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Research Article

Analysis of the Relationship between Vehicle Behaviors of Changing Lane and Volume of Traffic under Different Operating Ratios of Autonomous Vehicles

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The lane-changing behavior is one of the important causes in traffic accident in congest traffic, and many behaviors of change lane affect volume of traffic. When autonomous driving vehicles are running on road with human-driven vehicles, the effects of change lane on traffic are different. In all human-driven vehicles traffic, the vehicle behaviors of changing lane are more competent. When autonomous driving vehicles are running in mixed traffic, the behaviors of changing lane decrease and the volume of traffic increases. However, a few studies have involved the relationship between traffic volume and lane-change behavior. In a sense, the study of this relationship is good for understanding the operation mechanism of mixed traffic. In this paper, we proposed the linear regression model to describe the relationship between traffic volume and lane-change behavior. The model can be used to establish the basic graph model. Here, we used empirical, simulation, and data-driven methods to obtain data and established a multiple linear regression model. First, we empirically study the continuous traffic with all human-driven vehicles. Then, the corresponding simulation model is established, and the availability of the simulation model is proved by data comparison with empirical study. Finally, 9 rounds of simulation experiments are carried out with the established simulation model. The number of autonomous driving vehicles in each round of simulation experiment increases by 10%. Then, we analyze the data of the behaviors of changing lane and the volume of traffic from simulation experiments. The following was found: (1) an increase in autonomous driving vehicle leads to an increase in traffic volume and a slight decrease in lane changing behaviors; (2) the influence of different proportions of autonomous vehicles on the traffic volume of lanes at different locations is slightly different; and (3) the relationships among the rate of vehicles entering lane, the rate of vehicles exiting lane together, and the volume of traffic show obvious linear relationships with the increase in autonomous driving vehicles. We used multiple linear regression models to carry out description, and the obtained parameter value intervals are close under different operating ratios of autonomous vehicles. To sum up, on multilane roads, especially 4-lane urban expressways, autonomous driving vehicles join in the traffic, which can effectively increase the volume of traffic of each lane while reducing vehicle behaviors of changing lane. The relationships between vehicle behaviors of changing lane and the traffic volume in mixed traffic show linear relationships with the increase in autonomous driving vehicles. In the future, we will further study whether this relationship model can be used in discrete traffic flow.

1. Introduction

In the last decade, autonomous driving vehicles have developed vigorously. With the prominence of energy problems, people have become very interested in vehicle under controlled environment. In many places, the regulators approve designated lanes for autonomous car. Although they are only partial roads, the energy savings brought by automatic car are still attracting attention. However, the construction of special roads increases the social operation cost. The best way to achieve the purpose of saving energy without increasing the cost is to make autonomous car running on the existing roads. Fortunately, this situation will appear with the development of autonomous vehicles. Optimistically, autonomous driving vehicles and human-driven vehicles will soon colocate on the same road. Since traffic lights are easy to interrupt the traffic, autonomous vehicles are most likely to first appear in the road with uninterrupted traffic flow. The traffic in highway is an uninterrupted traffic, but the distance between the entrances and exits of the highway is relatively long, and the congest traffic only happens in some sections of the road. The impact of lane changing behavior on traffic is more obvious in the case of large traffic flow. As another road with uninterrupted traffic flow, the urban expressway has large traffic flow, and the small distance between the entrances and exits, which is located the city. Therefore, urban expressways are the most likely to first appear mixed traffic. Autonomous cars will affect traffic on a certain degree [1–8], in which the most influential parameters are naturally various parameters of traffic flow. In the existing researches, most focus on parameters such as flow, speed, density, headway, and behaviors on the road (such as car-following behaviors and behaviors of changing lanes). The researches on volume of traffic mainly focus on the relationship among flow, speed, and density, as well as the relationship among flow, space headway, and time headway, and less researches study the relationship between behaviors of changing lane and the volume of traffic. The researches of lane changing behaviors focus on the behaviors of autonomous car [9, 10], and a few studies focus on behaviors of changing lane impact on the volume of traffic. Behaviors of changing lane are one main behavior of vehicles, and volume of traffic is also one parameter to characterize the traffic. Research of the relationship between the behaviors of changing lane and volume of traffic is significance to understand operation mechanics of the mixed traffic. The understanding of the operation mechanism of mixed traffic has great significance for establishing multimodal traffic control model.

Volume of traffic is one traffic flow parameter. Now, researches on traffic are mainly carried out from the fundamental graph theory. When all vehicles are driven by humans, the traffic is mainly described by three basic parameters: flow, speed, and density. The volume of traffic used in this paper is consistent with the flow. Fundamental graph theory describes the nonlinear relationship among the three parameters. In mixed traffic, the fundamental graph theory is still a method to describe traffic flow, and the fundamental graph theory of mixed traffic is proposed. The research types are mainly carried out from simulations and theoretical researches. Simulations mainly focus on the flow-density relationship in non-full-density regimes [11–13]. Through simulation research, the flow-density relationship in the non-full-density state has been proposed by the fundamental diagram. Theoretical research types mainly derive the relationship diagrams among flow, velocity, and density from the average value of space headway [14–17]. So, the relationship among flow, speed, and density is analyzed by both research methods, and the fundamental diagram of mixed traffic was proposed. However, a few studies focus on relationship between the behaviors of changing lane and the volume of traffic in the mixed traffic.

In all vehicles driven by human, the studies of lane-changing behaviors are almost based on the LWM, using behaviors of changing lane as a parameter), [18, 19] or a factor [20] for corrected traffic flow factors. In HCM2010 [21], the lane change rate was introduced to study the highway weaving area. However, due to the long distance between the highway ramps, lane changing behaviors have small impact on the traffic, and the relationship between behaviors of changing lane and the volume of traffic was not analyzed. In mixed traffic, research types mainly focus on the autonomous vehicles action [22–26], such as the angle of changing lane, the speed of changing lane, and the intention of changing lane. Moreover, the influence of behaviors of changing lane on the traffic volume is uninvolved. In the future, mixed traffic will be a phenomenon that exists for a long time. Understanding the impact of vehicle behavior on traffic volume in mixed traffic is crucial to understanding the operating method of mixed traffic. The relationship between lane changing behaviors and volume of traffic is one main characteristics of traffic.

To sum up, this paper adopts the simulation method to research the relationship between behaviors of changing lanes and the volume of traffic in mixed traffic. Taking the 3rd Ring Road in Chengdu, China (this road is a typical urban expressway with multilane ring-shaped) as the research object, a corresponding urban expressway simulation model is established. By running 9 rounds of simulation experiments, the operating ratio of autonomous vehicles on the road increases 10% in each round experiment. At various ratios of autonomous vehicles, the data of the traffic volume, the rate of vehicles entering lane, and the rate of vehicles exiting lane are collected, respectively. Using the data-driven method to model and analyze, the multiple linear regression model and parameter value intervals of the relationship between behaviors of changing lane and the volume of traffic in mixed traffic are proposed for the first time. The model can better describe the relationship between the behaviors of changing lane and the volume of traffic in each lane of the urban expressway when traffic volume is large in the mixed traffic.

This paper is mainly divided into five parts. The first part is the introduction of the researches background. The second part is the establishment of the simulation model. The empirical method is used to study the relationship between the lane-change behaviors and traffic volume on the urban expressway of the 3rd Ring Road in Chengdu, China. The corresponding simulation modeling is established. The third part runs the simulation experiments and gets experimental results. This part uses the established simulation model to collect data of lane-changing behaviors and traffic volume from 9 round experiments in which the proportion of autonomous driving vehicles increase 10% in each round. The fourth part proposes the relationship model between behaviors of changing lanes and the volume of traffic from the experimental results. In this part, the multiple linear regression model of the behaviors of changing lane and the traffic volume is obtained by the data-driven method, and got the value intervals of the model parameters. The last section is summary and conclusions.

2. Establishment of the Road Network Simulation Model

This part is carried out in two steps. First, empirical analysis is carried out by using the data collected on the 3rd Ring Road in Chengdu, China, and the data validity is verified. Second, we established simulation model based on the corresponding collection points. The usability of the simulation model is verified by compared the data from simulation model and empirical study.

2.1. The Empirical Study in Urban Expressway. In this paper, we study the traffic on 3rd Ring Road of Chengdu, China, by shooting videos. The relevant data from the videos are collected by manual and software. Videos were collected in 2011, 2015, and 2018. The shooting locations are shown in Figure 1.

In Figure 1, 9 collection points are shown. In the selection of collection points, it is considered the conditions such as land usage beside the road. The points must fit the requirements as follows:

(1) The segments have entrances and exits, pedestrian bridges
(2) The land usage beside the road is commercial or residential
(3) The connection method to the overpass is one of the four ways that the road segment connects the straight road section and the overpass, the road segment connects the curve road section and the overpass, the road segment connects the straight road section and does not connect to the overpass, and a road segment connects to a curve road section and does not connect to an overpass

After careful sifting of each road section, 9 sections are obtained. Data were collected on weekdays with large traffic flow. The data types include volume of traffic, the rate of vehicles entering lane, and the rate of vehicles exiting lane.

In this paper, volume of traffic q is the number of vehicles passing through each lane of a specified location on the road per unit time [27], and the unit is vehicle/h. The behaviors of changing lane are described by the rate of vehicles entering lane and the rate of vehicles exiting lane. The behaviors of changing lane are shown in Figure 2.

In Figure 2, the gray vehicle at the starting point of the yellow arrow is dissatisfied with the white vehicle driving in front of the lane. It seems that the distance between the adjacent vehicles in the adjacent lane is far, and the vehicle speed is slow. The gray vehicle has the possibility of entering the adjacent lane. The behavior of vehicle entering adjacent lane is called vehicle behaviors of entering lane. When the gray vehicle enters the adjacent lane, the vehicle behavior is recorded in the rate of vehicles exiting lane of current lane, and the rate of vehicles entering lane of adjacent lane.

The rate of vehicles entering lane (RLC_{in}) is the number of vehicles swapping into the counted lane within the 1 h and 1 km. The rate of vehicles exiting lane (RLC_{out}) is the number of vehicles swapped out of the counted lane. The definitions of the rate of vehicles entering lane and the rate of vehicles exiting lane are consistent with those in HCM2010 [21].

In this paper, the collected time interval is 5 min, and the collected road length is 100 m or 200 m. On the collection, if there are more than half of a car in the lane, the relevant data of this vehicle are recorded in the lane. Then, statistical data were standardized with a time interval of 1 h and 1 km. The data of the three parameters collected at each 5-minute time interval were grouped into one group, and the minimum sample size of collected data was calculated, as shown in the following equation [27]:

$$n \geq \left(\frac{\sigma \cdot K}{E}\right)^2. \quad (1)$$

In the formula, n means the minimum sample size of the collected data; σ means the standard deviation of vehicle speed and takes 7 km/h for two-way eight lanes; K means the confidence-level constant of the collected data, which is 1.96 under the 95% confidence level; and E means the allowable error of speed. Here, we used 2 km/h (1.5~2 km/h).

The minimum sample size is calculated as 48; that is, if the collected data are over or equal to 48 groups, the data can describe the traffic flow characteristics.

All the collected data are compared with the video data, and the valid data of each collection point are between 55 and 179 groups. The groups of each collection point fit the requirement of the minimum sample size, and the data can represent the characteristics of the road section. For the collected data, the time difference method is used to reorganize the data for the discontinuous time and the missing data. A total of 923 groups of data were collected after calculated. To better analyze the entire road, the data are combined to conduct an overall study. The data distribution of each lane is shown in Figure 3.

