Impact of dedicated lanes for connected and autonomous vehicle on traffic flow throughput

Lanhang Ye [a,*], Toshiyuki Yamamoto [b]

[a] Department of Civil Engineering, Nagoya University, Nagoya, 4640803, Japan, E-mail: ylhlxyz@gmail.com

[b] Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, 4640803, Japan

Abstract

This paper presents an application of a recently proposed methodology for modeling connected and autonomous vehicles (CAVs) in heterogeneous traffic flow, to investigate the impact of setting dedicated lanes for CAVs on traffic flow throughput. A fundamental diagram approach was introduced which reveals the pros and cons of setting dedicated lanes for CAVs under various CAV penetration rates and demand levels. The performance of traffic flow under different number of CAV dedicated lanes is compared with mixed flow situation. Simulation results indicate that at a low CAV penetration rate, setting CAV dedicated lanes deteriorates the performance of the overall traffic flow throughput, particularly under a low density level. When CAVs reach a dominant role in the mixed flow, the merits of setting dedicated lanes also decrease. The benefit of setting CAV dedicated lane can only be obtained within a medium density range. CAV penetration rate and individual CAV performance are significant factors that decide the performance of CAV dedicated lane. The higher level of performance the CAV could achieve, the greater benefit it will attain through the deployment of CAV dedicated lane. Besides, the performance of CAV dedicated lane can be improved through setting a higher speed limit for CAVs on the dedicated lane than vehicles on other normal lanes. This work provides some insights into the impact of the CAV dedicated lane on traffic systems, and helpful in deciding the optimal number of dedicated lanes for CAVs.

Keywords: connected and autonomous vehicles, dedicated lanes, heterogeneous flow, cellular automaton

1. Introduction

With the rapid development of self-driving technology, connected and autonomous vehicle (CAV) on the road is on the horizon. It is generally expected that at an early stage CAVs will exist in the heterogeneous traffic flow. Road traffic will consist of both CAVs and regular vehicles simultaneously, with CAVs under control of machine and algorithms and regular vehicles under the operation of human drivers. Existing studies also indicated that the potential efficiency of CAVs will be greatly reduced when CAVs at a low penetration rate among the heterogeneous flow [1]. Interaction between CAVs and regular vehicles in the heterogeneous traffic flow also brings uncertainty to current traffic system.

Enlightened from the managed lane strategy, CAV dedicated lane is believed as one of the potentially effective solutions to these challenges. For better accommodating CAVs under current road system and improving the efficiency of this emerging technology, increasing attention has been paid to the managed lanes approach. By allocating a number of lanes exclusive to CAVs, CAVs on the dedicated lanes can reveal their potentialities earlier than that in the heterogeneous traffic flow, even at a relatively low penetration rate stage. This strategy makes a separation of CAVs from the mixed traffic. CAVs are supposed to use the dedicated lane on which homogeneous traffic flow of CAVs is created. On the other hand, setting CAV dedicated lane will reduce the number of lanes for accommodating other regular vehicles. In particular, if not set properly, it will lead to a great waste of road resource and cause severe congestion in the traffic flow, decreases the overall throughput of the road.

Naturally, the question of when it will be necessary to set such dedicated lane arises. It is generally expected that a certain threshold of CAV penetration rate may exist, above which the overall traffic flow performance will be better by setting a number of CAV dedicated lanes, comparing to the performance of totally mixed traffic flow. Since the CAVs will be adopted gradually, and the CAV penetration rate among the heterogeneous flow will increase at a slow pace. Researchers have to decide how many lanes need to be allocated for CAVs considering the CAV penetration rate, in order to gain the maximum benefit of the dedicated lane approach.

However, the impact of CAV dedicated lane on overall traffic flow throughput is a complex problem. It involves not only the CAVs penetration rate but also the performance of the CAVs compared to regular vehicles. The performance of the overall traffic flow throughput also varies under different traffic demand levels. Thus, it is better to investigate this problem thoroughly than only determine a threshold penetration rate of CAVs for setting CAV dedicated lanes.

There is a lot of existing literature which studied the impact of the vehicle with adaptive cruise control on traffic flow. Ioannou and Chien developed an autonomous intelligent cruise control system. They evaluated the performance of the system via a computer simulation and found that the developed system contributes to a faster and smoother traffic flow [2]. Mardesden et al. studied the potential impacts of ACC on motorway driving via microscopic simulation, a potential comfort gain for the driver and environmental benefits were identified [3]. Arem et al. studied the impact of a cooperative ACC on the traffic-flow characteristics and found that the traffic-flow stability can be improved along with a slight increase in the flow efficiency [4]. Kesting et al. employed an ACC strategy to improve the traffic stability and increase the dynamic road capacity [5]. Shladover et al. estimated the effect on highway capacity under varying market penetrations of vehicles with adaptive cruise control (ACC) and cooperative adaptive cruise control (CACC) via microscopic simulation and found that CACC was able to increase capacity greatly after its market penetration reached moderate to high percentages [6]. Previous studies focused primarily on the impact of autonomous driving, while not yet sufficient attention has been paid to the connectivity in the process of autonomous driving. Recently, a lot of efforts have been made to model the heterogeneous traffic flow with CAVs, which are capable of both autonomous driving and vehicle connectivity. Talebpour and Mahmassani presented a simulation framework using different models with some technology-appropriate assumptions to study the influence of CAVs on traffic flow stability and throughput [7]. Levin and Boyles presented a multi-class cell transmission model to model the shared human and autonomous vehicle roads [8]. In our previous work, attempts were made to model the CAVs in heterogeneous flow, considering both autonomous driving through the ACC and inter-vehicle connection via short-range communication [9].

