IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 16, 2019, accepted March 29, 2019, date of publication April 12, 2019, date of current version April 25, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2910833

Influence of Exclusive Lanes for Connected and Autonomous Vehicles on Freeway Traffic Flow

KE MA AND HAO WANG
Jiangsu Key Laboratory of Urban ITS, Jiangsu Province Collaborative Innovation Center of Modern Urban Traffic Technologies, Southeast University, Nanjing 210096, China

Corresponding author: Hao Wang (haowang@seu.edu.cn)

This work was supported by the National Natural Science Foundation of China (Grant No. 51878161).

ABSTRACT The intelligence of connected and autonomous vehicle (CAV) is insufficient to deal with the complex road conditions. However, the application of exclusive lanes bypasses the long wait for the technology to mature. Prior to the maturity of intelligent transport systems (ITSs), it's a feasible solution in terms of technology and cost to set up exclusive lanes. In this way, CAVs will form an efficient and energy-saving autonomous fleet. An improved cellular automata model is used to study the effect of setting up exclusive lanes for CAVs on traffic flow throughput and stability on the freeway. A multi-lane freeway, equipped with intelligent sensors and road signs, is set up and three stages are designed according to the development degree of CAVs. This paper introduces two kinds of significant data by simulation: heterogeneous traffic flow and the degradation rate of CAV. They verify that setting up exclusive lanes for CAV will greatly improve the traffic condition of the freeway on the different penetration rates of CAV. Although the establishment of exclusive lanes can only slightly improve the traffic capacity, it can effectively inhibit the degradation of CAV within the range of CAV's penetration rates from 10% to 80%.

INDEX TERMS Connected and autonomous vehicles, exclusive lanes, cellular automaton, freeway.

I. INTRODUCTION

Recent years, advancements in internet technology, artificial intelligence, computing power, sensor technology, communication bandwidth and other aspects have made autonomous enter the real world from the realm of science fiction. The automakers and Internet companies have spent billions of dollars developing CAVs and have aggressively promoted the idea that CAVs will help create a safer, cleaner and more convenient society. Around the world, about 1.25 million people die in traffic accidents each year, and many more others suffer serious or minor injuries. Most experts [1]–[4] believe that once self-driving technology is perfected, CAVs will greatly reduce the casualties caused by traffic accidents and increase road capacity. However, it is not desirable to have a less mature autopilot system to face a real and complex road environment. Automakers may need many years to gain experience. On the other hand, some experts believe that early CAVs were highly sensitive to manual vehicles (MV) [5], [6]. Based on some real vehicle experimental data [7], many researchers further study the mode of operation of CAV rules and its impact on road capacity [8]. Different models have been applied in the research of autonomous driving successively: multi-vehicle cooperative driving stability control based on optimal control theory [9]; multi-vehicle cooperative driving stability control based on potential function method [10]; multi-vehicle cooperative driving stability control based on communication network topology [11]. The research of CAVs not only selects different analysis models, but also includes the characteristics of urban roads and highways. The model of CAVs on straight roads with no ramp and intersections was proposed [12]–[14]. Under complete Intelligent Transport System (ITS) environment, a design for future road intersection that does not require a signal light has been proposed [15] [16]. Some researchers have applied new models for car-following [17] and lane-changing [18]. A vehicle-to-vehicle (V2V) communication environment can be established to avoid the deterioration of traffic stability caused by CACC degradation to ACC [19]. The mature ITS still has a long way to go. The complexity of urban roads and the unpredictable human driving behaviors make the driving environment of CAVs worse. Therefore, freeway with simpler

The associate editor coordinating the review of this manuscript and approving it for publication was Zhengbing He.

conditions is more suitable for early CAVs. A scheme has also been proposed for autonomous vehicles to co-operate on the ramp on the freeway [20]. Stability analysis and fundamental diagram of heterogeneous traffic flow have been analyzed [21]. New speed optimization models have also been used in the freeway [22]. It is worth noting that CAVs with different market penetration rates can have an important impact on road capacity [23]. From low market penetration to high market penetration, not only the control model of CAV is changed, the operation and transformation of road also need to be changed accordingly. However, there is few researches on the adaptation of road policies to CAV with different market penetration rate.

Globally, there have been one to three fatal accidents in 100 million kilometers for human drivers. For autonomous vehicles, we want them to be safer than human drivers. And the fatal accident rate could be reduced by an order of magnitude, meaning that up to one fatal accident could occur in a billion kilometers. Statistically, to achieve enough confidence, researchers need to repeat the experiment several times, preferably more than 100 times. That means the total mileage an automated driving system needs to be tested is likely to reach 100 billion kilometers. For any company or university, it is impossible to accomplish in the early real vehicle test. Therefore, the simulation of autonomous vehicle is still necessary at the present stage.

As one of the traditional microscopic simulation models, CA model can well show the operational characteristics of CAV. The CA model first applied in traffic flow has only four simple rules, but some typical traffic phenomena are obtained [24]. Many researchers have improved and expanded it successively. Among them, STCA model [25], KKW [26] model and MCD model [27] are classic. Improved CA models are also used to describe autonomous vehicles. Such as, an ACC vehicles simulation model considering the variation of time headway [28], a CA model considering mixed vehicles in the weaving area of freeway [29] and a new CA model considering the bidirectional looking context under V2V environment [30]. And other scholars considered that communication between CAVs may lead to more aggressive lane changings [31], and CAVs improved the road operation under the information interaction of Internet of Vehicles (IoV) environment [27].

This paper designs a new method to the right of way on freeway: three stages will be established by setting up exclusive lanes for CAVs on freeway with the increase of CAV's market penetration. The maximum utilization of road with exclusive lanes and the rate at which CAV degenerate into general AV under various CAV's market penetration rates are given main consideration. The remainder of this paper is organized as follows: Section 2 introduces the three of the exclusive lanes for CAVs and the basic rules of CA model. Section 3 analyses the data results and the fundamental figure. Section 4 summarize some important conclusions and prospects after the research.

II. ESTABLISH MODEL

Cellular automata model is used as the car-following and lane-changing model in this study. The operation of ordinary vehicles is regulated according to typical NaSch model. Protocols that vehicle to vehicle (V2V) and vehicle to road side unit (V2R) will allow speed and location information to be shared between CAVs. It is assumed that the signal transmission protocol and related communication equipment are mature enough. This paper constructs a heterogeneous traffic flow model which takes the CAV's information communication and the traditional traffic flow model into account. Considering the cooperative relationship between CAVs, this research constructs the car-following and lane-changing behaviors during the information interaction. On the basis of traditional CA model, new rules are added to obtain the simulation model under V2V environment.

Since the exclusive lanes will not be affected by MVs, the aggressive car-following model for CAV can be adopted.

A. LONGITUDINAL CONTROL MODEL

The CA model typically consists of three key components: the road environment, the cell state, and local transition rules. First of all, this study establishes a simple four-lane model which is represented by a number L of cells per lane. The reason for the simulation in the one-way four-lane scenario is that it is a minimum condition that can satisfy the requirement that vehicles can change lanes in both exclusive lanes or ordinary lanes, which is helpful to obtain some complex traffic phenomena. The length of the cell is set as 0.5 meters, and L is set as 5,000 cells, namely 2,500 meters. The vehicle length is 7.5m in the simulation, and each vehicle occupies 15 cells. Each cell can have three states, 0 when there's no vehicle, 1 when there's a MV occupying the cell and 2 when there's a CAV occupying the cell. Each simulation will last 5600 times steps and the first 2,000 times steps will be removed. It represents about a 60-minute run. The maximum speed of the vehicle is set as 60 cells, namely 108 km/h. And the boundary condition is set as the periodical boundary. The numerical simulation experiment is carried out on MATLAB. Each group of experiments is run 5 times, and the average value is obtained as the final result. The cells that represent CAV and MV have different functions as running forward, acceleration, deceleration, random deceleration and changing lanes.