In Figure 3, the data concentrate between the 25% and 75% quantiles, where the median value, mean value, and mode value are all inconsistent. In Figure 3(a), the mean value of traffic volume from Lane 1 to Lane 4 shows a downward trend, which is in line with the actual road traffic. In actual traffic, Lane 1 is the far away from the ramps. The traffic volume in Lane 1 is less affected by the ramps, and the traffic is large. Moreover, volume of traffic in Lane 4 is greatly affected by the ramps, and in general, the traffic is small. Figures 3(b) and 3(c) show that the behavior of entering lane and the behavior of exiting lane occur more frequently in Lane 2 and Lane 3, respectively. On the actual road, Lanes 2 and 3 are the middle lanes connecting Lanes 1 and 4. After entering the road, most vehicles will choose to leave Lane 4 and enter other lanes to avoid being affected by the ramps. To leave the road, the vehicle must leave other lanes to enter Lane 4, and then drive out the road from the ramps. Therefore, Lane 2 and Lane 3 become lanes, which happen more behaviors of changing lane. This situation fits the actual situation. The mean values of three parameters are above the median values, and the median values are above the mode value, except for the traffic volume on Lanes 1, 2, and 3 where the mean values are below the median values.

Figure 1: The distribution of locations of shooting videos.

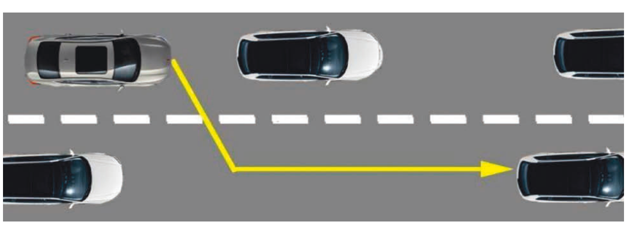


Figure 2: Exhibition map of vehicle behavior of changing lane (from the Internet).

The statistics data show that the traffic volume, the rate of vehicles entering lane, and the rate of vehicles exiting lane are all non-normal distributions. The data distribution is in line with the actual road conditions. The data are real and effective, and can be further used for simulation modeling.

2.2. Establishment and Verification of Road Network Simulation Model. For next study, the urban expressway is taken as the research object, and the corresponding road network simulation model is established. Therefore, 9 road sections in the empirical study are used for establishing simulation model. In the simulation model, the road network is simplified and retained exits and entrances. The simulation uses sumo as the platform and sets one-way 4 lanes road network. To ensure that all vehicles running in traffic basically fit the research requirements, four entrances and one exit are set up in each road section. Figure 4 shows the road network.

Figure 4 shows the simulation model. In this model, 9 road sections are designed to simulate 9 collection points, each road section is designed with 5 ramps, and the distance between the two ramps is 1 km. The road network is designed as a ring with length of 45 km, which is nearly the 51 km of the 3rd Ring Urban Expressway in Chengdu, China. The vehicles are set into four categories: lorries, medium-sized trucks, sedans, and autonomous vehicles (here is set as a sedan). The duration of one round of simulation is 86400 s, which equals to 24 h, and the step size is 0.1 s. The period of time is 8 hours in heavy traffic on the working day. The addition of traffic flow is controlled by tranCI. The data collection and time intervals were consistent with the empirical study.

To ensure the validity of the experiments under different operating ratios of autonomous vehicles, the usability test of the simulation model is carried out. The test adopts the method of comparing simulation data, which collected from running one round of simulation model with the empirical data. In the simulation, the vehicle type excludes self-driving vehicles, to ensure that the traffic composition of the simulated model is consistent with the actual traffic. After one round of simulation, a total of 2591 groups of valid data were collected. The characteristic distribution of simulated road traffic flow data is shown in Figure 5.

In Figure 5, the data distribution is as similar as Figure 3, such as concentrating between the 25% and 75% quantiles, and the mean value, median value, and mode value are inconsistent. Moreover, the specific distribution characteristics are slightly different. In Figures 5(b) and 5(c), the most

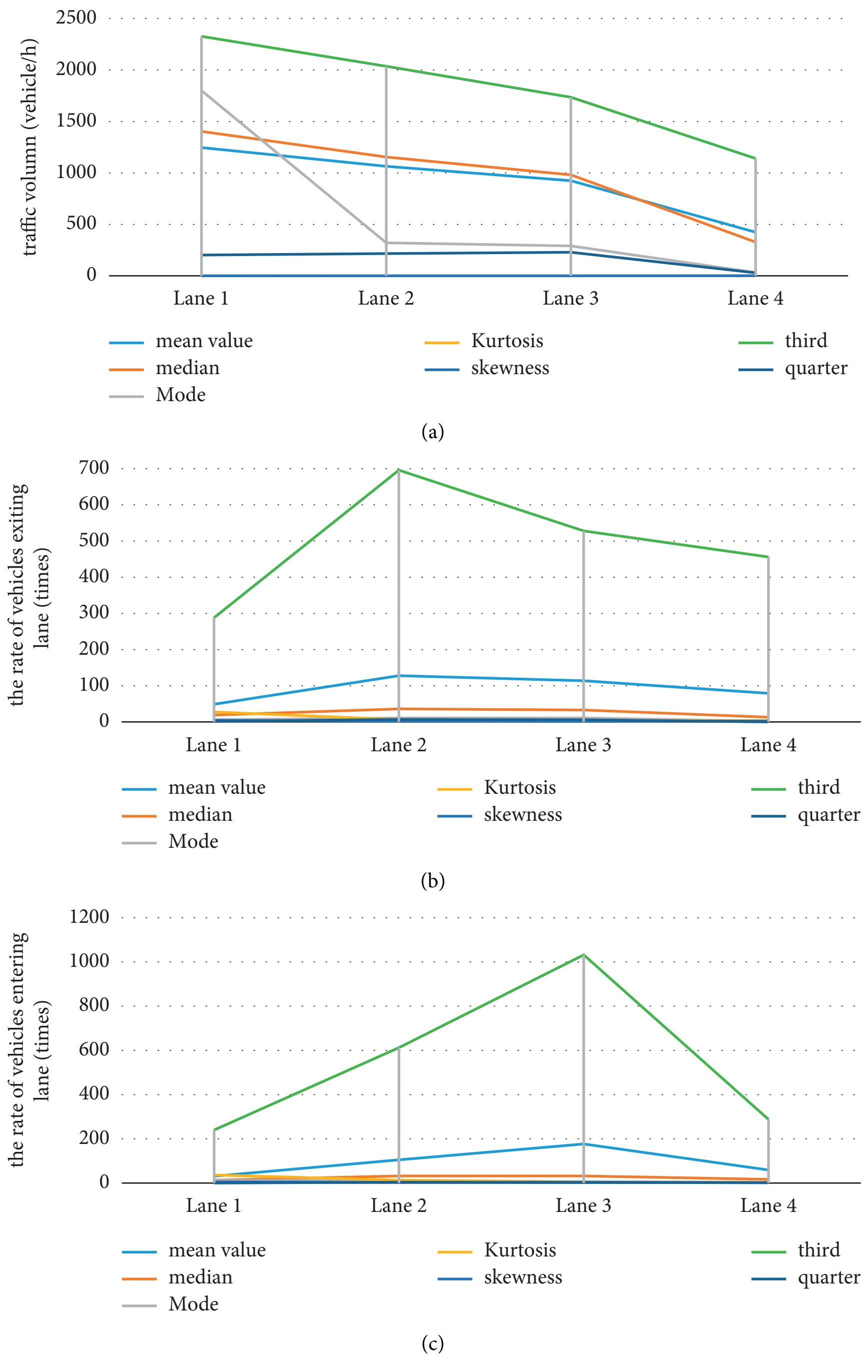
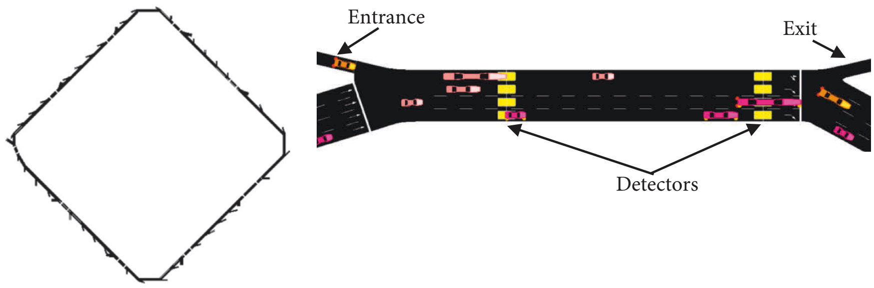


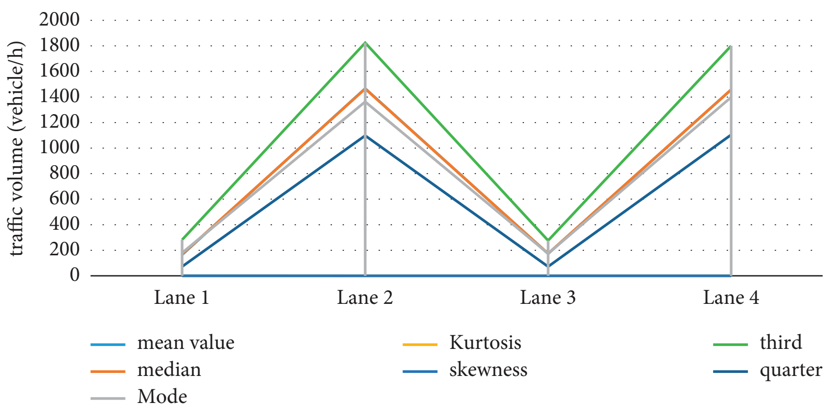
Figure 3: Distribution map of statistical characteristics of collected data on the 3rd Ring Road in Chengdu, China. (a) Distribution map of traffic volume by each lane. (b) Feature distribution map of the rate of vehicles exiting lane by each lane. (c) Feature distribution map of the rate of vehicles entering lane by each lane.

lane changing behaviors occur in Lane 3, while in Figures 3(b) and 3(c), this situation happens in Lane 2 and Lane 3, respectively. The main reason is that the simulation vehicle behaviors are not as random as human driving vehicle. Therefore, most simulation vehicles run on Lane 3. From the volume of traffic distribution in Figure 5(a), the large traffic happens in Lane 2 and Lane 4. They reflect the regularity of the simulation vehicle during the simulation process. If the vehicle wants to leave the road, the vehicle must enter Lane 4. Meanwhile, vehicles entering the road will enter Lane 2. Only when the traffic in Lane 2 is more congested, the vehicle will choose to enter Lane 1. Therefore, the traffic volume from Lane 1 to Lane 4 does not show a downward trend like actual road. However, we found that both the simulation data and the empirical data show a non-normal distribution. In the simulation experiment and empirical study, the relationship diagrams between the traffic volume-to-the rate of vehicles entering lane and the

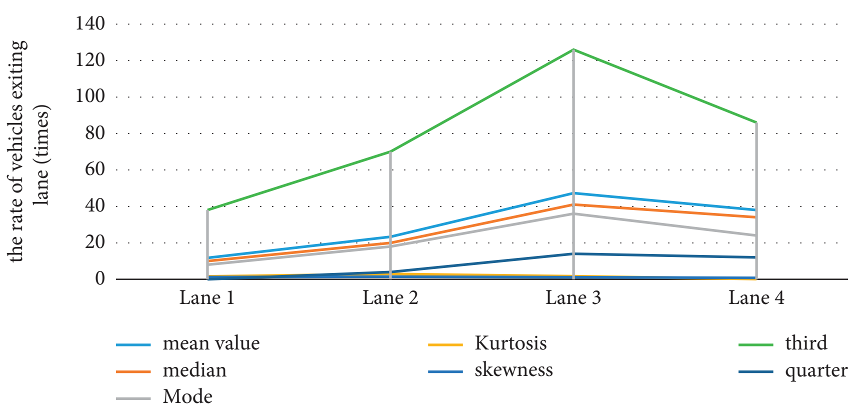


(a) (b)

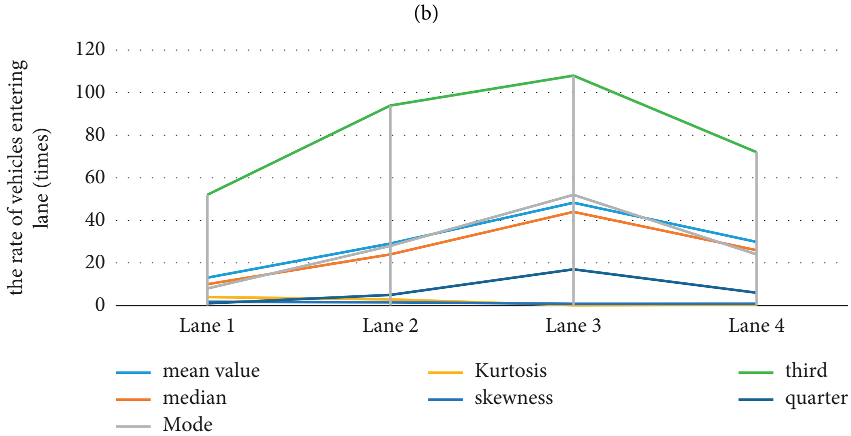
Figure 4: Design figures of simulation modeling. (a) Design figure of the road net. (b) Design figure of the road section.



