Hybrid Traffic Flow Characteristics of Connected and Automated Vehicles and Human-driven Vehicles

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Abstract: Aiming at the characteristics of the hybrid traffic flow in the intelligent network environment, four kinds of following modes and corresponding following models of the mixed traffic composed of (CAVs) and (HDVs) are analyzed. Then, a basic graph model of the relationship among the flow, density and speed of the mixed traffic flow under the stable state with the permeability of CAVs as the control parameter is constructed. Based on the basic graph model, the relationship between the road capacity of the mixed traffic flow and the penetration rate of CAVs is analyzed. Finally, SUMO simulation data is used to verify the hybrid traffic flow characteristics model. The results show that the flow-density data scatter and the model curve have a high agreement under different penetration rates of CAVs, which verifies the rationality and accuracy of the model.
Keywords: hybrid traffic flow; connected and automated vehicles; car following model; macro fundamental diagram

I Introduction

With the advancement of intelligent transportation systems and autonomous driving technologies, connected and automated vehicles (CAVs) have been widely adopted. Recent studies indicate that by 2050, approximately 75% of vehicles on the road are expected to be CAVs, and a prolonged coexistence of human-driven vehicles (HDVs) and CAVs will persist for a considerable period [1]. Therefore, studying the characteristics of hybrid traffic flow composed of HDVs and CAVs holds significant theoretical and practical value.

Early research on hybrid traffic flow primarily focused on the statistical and dynamic characteristics of traffic composed of motor vehicles and non-motorized vehicles [2][3]. With the development of intelligent connected vehicles and autonomous vehicles, hybrid traffic flow consisting of human-driven vehicles and intelligent connected vehicles has become a major research focus. Talebpour et al. [4] established following models for artificial driving vehicles, connected vehicles, and autonomous vehicles, and through experiments, they obtained the basic traffic flow models under different proportions. Gao Qinghe [5] established an intelligent connected vehicle following model and verified through simulation that the integration of intelligent connected vehicles is beneficial to the improvement of the stability of hybrid traffic flow. Chen Jie et al. [6] found that the following stability of traffic flow is affected by the number of communicating vehicles and sensitivity of the connected vehicles. The higher the penetration rate of connected vehicles, the greater the improvement in traffic capacity. Qin Yanyan et al. [7] processed the following-mentioned following-and-avoidance model using Taylor's formula and transfer function. The results showed that when the proportion of CAVs reached 23%, the hybrid traffic flow could be stable within the full speed range, and the higher the proportion of CAVs, the easier the traffic flow was to stabilize. Song Chengju et al. [8] analyzed the following-vehicle following characteristics of different following models' queues and conducted simulation studies using the CACC (connected adaptive cruise control, CACC, connected adaptive cruise control) model for both the fixed state and disturbed state of the following queue. The results showed that when the penetration rate of CAVs was high, the traffic flow speed was negatively correlated with the traffic volume, and as the penetration rate increased, the overall traffic volume showed an upward trend. Ye et al. [9] aimed to study the impact of intelligent connected vehicles on traffic capacity. They first established a two-lane cellular automata model and obtained the flow-density relationship diagrams of hybrid traffic flows under different proportions. Hou Peiguo et al. [10] based on the Nasch cellular automaton traffic flow model, taking into account the psychological factors and driving behavior differences of traditional drivers, established a manual driving - CACC autonomous driving hybrid traffic flow model, and concluded that as the proportion of autonomous driving vehicles increases, the traffic flow volume and average speed increase, etc. None of the above studies took into account the functional degradation phenomenon that occurs when intelligent connected vehicles follow manual-driven vehicles. To address this issue, Zhang Jianxu et al. [11] based on the Gipps following model and the ACC (adaptive cruise control) and CACC following model calibrated by real vehicles in the Path laboratory, constructed a continuous cellular automata model for hybrid traffic flow. The results showed that when the penetration rate of intelligent connected vehicles reached 60%, the proportion of congested vehicles in the traffic flow began to significantly decrease, and the road capacity increased as the penetration rate of intelligent connected vehicles increased. This paper employs various following models to describe the following and following behaviors of different vehicles. It takes into account the functional degradation that intelligent connected vehicles may experience when following manually-driven vehicles, and uses parameter differences to reflect the type distinctions among following vehicles. Additionally, it establishes a basic model of hybrid traffic flow affected by the proportion of intelligent connected vehicles, and explores the influence of intelligent connected vehicles on the characteristics of hybrid traffic flow. Finally, using the SUMO simulation software, experiments are designed to verify the validity of the hybrid traffic flow model presented in this paper.