For MV's modeling, KKW model [26] is adopted, because it can reproduce the real traffic flow mechanics such as metastable state, traffic oscillation and three-phase traffic flow. KKW model is divided into two parts: a dynamic part

$$\tilde{v}_n(t+1) = \max\left(0, \min\left(v_{max}, v_{s,n}(t), v_{c,n}(t)\right)\right) \quad (1)$$

$$v_{c,n}^{MV}(t) = \begin{cases} v_n(t) + a\tau, & \text{when } k_n^{MV}(t) > D_n(t) \\ v_n(t) + a\tau \cdot sgn\left(v_{n-1}(t) - v_n(t)\right), & \text{when } k_n^{MV}(t) \le D_n(t) \end{cases} \quad (2)$$

$$k_n^{MV}(t) = x_{n-1}(t) - x_n(t) \quad (3)$$

TABLE 1. Parameters for MV's modeling.

Parameters	a	k	τ	p	p_0	p_a	p_b	v_p	l
Units	m /s^2	-	s	-	-	-	-	m /s	m
Values	1	2.55	1	0.04	0.425	0.2	0.052	28	7.5

where $sgn(x)$ is 1 for $x > 0$, 0 for $x = 0$ and $x < 0$:

$$v_{s,n}(t) = g_n(t) = x_{n-1}(t) - x_n(t) - l \tag{4}$$

and a stochastic part:

$$v_n(t+1) = max(0, min(\tilde{v}_n(t+1) + a\tau \cdot \boldsymbol{\eta}_n(t), v_n(t) + a\tau \cdot v_{max}, v_{s,n}(t))) \tag{5}$$

$$\eta_n(t) = \begin{cases} -1 & if \quad rand() < p_b \\ 1 & if \quad p_b \le rand() < p_b + p_a \\ 0 & otherwise \end{cases} \tag{6}$$

$$p_b = \begin{cases} p_0 & when \quad v_n(t) = 0 \\ p & when \quad v_n(t) > 0 \end{cases} \tag{7}$$

$$p_a = \begin{cases} p_{a1} & when \quad v_n(t) < v_p \\ p_{a2} & when \quad v_n(t) \ge v_p \end{cases} \tag{8}$$

finally, update the location:

$$x_n(t+1) = x_n(t) + v_n(t+1) \tag{9}$$

where the position and speed of the vehicle n at time t are expressed as $x_n(t)$ and $v_n(t)$. τ is the unit time. v_{max} represents the maximum allowable speed of the vehicle in the state of free flow. a is the current acceleration of the vehicle; l_{veh} is the length of the vehicle; $rand()$ is a random number evenly distributed between [0,1]. The symbol function is defined as:

$$sgn(x) = \begin{cases} -1 & when \quad x < 0 \\ 0 & when \quad x = 0 \\ 1 & when \quad x > 0 \end{cases} \tag{10}$$

The definition of $v_{c,n}$ reflects the core update mechanism of KKW model——speed-adaptation mechanism: Set a synchronization distance $D_n(t)$. When the gap between vehicle n and front vehicle n-1 is greater than $D_n(t)$, the influence of the front vehicle on the rear vehicle is weak, and the acceleration behavior of the rear vehicle will not be affected by the front vehicle. When the gap between vehicle n and front vehicle n-1 is smaller than $D_n(t)$, The rear vehicle will adjust its speed to match that of the front vehicle. $D_n(t)$ can be expressed in two ways and this paper use the linear function:

$$D_n = l + kv_n\boldsymbol{\tau} \tag{11}$$

The model parameters refer to the calibration results in the literature.

CAV models are considered in two cases [32]. When the current vehicle is a CAV and the preceding vehicle is also a CAV, the two vehicles form an interconnection relation, and vehicle n can obtain the speed and position information of the front vehicle n-1.

$$k_n^{CAV}(t) = x_{n-1}(t) - x_n(t) + v_{n-1}(t) - d_{safe}^{CAV}(n) \tag{12}$$

$$d_{safe}^{CAV}(n) = v_n^2(t)/2b \tag{13}$$

$$v_n(t+1) = min(v_n(t) + a \cdot \tau, k_n^{CAV}(t), v_{max}) \tag{14}$$

$$x_n(t+1) = x_n(t) + v_n(t+1) \tag{15}$$

where, b represents the safe deceleration of the CAV with a number of 3 m/s^2. When the current vehicle is a CAV but the preceding vehicle is MV, there is no communication between the two vehicles. CAV loses communication function and only relies on the vehicle's own environmental awareness system, meaning that CAV degrades to AV at this point. The forward rule continues to adopt the KKW model. CAV degeneration to AV will result in significant decrease of traffic capacity. Therefore, it is a feasible method to reduce CAV degradation rate to specify the number and mode of designated lanes.

B. LATERAL CONTROL MODEL

Lane changing behavior is one of the most important parts of CA model and the most complicated behavior in CAV driving. Since CAVs have extremely short delay time information interaction, the switching behavior is thought to be cooperative and simultaneous.

For MV, vehicles can change lanes as long as they meet all three conditions at the same time. Vehicles will choose to change lanes to the left first.

$$d_n(t) < min(v_n(t) + 1, v_{max}) \tag{16}$$

$$d_{l,n}(t) > d_n(t) \tag{17}$$

$$d_{l,n,back}(t) > d_{safe}^{MV} \tag{18}$$

If the condition is not satisfied, then consider to the right lane, the formula is similar to the above. $d_{l,n}(t)$ represent the distance between vehicle n and the front vehicle on the target lane at time$t$, $d_{l,n,back}(t)$ represents the distance between vehicle n and the rear vehicle. d_{safe}^{MV} is the safe distance to make sure there is no crash (similar formula representation will continue to be used later).

However, CAV's lane changing model will not only seek the optimal path at present, but also try to find the road with front vehicle as CAV, so as to avoid the possibility of degeneration to AV.