In order to better accommodate CAVs, several strategies have been proposed in the recent literature. At the network level, Chen et al. developed a mathematical framework for the design of autonomous vehicle zones [10]. At the roadway level, Chen et al. also developed a mathematical framework for the optimal deployment of autonomous vehicle lanes in a road network [11]. Optimal solutions to accommodate CAVs in terms of managed lanes were analyzed along with attempts to formulate the road capacity of the mixed traffic. Chen et al. proposed a set of capacity formulation which takes into consideration the AV penetration rate, micro/mesoscopic characteristic and different lane policies for accommodating AVs [1]. Hussain et al. developed an analytical model to estimate the freeway overall performance by formulating the average headway of the mixed traffic [12]. Ghiasi et al. proposed an analytical capacity model and lane management model of the mixed traffic using a Markov chain method [13].

Simulation is another effective approach that can be utilized to investigate this problem. Talebpour et al. investigated the effects of reserved lanes for AVs on congestion and travel time reliability [14]. In their work, three different strategies were assessed and compared, it found that optional use of the CAV dedicated lane for CAVs can ease congestion and has better performance over other policies. Chen's work also verified that mixed-use policies can realize higher capacities than strict segregation of CAVs and regular vehicles [1].

These works serve the base for this study. This work is intended to provide some insights into the impact of CAV dedicated lanes on overall throughput considering CAV penetration rate in the heterogeneous flow, CAVs performance and traffic density. A fundamental diagram approach is introduced which reveals the pros and cons of setting CAV dedicated lanes, under different CAV penetration rates and varying demand levels. There is a fundamental difference between this study and macroscopic analysis. In this study, the mixed traffic flow is modeled at a microscopic level, mixed flow dynamics are considered when analyzing the impacts of CAV dedicated lanes. The results are presented at a macroscopic level, these results will be more reliable than solely macroscopic analysis since macroscopic analysis is not able to reflect mixed flow dynamics at a microscopic level. The proposed approach covered the whole density spectrum in order to form a comprehensive understanding of impacts of CAV dedicated lanes. It will be beneficial for the understanding of heterogeneous flow dynamics and also be helpful in deciding the optimal number of dedicated lanes for CAVs.

2. Model

The methodology for modeling CAVs in heterogeneous flow is identical with our previous work [9]. A cellular automaton (CA) model was developed, wherein both the CAVs and conventional vehicles were incorporated in the heterogeneous traffic flow. The established model considered both autonomous driving through the adaptive cruise control and inter-vehicle connection via short-range communication. For the sake of completeness, the heterogeneous flow model is first reviewed. For modeling of regular vehicles, the two-state safe-speed model is applied, which is able to reproduce the metastable state, traffic oscillations, phase transitions, and other real traffic flow dynamics [15, 16]. For modeling the CAVs, new rules were established in the heterogeneous-flow model. The steps involved in the model are as follows [9].

2.1 Deterministic speed update:

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

Here, v and v' denote the speed at the current and subsequent time steps, respectively. a and $v_{\max}$ are the acceleration rate and maximum velocity of the vehicle, respectively. d_{anti} denotes the anticipated space gap, v_{safe} denotes the safe speed.

For regular vehicles, d_{anti} and v_{safe} are defined as follows.

$$d_{\text{anti}} = d + \max(v_{\text{anti}} - g_{\text{safety}},\ 0) \tag{2}$$

$d = x_l - x - L_{\text{veh}}$ is the real space gap. x and x_l denote the position of the object vehicle and its preceding vehicle. L_{veh} is the length of the vehicle. $v_{\text{anti}} = \min(d_l,\ v_l + a,\ v_{\max})$ denotes the expected velocity of the preceding vehicle. d_l, and v_l denote the real space gap and speed of the preceding vehicle, respectively. g_{safety} is a safety parameter that helps in avoiding accidents considering the limitation of human perception.

$$v_{\text{safe}} = \left[-b_{\max} + \sqrt{b_{\max}^2 + v_l^2 + 2b_{\max} d} \right] \tag{3}$$

$b_{\max}$ is the maximum deceleration rate. The round function $[x]$ helps return the integer nearest to x. This equation assumes (i) a reaction time of 1 s (which is presumably the time step of the CA model), (ii) no acceleration at the present time.

For CAVs, corresponding $d_{\text{anti}}^{\text{cav}}$ and $v_{\text{safe}}^{\text{cav}}$ are defined as follows.

Based on the capability of obtaining an exact value of the space gap, the anticipation distance for CAVs can be transformed to the following function.

$$d_{\text{anti}}^{\text{cav}} = \begin{cases} d + v_{\text{anti}}^{\text{cav}} & \text{if } v_l \text{ is a CAV} \\ d + v_{\text{anti}} - b_{\text{defense}} & \text{otherwise} \end{cases} \quad (4)$$

$$v_{\text{anti}}^{\text{cav}} = \min(d_l, v_l + a, v_{\max}, v_{li}) \quad (5)$$

Connectivity is incorporated in Equation (5), where v_{li} denotes the average velocity of the preceding connected vehicles within the connected range (*CR*). If there is no CAV within the *CR*, a default value of $v_{\max}$ is applied for v_{li}. The CAVs are able to obtain the driving condition within the *CR* via dedicated short-range commutation (DSRC) technology. *CR* is larger than *DR*. Connectivity of the CAVs is another approach of obtaining additional road condition from a wider connected range (*CR*) compared to its sensor-detection range. b_{defense} is the randomization-deceleration rate under the defensive state. Here, a worst case is assumed to ensure the safety during the operation of the CAVs when following a conventional vehicle. Because the driving behavior of humans is unpredictable, a conventional vehicle is always assumed to stay in the defensive state in the operation of a CAV.