II Hybrid Traffic Flow Following Model

A. Following Mode

Consider a hybrid traffic flow on a single lane consisting of intelligent connected vehicles (CAVs) and human-driven vehicles (HDVs). Assuming the penetration rate of CAVs is , then the penetration rate of HDVs is , and there are four following modes:

1) CAVs following CAVs

Both the front and rear vehicles are intelligent connected vehicles. They share information and can achieve "vehicle-to-vehicle communication". The rear vehicle can adjust in real time according to the running status of the front vehicle, and the two following vehicles can be regarded as a single entity. Let the proportion of this following mode be p_1 , then:

$$p_1 = p^2 \tag{1}$$

2) CAVs following HDVs

When an intelligent connected vehicle follows a manually-driven vehicle, since the manually-driven vehicle cannot achieve real-time information sharing with the intelligent connected vehicle, the following performance of the intelligent connected vehicle compared to mode (1) will show certain degradation. That is, the intelligent connected vehicle with degraded functions, DCAVs. Let the proportion of this following mode be p_2, then:

$$p_2 = p(1-p) \tag{2}$$

3) HDVs following CAVs

The human-driven vehicle follows the intelligent connected vehicle. When the running status of the preceding vehicle changes, the driver of the following vehicle needs to make a judgment and adjustment based on their own experience after a certain reaction time, thereby changing the running status of the following vehicle. Let the proportion of this following mode be p_3, then:

$$p_3 = (1-p)p \tag{3}$$

4) HDVs following HDVs

The driverless vehicle follows the driverless vehicle, which is similar to the situation in mode (3). Let the proportion of this following mode be p_4, then:

$$p_4 = (1-p)^2 \tag{4}$$

Based on the above four following modes, there are three types of following vehicles: CAVs, DCAVs and HDVs. And depending on the type of following vehicles, three different following-vehicle models can be constructed.

B. Following Model

1) Intelligent Connected Vehicle (CAV) Following Model

Regarding the following and preceding situations of intelligent connected vehicle (CAV) traffic, based on the cooperative adaptive cruise control model CACC described in reference [12], this paper adopts the CACC model with a constant expected headway to represent the following and preceding mode (1) of the following situation. The model structure is as follows:

$$\begin{aligned} a_n(t) = {} & k_1 a_{n-1}(t) + k_2[x_{n-1}(t) - x_n(t) \\ & - t_c v_n(t) - l - s_0 + k_3[v_{n-1}(t) - v_n(t)] \end{aligned} \tag{5}$$

In the formula, $a_n(t)$ and $a_{n-1}(t)$ represent the acceleration of vehicle n and vehicle $n-1$ at time t, with units of m/s^2 ; $x_n(t)$ and $x_{n-1}(t)$ represent the displacement of vehicle n and vehicle $n-1$ at time t, with units of m; $v_n(t)$ and $v_{n-1}(t)$ represent the speed of vehicle n and vehicle $n-1$ at time t, with units of m/s ; t_c is the expected vehicle spacing, which is set to 0.6s based on real vehicle experiments in the PATH laboratory [13]; l is the vehicle length, which is set to 5m; s_0 is the safety stopping distance, which is set to 2m; k_1, k_2 , and k_3 are weight coefficients [12], with values of $k_1 = 1.0$, $k_2 = 0.2$,and $k_3 = 3.0$.