As shown in Figure 1, where vehicles in red represent CAVs, vehicles in black represent MVs and grey rectangular

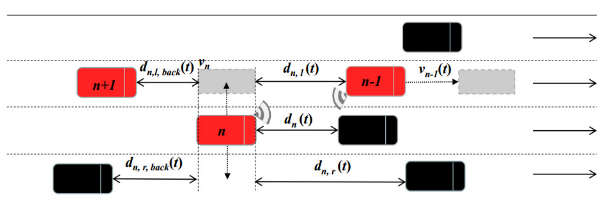


FIGURE 1. Lane-change model for CAV under the V2V environment.

region represent the position occupied by CAVs at the next moment (similar settings will continue to be used later). When the vehicle meets the lane changing requirements, CAV will pre-evaluate for road conditions on both sides and calculate two types distance: $d_{x,n}(t)$ and $d_{safe,x,n}(t)$. $d_{x,n}(t)$ type contains $d_n(t)$, $d_{l,n}(t)$ and $d_{r,n}(t)$. They represent the front gap of vehicle n on the same lane, the front gap of vehicle n on the left lane, and the front gap of vehicle n on the right lane. $d_{safe,x,n}(t)$ contains $d_{safe,l,n}(t)$ and $d_{safe,r,n}(t)$, and they represent the rear gap of vehicle n on the left lane, and the rear gap of vehicle n on the right lane. When the front vehicle or rear vehicle is a CAV on the corresponding lane, CAV n will use Formula (17) and Formula (18) to calculate the distances of the two types:

$$d_{x,n}(t) = x_{n-1}(t) - x_n(t) + v_{n-1}(t) - v_n(t) \quad (19)$$

$$d_{safe,x,n}(t) = x_n(t) - x_{n+1}(t) + v_n(t) - v_{n+1}(t) \quad (20)$$

Under the condition of $d_{safe,x,n}(t) > d_{safe}^{CAV}(n+1)$, CAV n will be preferred to choose the lane which offers the $max(d_{safe,x,n}(t))$. Formula (19) and (20) are actually a motivator. They encourage CAV to seek higher and smoother cruising speeds as a driving factor for increased exclusive lane utilization rate. In addition, for traditional vehicles, the probability of left lane change is the same as right lane change, but CAV usually give priority to left lane change. CAV gives priority to change to the left lane when both lanes provide the same incentives and enough safe distance. In the preference model, CAV would be more inclined to choose the lane on which the front vehicle is a CAV, so as to improve the utilization rate of the exclusive lane. In this model, CAV can be ensured to pass at maximum speed under all circumstances and degradation rate can be effectively reduced.

III. SCENARIO DESCRIPTIONS

In 1999, the San Diego Association of Governments (SANDG) and the California department of transportation officially used High-Occupancy Tolling (HOT) technology to manage interstate 15 north of San Diego [13]. The goal of the High-Occupancy Vehicle (HOV) lanes is to encourage carpooling, reduce gasoline use and protect the environment. However, due to inadequate planning, HOV lanes are often not fully utilized. Therefore, the transition from CAVs preliminary appearance on the road to their full claim on the road rights needs to be carefully considered. Policy makers can replace some poorly operated HOV lanes with CAV exclusive lanes. The steps are as follows:

(1) The First Stage: In the initial stage of transformation, policymakers can replace some poorly operated HOV lanes with CAV lanes.

In the early days of CAV's practical application, there was an exclusive road on the freeway separated by a single yellow line, as shown in Figure 1. The lane is only open to vehicles equipped with autonomous driving technology and other vehicles can't enter it. Similar to the HOV lane, the CAV exclusive lane is set in the left-most and only CAVs are allowed to run on this lane (But CAV can be moved from the exclusive lane).

In Figure 2, the yellow line marks the border between CAVs and MVs. On the exclusive lane, two contiguous CAVs can exchange speed and location information to maintain higher car-following speed without frequent deceleration. However, in normal lanes, a CAV will degenerate to AV if it follows a MV. Therefore, CAVs will gradually move towards exclusive lane, according to the lane-change model from Formula (19) and (20). Obviously, one exclusive lane can have significant effect only with low penetration rate of CAV. Therefore, with CAV's penetration rate increasing, road right distribution will enter The Second Stage.

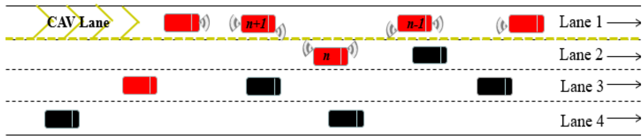


FIGURE 2. One Exclusive Lane for CAVs.

(2) The Second Stage: When more CAVs appear on the freeway, two exclusive lanes can be set up as shown in Figure 3. Two lanes will greatly improve the transmission capacity of the road to CAVs. Considering that it does not affect normal following and lane change of ordinary vehicles, the number of exclusive lanes for CAVs should be no more than two.

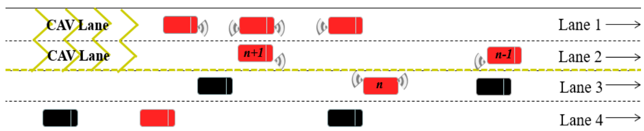


FIGURE 3. Two Exclusive Lanes for CAVs.

(3) The Third Stage: When more and more CAVs appear and MVs are still not completely replaced, it's worth noting that vehicle-mounted high-precision sensors carried by CAVs can precisely control the vehicle's horizontal ground spacing, so there will be three rows of vehicles running on two lanes at the same time as shown in Figure 4.

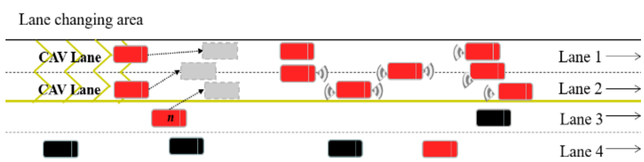


FIGURE 4. Three Exclusive Rows for CAVs on Two Lanes (a).

At present, the sensors used by enterprises in CAVs mainly include Image Sensor, Lidar, Millimeter Wave Radar, Ultrasonic Radar and Biological Sensor. According to their different attributes, they have different functions in the driving process to ensure the normal operation of CAVs.

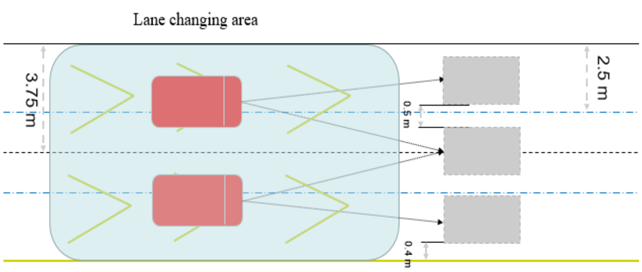


FIGURE 5. Three Exclusive Rows for CAVs on Two Lanes (b).

Lidar is one of the most widely used sensors in CAVs. By sending laser beam to the target object and receiving the reflection from the target object, it can measure the target's position, speed and other characteristics, perceive the surrounding environment of the vehicle. Then it will form a 3D environment map with accuracy up to centimeters. Thus a decision is established basis for the next step of vehicle control. Lateral control can track the output path and curvature of the system to reduce tracking errors and ensure the stability and comfort of the vehicle. Depending on the vehicle model used for lateral control, it can be divided into two types: traditional PID control algorithm and vehicle model lateral control method [33]. In addition, a vision - based embedded PID steering control system for CAV has been applied in real vehicle experiments [34]. Comprehensive control can keep the maximum side deviation of the vehicle under 0.4 m (Speed less than 110 km/h) when it moves in a straight line [35]. However, when the vehicle changes lanes, the control precision will be greatly reduced. In The Third Stage: The width of a conventional vehicle is 1.9m and the width of Chinese freeways lanes are 3.75 meters. Thus, the lateral distance between two CAVs on exclusive lanes is only 0.5 m in The Third Stage and the control system will not be able to change lane at such a distance. In other words, the exclusive lanes will enter a closed state to ensure that a large number of CAVs can operate safely and efficiently. At this point, CAVs must slow down.

