Dynamic characteristics of mixed traffic flow in ramp merging area under connected and automated environment

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ABSTRACT

In order to analyze the impact of ramp convergence in merging area on the dynamic characteristics of expressway mainline traffic flow under the mixed traffic flow environment composed of connected and automated vehicle (CAV) and human-driven vehicle (HV), this paper selects the intelligent driver model (IDM), the adaptive cruise control (ACC) car-following model, and the cooperative adaptive cruise control (CACC) car-following model to model the HV, the DCAV (degraded connected and automated vehicle), and the CAV following behavior, respectively. The proportions of different types of vehicles are determined by platooning intensity, and the effects of changes in penetration rate on the dynamic characteristics of mainline traffic flow on expressways are investigated in terms of operational efficiency, traffic safety, emission, and fuel. The results show that the increase of penetration rate is more significant to the improvement of free flow operation efficiency compared with congested flow, and can effectively inhibit the diffusion of blockage to the upstream. With the increase of penetration rate, the overall safety of mainline mixed traffic flow is improved based on time-to-collision (TTC) analysis. However, when the proportion of connected and automated vehicles is 0.7, the mainline mixed traffic flow locally has the highest risk of rear-end collision, and the time exposed time-to-collision (TET) and time integrated time-to-collision (TIT) achieve peak values. In addition, increased penetration rate significantly reduces exhaust emissions and fuel consumption in mixed traffic flows.

Keywords: ramp merging area, mixed traffic flow, platooning intensity, penetration rate

1. INTRODUCTION

With the rapid development of technology in the fields of computers and communications as well as the increasing severity of urban transportation problems, the mixing of connected and automated vehicles has gradually become a research hotspot for enhancing transportation efficiency and improving road safety. In the process of marketization of connected and automated vehicles, the heterogeneous traffic flow composed of HV and CAV will persist. However, as an important traffic node of the expressway system, the ramp merging area has frequent acceleration and deceleration, lane changing, and other driving behaviors. Under the heterogeneous mixed traffic flow environment, the influence of the merging area on the traffic flow characteristics of the expressway mainline will be more uncertain. Therefore, it is of great significance to analyze the influence of different penetration rates on the dynamic characteristics of expressway mainline traffic flow for the ramp merging area of the expressway.

In recent years, many scholars have conducted research on the operational characteristics of mixed traffic flow under the connected and automated environment. In terms of operational efficiency, by developing cooperative on-ramp merging rules for ACC vehicles, Davis shows that cooperative merging can increase throughput by 20% if ramp demand is low. At a penetration rate of 50%, mixed traffic can increase the distance traveled by up to 3.6 km in 600 seconds[1]. Zheng develops a stochastic Lagrangian model to reveal the effects of stochastic behaviour and stability of mixed traffic flows. It is shown that increasing the AV penetration rate from 5% to 50% significantly reduces the uncertainty of the mixed traffic system under both free and congested conditions[2]. Arnaout developed the F.A.S.T. stochastic micro-traffic simulation model to show that traffic congestion can be reduced even with low CACC penetration rates[3]. Zhu considers driver personality differences to classify drivers of autonomous vehicles into adaptive and non-adaptive drivers, and the results show that increasing the prevalence of CACC can effectively reduce traffic congestion, and with the increase of adaptive drivers, CACC can perform better[4]. Letter proposed a CAV merging algorithm for highway merging area, and verified that the CAV always outperforms the HV in terms of average speed and travel time under free-flow conditions[5].

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In terms of traffic safety, Yao evaluates the stability of the mixed traffic flow through safety indicators and shows that when the penetration rate is higher than 50%, the increase of CACC vehicles significantly reduces the traffic safety risk but leads to deterioration of TET and TIT[6]. Through the development of a simulation framework, Ramin's research has shown that security performance only improves significantly when penetration rates exceed 40% and that additional security improvements can be achieved more quickly by increasing collaboration and connectivity through CACC[7]. Anshuman demonstrated through simulation that CAV can suppress traffic flow disturbances and improve the efficiency and safety of traffic flow under a given penetration rate and also verified the importance of spatial alignment of CAV[8].

In terms of fuel consumption and emissions, the results of the Stogios study show that autonomous vehicles can make a positive difference in terms of emissions and traffic flow performance. The effects are more pronounced when autonomous vehicles are adapted to a more aggressive driving style, especially during high traffic demand[9]. Stern E R infiltrated a small number of automatic driving cars into a manually driven traffic stream to suppress the traveling stop wave, and the experiment showed that at low penetration rates, automated vehicles can reduce a large amount of traffic emissions[10].