(a)

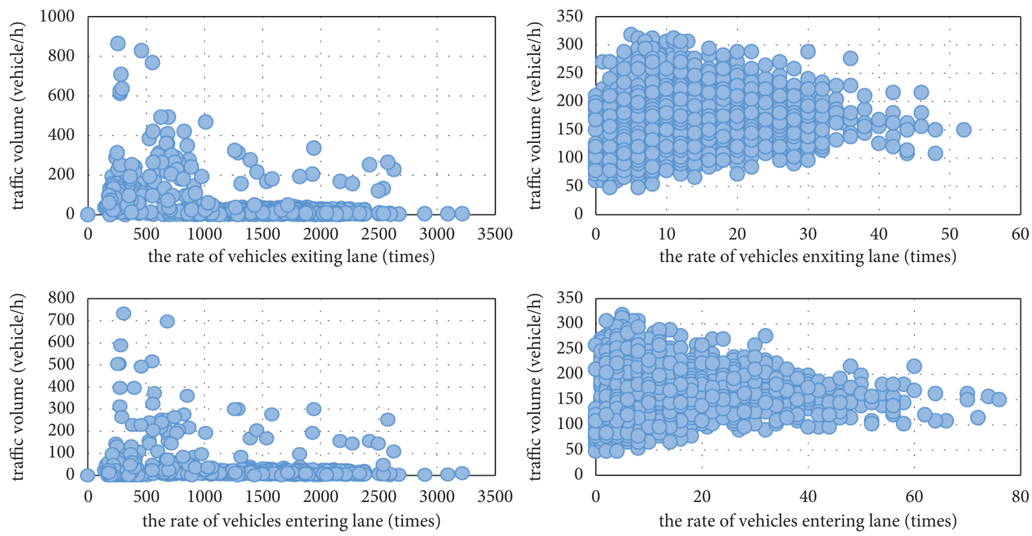


(b)

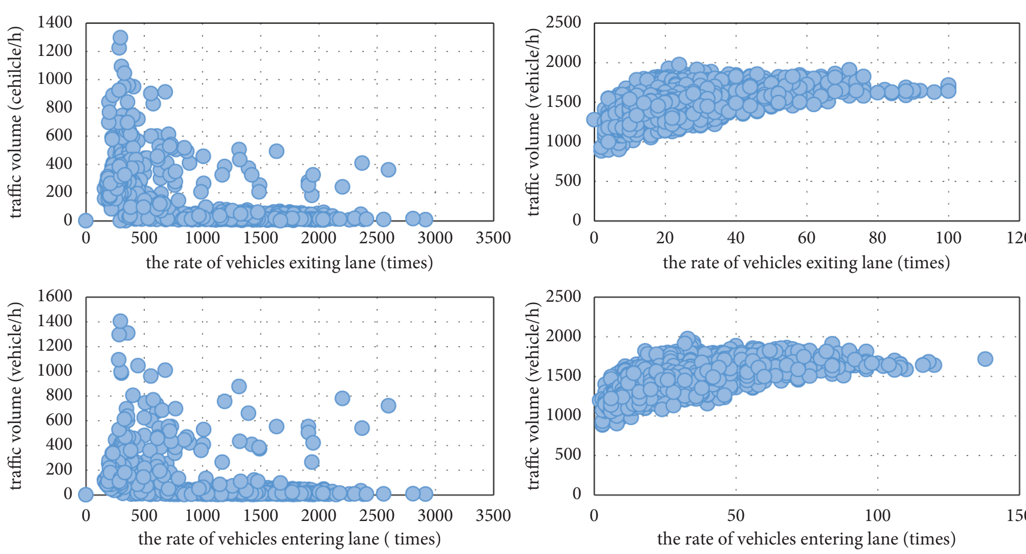


(c)

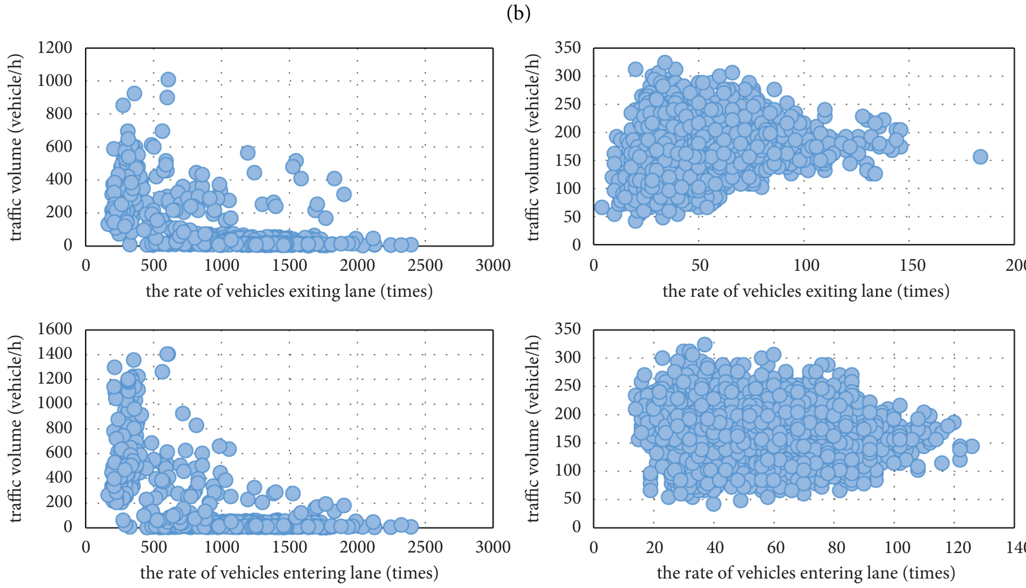
Figure 5: Feature distribution diagram of simulated traffic. (a) Distribution map of traffic volume by each lane. (b) Feature distribution map of the rate of vehicles exiting lane by each lane. (c) Feature distribution map of the rate of vehicles entering lane by each lane.



(a)

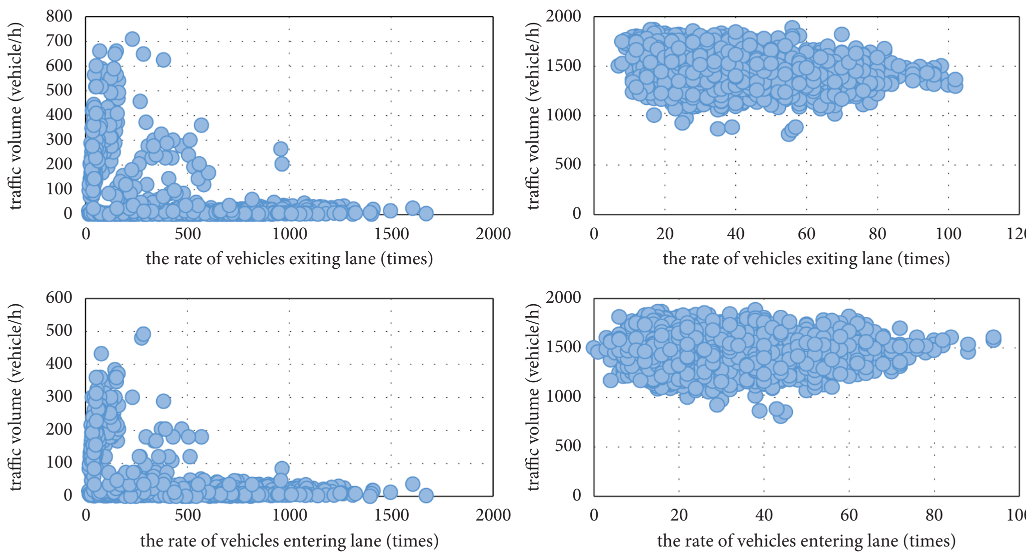


(b)



(c)

Figure 6: Continued.



(d)

Figure 6: The relationship between traffic volume and behaviors of changing lane in different lanes in empirical study and simulation module. (a) Graph of traffic volume versus behaviors of changing lane in lane 1. (b) The relationship between traffic volume and behaviors of changing lane in lane 2. (c) Graph of traffic volume versus behaviors of changing lane in lane 3. (d) The relationship between traffic volume and behaviors of changing lane in lane 4.

traffic volume-to-the rate of vehicles exiting lane are relatively close, as shown in Figure 6.

In Figure 6, the data on left side collect from the empirical study, and the data on right side collect from the simulation model. Comparing the relationship between behaviors of changing lane and the traffic volume in each lane, the relationships are relatively discrete, and they are aggregation in areas with less lane-changing behaviors. Although the specific morphology is inconsistent in the simulation data and empirical data, the aggregation state is relatively close. Therefore, we believe that the simulation model reflects the state of traffic in the real road, and the model can be used for further simulation experiments.

3. Simulation Experiments and Results

3.1. Simulation Experimental Design of Different Operating Ratios of Autonomous Vehicles. The availability of the simulation model has been checked previously, and then, the established simulation model is used to conduct simulation experiments with different operating ratios of autonomous vehicles to research the relationships between traffic volume and behaviors of changing lane in each lane. In existing studies, the optimization of traffic status by autonomous vehicles is part conclusions, but few studies focus on behaviors of changing lane effect on traffic volume. In the simulation model, the autonomous vehicles only choose to change lane when the road ahead is impassable or vehicle must leave the road; otherwise, it will keep following.

In the design of the simulation experiments, we set the CACC vehicles as the automatic vehicle, the DK2008 model as the lane changing behavior model, and the other settings are consistent with the previous simulation model settings. Experiments are designed autonomous vehicles ratios from 10% to 90%. In each round, there is 10% increase of autonomous vehicle ratio and relevant experiment data are collected. Here, the operating ratio of autonomous vehicle is described by the penetration rate (P).

3.2. Simulation Results of Different Autonomous Vehicle Operating Ratios. The above experiment design runs for 9 rounds, and the traffic parameter data of the simulated road for 9 rounds are obtained. To get the autonomous driving vehicles effect on the traffic, the experimental data of 9 rounds compare with the experiment without autonomous driving vehicles, and the data characteristic diagrams of traffic are shown in Figures 7–9. Among them, Figure 7 is a data characteristic diagram of traffic volume.