In determining safe speed v_{safe} for the regular vehicles, a reaction time of 1 s is incorporated in Equation (3) for human driving. For the CAV, this reaction time is eliminated. Compared to conventional vehicles, CAVs are only able to detect vehicles located within the detection range of the sensors. Based on this characteristic, the maximum velocity of a CAV is limited to the detection range (*DR*) of the sensors.

$$v_{\text{safe}}^{\text{cav}} = \left\lfloor \sqrt{v_l^2 + 2b_{\max} \min\left(d_{\text{anti}}^{\text{cav}}, DR\right)} \right\rfloor \quad (6)$$

Here, the velocity of a CAV is assumed to be sufficiently low such that the vehicle can be completely stopped within the *DR*, i.e., the maximum velocity of the CAVs $v_{\max}^{\text{cav}} = \left\lfloor \sqrt{2b_{\max} DR} \right\rfloor$.

For regular vehicles, acceleration rate a is a constant value. While for CAVs, a classical ACC model is employed to determine the acceleration rate a_{ACC} for the autonomous driving [17], which is defined as follows.

$$a_1 = K_1(d - vT_{\text{ACC}}) + K_2(v_l - v),\ a_{\text{ACC}} = \lfloor \max(\min(a_1, a_{\max}), b_{\max}) \rfloor \quad (7)$$

Here, K_1 and K_2 are coefficients with respect to the ACC, and T_{ACC} is a desired net time gap of a CAV with respect to the preceding vehicle. $\lfloor x \rfloor$ is the floor function used to return the maximum integer no greater than x.

2.2 Stochastic deceleration for regular vehicles:

$$v' = \begin{cases} \max(v'_{\text{det}} - b_{\text{rand}}, 0) & \text{with probability } p \\ v'_{\text{det}} & \text{otherwise} \end{cases} \quad (8)$$

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

$$b_{\text{rand}}=\begin{cases} a & \text{if } v < b_{\text{defense}} + \lfloor d_{\text{anti}}/T \rfloor \\ b_{\text{defense}} & \text{otherwise} \end{cases} \quad (9)$$

$$p=\begin{cases} p_{\text{b}} & \text{if } v = 0 \\ p_{\text{c}} & \text{else if } v \le d_{\text{anti}}/T \\ p_{\text{defense}} & \text{otherwise} \end{cases} \quad (10)$$

Where b_{rand} denotes the randomization-deceleration rate. $p_{\text{defense}} = p_{\text{c}} + \frac{p_{\text{a}}}{1+e^{\alpha(v_{\text{c}}-v)}}$ 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. b_{defense} is the randomization-deceleration rate under the defensive state. Under the normal state, the randomization-deceleration rate equals to a.

For CAVs, no randomization-deceleration is applied.

2.3 Position update

$$x' = x + v' \quad (11)$$

x' denotes position at subsequent time step. The time step of the model is 1 s and the vehicle will move forward at a distance of its updated velocity. Tables 1 and 2 list the parameters of the model for modeling the mixed traffic flow.

Table 1 Parameters for modeling regular vehicles [15]

Parameters	L_{cell}	L_{veh}	$v_{\max}$	T	a	$b_{\max}$	b_{defense}	P_{a}	P_{b}	P_{c}	g_{safety}	v_{c}	α
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	27	1.8	0.5	−3	1	0.85	0.52	0.1	20	30	10

Table 2 Parameters for modeling CAV [9, 17]

Parameters	DR	CR	P_{lc}	K_1	K_2	$a_{\max}$
Units	m	m	-	s^{-2}	s^{-1}	m/s^2
Values	120	300	0.2	0.14	0.9	3

2.4 Lane-changing rules and lane policies

The following section focus on the new aspects of the model that applied in this work. The difference lies in the lane-changing process, in which different lane policies for CAVs are embedded. In order to compare the traffic flow throughput under various scenarios with a different number of CAV dedicated lanes, a three-lane heterogeneous flow model was applied.

The simulation was conducted on a 10-km three-lane road segment under the periodic boundary condition. First, the simulation involved conventional vehicles and CAVs randomly distributed in a mega-jam on the road segment. Three policies are defined. Namely, 0 CAV dedicated lane, 1 CAV dedicated lane, and 2 CAV dedicated lanes. There are primarily two categories of situation in the lane-changing process. One is lane-changing behavior between lanes with identical lane policy, such as between two CAV-dedicated lanes or two regular lanes. For this kind of lane-changing behaviors, as long as the traffic condition in the target lane is better than its current lane, the vehicle, including both regular vehicle and CAV, would change to target lane with a lane-changing probability P_{lc}. The other is lane-changing behavior between lanes with different lane policies, such as lane-changing behavior between the CAV dedicated lane and regular lane.

$d(i, t)$ denotes the space gap ahead of vehicle i at time step t. v and a are the velocity and acceleration rate of the vehicle, respectively. v_{max} is the maximum velocity. $d(i, t)_{other}$ denotes the space gap ahead of vehicle i on target lane at time step t, $d(i, t)_{back}$ is the space behind vehicle i on target lane.