2) The following model of DCAVs after functional degradation

According to reference [16], the PATH laboratory conducted real vehicle experiments and proved that the ACC model can effectively be applied to the following-aging intelligent connected vehicle following scenarios. The ACC model is:

$$\begin{aligned} a_n(t) = {} & j_1[x_{n+1}(t) - x_n(t) - t_d v_n(t) - l - s_0] \\ & + j_2[v_{n+1}(t) - v_n(t)] \end{aligned} \tag{6}$$

In the formula: $x_{n+1}(t)$ and $v_{n+1}(t)$ represent the displacement and velocity of vehicle $n+1$ at time t , with units of meters and meters per second respectively; t_d is the expected distance interval of the ACC model, according to reference [13], it is set at $1.1s$; j_1 and j_2 are model parameters, calibrated according to reference [16], $j_1 = 0.23s^{-2}$, $j_2 = 0.07s^{-2}$.

3) The following model of human-driven vehicles

The following model for human-driven vehicles mostly adopts the Intelligent Driver Model (IDM) [15,16]. Studies have shown that this model can well reflect the characteristics of manual driving. The model is as follows:

$$a_n(t) = a\left[1 - \left(\frac{v_n(t)}{v_f}\right)^4 - \left(\frac{s_0 + v_n(t)T + \frac{v_n(t)\Delta v_n(t)}{2\sqrt{b}}}{h - l}\right)\right] \quad (7)$$

In the formula: represents the maximum acceleration, which is set at; is the free-flow speed, which is set at ; is the safe headway time, which is set at ; is the speed difference between vehicle and the vehicle in front at time , measured in ; is the comfort deceleration, which is set at ; h is the vehicle headway, measured in .

III Macro Fundamental Diagram Model of Hybrid Traffic Flow

A. The analytical formula of the Macro Fundamental Diagram Model for mixed traffic flow

When the traffic flow is in a stable state, the acceleration of the above following model and the speed difference between the front and rear vehicles are both zero. When the traffic flow is in a stable state, the acceleration of the above following model and the speed difference between the front and rear vehicles are both zero. From this, the headway distances of the four following modes analyzed earlier in the stable state of the traffic flow can be obtained, as shown below. Thus, the headway distances of the four following modes analyzed earlier in the stable state of the traffic flow can be obtained, as shown below.

$$h = t_c v + l + s_0 \quad (8)$$

$$h_d = t_d v + l + s_0 \quad (9)$$

$$h_e = (s_0 + vT)\left(\sqrt{1 - (vv_f^{-1})^4}\right)^{-1} + l \quad (10)$$

In the formula: k represents the density of the hybrid traffic flow, with the unit being veh/km.

In the formula, Q represents the flow of the hybrid traffic flow, with the unit being veh/h.

In the formula: h_c, h_d and h_e represent the headway distance of the intelligent connected vehicle in following mode, the headway distance of the intelligent connected vehicle in degraded function mode and the headway distance of the human-driven vehicle in following mode, all in meters; v is the stable speed of the traffic flow, in meters per second.

Considering the mixed traffic flow composed of intelligent connected vehicle (CAV) and human-driven vehicle (HDV), the four following modes can be described by the three following models established above. Therefore, the average headway distance of the hybrid traffic flow in the stable state can be regarded as the stable headway distance of the hybrid traffic flow. Based on the proportion of the four following modes, the stable headway distance of the hybrid traffic flow can be expressed as:

$$H \quad p_1 h_c \quad p_2 h_d \quad p_3 h_e \quad p_4 h_e \quad (11)$$

In the formula:represents the headway of the hybrid traffic flow, measured in meters.