Existing studies have performed microscopic modeling of mixed traffic flow to analyze its operational characteristics and achieved significant results, but there are still deficiencies in the impact of ramp convergence in merging areas on the dynamic characteristics of expressway mainline traffic flow in the connected and automated environment. Therefore, this paper simulates and analyzes the ramp merging area of expressway entrance ramps based on the selected car-following model, and explores the influence of the change of penetration rate of CAV in the area on the dynamic characteristics of expressway mainline traffic flow from the aspects of operational efficiency, traffic safety, emissions and fuel consumption.

2. CAR-FOLLOWING MODELING

2.1 Car-following model for human-driven vehicles

The Intelligent Driver Model (IDM) is a kind of car-following model proposed by Treiber, which takes the driver's expectation as the starting point[11]. Because its parameter physical meaning is clear and can describe the change of the time headway under different traffic conditions, it is used by the majority of scholars in the theory of human-driven vehicle car-following model as well as simulation research, the model formula is as follows:

$$a_i = a\left[1-\left(\frac{v_i}{v_f}\right)^{\delta}-\left(\frac{s_0+v_iT+\frac{v_i\Delta v_i}{2\sqrt{ab}}}{s}\right)^2\right] \tag{1}$$

Where: a_i and v_i are the acceleration and velocity of the vehicle i, a and b are the maximum acceleration and comfortable deceleration of the vehicle, which take values of 1 and 2.8, respectively, v_f is the free stream velocity, s is the headspace between two neighboring vehicles, s_0 is the static minimum safe spacing and takes the value 2, T is the safe time headway and takes the value 1.5, Δv_i is the velocity difference between the front and rear of the two vehicles, and δ = 4.

2.2 Car-following model for connected and automated vehicles

The PATH Lab at UC Berkeley calibrated a cooperative adaptive cruise control CACC car-following model based on constant desired headway based on real-vehicle test data, which can well validate the current car-following characteristics of the CAV, and the model equations are as follows:

$$\begin{cases} v = v_p + k_pe + k_d\dot{e} \\ e = \Delta x - s_0 - l - t_cv \end{cases} \tag{2}$$

Where, v_p is the velocity of the car-following vehicle in the previous moment, e is the actual and the desired vehicle gap error, $\dot{e}$ is the differential term of e against time t, k_p, k_d are the control coefficients taking values of 0.45 and 0.25, respectively, and t_c is the desired time headway of CACC, which takes the value of 0.6s.

2.3 Degraded car-following model for connected and automated vehicles

For the car-following model of the CAV following the HV that lacks the vehicle-vehicle communication device, this paper chooses the ACC-following model based on the constant desired headway calibrated and verified by the PATH laboratory as the degraded car-following model of the CAV, and the simulation results obtained by the use of this model have a high consistency with its application to the data measured in real-world scenarios, and the model formulas are as follows:

$$\begin{cases} e = x_{i-1} - x_i - t_a v_i \\ a_i = k_1 e + k_2 (v_{i-1} - v_i) \end{cases} \tag{3}$$

Where a_i and v_i is the acceleration and velocity of the vehicle i, e is the actual and the desired vehicle gap error, k_1 is the vehicle gap error weight and k_2 is the velocity difference weight, which take the value of 0.23 and 0.07, respectively, and t_a is the ACC desired time headway, which takes the value of 1.1s.

3. CAR-FOLLOWING PATTERNS AND PLATOONING INTENSITY

3.1 Analysis of car-following patterns

For the mixed traffic flow composed of CAV and HV, the following three different car-following patterns exist.

(1) CAV follows CAV

When both the front and rear vehicles are CAVs, the rear vehicle can utilize the vehicle-vehicle communication technology to interact with the front vehicle, obtain the front vehicle's speed, position, acceleration, and other information, and realize the coordinated driving of the front and rear vehicle, so the above CACC car-following model is adopted.

(2) CAV follows HV

When the front vehicle is HV and the rear vehicle is CAV, due to the lack of vehicle-vehicle communication equipment in the front vehicle, the CAV cannot receive the driving status of the HV, and the CAV can only obtain the information of the front vehicle, so the timeliness and accuracy of the information obtained by the CAV is reduced, and the vehicle degrades to DCAV, so the ACC car-following model is adopted.

(3) HV follows HV or CAV

When the rear vehicle is HV, the vehicle relies on the driver's perception, identification, judgment, and strategic decision to control and follow. Compared with the on-board equipment, this pattern has a longer reaction time and operation uncontrollability, so the IDM car-following model is used.

Therefore, based on the adoption of different car-following models, this paper classifies the mixed traffic flow into three vehicle types accordingly: CAV, DCAV (functionally degraded CAV vehicle), and HV. In this paper, the effects of different penetration rates of the mainline mixed traffic flow on operational efficiency, traffic safety, emission, and fuel consumption are investigated in the entrance ramp convergence scenario using the abovementioned car-following models.