(1) Lane-changing rules between lanes with identical lane policy [18]:

Incentive criteria: $d(i, t) < \min\{v + \mathrm{a}, v_{max}\}$ and $d(i, t)_{other} > \min\{v + \mathrm{a}, v_{max}\}$ indicate space ahead of the object vehicle i is not enough for traveling with a higher velocity, and the driving condition in the target lane is better than that in the current lane.

The safety criteria $d(i, t)_{back} > v_{max}$ indicates that, when changing the lanes, the vehicle immediately behind the object vehicle moving on the target lane will not crash 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) Lane-changing rules between lanes with different lane policies:

For the regular vehicles initially located on the CAV-dedicated lane, as long as the safety criteria $d(i, t)_{back} > v_{max}$ is satisfied, regular vehicles are ordered to change to the normal lanes with a lane-changing probability of 1, thus, they will gradually change lanes to regular lanes in the initial transition period. For all regular vehicles on regular lanes, they are not allowed to change lanes to the CAV dedicated lane.

For all CAVs on 3 lanes, identical lane-changing rules of the situation (1) are applied, which indicate that CAVs can use both CAV dedicated lane and other normal lanes. Whether a CAV will choose a CAV-dedicated lane or a regular lane is just based on the traffic condition on its current lane and that on the target lane.

In the simulation, CAVs and regular vehicles are distinguished and labeled with different feature. Before lane-changing rules are applied, vehicle type is first determined, and for these two types of vehicle, the afore-mentioned different lane-changing rules are employed respectively. For vehicles on middle lane, the default setting is to consider the left lane as target lane first, then the right lane. For a multi-lane highway, inner lanes normally attain a higher average speed than outside lanes and the incentive goal of lane-changing is to attain a higher travel speed. If its left and right lane both meet the lane changing conditions, possible results will include changing to the left lane, changing to the right lane or maintaining its current lane. As for the conventional vehicle, the lane-changing behavior still will be decided by the lane-changing probability. The lane-changing probability represents the stochastic factor in the lane-changing process. CAVs are able to travel on each lane of the road segment. In some of the tested scenarios, such as with 80% CAV market penetration and 1 lane (out of 3 lanes) dedicated to CAVs, a mixed flow of the two types of vehicle can be expected on both of the two normal lanes. Also, there is a physical limitation when attributing too many lanes to CAVs while CAV penetration rate is low, since the normal lane may not be able to accommodate all the conventional vehicles. In the practical simulation, it is physically impossible to reach certain aforementioned situations. Under such cases, it either leads to ever-growing jam, or a mis-obedience of the rules by the human drivers. Simulation results are excluded when such a physical limitation is exceeded.

3. Simulation results and discussion

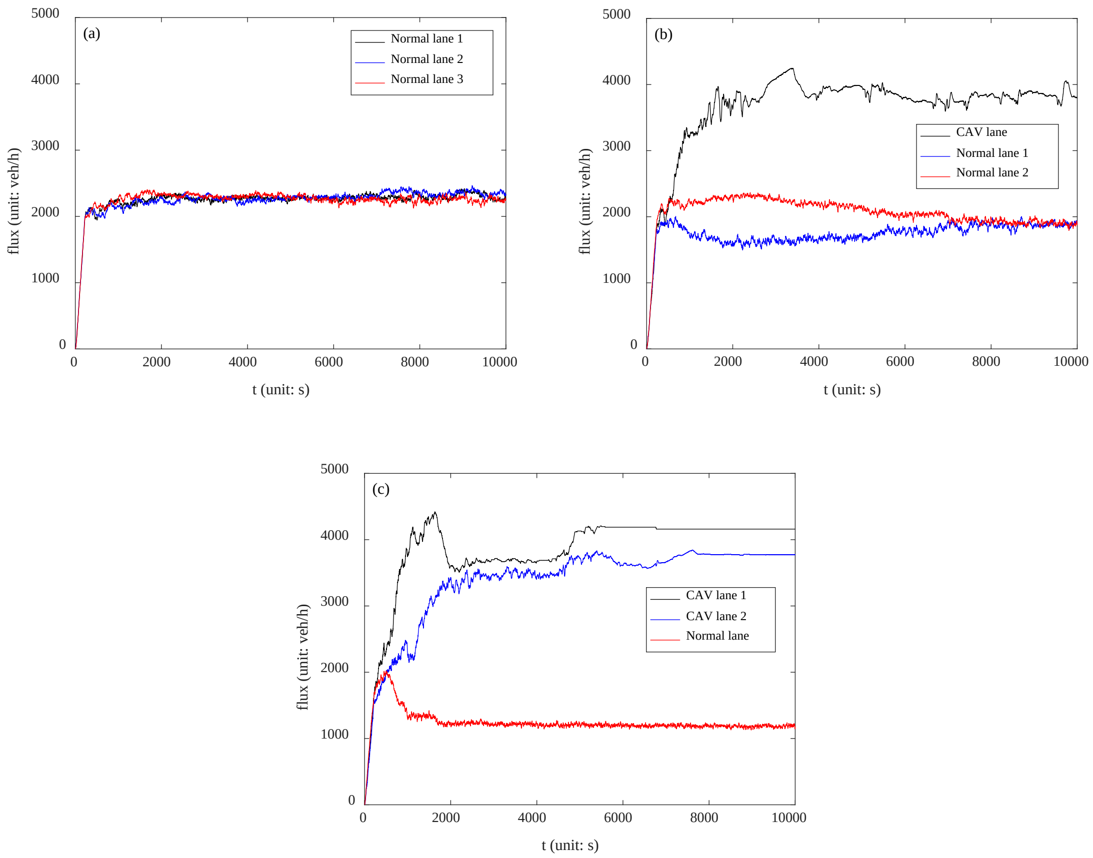

Fig.1. Flow-time diagrams under different CAV dedicated lanes policies P_{av}=60%, vehicle density is 60 veh/km/lane, T_{ACC} = 0.5 s. (a) 0 CAV dedicated lane, (b) 1 CAV dedicated lane (c) 2 CAV dedicated lanes.