In Figure 7, the traffic volume in different lanes responds differently to the autonomous vehicles. Among them, the trends of traffic volume in Lane 1 and Lane 3 (shown in Figures 7(a) and 7(c)) increase with the increase of permeability of autonomous driving vehicles. In Figures 7(b) and 7(c), the trends shown in Lanes 2 and 4 are opposite to Lanes 1 and 3, and the traffic volume tends to decrease as the autonomous driving vehicles increase. The location of Lane 1 is the far away from the ramps. With the increase autonomous driving vehicles, the traffic order becomes more and more standardized, and more and more vehicles run on Lane 1, all that result in increasing traffic volume in Lane 1. Meanwhile, the location of Lane 3 is in the middle position of the road. The increase in traffic volume by increasing of autonomous vehicles will affect traffic volume of Lane 3. With the increase autonomous driving vehicles in Lane 4, the sense of order in traffic increases, and more and more

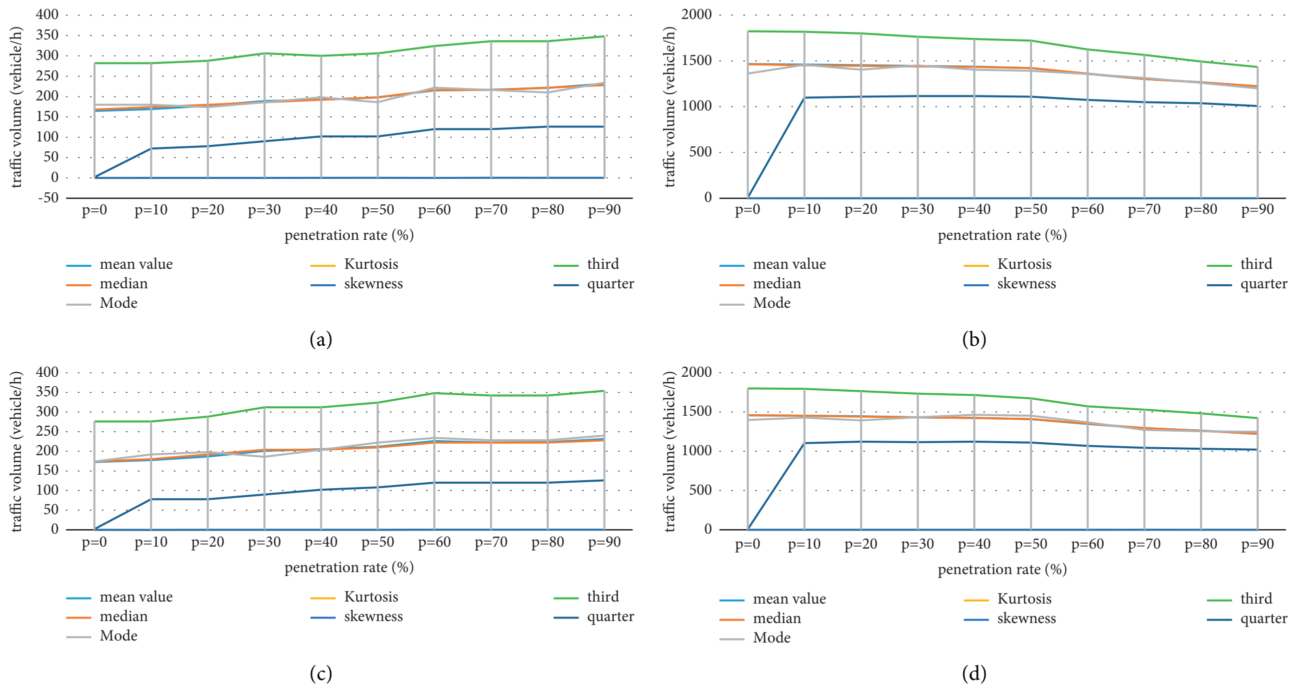


FIGURE 7: Traffic volume characteristic map of different lanes under different penetration rate of autonomous vehicles. (a) Traffic volume characteristic map in lane 1. (b) Traffic volume characteristic map in lane 2. (c) Traffic volume characteristic map in lane 3. (d) Traffic volume characteristic map in lane 4.

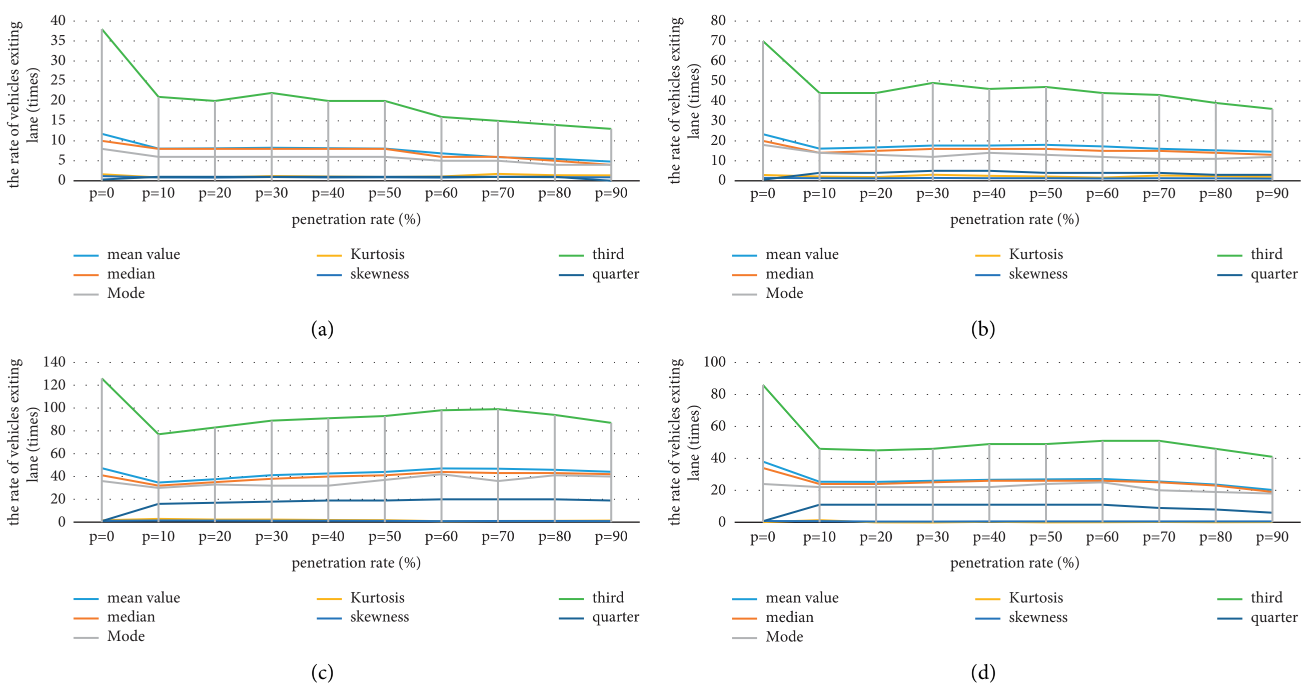


FIGURE 8: Feature map of the rate of vehicles exiting lane under different penetration rates of autonomous driving vehicles. (a) Feature map of the rate of vehicles exiting lane in lane 1. (b) Feature map of the rate of vehicles exiting lane in lane 2. (c) Feature map of the rate of vehicles exiting lane in lane 3. (d) Feature map of the rate of vehicles exiting lane in lane 4.

vehicles follow the rule that they should change to the lane far away from the ramps without leaving the road, all that result in a slight decrease in the traffic volume in Lane 4. When vehicles enter in Lane 3, the traffic volume in Lane 2 decreases. At the same time, from graphical view, all data occur within the 25% to 75% quantile, and the mean value and median value are relatively close, while the mode value is different from the mean value and median value. The mode value hovers around the median value and mean value as autonomous vehicles running on the road. The 75% quantiles and 25% in Lane 1 and Lane 2 are toward the median value, and the mode value and mean value have no obvious trend of convergence. The figure shows that the traffic volume has a trend of convergence toward the mode value and mean value as the increase in the operating proportion of autonomous driving vehicles. However, the data still exhibit a non-normal distribution. The characteristics of the rate of vehicles entering lane and the rate of vehicles exiting lane are shown in Figures 8 and 9, respectively.

Figures 8 and 9 are graphically similar. The data are still distributed between the 25th percentile and the 75th percentile. When the operating ratio of autonomous driving vehicles is 10%, the lane-changing behaviors show significant decrease. After that, the change of lane-changing behavior is not obvious as the increase of the operating ratio of autonomous vehicles. From the view of mean value and mode value, there is an increase sometimes and a decrease sometimes. When the operating ratio of autonomous vehicles increases to 90%, the lane-changing behaviors are still a big reduction, which compared with the traffic without autonomous vehicles. The increase of autonomous driving vehicles can impact on traffic. The impact on each lane was not uniform. In Figure 8, the average value of the rate of vehicles exiting lane in the four lanes decreases as the running ratio of autonomous vehicles reaches 10%, and then, the value shows an upward trend as the running ratio of automatic cars increases. In Lane 1, the average value begins to increase with the running ratio of autonomous vehicles when the running ratio of automatic cars reaches 40%. The decrease point of average value is 60% in Lane 2 and 70% in Lanes 3 and 4. The median value and mode value, except for Lane 3, show a decrease trend with the increase of the running proportion of automatic cars. In Figure 9, the mean value of the rate of vehicles entering lane is as similar as the mean value of Figure 8, except for Lane 4. In Lane 4, the trend of average value with the increase autonomous driving vehicles first drops sharply and then gradually increases. From the graphical representation, the most lane-changing behaviors happen in Lane 3, while behaviors in Lane 4 have few effects by the increase autonomous driving vehicles.

All data in Figures 7 to 9 show that a certain convergence shows in the traffic volume, the rate of vehicles exiting lane, and the rate of vehicles entering lane with the increase of the operating proportion of autonomous driving vehicles. The relationship between behaviors of changing lane and the traffic volume needs further analysis.

4. Analysis and Comparison of Simulation Experiment Data

4.1. Analysis of the Relationships between Traffic Volume and Behaviors of Changing Lane under Different Operating Proportions of Autonomous Vehicles. From the characteristic analysis of the data that collect in the previous 9 rounds of simulation experiments and the experiment without autonomous vehicles, the impact of behaviors of changing lane on traffic volume under different ratios of autonomous vehicles needs further analysis. From the analysis of data characteristics, the increase in the number of autonomous driving vehicles can reduce behaviors of changing lane and improve traffic condition. Before conducting research on the relationships between behaviors of changing lane and the traffic volume, the data correlation analysis is conducted in Table 1.

In Table 1, the correlations of the lane-changing behaviors and traffic volume in Lane 1 increase with the increase of the operating proportion of autonomous driving vehicles, in Lane 2 decreases, in Lane 3 is not obvious, and in Lane 4 increases. Although the correlation has increased and decreased, in general, the correlation is low, except in Lane 2. The correlation coefficients in Lane 2 reach 0.6, and in the other lanes are below 0.4. To intuitively observe the relationship between behaviors of changing lanes and the traffic volume, the relationships between the rate of vehicles exiting lane and traffic volume and between the rate of vehicles entering lane and traffic volume are plotted in Figures 10 and 11, respectively.

In Figures 10 and 11, the relationships are basically similar in the corresponding lanes, although they vary slightly with the different ratios of autonomous driving vehicles. In Figure 10, the graphs in Lane 1 and Lane 3 are triangular, and in Lane 2 and Lane 4 are linear. In Figure 11, the graphs are as same as Figure 10, except ellipse in Lane 3. However, the graphs in Figures 10 and 11 show a certain degree of dispersion with the increase autonomous driving vehicles. Therefore, further analysis is required.

4.2. Relationship between Traffic Volume and Behaviors of Changing Lanes in Mixed Traffic. From Figures 10 and 11 and Table 1, there are a linear relationship between the traffic volume and lane-changing behaviors. The multiple linear regression method is proposed to describe the relationship, in which the rate of vehicles exiting lane and the rate of vehicles entering lane are used as independent variables, and the traffic volume is the dependent variable.