3.2 Platooning intensity and proportion

Due to the random distribution of CAVs and HVs in the traffic flow, it is difficult to describe the proportion of complex car-following patterns in the traffic flow by relying only on the penetration rate. The platooning car-following composition varies greatly at the same penetration rate. Ghiasi proposed the concept of platooning intensity to describe the formation of CAVs into a platoon in a mixed traffic flow, which is denoted by the symbol O and takes the value of [-1,1][12]. At the same penetration rate, a larger value of the platooning intensity indicates a higher connection intensity between CAVs and a higher vehicle-to-vehicle communication coverage. When the platooning intensity is -1, the platooning intensity is minimized, the CAVs and HVs cross the road, the vehicle-vehicle communication fails, and all the CAV car-following modes are degraded. When the platooning intensity is 1, the platooning intensity is maximum, and the probability of CAV degradation is minimized under the condition that the penetration rate is kept constant, and the CAVs follow each other to maximize the advantage of vehicle-vehicle communication. Ghiasi established a mathematical model describing the relationship between the probability of occurrence, penetration rate, and platooning intensity for different car-following scenarios by abstracting the platoon as a Markov chain, and the model equation is as follows[13]:

$$p_{10}(p_1,O)=\begin{cases} p_0(1-O) \quad , \quad O\geq 0 \\ p_0+O(p_0-\min(1,\dfrac{p_0}{p_1})) \quad , \quad O<0 \end{cases} \tag{4}$$

$$p_{11}(p_1,O)=1-p_{10}(p_1,O) \tag{5}$$

$$p_{01}(p_1,O)=\begin{cases} p_1(1-O) \quad , \quad O\geq 0 \\ p_1+O(p_1-\min(1,\dfrac{p_1}{p_0})) \quad , \quad O<0 \end{cases} \tag{6}$$

$$p_{00}(p_1,O)=1-p_{01}(p_1,O) \tag{7}$$

where $p_{10}(p_1,O), p_{11}(p_1,O), p_{01}(p_1,O), p_{00}(p_1,O)$ denote the probability of CAV following HV, CAV following CAV, HV following CAV, and HV following HV, respectively, p_1, p_0 are the penetration rate of CAV and HV, $p_0+p_1=1$, O is the platooning intensity.

Based on the relationship between platooning intensity and penetration rate, it is possible to compute more accurately the proportions accounted for by different car-following patterns in a mixed traffic flow, and to describe the car-following characteristics and degradation phenomena of the mixed traffic flow.

4. TRAFFIC FLOW SIMULATION ANALYSIS

To visually evaluate the effect of penetration rate change on the dynamic characteristics of mainline mixed traffic flow under ramp merging interference, SUMO is used to construct simulation scenarios. The upstream of the mainline is set to be 500 m, and the ramp merging area is 150 m. The maximum speed of the expressway is set to be 80 km/h, and the maximum speed of the ramp is set to be 50 km/h. The vehicle lateral motion model is the LC2015 model, and the platooning intensity is 0. To exclude the effect of the transient state, each simulation step Δt is 0.5s, and the simulation time is from 1000 to 2800s, with a total of 1800s. The required traffic data for analysis are collected after the operation reaches the steady state, and the influence of the change in the penetration rate of CAVs in the region on the dynamic characteristics of the traffic flow on the mainline is explored in terms of operational efficiency, traffic safety, emission, and fuel.

4.1 Analysis of traffic flow operation efficiency

To analyze the influence of CAV penetration rate on the traffic flow efficiency of the mainline, two sets of simulation test scenarios are set up. The free flow (3500veh·h^{-1}) and congested flow (4500veh·h^{-1}) demand scenarios of the mainline are selected for simulation respectively, and the simulation results at p = 0 are used as the benchmark to calculate the average operating speed improvement ratio under each penetration rate, as shown in Table 1. The analysis shows that with the increasing penetration rate, there is a significant enhancement trend of the average operating speed under the mainline traffic flow of free flow demand and congested flow demand. In the free flow demand, when the penetration rate p =1, the average speed has a more significant improvement, and the free speed can reach 19.61m/s, which is equivalent to the improvement of 72.53%. In the congested flow demand, compared to the free flow, the enhancement ratio is slightly smaller at p <0.8, but when p =1, the enhancement ratio suddenly increases to 68.89%. The reason is that CAV has a shorter reaction time and time headway than HV, and can react quickly according to the state of the front vehicle. Due to the smoother speed control of CAV and the absence of random slowing phenomenon in the driving behavior of HV, the efficiency of traffic operation on the mainline is dramatically improved. Compared to congested flow, the increase in penetration rate of mixed traffic is more obvious for the improvement of free flow operation efficiency.