IV. SIMULATION RESULT

In this paper, different proportions of CAVs are simulated (from 0% to 90% with an interval of 5%) and the three stages are simulated respectively (One Exclusive Lane for CAVs, Two Exclusive Lanes for CAVs and Three Exclusive Rows for CAVs on Two Lanes). Road capacity is analyzed under different vehicle density. The results of the relationship between the traffic flow and its density by simulation are shown from Figure 6 to Figure 9. Figure 6 shows the freeway with no exclusive lane, Figure 7 shows the different penetration rate of CAV in The First Stage and Figure 8 in The Second Stage.

As Figure 6 shows, the penetration rate of CAV changes have little impact on road capacity in the free flow phase (density < 18 veh/km). However, the density range of the free flow phase is different among cases with high CAV penetration rates (more than 80%) on the freeway with no exclusive

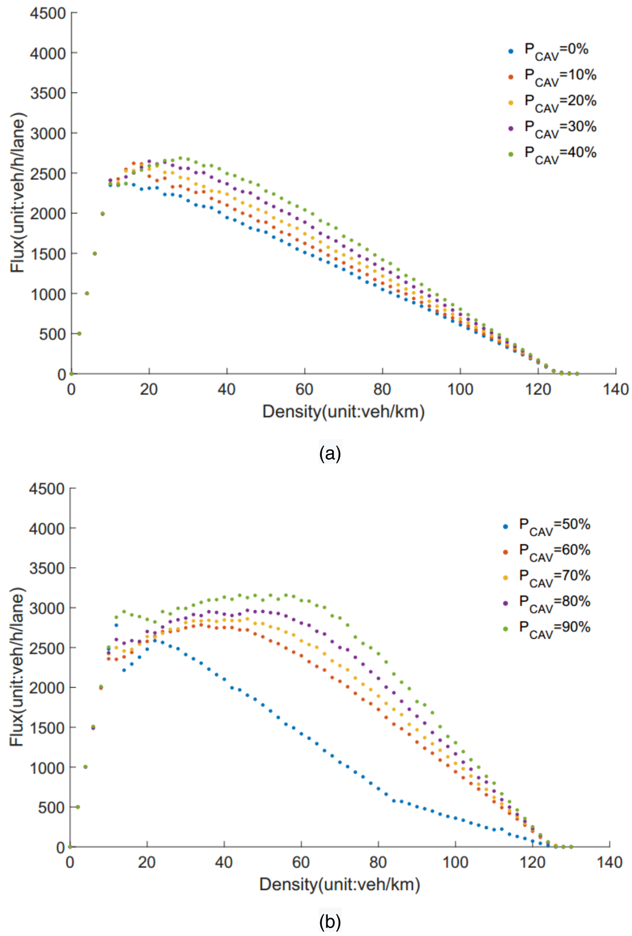


FIGURE 6. The flow–density simulation result of the freeway with no exclusive lane under different CAV's penetration rates.

lane. In congestion, it is obvious that no penetration rates of CAV can improve road condition. Between free flow phase and congested flow phase, CAVs with different penetration rates have significant influence on traffic flow. In this range, CAVs' improvement on traffic flow mainly manifests in two aspects. On one hand, the maximum capacity of the road is increased from 2300 veh/h/lane to 3150 veh/h/lane. This is because CAV has better performance than MV in vehicle-following, and result in higher capacity. On the other hand, maximum traffic volume can be maintained over a wider density range with CAV penetration rate increasing. And CAVs will not easily decline from free flow phase to congested phase by the influence of MVs. CAVs' communicable lane changing behaviors will make them easier to maintain high speed as the number of CAV vehicles increases. Obviously, such changes are uniform with the increasing of CAV penetration rate.

As the Figure 7 and Figure 8 show, traffic flow on the freeway with exclusive lanes become very congested under low CAV's penetration rates and high density. This is because the quantity of CAVs on an exclusive lane is insufficient, resulting in waste of road resources. CAVs can be maintained at high speed under low CAV's penetration rates, but normal

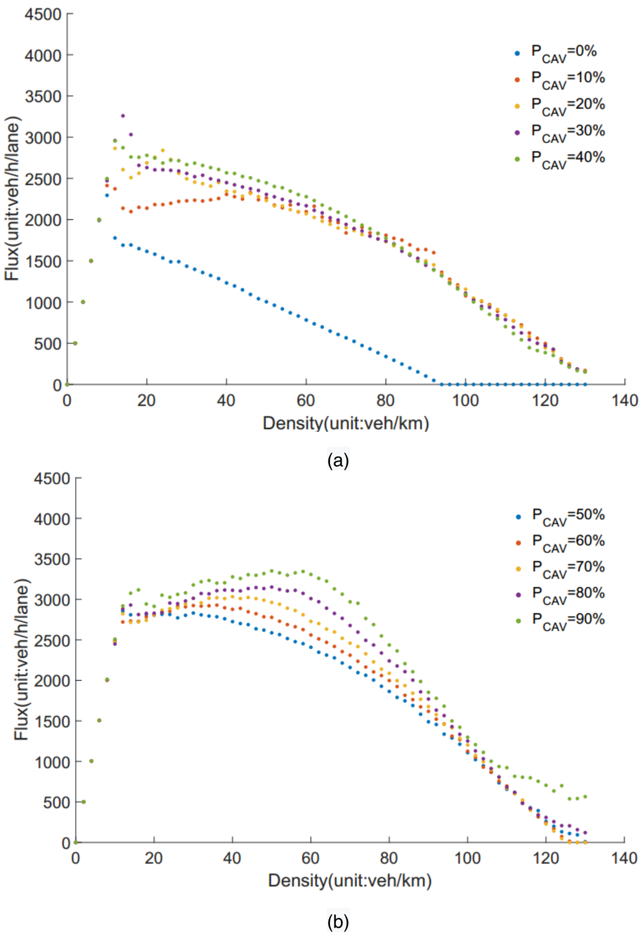


FIGURE 7. **The flow–density simulation result in The Second Stage under different CAV's penetration rates.**

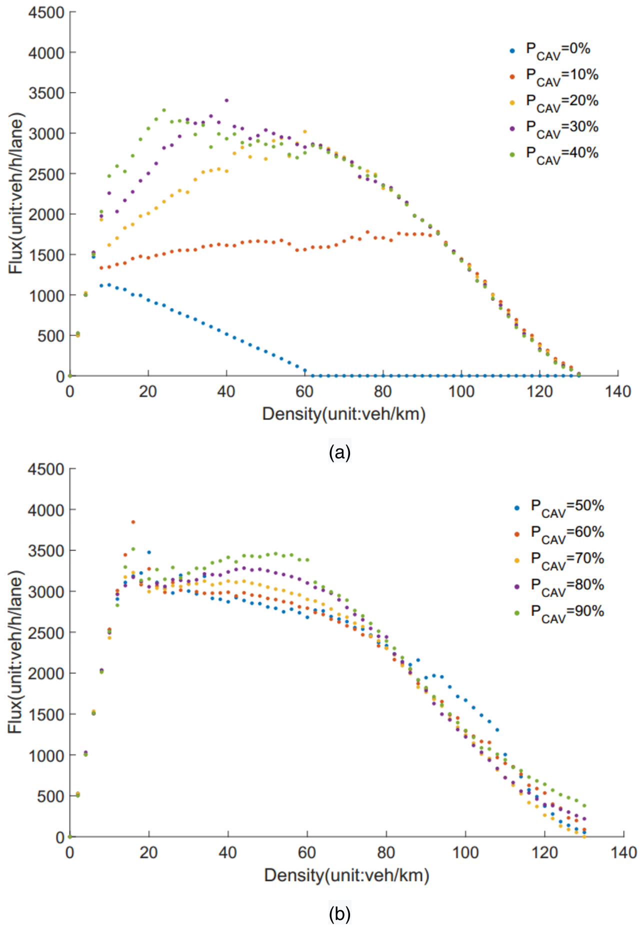


FIGURE 8. **The flow–density simulation result in The Third Stage under different CAV's penetration rates.**