We assume the relationship among the traffic volume q, the rate of vehicles exiting lane $\mathrm{RCL_{out}}$, and the rate of vehicles entering lane $\mathrm{RCL_{in}}$ is expressed by the following equation:

$$q = f\left(\mathrm{RCL_{out}}, \mathrm{RCL_{in}}\right). \quad (2)$$

The multiple linear regression model is established as the following equation:

$$q = a\mathrm{RCL_{out}} + b\mathrm{RCL_{in}} + c. \quad (3)$$

Here, the constants are represented as a, b, and c.

By performing multiple linear regression analysis on the collected in 9 rounds of simulation experimental data, the fitting degree of each round of simulation experimental data is shown in Table 2.

In Table 2, the fit R is slightly different in different lanes. In Lane 1, the R increases with the increased number of

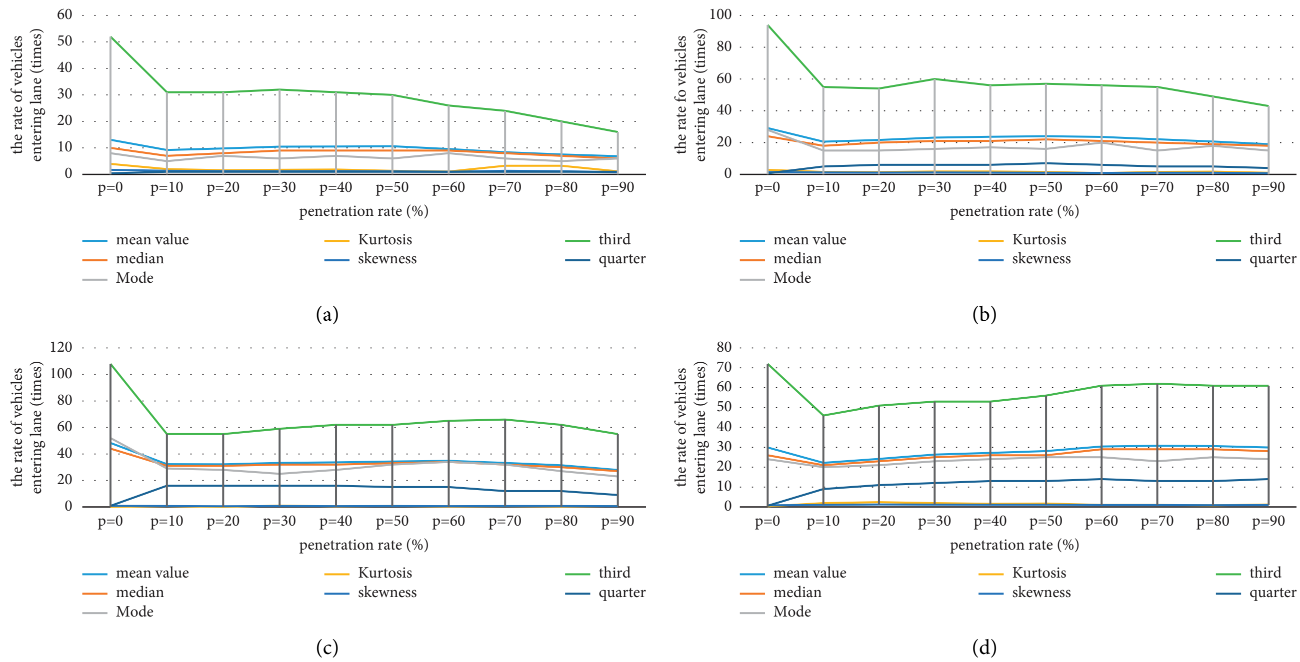


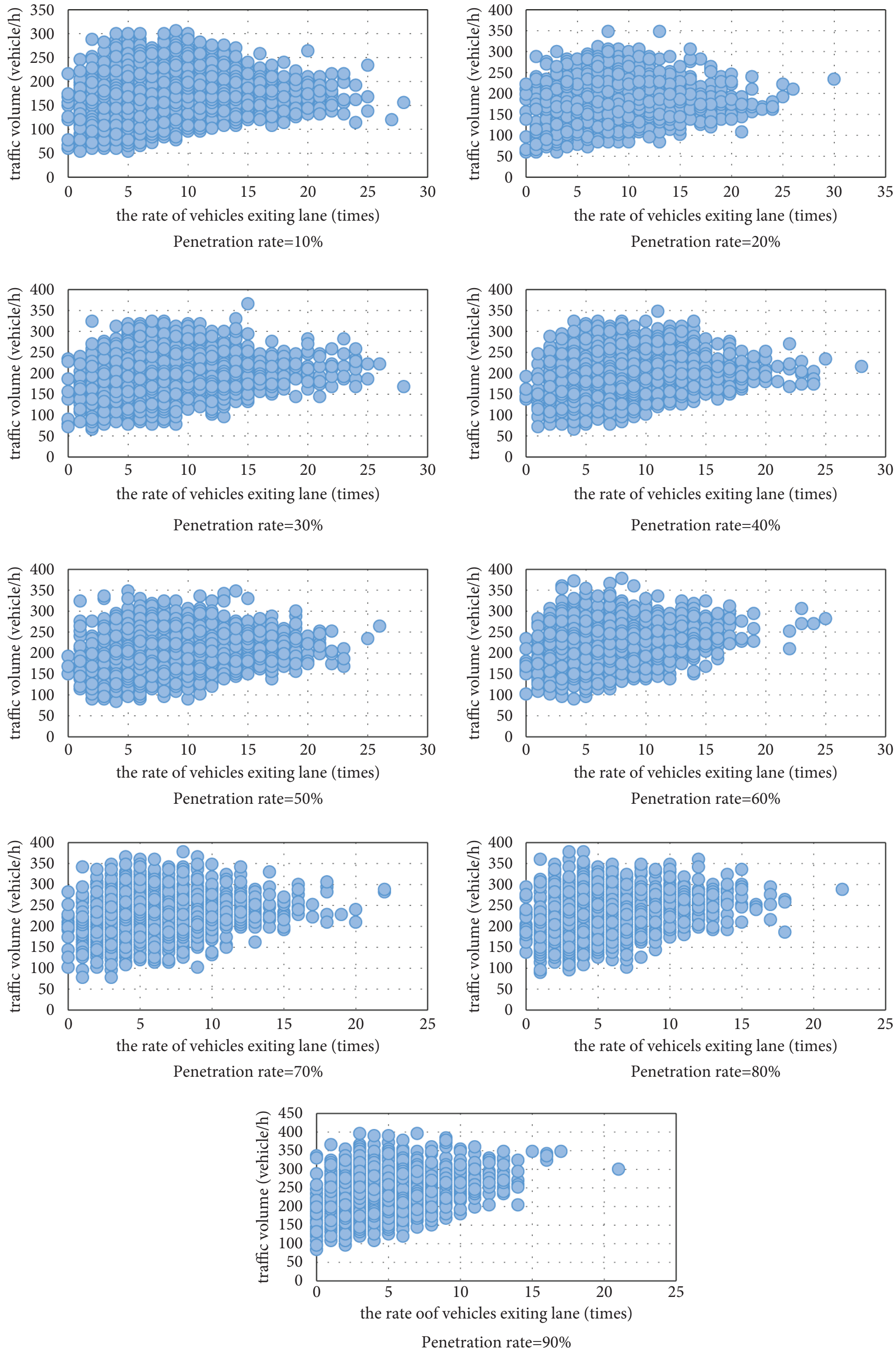
Figure 9: Feature map of the rate of vehicles entering lane under different penetration rate of autonomous driving vehicles. (a) Feature map of the rate of vehicles entering lane in lane 1. (b) Feature map of the rate of vehicles entering lane in lane 2. (c) Feature map of the rate of vehicles entering lane in lane 3. (d) Feature map of the rate of vehicles entering lane in lane 4.

Table 1: The liner correlation table of traffic volume q and the rate of vehicles exiting lane (RLC_{in}) and the rate of vehicles entering lane (RLC_{out}) under different operation ratios of autonomous vehicles.

		Lane 1		Lane 2		Lane 3		Lane 4	
		RLC_{out}	RLC_{in}	RLC_{out}	RLC_{in}	RLC_{out}	RLC_{in}	RLC_{out}	RLC_{in}
Penetration rate = 10%	Pearson correlation	0.182**	0.056**	0.652**	0.691**	0.219**	−0.298**	−0.245**	0.081**
	Sig. (2-tailed)	0	0.004	0	0	0	0	0	0
Penetration rate = 20%	Pearson correlation	0.202**	0.048*	0.650**	0.683**	0.165**	−0.227**	−0.142**	0.207**
	Sig. (2-tailed)	0	0.015	0	0	0	0	0	0
Penetration rate = 30%	Pearson correlation	0.241**	0.103**	0.639**	0.664**	0.253**	−0.018	−0.042*	0.258**
	Sig. (2-tailed)	0	0	0	0	0	0.361	0.031	0
Penetration rate = 40%	Pearson correlation	0.214**	0.046*	0.640**	0.683**	0.244**	−0.036	−0.041*	0.243**
	Sig. (2-tailed)	0	0.02	0	0	0	0.07	0.035	0
Penetration rate = 50%	Pearson correlation	0.235**	0.087**	0.648**	0.670**	0.262**	0.068**	0.064**	0.295**
	Sig. (2-tailed)	0	0	0	0	0	0	0.001	0
Penetration rate = 60%	Pearson correlation	0.285**	0.152**	0.617**	0.649**	0.321**	0.214**	0.143**	0.330**
	Sig. (2-tailed)	0	0	0	0	0	0	0	0
Penetration rate = 70%	Pearson correlation	0.285**	0.195**	0.569**	0.618**	0.252**	0.167**	0.136**	0.319**
	Sig. (2-tailed)	0	0	0	0	0	0	0	0
Penetration rate = 80%	Pearson correlation	0.314**	0.229**	0.539**	0.585**	0.217**	0.118**	0.116**	0.348**
	Sig. (2-tailed)	0	0	0	0	0	0	0	0
Penetration rate = 90%	Pearson correlation	0.338**	0.247**	0.431**	0.443**	0.173**	0.056**	0.110**	0.313**
	Sig. (2-tailed)	0	0	0	0	0	0.004	0	0

