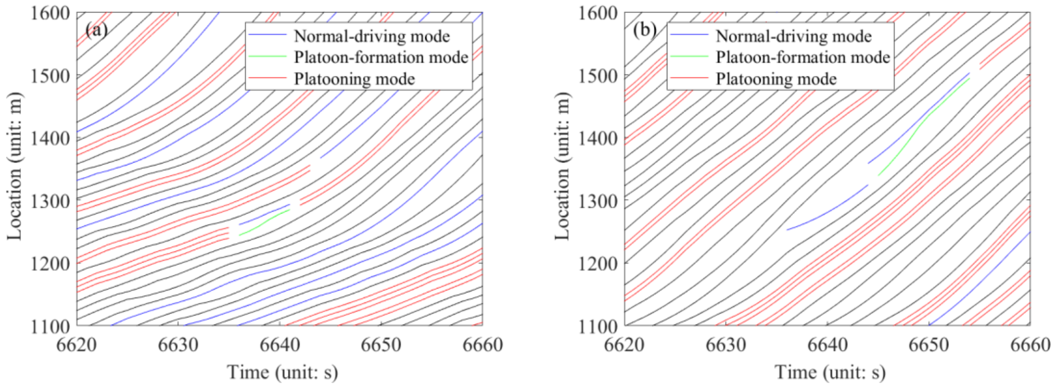


Fig. 3. Vehicle trajectory of platoon formation and split with density of 60 veh/km and P_{av} of 50%.

Figure 3 shows a specific case, which includes the processes of platoon-formation and the process of platoon split. Fig. 3 (a) and (b) show the trajectory of each lane of the established two-lane mixed flow model. Discontinuous trajectories marked in different colors represent the switching logic in the hybrid automaton model. The trajectories marked in black represent conventional vehicles, the others represent the trajectories of CAVs. The trajectory marked in blue indicates that the CAV is in normal driving mode; the trajectory marked in green indicates the CAV is in platoon-formation mode; the trajectory marked in red indicates the CAV is in platooning mode. Interrupted trajectories involve either lane-changing behavior or change in the operational modes for CAVs in the platooning operation processes, which are induced by the plotting mechanism.

4.2 Platooning ratio at different traffic demand levels

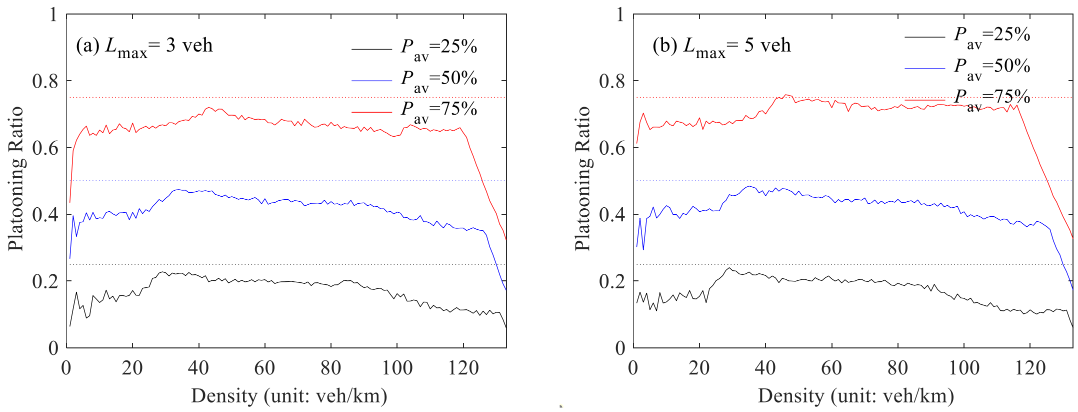


Fig.4. Density-dependence of platooning ratio under various P_{av}.

Figure 4 shows the proportion of platooning CAVs in the mixed traffic flow. The three curves marked in black, blue, and red represent the actual proportion of platooning vehicles achieved in the simulation; the three dash lines represent the penetration rate of CAV P_{av} in the above three scenarios, respectively. In Fig. 4 (a), the three curves show similar trends, first gradually increasing with the increase in density and then gradually decreasing after reaching the peak of the whole curve. The fluctuations in the low-density part of the curves are relatively stronger than those in the denser part.