Table 1. Percentage increase in average operating speed of traffic

Penetration rate	Percentage of improvement (%)		Penetration rate	Percentage of improvement (%)	
	3500veh·h^{-1}	4500veh·h^{-1}		3500veh·h^{-1}	4500veh·h^{-1}
0	0.00	0.00	0.6	33.6	13.85
0.2	8.7	-8.18	0.8	59.19	23.29
0.4	21.16	1.23	1	72.53	68.89

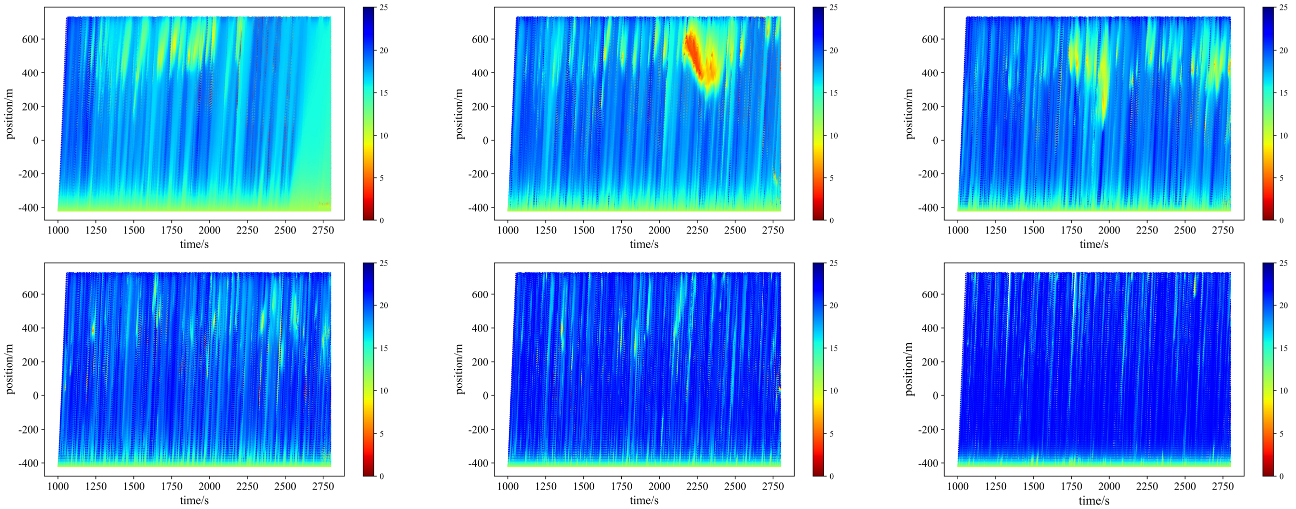

Figure 1. Speed spatio-temporal diagram of free flow

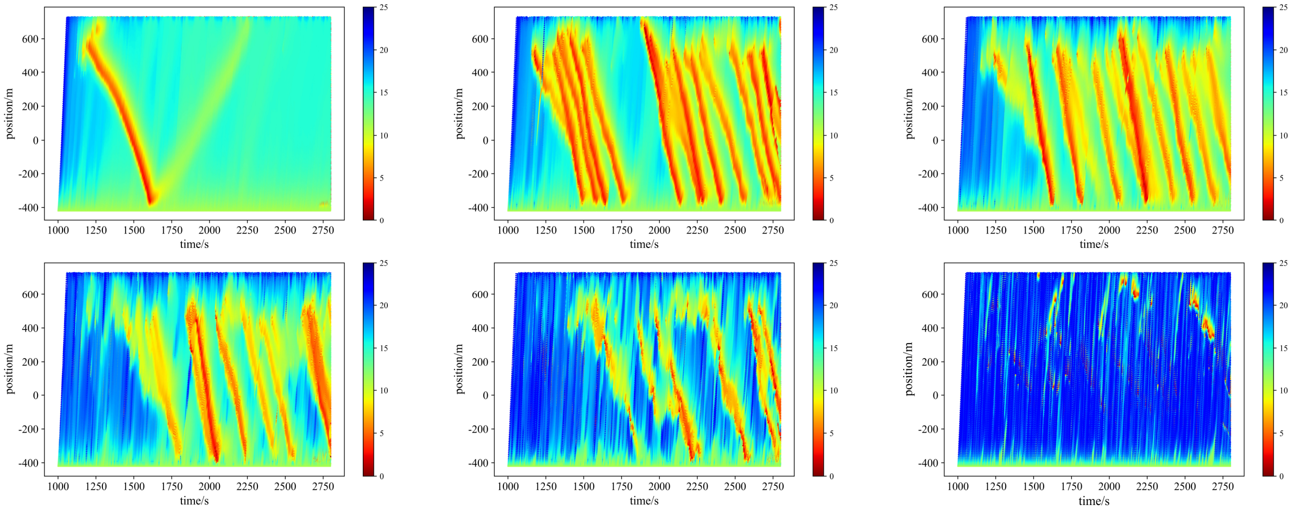

Figure 2. Speed spatio-temporal diagram of congested flow

Figures 1 and 2 show the speed spatio-temporal diagrams of the mainline mixed traffic flow with different penetration rates from 1000 to 2800 seconds for free flow and congested flow, respectively, with the horizontal axis representing the time and the vertical axis representing the position of the mainline of the expressway. From the speed spatio-temporal diagrams, it can be clearly seen that the increase of penetration rate can effectively improve the operation speed and relieve traffic congestion in the ramp merging area and bottleneck area of the expressway, both in the free flow and congested flow demand scenarios. In the congested flow demand, when $p=0$, the ramp vehicles have stayed in the acceleration lane and cannot merge, forming congestion accumulation, but in the actual situation the vehicles in the acceleration lane will be forced to merge, resulting in forced congestion on the mainline. Comparing the speed spatio-temporal diagrams, when the flow rate upstream of the bottleneck is 4500 veh·h^{-1}, the congestion in the manual driving scenario forms and gradually propagates upstream. However, as the proportion of CAV introduction increases, the impact area of slow speed is mainly concentrated in the bottleneck area of 80-230m. The spreading of the blockage upstream was effectively suppressed, and the blockage was significantly alleviated by the significant increase of vehicles with speeds up to 20m/s.

4.2 Traffic safety analysis

Simulation experiments can output the trajectory data of simulated vehicles at each time step, but they do not visually represent the impact of ramp convergence on the safety of mainline mixed traffic flow. Existing studies evaluate traffic safety with the help of microscopic traffic safety indicators. To comprehensively evaluate the safety of heterogeneous traffic flow mixed with CAVs, this paper proposes to use four indicators, namely, speed standard deviation (SD), time-to-collision (TTC), time exposed time-to-collision (TET), and time integrated time-to-collision (TIT), to analyze the impact of mainline traffic flow on the risk of rear-end collision of vehicles at different penetration rates.