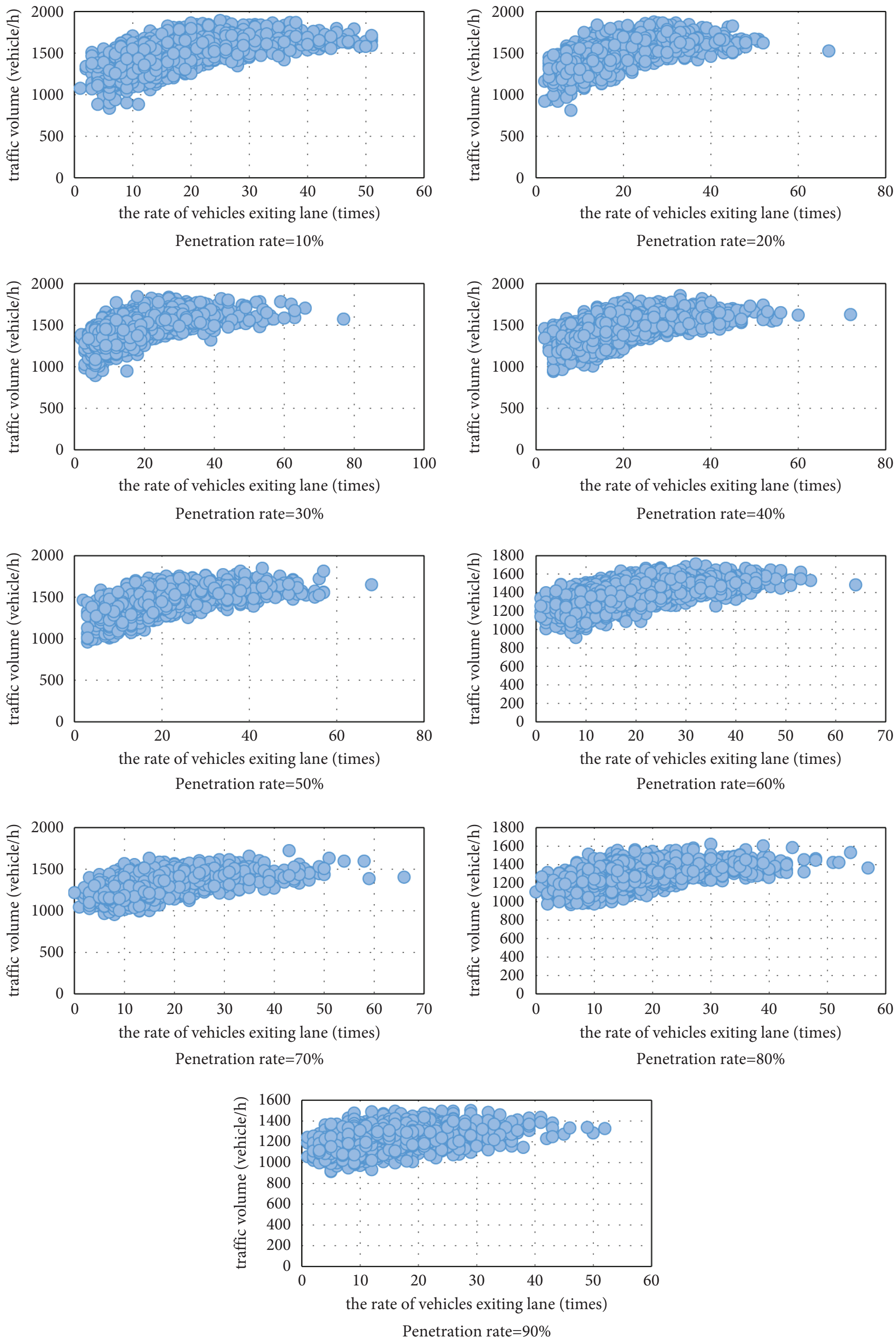
*The obvious correlation when the level is 0.05 (two tail); (b) **the obvious correlation when the level is 0.01 (two tail).

autonomous vehicles and finally reaches 0.846. In Lanes 2 and 3, the R is relatively stable. Meanwhile, the R in Lane 4 shows a slight downward trend. The fitting degree of all lanes under different operating ratios of autonomous vehicles is above 0.7. The lane closer to ramps has little effect by the number of autonomous vehicles, while the lanes farther from ramps have more effect by. Overall, the multiple linear regression effect of all lanes is good, and the multiple linear regression relationship can be considered to describe the influence of behaviors of changing lane on traffic volume. And then, we get the parameter value ranges of the multiple linear regression models of traffic volume and behaviors of changing lane under different operating proportions of autonomous vehicles in Table 3.



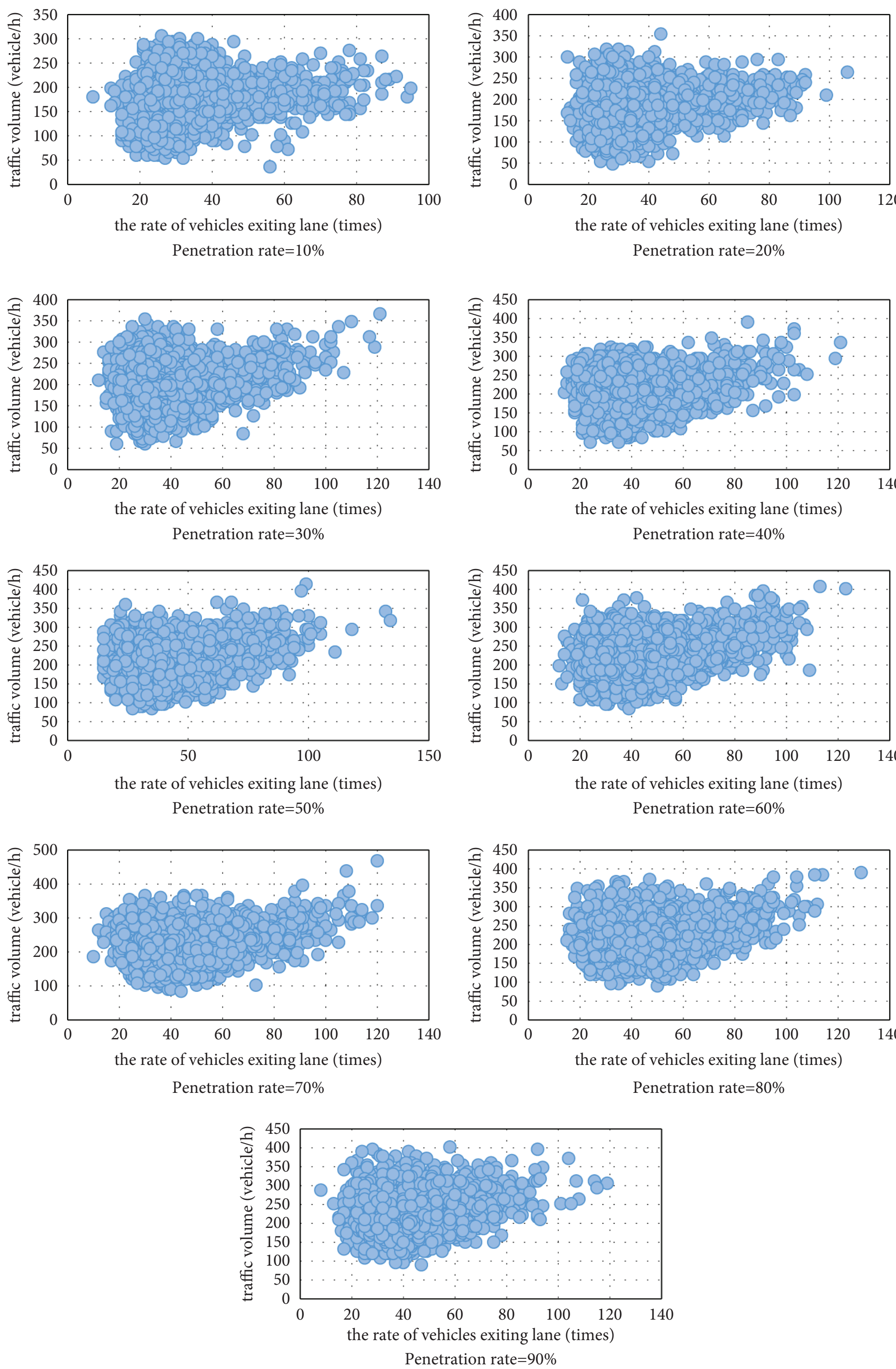
(a)

Figure 10: Continued.



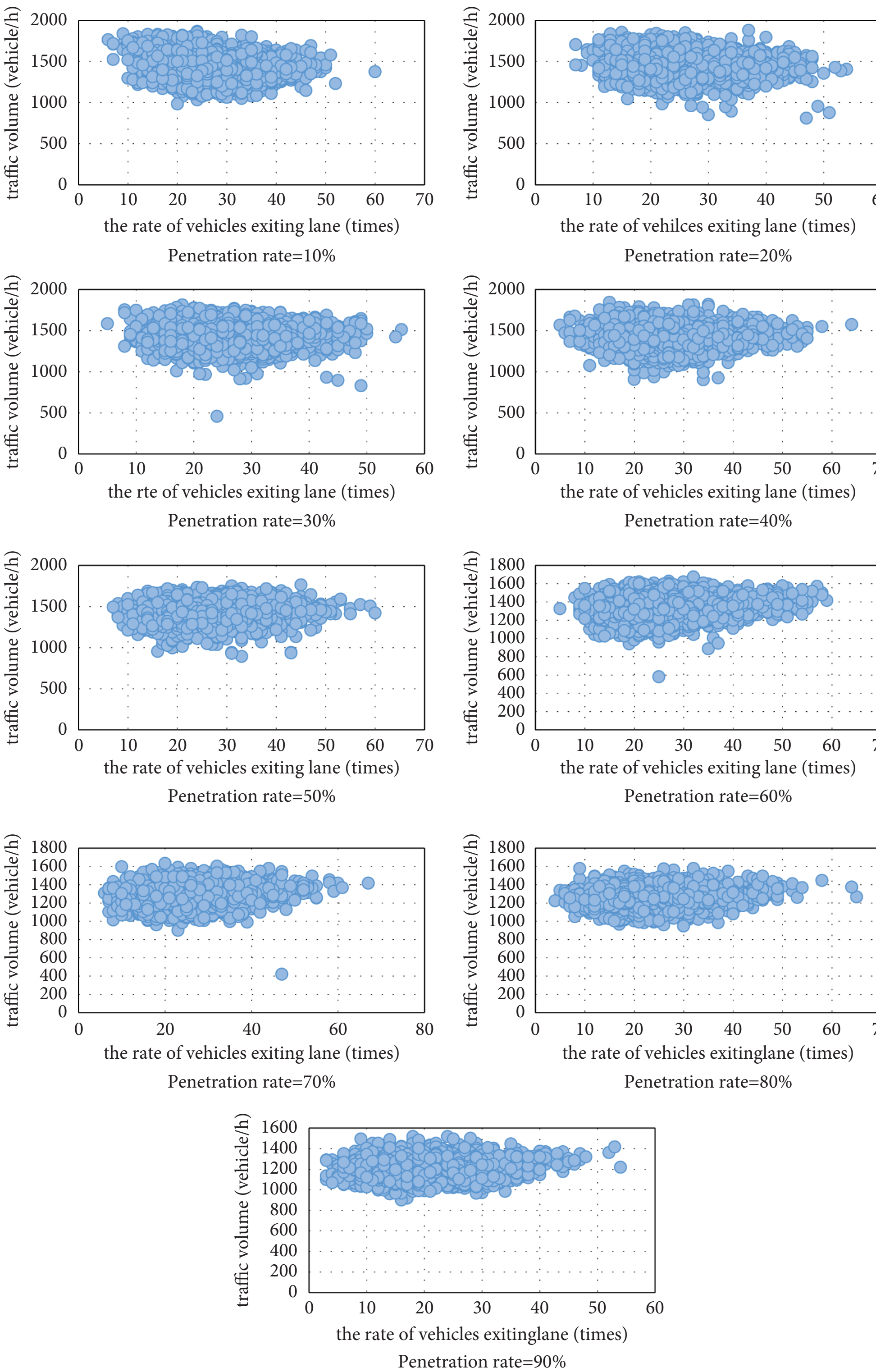
(b)

Figure 10: Continued.