This is because, under low-density conditions, CAVs are sparsely distributed in the mixed traffic flow, and the likelihood of forming a platoon depends largely on the initial spatial distribution of all vehicles. The area between the proportion of platooning CAVs and the corresponding CAV penetration rate represents the percentage of CAVs that did not join or form any platoons. Simulation results show that both the penetration rate of CAVs and the level of traffic demand have an impact on the formation of vehicle platoons in mixed traffic flow. The peak proportion of platooning CAVs in the mixed traffic flow is always reached near the density at which the road reaches its capacity, which is understandable and consistent with traffic flow theory, as higher platooning proportions result in smaller average headway, and the greater the flow.

4.3 Average formation time at various levels of traffic demand

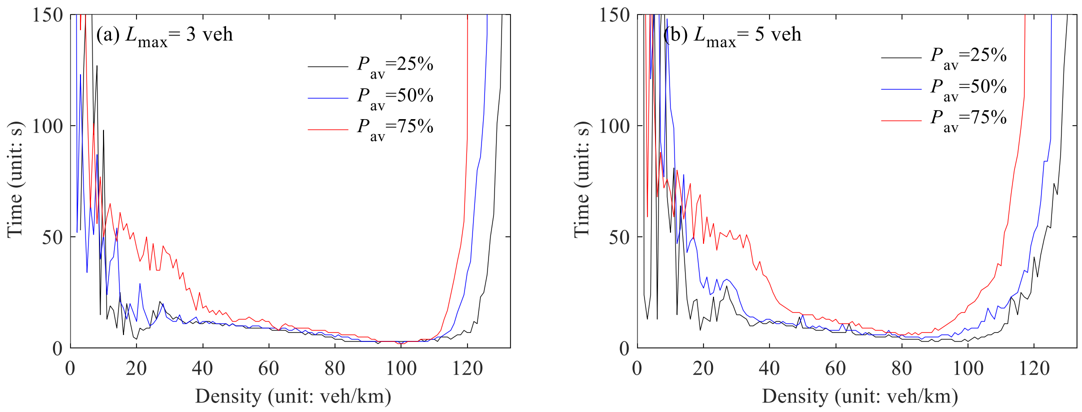


Fig.5. Density-dependence of average formation time under various P_{av}.

Figure 5 shows the average time for CAVs to successfully join or form platoons during the platoon-formation process. Four plots are presented under different platooning-related configurations. The average formation time was defined as the total time CAVs operated in platoon-formation mode during the simulation divided by the number of times CAVs successfully switched from platoon-formation mode to platooning mode. The obtained results cover the full density area, corresponding to various traffic demand levels. The three curves with different proportions of CAVs show similar patterns; the platoon-formation time in the medium-density region is much lower than that in low-density or high-density regions. In the low-density region (k<35 veh/km), vehicles can travel at maximum speed because the traffic flow is in the free-flow state. In this case, the average time for CAVs to join or form platoons is much greater than that in the medium-density region. The curves in the low-density region fluctuate much more intensely and show smoother with the increase of density. In the medium-density region (35<k<90 veh/km), the average platoon-formation time remains at a low level, around 10 seconds. When the density exceeds 90 veh/km, the average platoon formation time increases rapidly with further increases in density.