P_{av} denotes CAV penetration rate in the mixed traffic flow. T_{ACC} is the desired net time gap of a CAV with respect to the preceding vehicle in the ACC process. Fig. 1 indicates the flow rate results with regard to time under a specific scenario, in which the CAV penetration rate is 60%, vehicle density at 60 veh/km/lane and T_{ACC} is 0.5 s. The simulation involved conventional vehicles and CAVs initially randomly distributed in a mega-jam on the road segment. Then all the vehicles will gradually change lanes based on the set lane policy. Fig. 1 shows the initial transition process. For the first case, since there is no CAV dedicated lane set under this case, the flow rate results are similar between lanes. While in the latter two cases with a different number of CAV dedicated lanes, flow rates differ between lanes. As expected, the CAV dedicated attained a greater flow rate than other normal lanes, this is the merit of setting CAV dedicated lane, while its negative effect on other lanes also should not be neglected. Due to the setting of CAV dedicated lanes, the flow rate of other lanes also is decreased. This phenomenon is much clearer in case c with two CAV dedicated lanes. To evaluate the overall effect of CAV dedicated lanes on traffic system, instead of focusing on the improvement on specific lanes, it is the overall throughput that should be considered.

To form an overall understanding of this problem, in the following part, the overall flow-density relationship is presented. Each simulation last 20000 time steps, data from the initial 10000 time steps is eliminated to avoid the transition effect. Four sets of simulation were conducted, with results presented as follows. Among former three experiments, only the value of T_{ACC} is different. Namely, a series of values including 0.5 s, 0.8 s, and 1.1 s were applied, which represents a decreasing level of ACC performance. The maximum speed for all vehicles in the simulation is identical. In the last experiment, T_{ACC} equals 0.5 s, and the maximum speed for CAVs on CAV dedicated lane is higher than vehicles on normal lanes.

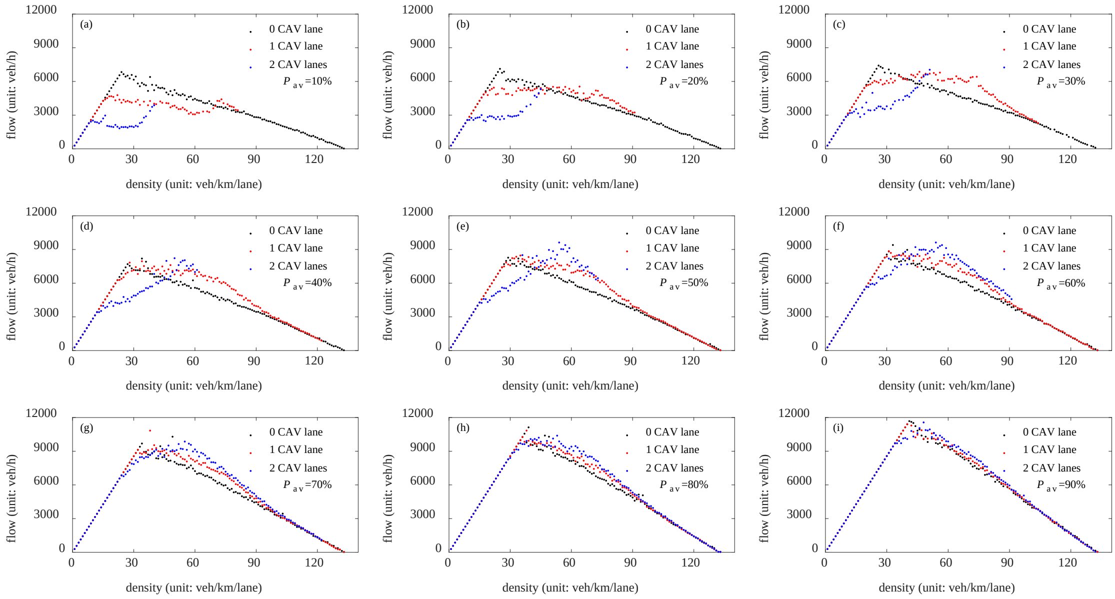

Fig. 2. Flow-density diagrams under different CAV dedicated lanes policies,

each subplot corresponds to a CAV penetration rate P_{av}, which increase from 10% to 90%, T_{ACC} = 0.5 s.

Fig. 2 shows the results of the relationship between the traffic flow with respect to the density. The T_{ACC} for CAVs is set as 0.5 s. Each subplot represents a case with a fixed CAV penetration rate, with P_{av} ranging from 10% to 90%. Fig. 3. Fig. 4 and Fig. 5 share the same setting. In each subplot, the results of three scenarios are presented simultaneously. Each scenario corresponds to a different lane policy. Namely, 0 CAV dedicated lane, 1 CAV dedicated lane and 2 CAV dedicated lanes. In the case of 0 CAV dedicated lane, the traffic flow is completely heterogeneous flow on all the three lanes of the road segment. In the other two cases, a different number of CAV dedicated lanes include 1 lane and 2 lanes are set. Under normal cases, traffic flow on the CAV dedicated lane should be homogeneous flow, while that on other lanes is heterogeneous flow. Generally, the overall traffic flow throughput increases with the increase of the CAV penetration rate in the heterogeneous flow.