The degree of speed dispersion is an important index to characterize the unsteady traffic flow, and is widely used to assess the overall safety of the entire traffic flow, which is calculated as follows:

$$SD=\sqrt{\frac{\sum_{i=1}^{n}(v_i-\overline{v})^2}{n-1}} \tag{8}$$

Where v_i is the speed of the vehicle i, m/s; $\overline{v}$ and n are the average speed and total number of the traffic flow. Usually the larger the degree of speed dispersion, the more complex the traffic environment, the more unstable the traffic flow, and the lower the safety.

Time-to-collision (TTC) represents the remaining time before a rear-end collision occurs with the front vehicle maintaining the current speed difference with the rear vehicle, whose TTC for the vehicle n at time t is calculated as follows:

$$TTC_{\mathrm{n}}(t)=\frac{\Delta \mathrm{x}_{\mathrm{n}}(\mathrm{t})\text{-}\mathrm{L}}{\Delta v_{\mathrm{n}}(\mathrm{t})} \tag{9}$$

Further, based on TTC, considering the length of time that the vehicle is at risk of collision, the time exposed time-to-collision (TET) and time integrated time-to-collision (TIT) are proposed for safety evaluation based on the extended evaluation indexes of TTC. See equations 10 and 11 for calculations.

$$TET=\sum_{n=1}^{N}\sum_{t=0}^{T}\delta_n(t)\Delta t, \qquad \delta_n(t)=\begin{cases}1, & 0<TTC_n(t)<TTC^* \\ 0, & else\end{cases} \tag{10}$$

$$TIT=\sum_{n=1}^{N}\sum_{t=0}^{T}\left[TTC^*-TTC_n(t)\right]\Delta t, \qquad 0<TTC_n(t)<TTC^* \tag{11}$$

Where, $\Delta x_n(t)$ is the vehicle gap between the vehicle n and the front vehicle, $\Delta v_n(t)$ is the speed difference between the vehicle n and the front vehicle, T is the total number of simulation steps, N is the total number of vehicles, Δt is the simulation step, TTC^* is the time-to-collision threshold, generally taken as 1~3 s. Rear-end collisions can occur only when the rear vehicle speed is greater than the front vehicle speed, and the TTC, TET, and TIT indicators are valid. The larger the extended safety indicator, the higher the risk of collision.