4.4 Average platoon size with different maximum platoon size settings

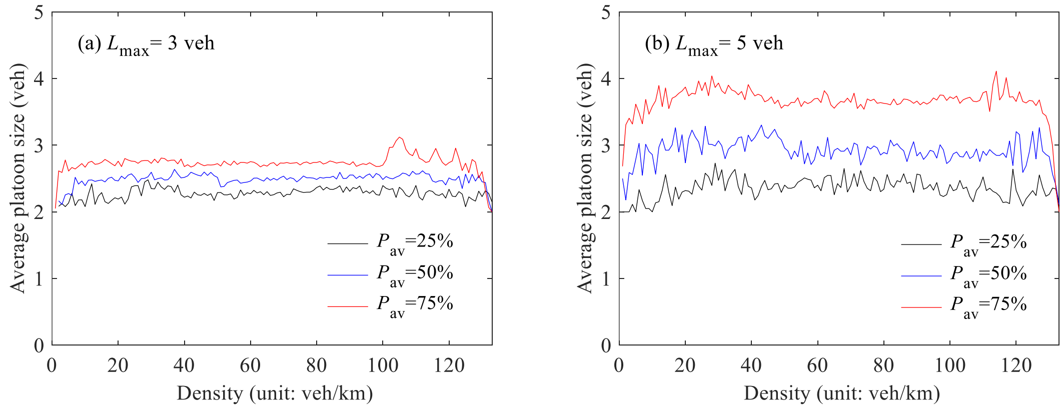


Fig.6. Density-dependence of average platoon size under various P_{av}.

Figure 6 shows the relationship between average platoon size and density under two cases with different maximum platoon sizes, 3 vehicles, and 5 vehicles, respectively. Each graph consists of three curves corresponding to different proportions of CAV in mixed traffic flow, including 25%, 50%, and 75%. In general, except for very light and dense traffic, the average platoon size curves maintain small fluctuation in most density regions. The value of average platoon size is determined by the combination of the maximum platoon size and the penetration rate of CAV in the mixed traffic flow. Fig. 6(a) shows that the average platoon size curves for the three different CAV ratios lie between 2 and 3 vehicles. The difference in average platoon size for different CAV ratios is relatively smaller than in fig. 6(b).

4.5 Platoon size distribution under different maximum platoon size settings

Fig.7. Platoon size distributions under different P_{av} and various traffic demand levels

Figure 7 shows the platoon size distribution at various CAV penetration rates P_{av}, including 25%, 50%, and 75%. Three scenarios with different levels of traffic demand are considered, including 30 veh/km, 60 veh/km, and 90 veh/km, representing light, medium, and dense traffic, respectively. Simulation results were obtained for two cases with different maximum platoon sizes are (L_{max} equal 3 vehicles in the upper graph and 5 vehicles in the lower graph). The platoon size distribution showed different patterns under different CAV penetration rates P_{av}. With the maximum platoon size set to 5 vehicles, P_{av} is equal to 25%, and in subplots (a), (b), and (c), it can be observed that most of the formed platoons consist of 2 vehicles. This is because in this case, the distribution of CAVs in the mixed traffic flow is sparse, which is not a favorable condition for the formation of larger-scale platoons. With the further increase of P_{av}, the distribution of platoon size changed significantly, and the proportion of platoons with larger platoon sizes increased. At 75% CAV penetration, most platoons consist of 5 vehicles, which is the maximum platoon size in this case. A similar trend can be seen with the maximum platoon size equal to 3.