The diagrams in scenarios with CAV dedicated lanes can be roughly divided into three parts: the free flow phase, the congestion phase and the intermediate phase between aforementioned two phases, which is divided by the cross points between diagrams with CAV lane and the mixed flow diagram without CAV lane. In the free flow phase and the congestion phase, traffic flow on all three lanes is free flow and congestion flow. While for the intermediate phase, traffic flow states on different lanes may be different, due to the impact of different lane policies.

For the congestion phase, there is no significant differences among all of the scenarios with different CAV dedicated lane policies. This is easy to understand because the traffic flow on all of the three lanes is congested. While for the free flow phase and the intermediate phase between free flow phase and the congested flow phase, a considerable difference can be observed easily. In the free flow phase, when density is low enough, the traffic flow on all of the three lanes is free flow, and there is no significant difference even under different CAV dedicated lane policies. However, the density range of the free flow phase is different among cases with different CAV penetration rates. Namely, in cases with lower CAV penetration rates, the density ranges of free flow phase are shorter than that with a higher CAV penetration rate. This is due to the fact that CAVs have a better performance than regular vehicles, a larger free flow phase corresponds to a higher capacity.

Even in a case with a fixed CAV penetration rate, the density ranges of free flow under three scenarios with a different number of CAV dedicated lane are also distinct from each other. Particularly in cases with a relatively lower CAV penetration rate, the free-flow density range under the scenario with 2 CAV dedicated lanes is much smaller than that with fewer CAV dedicated lane. This is because there are not enough CAVs on the CAV dedicated lanes, which result in a waste of the road resource. While the normal lanes have to deal with the heavy traffic of regular vehicles, the normal lane will soon be congested, with CAV dedicated lanes still in free flow state. In Fig. 2. (a), the flow-density diagrams of cases with CAV dedicated lanes (marked with blue and red points) are lower than that of the case without CAV dedicated lane (marked with black points). The area between them represents the negative effect of setting CAV dedicated lane under a CAV penetration rate of 10%. For simplicity, we name it the negative effect area of setting CAV dedicated lane. The negative effect area in the case with two CAV dedicated lanes is even larger than that with one CAV dedicated lane.

In Fig. 2. (b), the CAV penetration rate is 20%, from the flow-density diagram two kinds of areas can be observed, which are divided by a cross point of the flow-density diagrams under three different scenarios, namely around the density of 50 veh/km/lane. For the right part, the flow-density diagrams of cases with CAV dedicated lanes are above the flow-density diagram in the case without CAV dedicated lane. It shows that the setting of CAV dedicated lane is beneficial under a CAV penetration rate of 20% when the density exceeds 50 veh/km/lane. For this kind of area, correspondingly, we name it the positive effect area of setting CAV dedicated lane.

With further increase in CAV penetration rate, the negative area gradually decreases. When the CAV penetration rate reaches a rate of 50%, namely in Fig. 2. (e), the negative area of setting 1 CAV dedicated lane nearly vanishes. The negative area of setting 2 CAV dedicated lanes continues to decrease until the CAV penetration rate reaches a rate of 80%, then it also nearly vanishes. By comparing these two kinds of areas, the optimal strategy for setting CAV dedicated lane can be developed. Fig. 2. reveals the pros and cons of setting CAV dedicated lane, considering the CAV penetration rate and density. For a three-lane highway, it is beneficial to set 1 CAV dedicated lane when CAV penetration rate exceeds 40%, and 2 CAV dedicated lanes when CAV penetration rate exceeds 60% in the considered case.

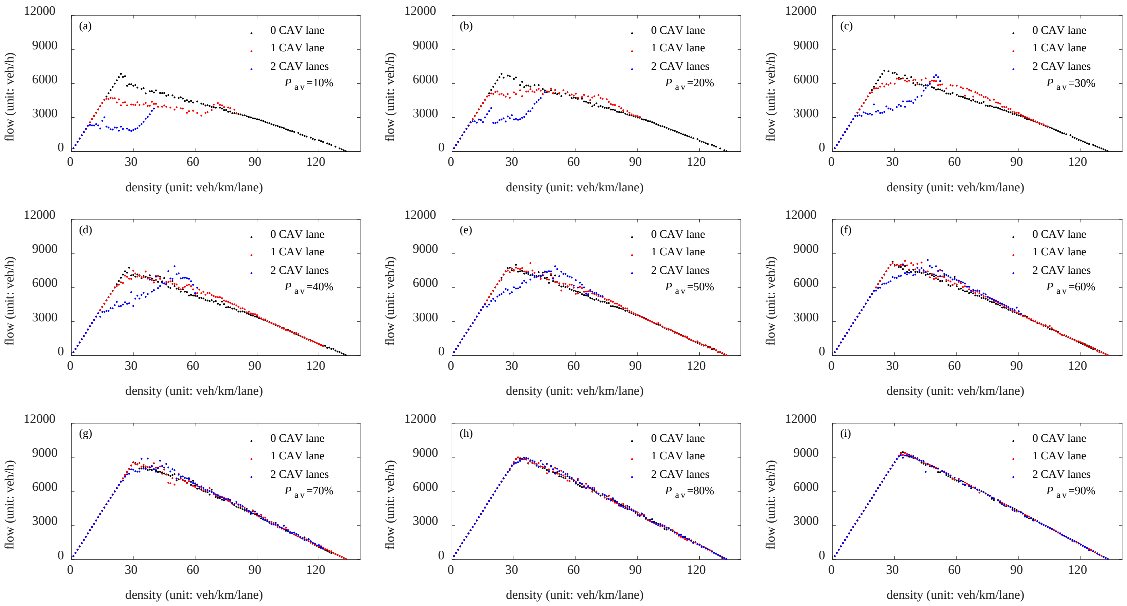

Fig. 3. Flow-density diagrams under different CAV dedicated lanes policies,

each subplot corresponds to a CAV penetration rate P_{av}, which increase from 10% to 90%, T_{ACC} = 0.8 s.