Substituting formulas (1), (2), (3), and (4) into formula (11), we obtain:

$$H = p^2 h_c + p(1-p)h_d + (1-p)h_e \quad (12)$$

Based on the relationship between the headway of vehicles and the traffic flow density, and by substituting into formulas (8), (9), and (10), the relationship between the hybrid traffic flow density and speed can be obtained as shown in Equation (13).

$$k = \frac{1000}{H} = \frac{1000}{p^2(t_c v + l + s_0) + p(1-p)(t_d v + l + s_0) + (1-p)\left[(s_0 + vT)\left(\sqrt{1-(vv_f^{-1})^4}\right)^{-1} + l\right]} \quad (13)$$

Based on the relationship among traffic flow volume, density and speed, the relationship between hybrid traffic flow volume and speed can be obtained as shown in Equation (14).

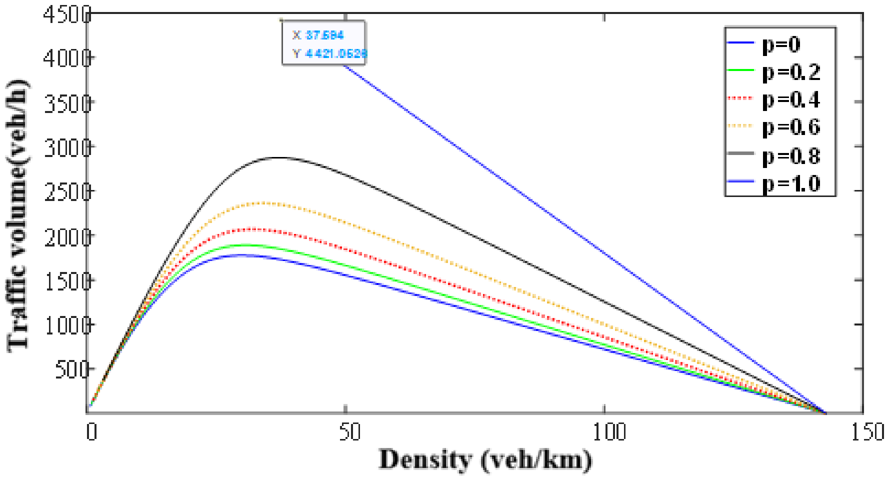
$$Q = 3.6kv = \frac{3600v}{p^2(t_c v + l + s_0) + p(1-p)(t_d v + l + s_0) + (1-p)\left[(s_0 + vT)\left(\sqrt{1-(v v_f^{-1})^4}\right)^{-1} + l\right]} \quad (14)$$

B. Traffic Capacity Analysis

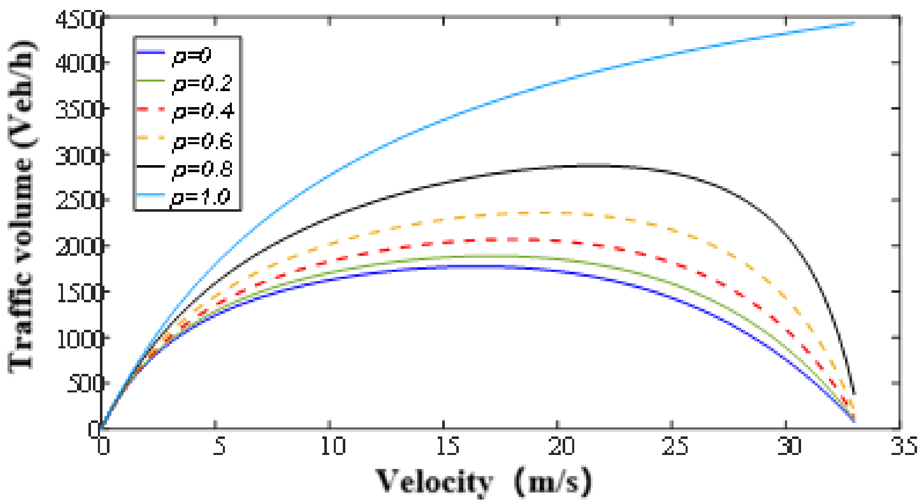
Referring to the parameter values of the following-following model given earlier, taking $t_c = 0.6s$, $t_d = 1.1s$, $T = 1.5s$, $s_0 = 2m$, $l = 5m$, and $v_f = 33.3m/s$, then equation (14) can be expressed as:

$$Q = \frac{3600v}{p^2(0.6v+7) + p(1-p)(1.1v+7) + (1-p)\left[(2+1.5v)\left(\sqrt{1-(0.03v)^4}\right)^{-1} + 5\right]} \quad (15)$$