The safety of ramp convergence on mainline heterogeneous traffic flow under different CAV penetration rates is analyzed from four aspects: SD, TTC, TET, and TIT. The upstream traffic demand of the mainline is set to be 3500 veh·h^{-1}.

After obtaining the microsimulation data, the SD values of speed under different CAV penetration rates were calculated, as shown in Table 2. It is obvious that with the increasing CAV penetration rate, SD has a significant decreasing trend. Before $p<0.6$, the change of SD was slight, decreasing from 5.72 to 4.37, with a reduction ratio of 23.6%. When $p>0.6$, SD decreases significantly, and when the proportion of CAV is 1, SD is 1.34, which is 76.6% lower than that when $p=0$. It indicates that under the influence of ramp converging vehicles, the mainline mixed traffic flow has a larger degree of speed dispersion between vehicles when the penetration rate is low, and the traffic flow stability is insufficient, implying that the overall safety is lower. However, as the penetration rate continues to increase, the communication advantage between CAVs can be fully exploited, the collaboration between the vehicles is more consistent, the speed disparity is reduced, and increasing the proportion of CAV can effectively improve the safety of the mainline traffic flow.

Table 2. SD at different penetration rates

Penetration rate	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
SD	5.72	5.21	4.81	4.74	4.68	4.34	4.37	3.86	2.01	1.57	1.40

Further, under the same conditions, the frequency of TTC less than 10s for mainline traffic flow under different penetration rates is counted and the distribution is shown in Figure 3. The frequency of TTC less than 10s decreases with the increase of penetration rate, which implies that the risk of rear-end collision between vehicles under a high penetration rate is lower. This is due to the shorter information transmission reaction time and precise vehicle control of CAVs, which allows vehicles to accurately grasp the operating environment to adjust their speed. Meanwhile, a comparative analysis of the overall TTC less than 10s shows that when the penetration rate is 1, it reduces by 85.1% compared to that when $p=0$, indicating that the speed between vehicles with high penetration rate gradually converges.

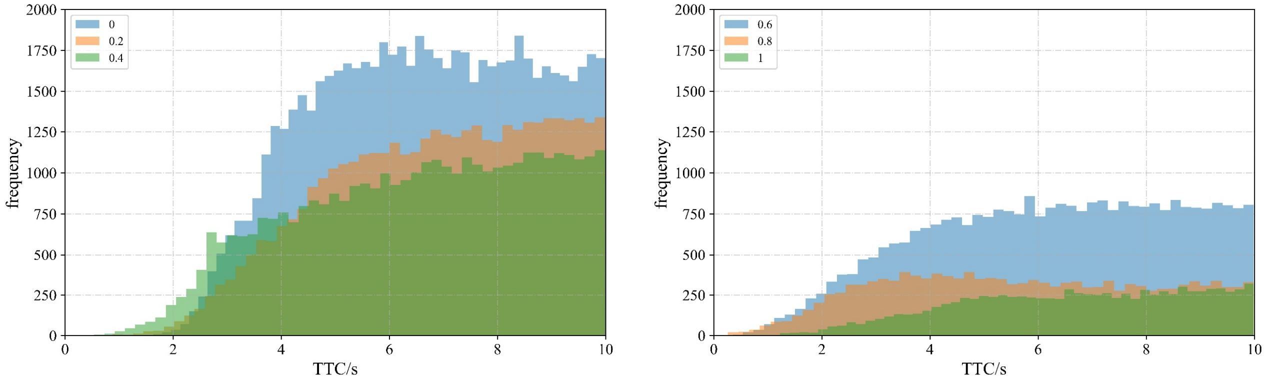

Figure 3. TTC frequency distribution figure

The formulas for TET and TIT indicate that the TET metric describes the time exposed time-to-collision safety hazard as a whole, while the TIT metric further takes into account the severity of the rear-end collision safety hazard at the time of occurrence by means of the threshold TTC*. The time-to-collision threshold indicates the acceptable level of the rear-end collision risk, which is usually taken as 1~3s. Therefore, in this paper, the threshold TTC* of 1s, 2s, and 3s are selected to analyze the effects of different penetration rates on the TET and TIT safety indicators of the main expressway, as shown in Figure 4. The TET and TIT values for the thresholds of 2s and 1s are synchronously enlarged by 2 and 10 times, respectively.

Analyzing Figure 4, it can be seen that both TET and TIT show a trend of first increasing and then decreasing with the increase of CAV penetration rate, and both reach the peak at $p=0.7$. It shows that the risk of mainline rear-end collision is the largest, and the value of TTC* threshold does not affect the trend of TET and TIT with penetration rate. Meanwhile, when $p<0.3$, the increase of penetration rate does not have a significant change on TET and TIT. However, when p=1 and TTC*=3s, TET is reduced by 70.1% and TIT by 42.6% compared to $p=0$, indicating that the traffic flow consisting entirely of CAV has a significantly lower collision risk compared to the HV traffic flow.