4.6 Sensitivity analysis of the intra-platoon spacing

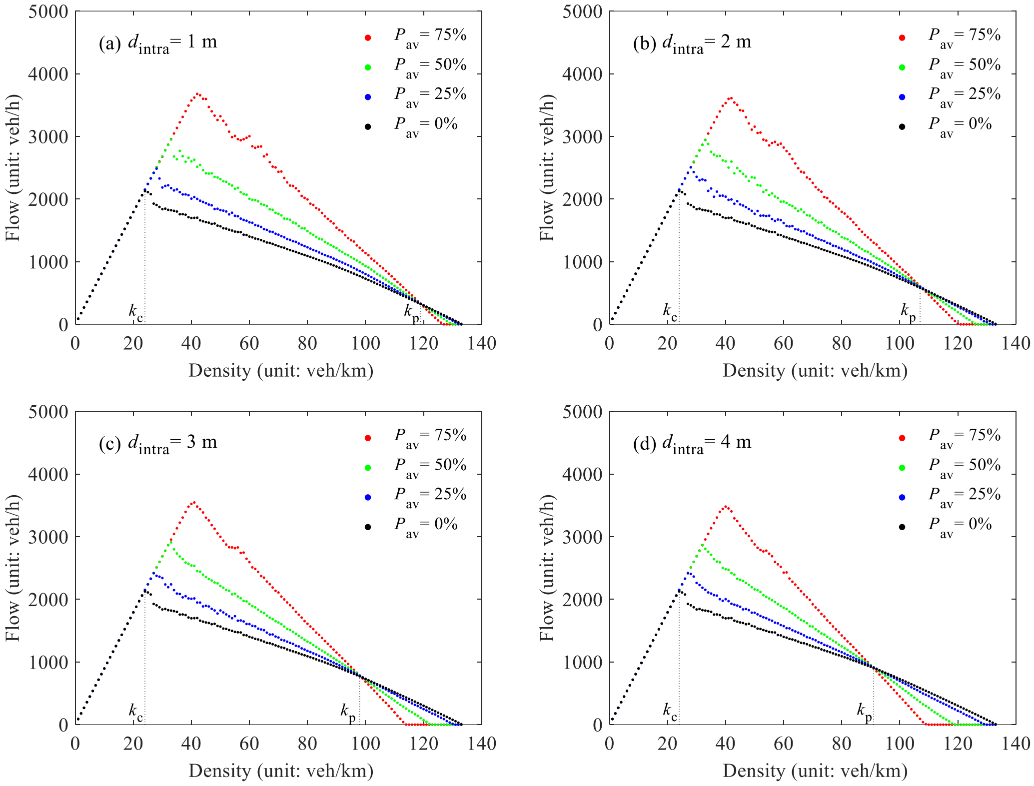


Fig.8. Flow-density diagrams under different intra-platoon spacing d_{intra}, L_{max}=3 veh.

Figure 8 presents the flow-density diagrams for 4 scenarios with different intra-platoon gaps d_{intra}, 1 m (a), 2 m (b), 3 m (c), and 4 m (d). The maximum platoon size is 3 vehicles. In each scenario, 4 cases with different CAV penetration rates P_{av} were included. The fundamental diagrams presented in this study demonstrates single-lane flow-density relationships. In the case of 0% CAVs, the model is equivalent to a two-lane TSM model simulating homogenous regular traffic flow, since no vehicle platoon are formed in the simulation. The flow-density relationship marked in the black dots is in a triangular shape. Capacity is achieved at the peak of the flow-density diagram, where density is defined as the critical density k_c. The critical density divides the flow-density diagram into two parts: the free-flow region and the congested-flow region. In the free-flow region ($k<k_c$), the introduction of platooning has no effect on traffic throughput. The introduction of vehicle platooning strategy starts to show its positive effects when the density exceeds the critical density. The road capacity increases with the increase of P_{av}, and the critical density also increases accordingly; In the congested-flow region, there is an intersection in the flow-density relationship, which further divides the congested flow region into two parts. Let the density at the intersection be denoted k_p. The intersection point

represents a specific scenario where the average clearance of the simulated traffic flow is equal to the intra-platoon spacing. More specifically, $k_p \approx 1000/(L_{veh}+d_{intra})$. Traffic throughput is positively correlated with the increase in P_{av} until the density reaches k_p. In contrast, traffic throughput is negatively correlated with further increase in P_{av} after density exceeds k_p. The area between the traffic-density plots for different cases of CAV penetration rate shows the advantages and disadvantages of the platooning strategy on traffic throughput. That is, the area above the flow density plot of 0% CAV indicates the advantage of the platooning strategy. Mixed-flow systems can only achieve additional throughput through the platooning strategy in the density range of (k_c, k_p), where k_c represents the critical density of regular traffic flow.k_p is related to the intra-platoon spacing. When the density exceeds k_p, the flow-density relationship with higher CAV penetration is lower than without platooning vehicles, because in very dense traffic the average gap between vehicles may even be lower than the intra-platoon spacing of CAV platoons. In this case, maintaining a large intra-platoon spacing between CAVs will inevitably have a greater negative impact on traffic flow. Comparing the capacity of the presented flow density plots, we can conclude that the increase in capacity is mainly due to the increase in CAV penetration. In contrast, the intra-platoon spacing d_{intra} has no significant effect on road capacity. The intra-platoon spacing d_{intra} mainly affects the density range of the positive impact of vehicle platoons on traffic throughput; The smaller the intra-platoon spacing, the wider the density region of the positive impact of the platoon strategy on the congested traffic flow.