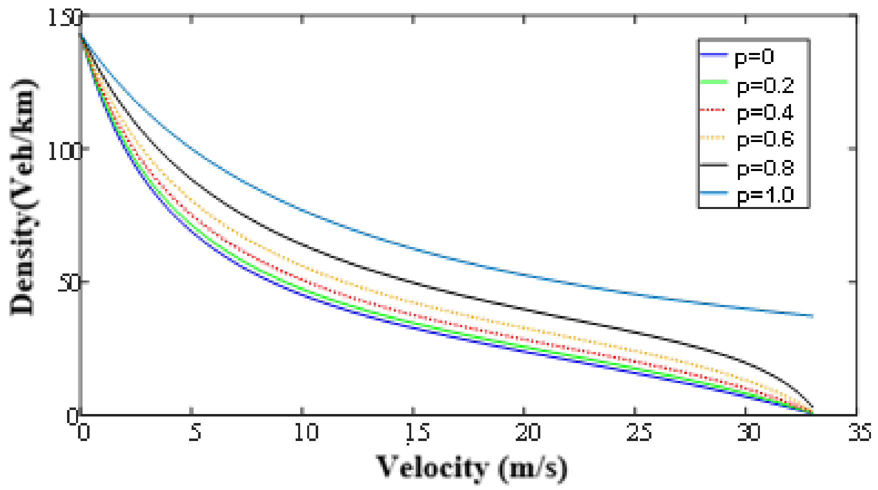
Equation (15) describes the relationship between the speed and flow of the hybrid traffic flow under different penetration rates of intelligent connected vehicles. Using the Matlab software, the flow-density (a), flow-speed (b), and density-speed (c) relationship curves of the hybrid traffic flow as shown in Fig.1 can be obtained.



(a) Hybrid traffic flow flow-density relationship



(b) Hybrid traffic flow flow-speed relationship



(c) Hybrid traffic flow density-speed relationship

Figure 1. Relationship diagram of hybrid traffic flow volume, density and velocity

Table I. Relationship table of maximum flow, density and speed of mixed traffic flow

Permeability	Maximum volume(veh/h)	Optimal density (veh/km)	Critical speed(m/s)
0	1774.9	30.2	16.3
20%	1888.5	30.3	17.3
40%	2070.0	31.9	18.0
60%	2361.8	33.9	19.3
80%	2874.0	36.8	21.7
100%	4421.1	37.6	32.7

Under different penetration rates, the maximum flow, optimal density, and critical speed relationships of the hybrid traffic flow are presented in Table 1. From this, it can be seen that when $p=1$, the hybrid traffic flow consists of a single intelligent connected vehicle, and the road capacity is at its maximum, which is $4421 veh/h$, with a corresponding density of $38 veh/h$ and a speed of $33/m/s$; while when $p=0$, the hybrid traffic flow consists of a single manually-driven vehicle, and the road capacity is at its minimum, which is $1775 veh/h$, with a corresponding density of $30 veh/km$ and a speed of $16 m/s$.

C. Permeability sensitivity analysis

From Figure 1 (a), it can be seen that the traffic capacity of the hybrid traffic flow increases as the penetration rate p value of intelligent connected vehicles rises. When the penetration rate $p \le 0.4$, the improvement effect on the traffic capacity of the hybrid traffic flow is not significant. When $p \ge 0.6$, the traffic capacity of the hybrid traffic flow will increase significantly. When increases from 0 to 0.4, the traffic capacity increases by 16.63%; when p increases from 0.4 to 0.6, the traffic capacity increases by 14.09%; when increases from 0.6 to 0.8, the traffic capacity increases by 21.69%; when increases from 0.8 to 1.0, the traffic capacity increases by 53.83%.