Fig. 3 shows the simulation result under a case with a less advanced CAV in ACC performance, in which T_{ACC} is set as 0.8 s. The evolution pattern with regard to P_{av} is similar to that in Fig. 2. However, the positive areas in Fig. 3 are smaller than its counterparts in Fig. 2. This phenomenon indicates that the performance of individual CAV is literally a decisive factor in the performance of CAV dedicated lanes. A more advanced performance in CAV corresponds to a larger benefit it will attain through the deployment of CAV dedicated lanes. Moreover, when the CAV penetration rate exceeds 70%, the difference between the scenarios with CAV dedicated lanes and scenario without CAV dedicated lane becomes smaller and smaller with further increase in CAV penetration rate. This phenomenon indicates that when CAVs reach a dominant role in the mixed traffic flow, the benefit of setting CAV dedicated lane also decreases. Compared with the cases in Fig. 3, we can find that this trend is much more obvious in Fig. 4 with a less advanced CAV performance.

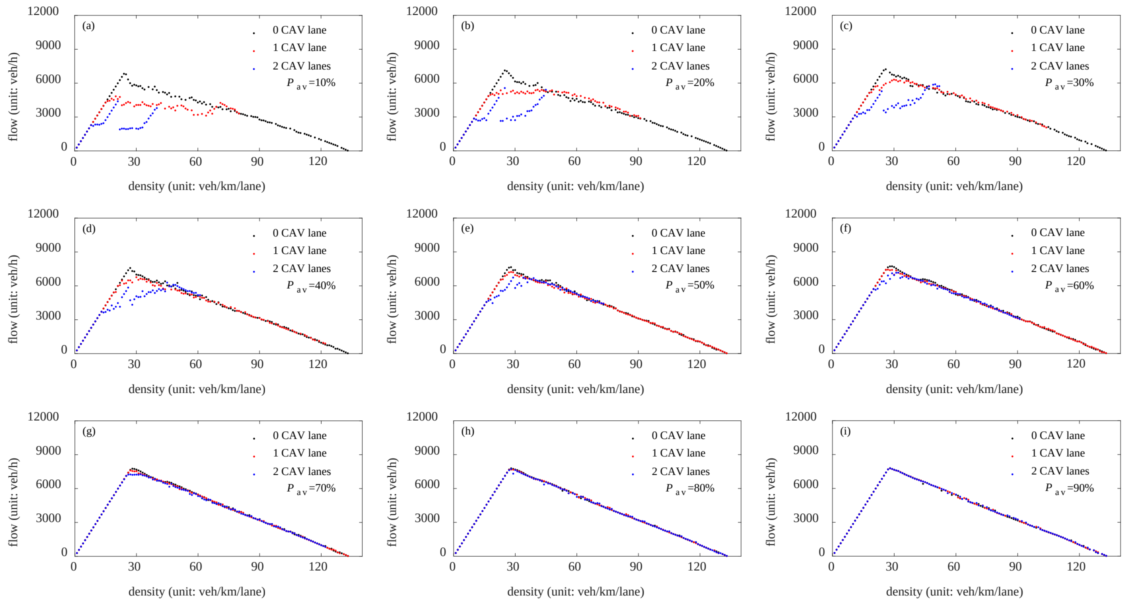

Fig. 4. Flow-density diagrams under different CAV dedicated lanes policies,

each subplot corresponds to a CAV penetration rate P_{av}, which increase from 10% to 90%, T_{ACC} = 1.1 s.

Fig. 4 shows the results of the relationship between the traffic flow with respect to the density. In which case the T_{ACC} is set as 1.1 s. At the early stage, when CAV penetration rate and density is relatively small, setting CAV dedicated lane only deteriorates the overall throughput performance, since there are not enough CAVs on the road and CAV lanes are underused. With the increase in CAV penetration rate, the negative impact eased gradually. However, no positive effect can be observed in this case due to a less advanced level in the ACC performance.

Under some extreme cases, the lane policy is not always obeyed strictly. Such as in Fig. 4 (a), in which case the CAV penetration rate is only 10% while there are two CAV dedicated lane is set among the total three lanes. With the increase in density, some regular vehicles may fail to change to the normal lane, due to the severe congestion caused by the improper setting of the CAV dedicated lanes. Under such cases, the normal lane will first reach the congestion phase, with other two CAV dedicated lanes still in free flow phase. And the CAV dedicated lane adjacent to the normal lane will be occupied by the heterogeneous flow. With further increase in density, it will soon reach the congestion phase. The similar situation will occur in the last CAV dedicated lane. This explains the intermittent curve shown in the case of setting 2 CAV lanes.