4.7 Sensitivity analysis of the maximum platoon size

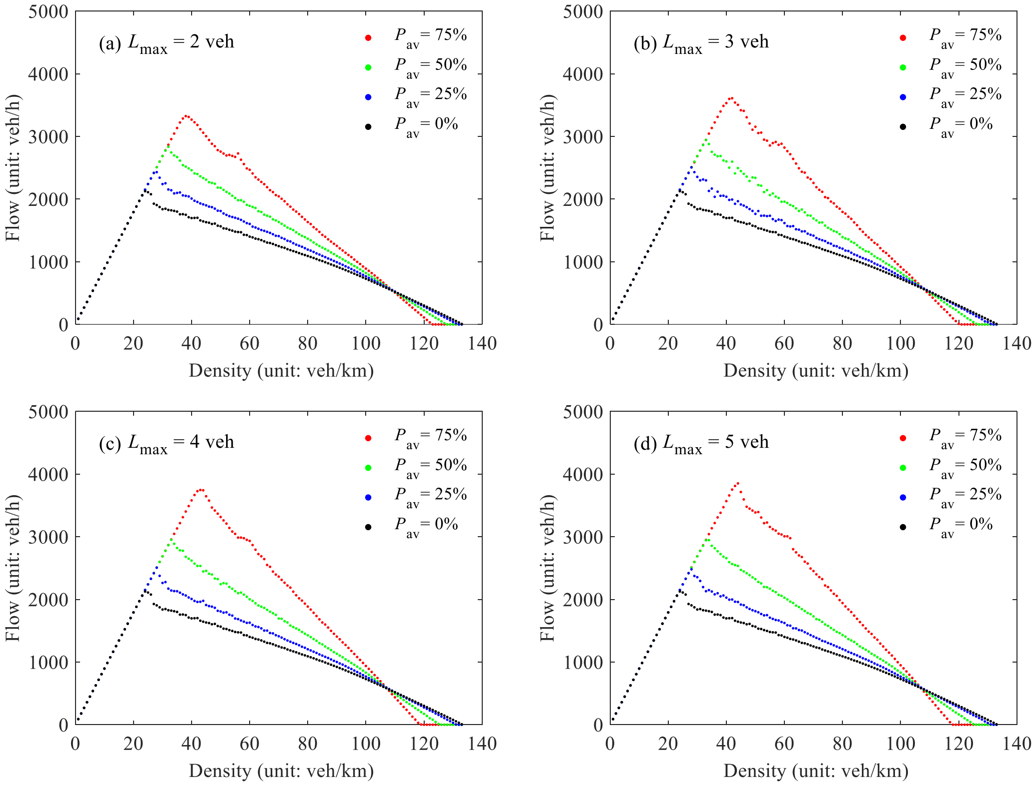


Fig.9. Flow-density diagrams under different maximum platoon size L_{max}, d_{intra}=2 m.

Figure 9 shows the traffic density plots for scenarios with 4 different maximum platoon sizes, including 2, 3, 4 and 5 vehicles. In each case, four cases with different P_{av} are included. Maximum platoon size is defined as the maximum number of vehicles in CAV platoons. Due to the spontaneous formation of platoons in the simulation, the number of vehicles in the platoon is different from L_{max} in cases (b), (c) and (d). In case (a), the platoons share the same size, equal to 2 vehicles, which is the minimum number of vehicles in a platoon. Road capacity increases as P_{av} increase. The area above the 0% CAV flow density plot indicates the positive effect of an increased percentage of CAV in the mixed traffic flow. In case (b), the maximum platoon size is set to 3 vehicles. Compared with the results of case (a), the positive impact area of the increase in the proportion of platooned vehicles is larger, and the road capacity achieved by case (b) is also slightly higher than that of case (a). This effect becomes more evident as L_{max} is further increased, as shown in case (c) and case (d). This phenomenon shows that both the penetration rate of CAV P_{av} and the maximum platoon length L_{max} directly affect the performance of the platoon strategy. Higher percentages of CAV and larger maximum platoon size result in higher capacity under mixed flow conditions.