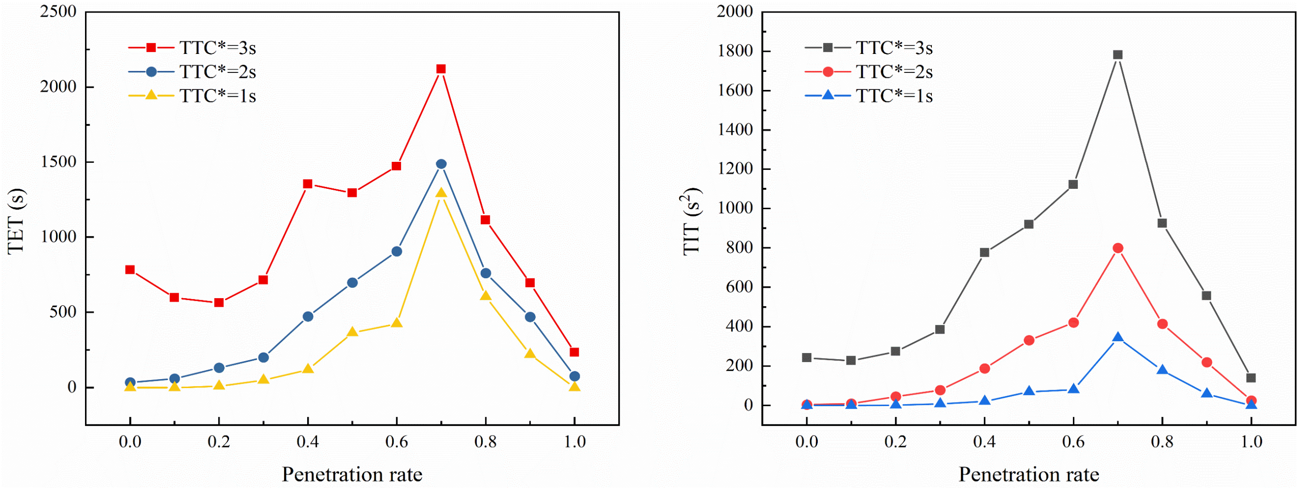

Figure 4. TET and TIT at different penetration rates, (a) TET (b) TIT

When the penetration rate takes the lower value, HV, DCAV, and CAV are randomly distributed in the mainline. This leads to the fact that the HV, which accounts for a larger proportion of the traffic flow, is interfered by the two streams of DCAV and CAV under conditions of relatively slow reaction and rough speed control, resulting in a more serious problem of safety in the mainline. Meanwhile, as the platooning intensity takes the value of 0, the probability of CAV degradation to DCAV is higher. With the interference of on-ramp traffic, it makes the safety problem more prominent. However, from the frequency distribution figure for TTC<10s, the overall safety is reduced, indicating that low penetration rate aggravates the risk of collision between vehicles with smaller time headway, but greatly reduces the probability of conflict between vehicles with larger time headway. After $p > 0.7$, CAV becomes the main body of vehicles with the highest proportion in the mixed traffic flow. CAV can better utilize the advantages of intelligent network connection, perceive the operating status of the front vehicle in advance, and maintain a stable and sensitive spacing and speed with the front vehicle, which makes the risk of rear-end collision continue to decrease as the penetration rate continues to increase.

4.3 Traffic flow fuel consumption and emission analysis

Based on the vehicle trajectory data in the simulation experiments, the fuel consumption and emission content are calculated for each update step in the collection time to investigate the effect of CAV penetration rate on CO, CO_2, HC, NO_X, PM_X, and fuel consumption of the mainline traffic flow of the expressway. The variation of percentage reduction of CO, CO_2, HC, NO_X, PM_X, and fuel consumption with penetration rate compared to $p = 0$ is shown in Figure 5.