lanes must accommodate a large numbers of MVs, leading to congestion in normal lanes quickly. In fact, regular lanes are already congested at this time. Therefore, this paper believes that such a phenomenon is harmful to road management. So that, under such a low CAV's penetration rates condition, it is not suitable to set up exclusivelanes. In order to better compare the impact of CAV on maximum traffic flow under different lane policies, we introduce the concept of ''optimal density''. It is defined as the density range where the free flow reaches its maximum value until there is no obvious decrease in the traffic flow. In the Figure 7 (b) and Figure 8 (b) (CAV's penetration rates>50%), it can be seen that the traffic flow in the optimal density area slightly increases compared with Figure 6, and it also drops more slowly in the high-density area.

In order to better show the impact of the number of exclusive lanes on road capacity, different penetration rates of CAVs are obtained from the freeway with no exclusive lanes. The First Stage and The Second Stage are compared with road capacity without exclusive lanes as shown in Figure 9. The simulation results show that the traffic flow is asymptotically stable and the influence of exclusive lanes on traffic flow starts to decrease gradually after the CAV penetration rate exceeds 60%.

According to Figure 9, the changes of traffic flow under different road policies are conspicuous. When the CAV penetration rate is only 10 percent, no exclusive lane maximizes traffic flow. In the Figure 9 (b), when it is 20 percent, two kinds of areas can be observed in the flow–density diagram. Traffic flow with one CAV exclusive lane in optimal density area is similar to that with no exclusive lane. In The First Stage, this phenomenon gradually starts to remit until CAV penetration rate reaches 50%. Similarly, in The Second Stage, when the CAV penetration rate is 10 percent, traffic flow is already higher than that without exclusive lanes and The First Stage in the range of density over 50 veh/km. However, because the two lanes are occupied only by CAVs, the traffic jam becomes worse at a low CAV penetration rate. This phenomenon gets better at 60 percent of penetration rate and basically eliminated at 70 percent. And now, the traffic flow in The Second Stage has been higher than that in the freeway with no exclusive lane.

A CAV is neither allowed to change between exclusive lanes and nor between a regular lane and an exclusive one. Therefore, only CAV exclusive lanes need to be simulated separately and compared with traffic flow of The Second Stage exclusive lanes. The CAV penetration rates with the

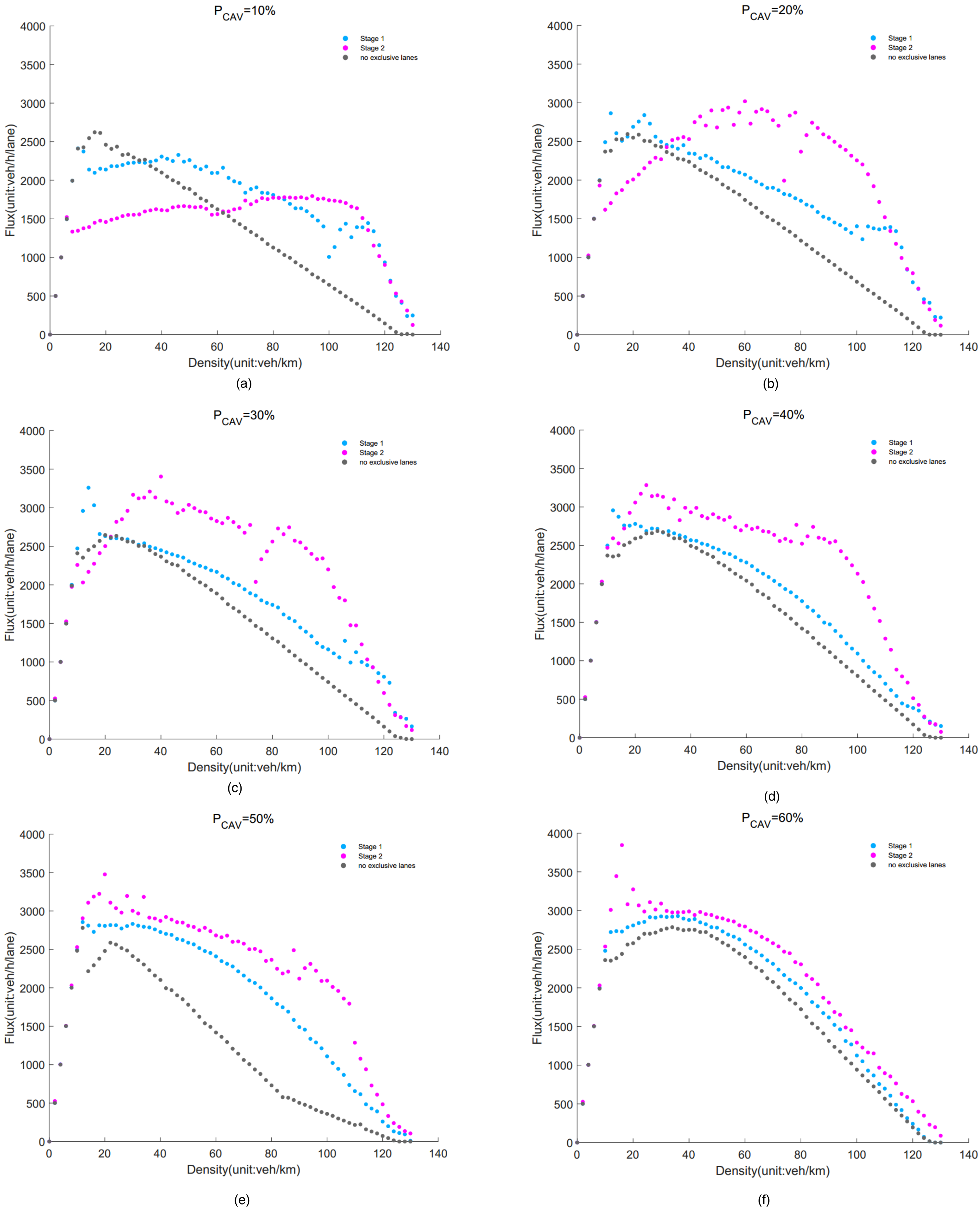


FIGURE 9. The flow–density simulation result of The Second Stage under different CAV's penetration rates.

