Simulation modeling and safety analysis of the mixed traffic flow with connected automated trucks platoon and human-driven vehicles

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Abstract. The rapid development of intelligent connected vehicles makes it possible to achieve breakthroughs in the application of technology in the connected automated trucks platoon(CATP) in the scenarios of ports, logistics parks, etc., but the safety of the mixed traffic flow formed by it and traditional human-driven vehicles has not been fully recognized. This paper builds a simulation scene based on SUMO(Simulation of Urban Mobility) simulation software, builds traditional human-driven vehicles and CATP car-following model, and studies the safety analysis of the mixed traffic flow of CATP and human-driven vehicles. According to the Traci interface of SUMO and PYTHON programming language, the functions of connected automated environment configuration and real-time data acquisition are realized, and the safety of mixed traffic flow is evaluated using multiple safety surrogate measures(SSM) such as time exposed time-to-collision(TET) and time-integrated time-to-collision(TIT). The simulation results show that when the CATP penetration rate is less than 0.5, the security risk of mixed traffic flow increases with the increase of penetration rate; When the CATP penetration rate exceeds 0.5, the safety risk of mixed traffic flow will be significantly reduced. The research conclusion of this paper has reference significance for the safety and practical implementation of CATP in ports and logistics parks.

Keywords: connected automated vehicles, truck platoon, SUMO simulation, safety surrogate measures, port logistics park.

1. Introduction

In recent years, with the continuous promotion of a new round of scientific and technological revolution represented by artificial intelligence and information and communication technology, the automobile, as one of the important carriers of the integrated application of new technologies, is accelerating its transformation to the direction of intellectualization and networking, and the connected automated automobile has also become the latest strategic direction and competitive focus of the development of the global automobile industry. However, it will take a long time to go from traditional driver-car to 100% connected automated[1], and most of the current landing vehicles are L1-L2 and other low-level automatic driving vehicles. Therefore, in the foreseeable future for a long period, connected automated vehicles will coexist with traditional human-driven vehicles in the road traffic system in a way of mixed traffic flow.

Since the 21st century, global car ownership has continued to grow, which has gradually brought a series of social problems such as rising accident rates, traffic congestion, and environmental pollution. In the connected automated environment such as ports and logistics parks, CATP(Connected Automated Trucks Platoon) mode is expected to effectively improve road traffic capacity, reduce traffic accidents and reduce fuel consumption and exhaust emissions, and bringing energy conservation and environmental protection benefits while improving road traffic safety.

At present, scholars domestic and abroad have carried out in-depth research on CATP and achieved certain results. Nieuwenhuijze [2] described the implementation and test of the Cooperative Adaptive Cruise Control(CACC)heavy truck control strategy; and verified the stability of the traffic flow mixed with the CACC truck. Yang [3] focused on the impact of the large-scale truck platoon on Dutch roads. It applies microscopic modeling to study the impact of large-scale connected automated CACC truck platoons on key traffic locations such as intersections. The results show that compared with the current situation, the large-scale truck platoon has a positive impact on the traffic safety and efficiency of Dutch roads. Zhou and Zhu [4] revealed the impact of platoon number on road capacity and traffic flow stability, and the results showed that a larger scale of platoon helps to improve traffic capacity. However, with the increase in the size of the platoon, the amount of increase becomes smaller. For traffic flow stability analysis, the smaller the platoon size, the better the traffic flow stability.

In the field of connected automated safety, Xing [5] studied the safety impact of Adaptive Cruise Control(ACC) parameter setting and CACC system on the risk of rear-end collision on the expressway time exposed time-to-collision(TET) and time-integrated time-to-collision(TIT) are used to measure safety under different penetration rates. The simulation results show that with the increase in the penetration rate of ACC or CACC vehicles, the rear-end collision risk of vehicles on the expressway can be effectively reduced. Tu [6] used the collision time index to quantify the rear-end collision risk of the vehicle under three different driving conditions. In addition, sensitivity analysis of key parameters such as deceleration frequency, number of degraded vehicles and time to collision(TTC) threshold is also carried out. Research shows that when the current vehicle decelerates suddenly, the performance degradation of CACC vehicles will significantly increase the risk of collision. REICH [7] carries out system construction for the solution to the problem of collision avoidance based on the safe distance of truck platoon, deduces and analyzes the theoretical model of the failure of the collision avoidance system, and establishes the comprehensive simulation model of driver, truck, environment, and platoon system through Simulink. In the research of SUMO simulation mixed traffic flow, Song et al. [8] studied the impact of connected automated vehicles controlled by three control modes (intelligent driver model (IDM), ACC, and CACC) on the safety of mixed traffic flow under different market penetration conditions.

In general, the academic community has made some progress in the research on the CATP, mainly focusing on the platoon control strategy and method, driving control test, etc., but the research on the safety of the mixed traffic flow of CATP and traditional people driving cars is still few. Given the characteristics of large inertia caused by large body weight, the consequences of truck accidents are often more serious than car accidents, and the harm to human life and property safety is also greater. Therefore, it is important to evaluate the safety of the mixed traffic flow formed by CATP and traditional people driving cars before the CATP is put into use and at the beginning of the operation process.