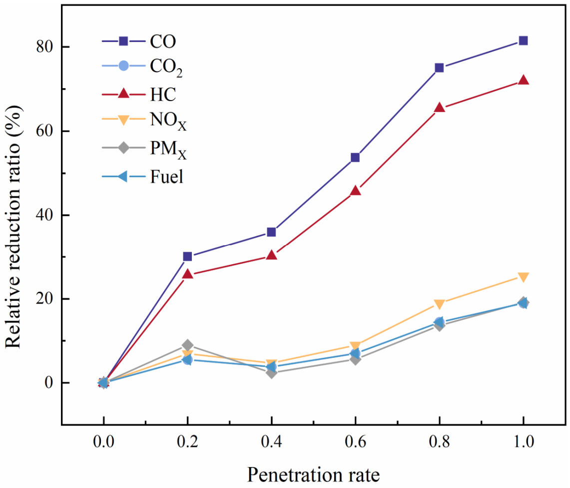

Figure 5. Fuel consumption and emission content

The results of the simulation data show that the increase in CAV penetration rate contributes to the reduction of fuel and pollutant emissions. Among them, CO and HC showed the most significant percentage reduction, which was 81.46% and 71.88%, respectively, when $p=1$. The other emissions did not change much with increasing penetration rate, but still decrease by 18.98%, 25.4%, and 19.2% respectively when the penetration rate is increased to 1. Meanwhile, fuel consumption also shows a smooth decreasing trend with the increase of penetration rate, and when the penetration rate reaches 1, the overall fuel consumption of the mainline traffic flow decreases by 18.9%. Most of the existing models on emissions and fuel are calculated using factors closely related to speed and acceleration, which side by side indicates that CAVs have better driving ecology and at the same time, their speed and acceleration also have better smoothness.

5. CONCLUSION

In this paper, different driving behaviours of HV, DCAV, and CAV are constructed using IDM, ACC, and CACC car-following models, respectively, and the dynamic characteristics of different penetration rates on the mainline mixed traffic flow under ramp merging disturbances are analyzed by taking into account the platooning intensity. The simulation results demonstrate that an increase in penetration rate has a positive impact on the operational efficiency, fuel consumption, and exhaust emissions of the mainline traffic flow. In addition, the operational efficiency of the free flow is more sensitive to changes in penetration rate compared to the congested flow. Furthermore, it can be clearly observed that the overall safety and stability of the mainline traffic flow are improved. However, when the penetration rate is 0.7 and the threshold $TTC^* < 3$, both TET and TIT peak, and the local safety deterioration on the mainline is the most serious. In this paper, other disturbing factors such as large vehicles and vehicle formation lengths were not considered when investigating the dynamic characteristics of the mixed traffic flow, which can be further explored in the future.

REFERENCES

[1] Davis L. Effect of adaptive cruise control systems on mixed traffic flow near an on-ramp[J]. Physica A: Statistical Mechanics and its Applications,2006,379(1).

[2] Zheng F,Liu C,Liu X, et al. Analyzing the impact of automated vehicles on uncertainty and stability of the mixed traffic flow[J]. Transportation Research Part C,2020,112.

[3] M.Arnaout G,Bowling S.A Progressive Deployment Strategy for Cooperative Adaptive Cruise Control to Improve Trafc Dynamics[J].International Journal of Automation and Computing,2014,11(01):10-18.

[4] Zhu H,Zhou Y,Wu W. Modeling traffic flow mixed with automated vehicles considering drivers ' character difference[J]. Physica A: Statistical Mechanics and its Applications,2020,549(prepublish).

[5] Letter C,Elefteriadou L. Efficient control of fully automated connected vehicles at freeway merge segments[J]. Transportation Research Part C,2017,80.

[6] Yao Z,Hu R,Jiang Y, et al. Stability and safety evaluation of mixed traffic flow with connected automated vehicles on expressways[J]. Journal of Safety Research,2020,75(prepublish).

[7] Ramin A,J. A K,Mohsen K, et al. Safety evaluation of connected and automated vehicles in mixed traffic with conventional vehicles at intersections[J]. Journal of Intelligent Transportation Systems,2020,25(2).

[8] Anshuman S,Zuduo Z,Jiwon K, et al. Assessing traffic disturbance, efficiency, and safety of the mixed traffic flow of connected vehicles and traditional vehicles by considering human factors[J]. Transportation Research Part C,2021,124.

[9] Stogios C,Kasraian D,Roorda J M, et al. Simulating impacts of automated driving behavior and traffic conditions on vehicle emissions[J]. Transportation Research Part D,2019,76(C).

[10] Stern E R,Chen Y,Churchill M, et al. Quantifying air quality benefits resulting from few autonomous vehicles stabilizing traffic[J]. Transportation Research Part D,2019,67.

[11] Martin T,Ansgar H,Dirk H. Congested traffic states in empirical observations and microscopic simulations[J]. Physical Review E,2000,62(2).

[12] Bose A,Ioannou P. Mixed manual/semi-automated traffic: a macroscopic analysis[J]. Transportation Research Part C,2002,11(6).

[13] Ghiasi A,Hussain O,Qian (Z, et al. A mixed traffic capacity analysis and lane management model for connected automated vehicles: A Markov chain method[J]. Transportation Research Part B,2017,106.