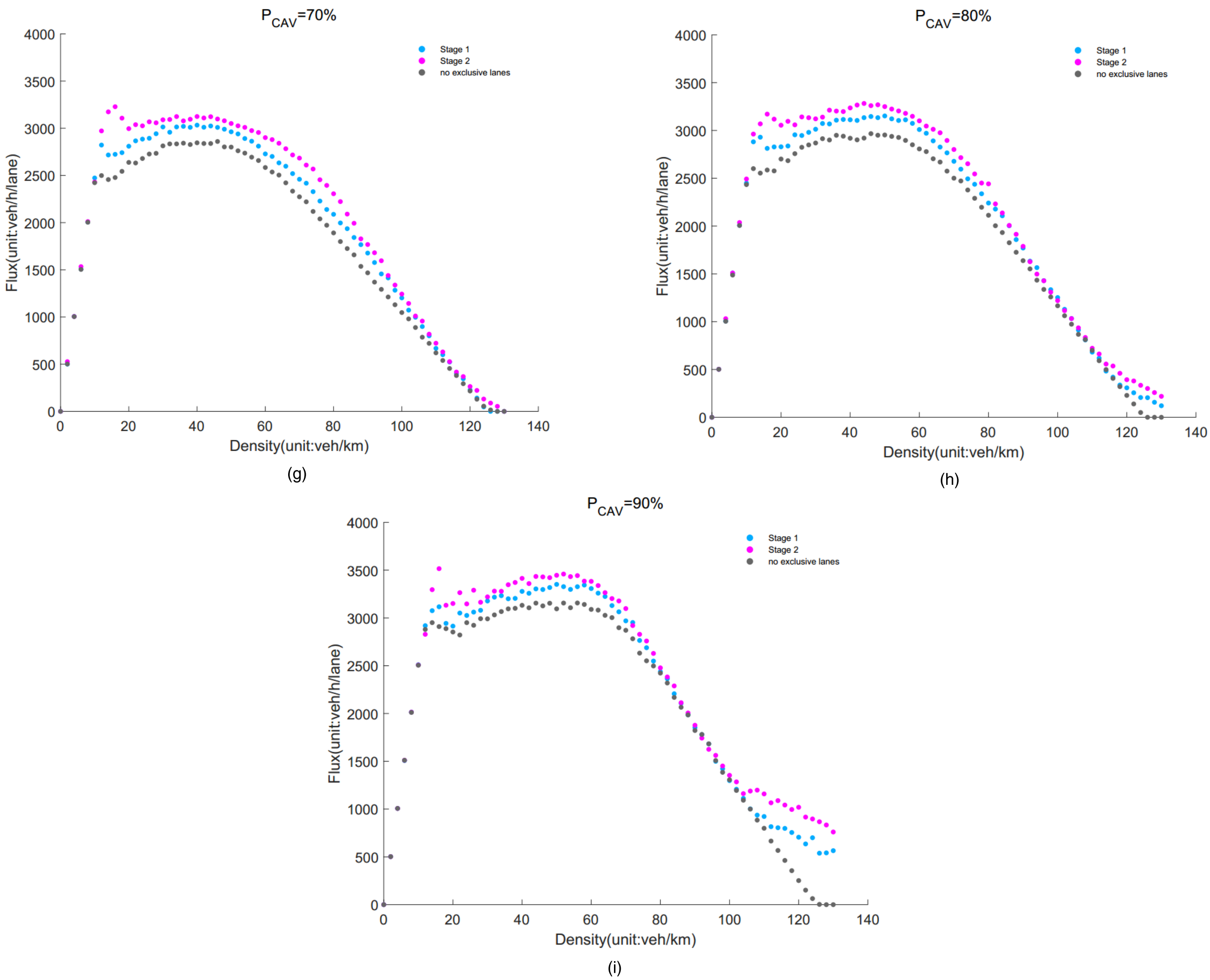


FIGURE 9. ***(Continued.)*** **The flow–density simulation result of The Second Stage under different CAV's penetration rates.**

highest traffic flow in exclusive lanes in The Second Stage (90%) are selected for comparison with that in The Third Stage.

The maximum speed of the vehicle must be reduced due to the reduction of the lateral distance. As Figure 10 shows, V'_{max} represents the maximum speed of a CAV on the exclusive lanes at The Third Stage. Three V'_{max} values were tested separately: $40\%V_{max}$, $60\%V_{max}$ and $80\%V_{max}$. To compare the capacity of the exclusive lanes at this stage, the traffic flow data on the exclusive lanes at The Second Stage with the 90% CAV penetration rate were set as the control group (gray data point). Although CAVs in The Third Stage in the optimal density range have a high traffic flow, they are prone to congestion when the density increases slightly due to the lack of lane change behavior. The Third Stage is no longer suitable for CAVs with density over 70 veh/km and the optimal CAV's density range for The Third Stage is 30 veh/km to 70 veh/km. Therefore, it is suggested The Third Stage can be set between 20 and 65 veh/km on the exclusive lane in case of favorable road condition.

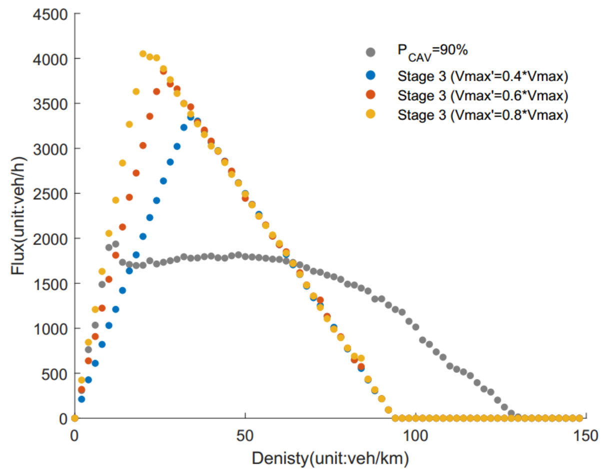


FIGURE 10. The flow–density simulation result in The Third Stage under different CAV's penetration rates.

In addition to the flow of road, the degradation rate of CAV is also an important indicator of the right of road. For the traffic capacity and safety of CAV can be better