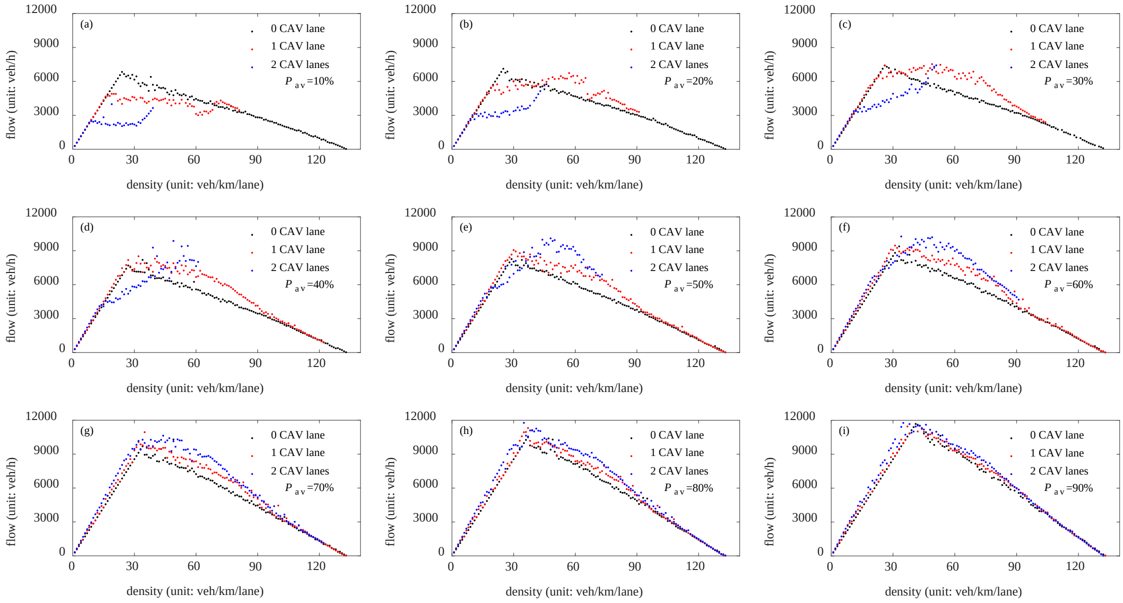

Fig. 5. Flow-density diagrams under different CAV dedicated lanes policies, with a higher maximum speed of CAV on the dedicated lanes. Each subplot corresponds to a CAV penetration rate P_{av}, which increase from 10% to 90%, T_{ACC} = 0.5 s.

Fig. 5 shows the results of the case in which the maximum speed of CAV on the dedicated lanes is 120 km/h, while the maximum speed for all vehicles on normal lanes is 95 km/h. Compared with Fig. 2, we can find that the benefit areas is larger than its counterparts in Fig. 2. This phenomenon indicates that the performance of CAV dedicated lane can be improved by setting a higher speed limit for CAVs on the dedicated lane.

In this case, for a three-lane highway, it is beneficial to set 1 CAV dedicated lane when CAV penetration rate exceeds 30%. When CAV penetration rate exceeds 50%, setting 2 CAV dedicated lanes can attain greater benefit than setting 1 CAV dedicated lane. These findings are qualitatively consistent with findings of previous work. It was found that setting a CAV dedicated lane is only advantageous at CAV penetration rates above 50% for a two-lane highway, and 30% for a four-lane highway [9]. In addition to CAV penetration rate, we further clarify the dynamic relationship between several factors in this problem, including traffic density, CAV performance, and maximum speed. Each of them has a direct impact on the throughput results. This work provided a much more comprehensive understanding of the CAV-dedicated lane problem than previous works [14].

4. Conclusions

In this work, the impact of CAV dedicated lane on the overall traffic flow throughput was investigated using a three-lane heterogeneous flow model. A fundamental diagram approach was introduced which is able to reveal the pros and cons of setting dedicated lanes for CAVs under various CAV penetration rates. Relations of overall flow throughput under different scenarios with regard to density are numerally investigated. The performance of traffic flow under a different number of CAV dedicated lanes is compared with mixed flow situation. The simulation results indicate that the capability of CAV plays a key role in the performance of CAV dedicated lanes. The higher level performance CAVs can achieve, the greater benefit will be through the deployment of CAV lanes. The performance of CAV dedicated lanes also varies under different CAV penetration rates. At a relatively low CAV penetration rate, the introduction of CAV dedicated lane has a negative impact on the overall throughput, particularly under low demand level. The negative effect will be eased with the increase in CAV penetration rate. When CAVs reach a dominant role in the traffic flow, the positive effect of introducing CAV dedicated lanes also decrease. The benefit of setting CAV dedicated lane can only be obtained within a medium density range. Besides, the performance of CAV dedicated lane can be improved by setting a higher speed limit for CAVs on the dedicated lane than vehicles on other normal lanes.

The dynamic relationship between CAV dedicated lane performance, CAV performance, CAV penetration rate and density was revealed, which is helpful in deciding the optimal number of lanes to be allocated to CAVs. The model can be easily extended to various multi-lane models based on specific scenarios, indicating great practical potentiality for CAV lane management in the near future.

Still, there are some shortages exist in this work, such as the validation of the CAV results. Due to a limited data of CAVs and behavioral shifts dynamic of CAVs in the mixed traffic flow have not yet been sufficiently understood. This work adopted different values of ACC parameter to describe possible future situations. The results of the high-density part are not as reliable as other parts of the density spectrum. Since in the very high-density region, lane-changing is almost impossible due to the physical condition, lane policy is not obeyed strictly.

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