IV Simulation Verification

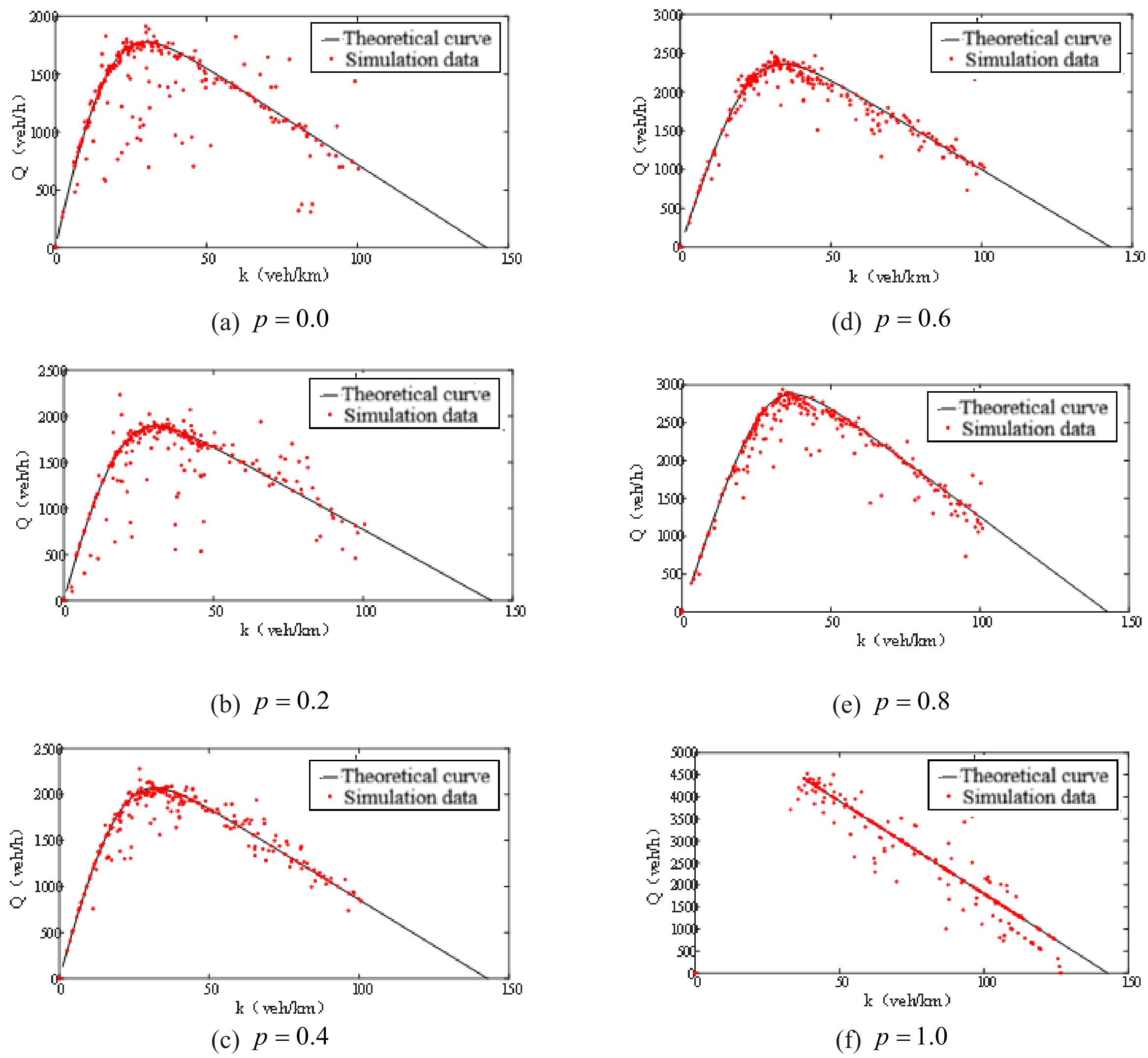
A. Simulation Settings

To verify the rationality and effectiveness of the fundamental diagram model of hybrid traffic flow constructed in this paper, the SUMO simulation software was selected to simulate the simulation environment of mixed traffic flow. The simulated section was a single lane with a total length of 10 km, divided into 10 segments, each 1 km long. An E2 detector was set up in each segment, and each detector was 1 km long. The three types of vehicles are defined as follows: "FCAVs" (representing "Full-CAVs"), "DCAVs", and "HDVs", which respectively stand for intelligent connected vehicles, intelligent connected vehicles with degraded functions, and manual driving vehicles. The parameters of these three types of vehicles are set according to the corresponding following model given earlier, and the different penetration rates of intelligent connected vehicles reflect different mixed traffic flow situations.

The simulation duration is set to 7200 seconds. The Lane area detectors (E2) are used to collect the flow, density and speed data of the hybrid traffic flow during the simulation. Each detector collects the simulation data every 30 seconds, forming a scatter plot. This scatter plot is then compared and analyzed with the theoretical curve of the basic model of the hybrid traffic flow drawn in this paper.

B.Analysis of Simulation Results

Fig. 2 presents the comparison chart of the scatter plot of the collected simulation data and the theoretical curve of hybrid traffic flow flow-density when the penetration rate of intelligent connected vehicles is $p=0$, $p=0.2$, $p=0.4$, $p=0.6$, $p=0.8$, $p=1.0$.



(a) $p=0.0$ (b) $p=0.2$ (c) $p=0.4$ (d) $p=0.6$ (e) $p=0.8$ (f) $p=1.0$

Figure 2. Simulation results