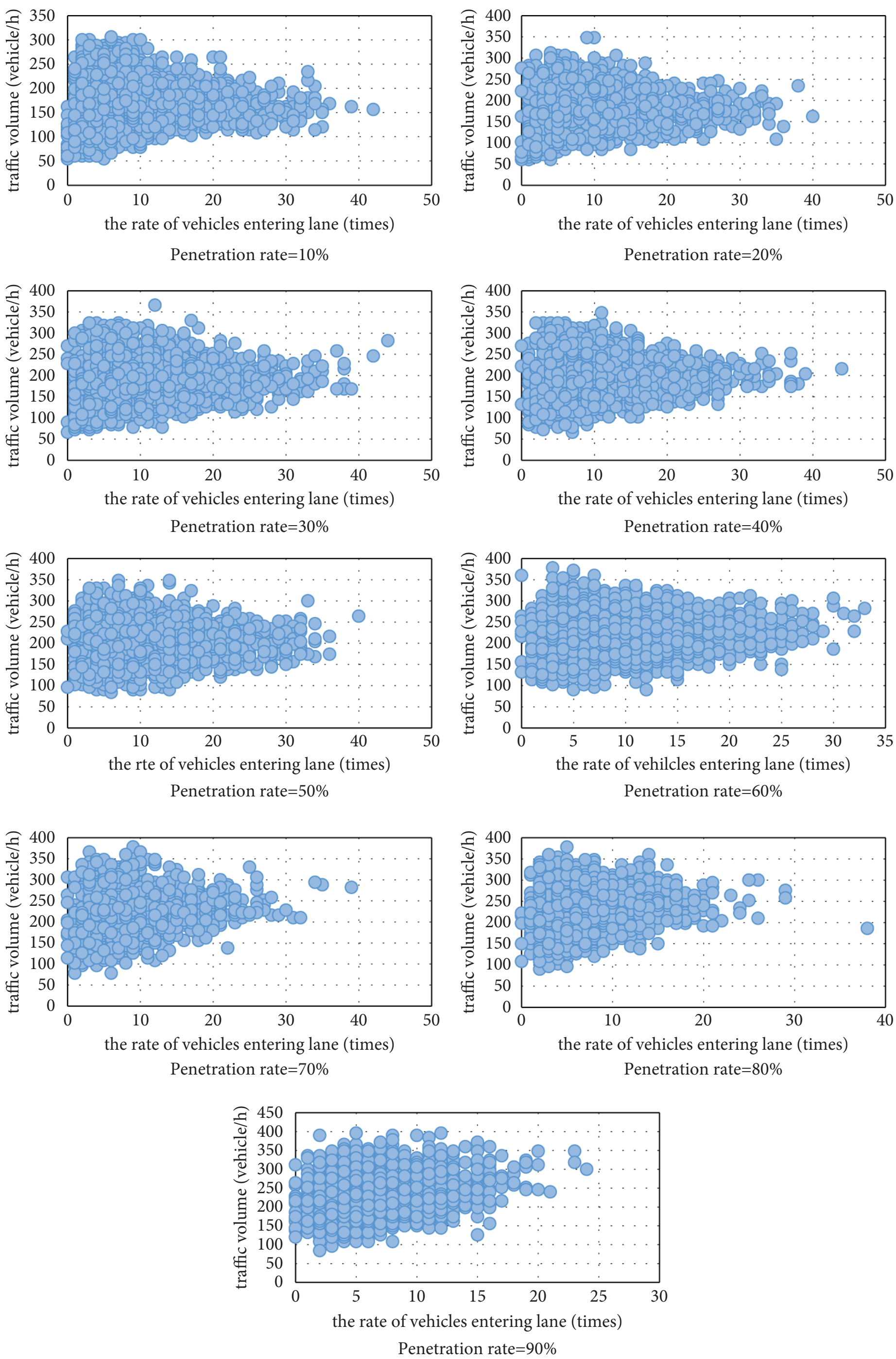
(c)

Figure 10: Continued.



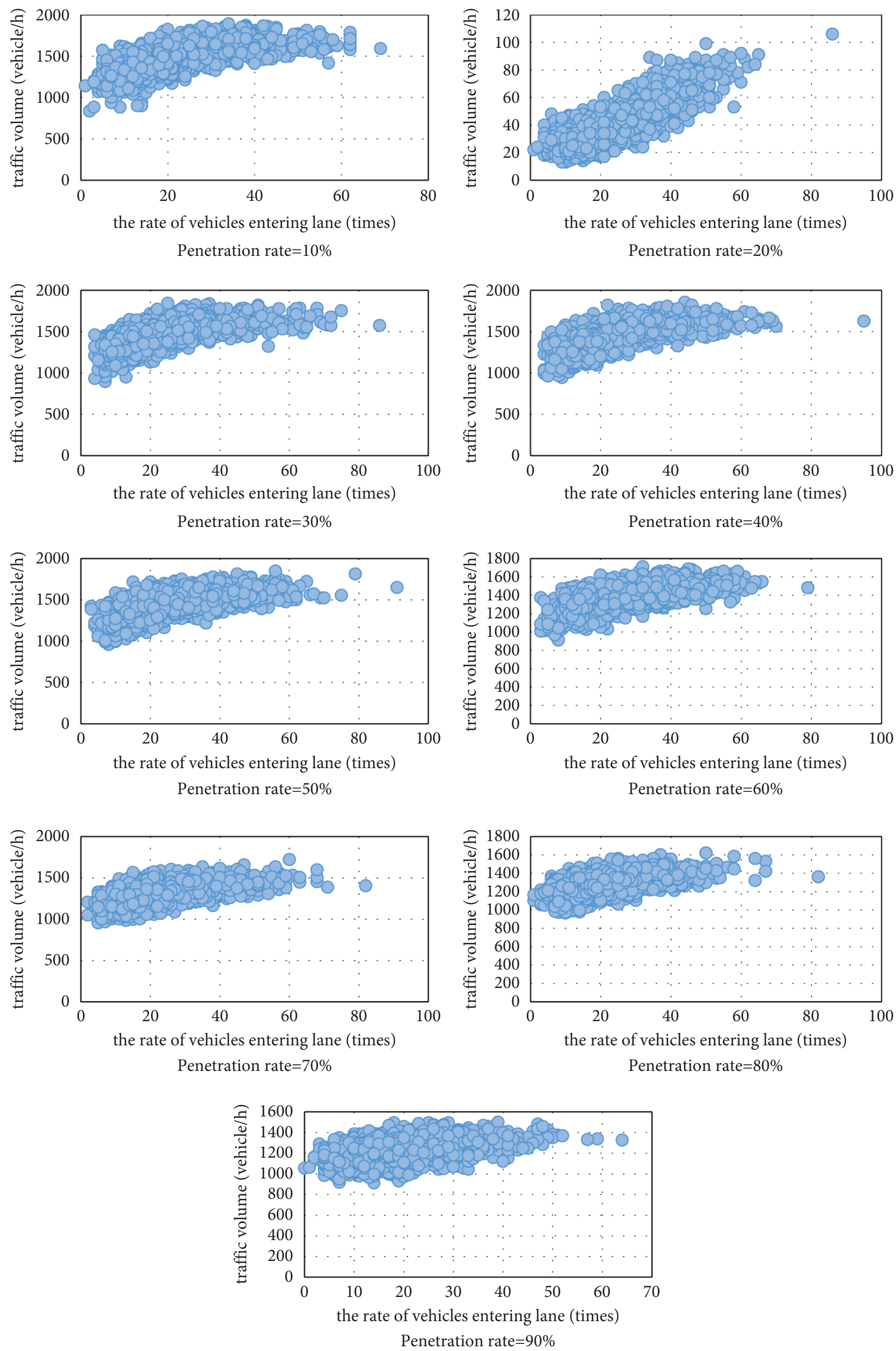
(d)

FIGURE 10: The relationship between traffic volume and the rate of vehicles exiting lane under different ratios of autonomous driving vehicles in different lanes. (a) Relationship diagram of lane 1. (b) Relationship diagram of lane 2. (c) Relationship diagram of lane 3. (d) Relationship diagram of lane 4.



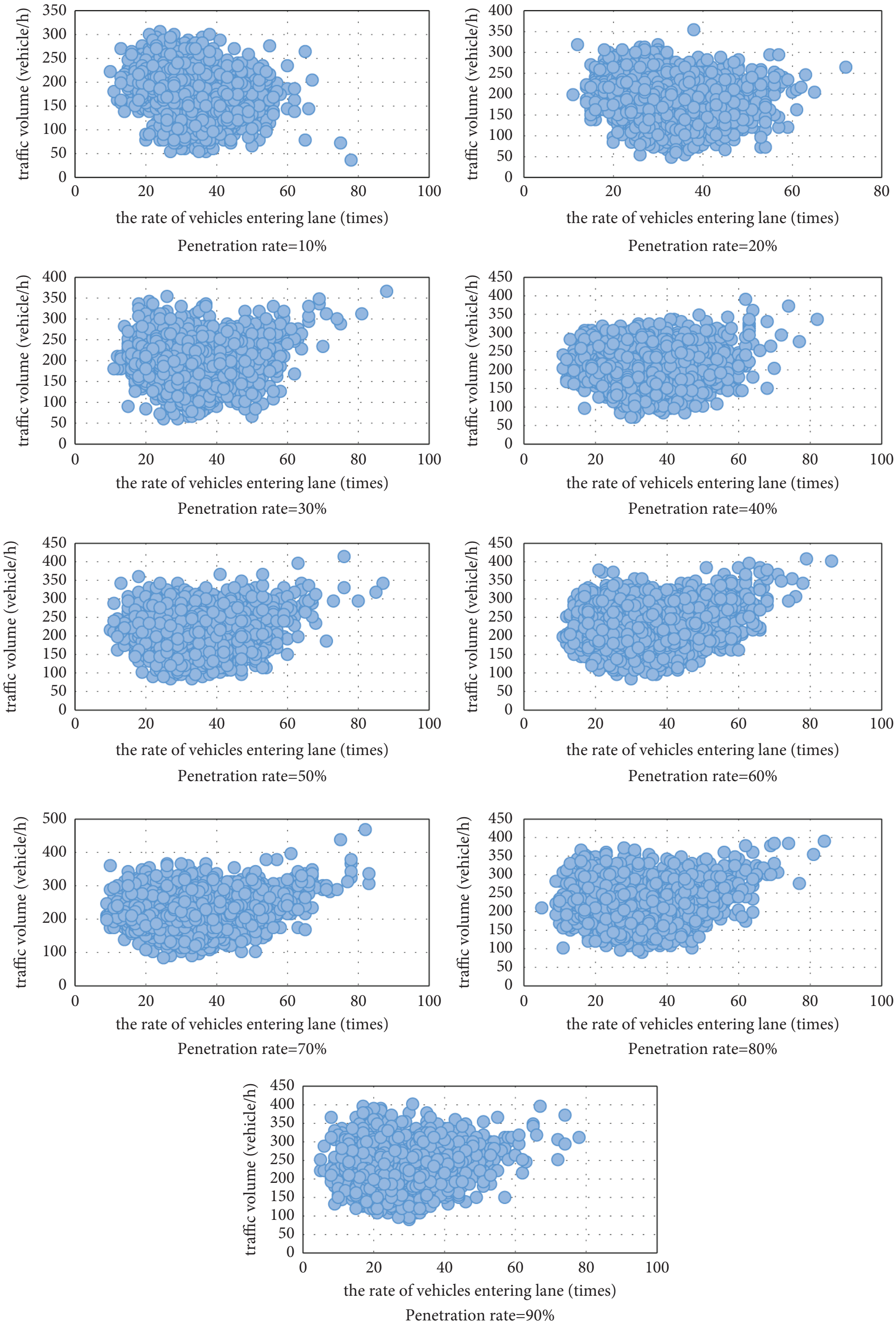
(a)

Figure 11: Continued.