4.8 Relationship between capacity and CAV penetration under various platooning configurations

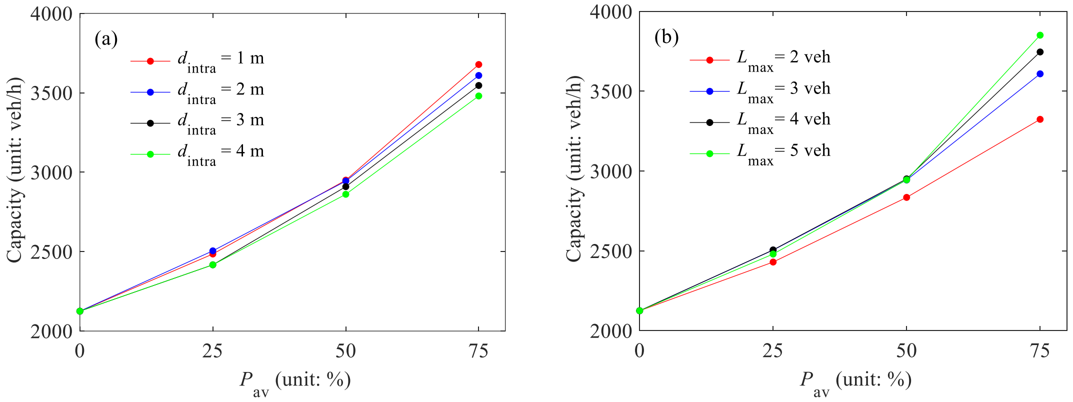


Fig.10. Relations between road capacity and CAV penetration rate P_{av}.

Figure 10 shows the relationship between road capacity and the proportion of CAV in mixed traffic flow. Fig. 10(a) includes 4 scenarios with different intra-platoon spacing d_{intra}, L_{max}= 3 veh, and Fig. 10(b) respectively has different maximum platoon sizes L_{max}, d_{intra}= 2 m. In general, road capacity increases with the increase in CAV penetration rate. In Fig.10(a), tighter intra-platoon spacing corresponds to higher capacity. This effect is more evident when CAV reaches a high proportion in mixed traffic flow. However, this effect is relatively insignificant compared to the increased capacity with increasing CAV proportions in the mixed traffic flow. In Fig. 10(b), a larger maximum platoon size results in higher capacity, particularly when CAV reaches a high proportion in mixed traffic flow.

5. Main findings and discussions

From the simulation results from subsections 4.1 and 4.2, it can be concluded that even with a fixed proportion of CAV penetration, not all of these CAVs will be able to travel in platoons. In other words, the penetration rate of CAV is not equal to the platooning rate finally achieved in the simulation. This phenomenon proves that the results of the simulation with preassembled platoons may not match the actual situation very well. The formation of platoons is influenced by several factors, including CAV penetration and the spatial distribution of CAVs in the mixed traffic flow. Under different traffic demand levels, the platooning ratio is also different, indicating that the level of traffic demand, or the vehicle density, also has an important impact on the performance of vehicle platooning. This point can also be proved by the results of average formation time from subsection 4.3, the average formation time is much higher in low-density and high-density regions than that in median density region. Platoon formation in medium-density region tend to be more efficient than low-density or high-density regions, which further results in higher platooning ratio even with the same CAV penetration in mixed traffic flow. In low-density areas, vehicles are sparsely distributed on the road segment, which is not conducive to form CAV platoons. In contrast, vehicles cannot move freely in congested traffic, which is also not a favorable condition for platoon formation.

The simulation results in subsections 4.4 and 4.5 show that the sizes of platoons formed in the system are determined by the maximum platoon size, the CAV penetration in the mixed traffic flow, as well as the level of traffic demand. These three factors shaped the platoon size distribution and the average platoon size in the simulation. For instance, the maximum platoon size in Fig. 6(a) is equal to 3 vehicles, which means that there are only two kinds of platoon sizes in the system, 2 or 3 vehicles. The average platoon size values for different CAV penetration in the mixed traffic flow, all between 2 and 3. In contrast, with the maximum platoon size of 5 vehicles in figure 6 (b), the CAV ratio in mixed traffic flow has a greater effect on the average platoon size value. What these two scenarios have in common is that the average platoon size value with higher CAV ratios in the mixed traffic flow is larger than the value with lower CAV ratios, indicating that the CAV ratio is the determining factor for the formation of larger platoon size in the mixed traffic flow. It is also understandable that the higher the penetration rate of CAVs, the higher the possibility of forming longer CAV platoons. Meanwhile, the proportion of CAVs in mixed traffic flow is the main factor that fundamentally determines the distribution of platoon size. Under the same traffic demand level, the ratio of platoons of maximum platoon size has a slight downward trend, indicating that traffic demand level also affects the platoon size distribution; the higher the level of traffic demand, the less likely it is to form a platoon of the maximum size than that when the level of traffic demand is low. However, this effect is not as strong as the effect of CAV penetration rate on platoon size distribution. In general, traffic flow with a larger maximum platoon size has higher heterogeneity than smaller one in terms of platoon sizes.