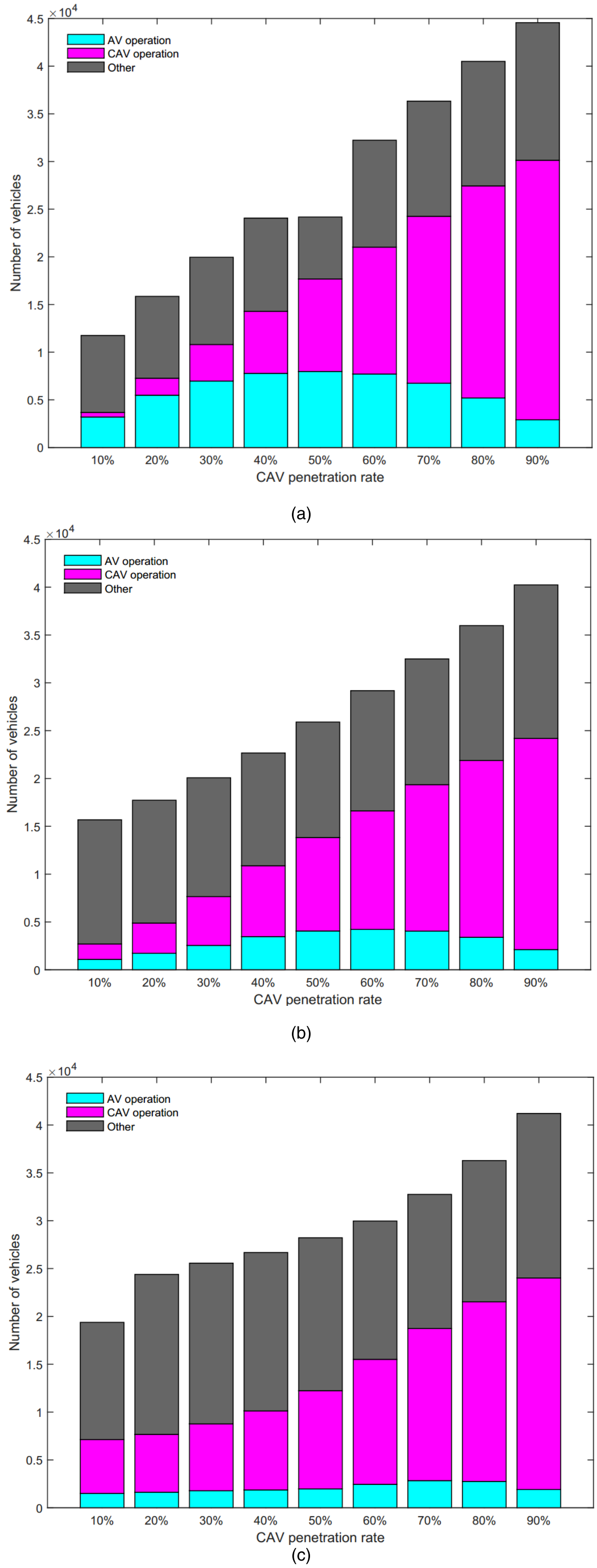


FIGURE 11. **The number of each operation states for CAV.**

protected if its front vehicle is also a CAV. In order to display the transformation of CAV degradation rate under different CAV's penetration rates, we use bar chart to represent the change of the number of CAVs in various states.

In Figure 11, AV operation represents that the front vehicle is a MV at this point. CAV operation represents that the front vehicle is also a CAV at this point. And the other operation represents that the vehicle in front is far away and the current vehicle can run without deceleration (In Figure 11, vehicles with a speed of 0 are not included.). Figure 11 (a) represents the freeway with no exclusive lane, (b) represents the freeway in The First Stage and (c) represents the freeway on The Second Stage. When the front vehicle of the CAV is a MV, CAV's connectivity characteristics will disappear. At this time, the traffic capacity of the CAV is degraded to AV and is even lower than that of the ordinary vehicle. As shown in Figure 11, AV operation has been significantly reduced after the use of exclusive lanes (20%-80% CAV's penetration rates). It means that exclusive lanes will improve efficiency and security for CAV.

V. CONCLUSIONS

In this work, the impact of exclusive lanes for CAVs on the overall traffic flow throughput is studied by a four-lane heterogeneous CA flow model. This paper introduces a basic graphic method which can reveal the advantages and disadvantages of the exclusive lanes with different CAV's penetration rates. In this paper, we introduce two kinds of significant data through simulation by a new CA model: traffic flow and the degradation rate of CAV. These data are important indicators of the determination of how exclusive lanes are set up. Firstly, the relationship between flow rate and density under different schemes is studied numerically. The performance of traffic flow under different lane numbers of autonomous vehicles is compared with that under mixed traffic. Obviously, with the exclusive lane for CAV, the traffic volume in many cases (when the CAVs rate ranges from 10% to 90%) will exceed the operation result of the roads without exclusive lanes. That is to say, only when the number of CAVs is very small or very large, there should be no exclusive lanes. It is also easy to understand from the respect of reality. Under the same case of four lanes, the setting-up of the exclusive lanes equals to the reduction in number of lanes, which makes it even harder to alleviate the traffic congestion on the whole roads. If the policy maker is to make a decision regarding traffic flow, when the percentage of CAV is from 10% to 40%, then The First Stage is the optimal choice. When the percentage of CAV is from 50% to 90%, The Second Stage is the optimal choice. Nonetheless, in the 90% area there is no obvious gap between the Stage with exclusive lane and one with no exclusive lane. It is worth mentioning that if the road conditions are well enough, the optimal Stage is The Third Stage from 30 veh/km to 70 veh/km. In addition, the degradation rate of CAV is also an important indicator. From the angel of promoting CAV and ensuring their stability, The First Stage can reduce CAV degradation rate by up to 60 percent compared with the freeway with no exclusive lane when the percentage of CAV from 10% to 30%. The

Second Stage can reduce CAV degradation rate by up to 75 percent compared with the freeway without exclusive lane when the percentage of CAV lies between 40% and 80%. When the penetration rates of CAV reaches around 90%, the gap gradually decreases.

This paper reveals the dynamic relationship among lane performance, CAV performance, degradation rate, density and penetration rates of CAV, which is helpful to determine the optimal lane number allocated to CAVs. This model can be easily extended to a variety of multi-lane models according to specific scenarios, indicating that the management of exclusive lanes for CAVs will have great practical application potential in the future.

However, there are still some shortcomings in this work. In some other typical road sections, such as highways with on-ramp or off-ramp, there are still some experimental schemes to verify. Such work will be further developed in the future.

REFERENCES

[1] Z. V. Laan and K. F. Sadabadi, "Operational performance of a congested corridor with lanes dedicated to autonomous vehicle traffic," *Int. J. Transp. Sci. Technol.*, vol. 6, no. 1, pp. 42–52, Jun. 2017.

[2] L. Zheng, P. J. Jin, and H. Huang, "An anisotropic continuum model considering bi-directional information impact," *Transp. Res. B, Methodol.*, vol. 75, pp. 36–57, May 2015.

[3] Y. Li, H. Wang, W. Wang, L. Xing, S. Liu, and X. Wei, "Evaluation of the impacts of cooperative adaptive cruise control on reducing rear-end collision risks on freeways," *Accident Anal. Prevention*, vol. 98, pp. 87–95, Jan. 2017.

[4] M. Wang, "Infrastructure assisted adaptive driving to stabilise heterogeneous vehicle strings," *Transp. Res. C, Emerg. Technol.*, vol. 91, pp. 276–295, Jun. 2018.

[5] M. Wang, W. Daamen, S. P. Hoogendoorn, and B. van Arem, "Cooperative car-following control: Distributed algorithm and impact on moving jam features," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 5, pp. 1459–1471, May 2016.

[6] T. H. A. van Den Broek, J. Ploeg, and B. D. Netten, "Advisory and autonomous cooperative driving systems," in *Proc. IEEE Int. Conf. Consum. Electron.*, Jan. 2011, pp. 279–280.

[7] R. E. Stern *et al.*, "Dissipation of stop-and-go waves via control of autonomous vehicles: Field experiments," *Transp. Res. C, Emerg. Technol.*, vol. 89, pp. 205–221, Apr. 2018.

[8] C. Xu, R. Lu, H. Wang, L. Zhu, and C. Huang, "TJET: Ternary join-exit-tree based dynamic key management for vehicle platooning," *IEEE Access*, vol. 5, pp. 26973–26989, 2017.

[9] Y.-M. Yuan, R. Jiang, M.-B. Hu, Q.-S. Wu, and R. Wang, "Traffic flow characteristics in a mixed traffic system consisting of ACC vehicles and manual vehicles: A hybrid modelling approach," *Phys. A, Stat. Mech. Appl.*, vol. 388, no. 12, pp. 2483–2491, Jun. 2009.

[10] K. D. Kusano and H. C. Gabler, "Safety benefits of forward collision warning, brake assist, and autonomous braking systems in rear-end collisions," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 4, pp. 1546–1555, Dec. 2012.