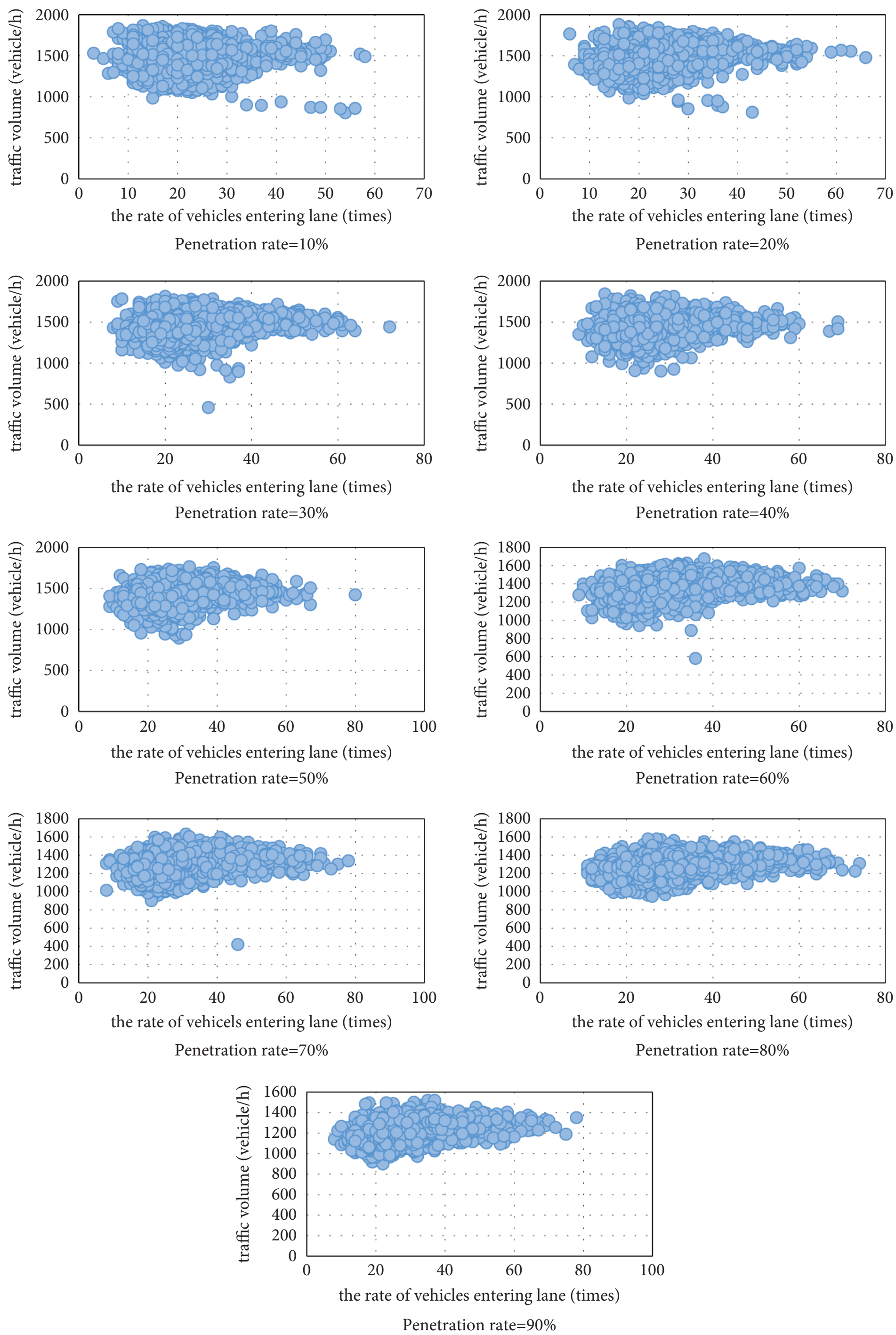
(b)

Figure 11: Continued.



(c)

Figure 11: Continued.



(d)

FIGURE 11: The relationship between the traffic volume and the rate of vehicles entering lane under different operating ratios of autonomous driving vehicles in different lanes. (a) Relationship diagram of Lane 1. (b) Relationship diagram of lane 2. (c) Relationship diagram of lane 3. (d) Relationship diagram of lane 4.

In Table 3, the parameter interval in the same lane is relatively close under different operating proportions of autonomous vehicles, and the multiple linear regression relationships can describe the relationship between behaviors of changing lane and traffic volume. That is to say, the relationships between behaviors of changing lane and the traffic volume have multivariate linear relationships under different operating proportions of autonomous vehicles. The establishment of relational model has a certain meaning for understanding the mixed traffic. Meanwhile, the model provides a certain theoretical basis for traffic control in mixed traffic.

Table 2: The degree of fitting table of multiple regression between traffic volume and lane-changing behaviors under different operation ratios of autonomous driving vehicles.

		Penetration rate = 10%	Penetration rate = 20%	Penetration rate = 30%	Penetration rate = 40%	Penetration rate = 50%	Penetration rate = 60%	Penetration rate = 70%	Penetration rate = 80%	Penetration rate = 90%
Lane 1	Multiple R	0.869	0.885	0.893	0.903	0.902	0.905	0.905	0.912	0.920
	R square	0.756	0.783	0.798	0.815	0.814	0.819	0.819	0.831	0.846
	Adjusted R square	0.755	0.782	0.797	0.814	0.814	0.819	0.819	0.831	0.846
	Standard error	86.603	85.312	87.366	84.887	87.277	93.395	93.942	92.567	92.708
Lane 2	Multiple R	0.923	0.929	0.924	0.934	0.932	0.929	0.925	0.929	0.935
	R square	0.853	0.864	0.853	0.873	0.869	0.862	0.855	0.863	0.874
	Adjusted R square	0.852	0.863	0.853	0.872	0.869	0.862	0.854	0.863	0.873
	Standard error	564.314	539.579	556.315	515.393	517.362	506.206	498.261	469.847	435.543
Lane 3	Multiple R	0.941	0.941	0.945	0.948	0.948	0.951	0.942	0.942	0.944
	R square	0.886	0.886	0.894	0.898	0.900	0.905	0.887	0.888	0.891
	Adjusted R square	0.885	0.885	0.893	0.898	0.899	0.904	0.887	0.887	0.891
	Standard error	62.039	64.835	67.357	67.056	68.605	71.359	76.298	76.400	78.003
Lane 4	Multiple R	0.966	0.968	0.968	0.967	0.967	0.964	0.959	0.959	0.960
	R square	0.932	0.938	0.938	0.936	0.936	0.930	0.919	0.920	0.921
	Adjusted R square	0.932	0.937	0.937	0.935	0.935	0.930	0.918	0.919	0.921
	Standard error	379.813	362.420	359.347	362.998	358.123	357.521	369.860	358.739	343.861

Table 3: The parameter value range of the multiple linear regression model of traffic volume and behaviors of changing lane under different operating ratios of autonomous driving vehicles.

		Lane 1		Lane 2		Lane 3		Lane 4	
		Lower 95%	Upper 95%	Lower 95%	Upper 95%	Lower 95%	Upper 95%	Lower 95%	Upper 95%
Penetration rate = 10%	c	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]
	a	[16.57,	18.53]	[30.37,	42.70]	[2.76,	3.11]	[24.91,	27.81]
	b	[−1.72,	−0.12]	[25.57,	35.20]	[1.83,	2.21]	[30.06,	33.35]
Penetration rate = 20%	c	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]
	a	[18.33,	20.42]	[16.96,	28.57]	[2.36,	2.73]	[23.99,	26.93]
	b	[−2.30,	−0.66]	[34.63,	43.67]	[2.22,	2.67]	[28.36,	31.41]
Penetration rate = 30%	c	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]
	a	[19.08,	21.28]	[3.63,	14.95]	[1.97,	2.37]	[23.78,	26.82]
	b	[−2.03,	−0.38]	[40.63,	49.39]	[2.71,	3.22]	[24.75,	27.74]
Penetration rate = 40%	c	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]
	a	[19.94,	22.12]	[10.41,	21.14]	[2.30,	2.70]	[18.95,	22.09]
	b	[−1.88,	−0.27]	[36.21,	44.30]	[2.26,	2.77]	[27.67,	30.75]
Penetration rate = 50%	c	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]
	a	[19.82,	22.23]	[3.53,	14.23]	[1.89,	2.32]	[21.37,	24.44]
	b	[−1.37,	0.39]	[39.74,	47.87]	[2.77,	3.33]	[23.67,	26.59]
Penetration rate = 60%	c	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]
	a	[19.49,	22.32]	[10.25,	20.38]	[1.69,	2.16]	[19.11,	22.40]
	b	[2.70,	4.68]	[33.89,	41.39]	[3.10,	3.74]	[21.15,	24.09]
Penetration rate = 70%	c	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]
	a	[19.84,	22.90]	[15.95,	25.59]	[2.02,	2.53]	[14.65,	18.32]
	b	[5.30,	7.42]	[30.93,	38.02]	[2.54,	3.26]	[23.40,	26.47]
Penetration rate = 80%	c	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]
	a	[16.83,	19.91]	[20.95,	29.77]	[2.60,	3.12]	[13.23,	16.85]
	b	[10.11,	12.36]	[30.06,	36.62]	[1.93,	2.69]	[24.84,	27.67]
Penetration rate = 90%	c	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]	[0.00,	0.00]
	a	[15.94,	18.95]	[24.80,	31.81]	[3.50,	4.00]	[14.96,	18.47]
	b	[15.55,	17.72]	[31.33,	36.75]	[1.32,	2.10]	[25.04,	27.46]

5. Summary

In this paper, a multiple linear regression model is proposed to describe the effect of behaviors of changing lane on urban expressway traffic under different operating ratios of autonomous vehicles. The establishment of model is divided into two parts: the simulation experiments and regression analysis. The establishment of simulation model and simulation experiments makes up the experiments. In the simulation model establishment part, the simulation method of objective to align the urban expressway of 3rd Ring Road in Chengdu, China, is adopted to make the simulation model closer to the actual traffic conditions. Before the benchmarking, the specific situation of the third ring urban expressway in Chengdu, China, was empirically studied. Through the analysis of the actual collected data, it was verified that the actual collected data conformed to the actual traffic, and the data were true and effective. By benchmarking the collection points in empirical study, a simulated road network model established. After running a round of simulation experiment without autonomous driving vehicles, we compare the obtaining experimental data with empirically collecting data and find that the relationship graphs of the data are close, and the availability of the simulated model is verified. In the simulation experiment part, the operating ratio of autonomous driving vehicles in each round increases 10%, and 9 rounds of simulation experiments are designed running on the simulated road network model. Simulation data characteristics analysis finds that there is a linear relationship between traffic volume and lane-changing behaviors. Then, multivariate linear regression analysis is carried out on the 9 rounds data, and multivariate linear relationships between behaviors of changing lanes and the traffic volume are found. This study found the following:

(1) The increase autonomous driving vehicles have different effects on the traffic volume of different lanes. The lane close to ramps is less sensitive to change in the number of autonomous vehicles, while the lanes farther away are more sensitive.

(2) The change in the number of autonomous vehicles has different effect on lane changing behavior in different lanes. But compared with the experiment without autonomous driving vehicles, the behaviors of changing lanes of all lanes obviously decrease when the penetration rate of automatic cars is over 10%. However, the responses of each lane are not consistent with the increased number of autonomous driving vehicles. The lane-changing behaviors in Lanes 1 and 2 have a significant decrease, while in Lanes 3 and 4 are relatively stable. But the behaviors of changing lane are less than the experiment without autonomous vehicles when the ratio of

autonomous vehicles reaches 90%. It is proved that the operation of autonomous vehicles can reduce the behaviors of changing lane in traffic and effectively improve the traffic situation.

(3) Linear relationships between behaviors of changing lane and the traffic volume are shown in our research. The regression fitting degree is above 0.7, although the distribution of each data under different ratios of automatic cars shows a non-normal distribution and the model parameter values interval under different ratios of autonomous vehicles are close. The fitting degrees of the liner model have little change under different operating proportions of autonomous vehicles, which prove that there are relatively obvious multivariate linear relationships between behaviors of changing lane and the traffic volume in mixed traffic.

To sum up, we believe that the autonomous vehicles can effectively improve heavy traffic in mixed traffic. With the increased number of autonomous driving vehicles, the fitting degrees of multivariate linear model are over 0.7, and the model parameter values interval in the same lane under different operating ratios of autonomous vehicles are close. All of those prove the stability of the model. In this paper, the proposed multivariate linear model can be used for the traffic management and control in mixed traffic. The applicability of the model to other roads will be the direction of future research.

Data Availability

The data used in this research can be made available from the corresponding author.

Conflicts of Interest

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

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