As shown in Fig. 2, with the increase in the penetration rate of intelligent connected vehicles, the maximum traffic flow gradually rises, which proves that the extensive application of intelligent connected vehicles can enhance the road capacity. The simulation data points are basically distributed on or near the theoretical curve, and the fitting degree of the simulation flow-density data increases with the increase in the penetration rate of intelligent connected vehicles, demonstrating the validity and feasibility of the hybrid traffic flow fundamental diagram model constructed in this paper. It should be noted that when the permeability is 1.0, in the high-density state, the traffic flow based on SUMO is in an unbalanced state and the collected data is distorted. Therefore, it cannot be used as accurate data for reference.

V Conclusions

The main conclusions drawn from this article are as follows:

(1) By analyzing the differences in following behavior between intelligent connected vehicles and manually-driven vehicles in the networked environment, different following models corresponding to different following parameters were selected, and a macro fundamental diagram model of hybrid traffic flow in the intelligent connected environment was constructed. Through SUMO simulation experiments, simulations were conducted under the conditions of intelligent connected vehicle penetration rates of 0, 0.2, 0.4, 0.6, 0.8, and 1.0. Based on the simulation data, the rationality and effectiveness of the model were verified.

(2) Under the condition that all other factors remain unchanged, the higher the penetration rate of intelligent connected vehicles, the greater the road capacity. According to the parameters set in this article, when the penetration rate of intelligent connected vehicles reaches 100%, the traffic capacity of the mixed traffic flow is , the corresponding traffic density is 38, and the traffic speed is .

(3) This paper does not consider the impact of vehicle lane-changing on traffic flow in the case of multiple lanes. In future research, the cellular automaton NaSch model can be adopted to consider the lane-changing principles of vehicles, and the macro fundamental diagram model of hybrid traffic flow obtained in this paper can be revised to obtain a multi-lane hybrid traffic flow model in the intelligent connected vehicle environment.

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