The fundamental diagrams in subsections 4.6 and 4.7 show that platooning configurations affect the traffic flow performance to varying degrees. Among the three configurations of maximum platoon size, intra-platoon spacing, and CAV penetration in mixed traffic flow, CAV penetration has the most significant effect on road capacity, while the effect of intra-platoon spacing is the least significant. As the penetration of CAVs in mixed traffic flows increases, the effect of maximum platoon size on road capacity also increases, as shown in the simulation results of subsection 4.8.

6. Conclusions

This study focuses on modeling platooning operations and evaluating the impact of platooning-related configurations on the performance of vehicle platooning in mixed traffic flow. A two-lane cellular-automata-based microscopic traffic flow model was developed for this purpose. Numerical simulations were performed for different CAV penetration rates and various levels of traffic demand. The platoon performance evaluation metrics, including platooning ratio, average formation time, average platoon size, and platoon size distribution, are analyzed to better understand platooning operations in mixed traffic flow. Also, sensitivity analysis of platooning-related configurations is performed to reveal potential relationships between platooning-related configurations and traffic flow performance, including intra-platoon spacing and maximum platoon size, enhancing a comprehensive understanding of vehicle platooning in mixed traffic flow.

The main findings of this study are summarized as follows:

(1) Platooning operation in mixed traffic flow is affected by various factors such as traffic demand level, CAV penetration rate, and platooning configuration (i.e. maximum platoon size, intra-platoon spacing, etc.), showing the complexity that cannot be fully described through simple relationships between factors. The platooning rate is always slightly lower than the CAV penetration rate and varies with different traffic demand levels, indicating that platoon formation is actually affected by the traffic demand level and the CAV penetration. Average formation time varies under different traffic demand levels. Under light and dense traffic, CAV spends much more time in the platoon formation process than in the medium-density region, showing that platoon formation can only achieve high efficiency in the medium-density region.

(2) Platoon size in mixed traffic flow exhibits different patterns under various conditions. The average platoon size is mainly determined by the maximum platoon size and CAV penetration rate in the mixed traffic flow, and is positively correlated with these two factors. Under different CAV penetration rates and traffic demand levels, the platoon size distribution presents different patterns. At a low CAV penetration rate, smaller platoons predominate, regardless of the maximum platoon size setting.

(3) The improvement of road capacity through CAV platooning in mixed traffic flow is determined by various influencing factors to varying degrees. Road capacity increase with the increase in the proportion of CAV in the mixed traffic flow. In free traffic flow, platooning-related

configuration has little effect on traffic flow performance; In the congested traffic flow, the intra-platoon spacing mainly affects the density area where platooning strategy has a positive impact on traffic throughput: the smaller the intra-platoon spacing, the wider the density area where the platooning strategy has a positive impact on traffic throughput. A larger maximum platoon size contributes to a higher capacity, especially when the proportion of CAVs in the mixed traffic flow exceeds 50%. At 75% CAV penetration, road capacity increased by more than 63%, and CAV penetration contributed more than 57% and 87% to the increase in road capacity compared to maximum platoon size and intra-platoon spacing.

This work mainly focuses on simulating dynamic platooning operations in mixed traffic flow consisting of conventional vehicles and CAVs. Future work will focus on the mixed traffic flow dynamics under the platooning strategy and its potential impact on different aspects of the transportation system, such as traffic safety and fuel efficiency.

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