[11] L. Yang, B. Wang, R. Zhang, H. Zhou, and R. Wang, "Analysis on location accuracy for the binocular stereo vision system," *IEEE Photon. J.*, vol. 10, no. 1, Feb. 2018, Art. no. 7800316.

[12] A. Kesting, M. Treiber, M. Sch nhof, and D. Helbing, "Adaptive cruise control design for active congestion avoidance," *Transp. Res. C, Emerg. Technol.*, vol. 16, no. 6, pp. 668–683, Dec. 2008.

[13] M. W. Levin and S. D. Boyles, "A multiclass cell transmission model for shared human and autonomous vehicle roads," *Transp. Res. C, Emerg. Technol.*, vol. 62, pp. 103–116, Jan. 2016.

[14] H. Wang, Y. Qin, W. Wang, and J. Chen, "Stability of CACC-manual heterogeneous vehicular flow with partial CACC performance degrading," *Transportmetrica B, Transp. Dyn.*, vol. 7, no. 1, pp. 788–813, 2019.

[15] F. Zhu and S. V. Ukkusuri, "A linear programming formulation for autonomous intersection control within a dynamic traffic assignment and connected vehicle environment," *Transp. Res. C, Emerg. Technol.*, vol. 55, pp. 363–378, Jun. 2015.

[16] Z. He, L. Zheng, L. Lu, and W. Guan, "Erasing lane changes from roads: A design of future road intersections," *IEEE Trans. Intell. Veh.*, vol. 3, no. 2, pp. 173–184, Jun. 2018.

[17] J. I. Ge and G. Orosz, "Dynamics of connected vehicle systems with delayed acceleration feedback," *Transp. Res. C, Emerg. Technol.*, vol. 46, pp. 46–64, Sep. 2014.

[18] U. Khan, P. Basaras, L. Schmidt-Thieme, A. Nanopoulos, and D. Katsaros, "Analyzing cooperative lane change models for connected vehicles," in *Proc. Int. Conf. Connected Vehicles Expo (ICCVE)*, Nov. 2014, pp. 565–570.

[19] Y.-Y. Qin, H. Wang, W. Wang, and Q. Wan, "Stability analysis and fundamental diagram of heterogeneous traffic flow mixed with cooperative adaptive cruise control vehicles," *Acta Phys. Sinica*, vol. 66, no. 9, 2017, Art. no. 094502.

[20] T.-Q. Tang, L. Caccetta, Y.-H. Wu, H.-J. Huang, and X.-B. Yang, "A macro model for traffic flow on road networks with varying road conditions," *J. Adv. Transp.*, vol. 48, no. 4, pp. 304–317, Jun. 2014.

[21] W. B. Qin, M. M. Gomez, and G. Orosz, "Stability and frequency response under stochastic communication delays with applications to connected cruise control design," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 2, pp. 388–403, Feb. 2017.

[22] F. Li and Y. Wang, "Cooperative adaptive cruise control for string stable mixed traffic: Benchmark and human-centered design," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 12, pp. 3473–3485, Dec. 2017.

[23] S. C. Calvert, T. H. A. van den Broek, and M. van Noort, "Modelling cooperative driving in congestion shockwaves on a freeway network," in *Proc. 14th Int. IEEE Conf. Intell. Transp. Syst. (ITSC)*, Oct. 2011, pp. 614–619.

[24] K. Nagel and M. Schreckenberg, "A cellular automaton model for freeway traffic," *J. Phys. I*, vol. 2, no. 12, pp. 2221–2229, Dec. 1992.

[25] D. Chowdhury, D. E. Wolf, and M. Schreckenberg, "Particle hopping models for two-lane traffic with two kinds of vehicles: Effects of lane-changing rules," *Physica A, Stat. Mech. Appl.*, vol. 235, nos. 3–4, pp. 417–439, Feb. 1997.

[26] B. S. Kerner, "Three-phase traffic theory and highway capacity," *Phys. A, Stat. Mech. Appl.*, vol. 333, pp. 379–440, Feb. 2004.

[27] R. Jiang and Q.-S. Wu, "The adaptive cruise control vehicles in the cellular automata model," *Phys. Lett. A*, vol. 359, no. 2, pp. 99–102, Nov. 2006.

[28] J. Vasic and H. J. Ruskin, "Cellular automata simulation of traffic including cars and bicycles," *Physica A, Stat. Mech. Appl.*, vol. 391, no. 8, pp. 2720–2729, Apr. 2012.

[29] R. Jiang and Q.-S. Wu, "Spatial-temporal patterns at an isolated on-ramp in a new cellular automata model based on three-phase traffic theory," *J. Phys. A, Math. Gen.*, vol. 37, no. 34, p. 8197, Aug. 2004.

[30] L. Zheng, B. Ran, and H. Huang, "Safety evaluation for driving behaviors under bidirectional looking context," *J. Intell. Transp. Syst.*, vol. 21, no. 4, pp. 255–270, 2017.

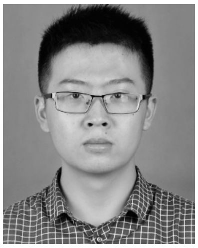
[31] L. Liu, X. Li, and B. Jia, "Traffic dynamics around weaving section with mixed slow and fast vehicles based on cellular automata model," *Procedia Soc. Behav. Sci.*, vol. 138, pp. 548–556, Jul. 2014.

[32] L. Ye and T. Yamamoto, "Modeling connected and autonomous vehicles in heterogeneous traffic flow," *Phys. A, Stat. Mech. Appl.*, vol. 490, pp. 269–277, Jan. 2018.

[33] X.-Y. Lu, H.-S. Tan, S. E. Shladover, and J. K. Hedrick, "Automated vehicle merging maneuver implementation for AHS," *Vehicle Syst. Dyn.*, vol. 41, no. 2, pp. 85–107, 2004.

[34] R. Marino, S. Scalzi, and M. Netto, "Nested PID steering control for lane keeping in autonomous vehicles," *Control Eng. Pract.*, vol. 19, no. 12, pp. 1459–1467, 2011.

[35] Z. Chu, Y. Sun, C. Wu, and N. Sepehri, "Active disturbance rejection control applied to automated steering for lane keeping in autonomous vehicles," *Control Eng. Pract.*, vol. 74, pp. 13–21, May 2018.



KE MA received the B.E. degree in traffic and transportation engineering from Central South University, Changsha, China, in 2018. He is currently pursuing the master's degree with the School of Transportation, Southeast University, Nanjing, China.

His research interests include the behavioral characteristics of connecting and autonomous vehicles, and micro simulation model of automated vehicle.

HAO WANG was born in 1980. He received the B.S. degree in traffic engineering and the Degree in mathematical modeling and computer application from Southeast University, in 2002, and the Ph.D. degree in transportation planning and management from Southeast University, in 2008. He has been a Visiting Scholar with the Delft University of Technology, since 2007. From 2013 to 2014, he served as a Visiting Scholar with the University of California at Davis. He is currently a Professor with the School of Transportation, Southeast University, Nanjing, China. His research interests include transportation planning and management, traffic flow theory and application, and traffic safety.

He is currently serving as a member of the committee of the Chinese Association for System Simulation, and a Reviewer for the journals of *Transportation Research Part C*, *Transportmetrica A&B*, and *Transportation Research Record*.