In addition to a few research teams with real vehicle and site conditions, the current research methods for the safety of mixed traffic flow in the CATP are mainly simulation research; The simulation methods include numerical simulation and methods based on the simulation software platform. SUMO simulation software can simulate the simulation scene more realistically, have a more intuitive understanding and understanding of the simulation results, and facilitate a more comprehensive analysis of the results later. Therefore, this paper is mainly based on the SUMO simulation platform software, and combined with PYTHON programming development, to study the safety of the mixed traffic flow composed of intelligent connected trucks and human-driven vehicles.

In the second part of this paper, the human-driven vehicles and CATP car-following model are constructed, and the safety evaluation indicators are introduced. The third part introduces the SUMO and PYTHON joint simulation platform, simulates the simulation scene, and draws the space-time map of the vehicle after the simulation. The fourth part calculates each safety index to analyze the safety. The fifth part is the sensitivity analysis of changing the parameters of the car-following model, TTC threshold, and platoon length. The sixth part is the summary.

2. Model

2.1 Car-following model

IDM [9] is widely used in the research of automatic driving simulation of connected automation. The driving control of the CATP mainly adopts the CACC mode, which interacts with adjacent vehicles through wireless communication, including speed, position, acceleration, and deceleration.

With the help of intelligent Internet V2V communication technology, the following car of CATP can obtain the motion parameters of the car in front of it in real-time, and use this as part of the input to complete the driving actions of its own, such as car-following, lane changing, etc. through calculation. When the leader truck of CATP follows the human-driven vehicle(HDV), because the HDV does not have the communication function, the lead truck of CATP cannot obtain the accurate driving parameter information of the vehicle in front, but can only be detected by on-board radar and other methods, so the CACC mode is degraded to ACC mode. In this study, the lead truck of CATP is an ACC truck, while the following truck is a CACC truck.

Due to the significant differences between truck and car in vehicle function and mass, wheelbase, field of vision, (acceleration) speed, and other design parameters, there are significant differences in the parameter values of the car-following model between the intelligent connected truck and the intelligent connected bus. For CACC trucks, drivers prefer 1.2 to 1.5 seconds as the time interval. Here, CACC truck t_c=1.5s [10]. Table 1 are the main differences between connected automated vehicles and connected automated trucks' car-following model parameters.

Table 1. Parameter Values of Cacc/Acc Human-Driven Vehicles and Cacc/Acc Trucks

	CACC/ACC car	**CACC/ACC truck**
reaction time t_c/t_a	0.6/1.1	1.5/3.1
Vehicle commander l	5	15
Speed v	120	80

To accurately capture the interaction between adjacent vehicles during driving, this study uses the car-following model to describe the characteristics of car-following. Because higher-level connected automated trucks such as L3 have not yet been commercialized on a large scale, most studies have adopted IDM because it can more accurately describe the car-following characteristics of vehicles than other models. However, IDM cannot fully capture the following characteristics of ACC and CACC trucks. To capture the car-following characteristics of CATP, PATH laboratory proposed ACC and CACC models based on real experiments. Therefore, IDM is used to reflect the following behavior of HDV, and ACC and CACC models are used to describe the following characteristics of ACC and CACC trucks respectively.

1) Human-driven vehicles[11]

Considering the acceleration trend in the free state and the deceleration trend of the vehicle approaching the front, Treiber et al. (2000) proposed the Intelligent Driver Model (IDM) to capture the following characteristics of HDV, whose definition is shown in (1).

$$\dot{v} = a[1 - (\frac{v}{v_f})^4 - (\frac{S^*(v,\ \Delta v)}{s})^2] \tag{1}$$

Where a is the maximum acceleration of 1m/s-2; S^* represents the expected distance between two vehicles; v_f refers to the free flow rate of 33.3m/s; s Actual distance between two vehicles; Δv is the speed difference between adjacent vehicles.

2) Connected automated trucks

Path Lab calibrated the parameters of connected automated vehicles' car-following model through real vehicle tests (Milan é s&Shladover, 2014) [11]. Therefore, this study uses ACC and CACC car-following models to capture the characteristics of ACC and CACC trucks in mixed traffic flow.

a) ACC model[12]

$$\dot{v} = k_1(\Delta x - l - s_0 - t_a v) + k_2 \Delta v \tag{2}$$

Where k_1 and k_2 is the control parameter of 0.23s-2 and 0.07s-1; Δx represents the space interval; l is the vehicle length, set at 15m; t_a is the expected constant time interval of ACC trucks.

b) CACC model[12]

$$\begin{cases} v = v_p + k_p e + k_d \dot{e} \\ e = \Delta x - l - s_0 - t_c v \end{cases} \tag{3}$$

Where, v_p is the speed of the target vehicle at the previous control time; e is the error between the actual clearance distance and the expected clearance distance, and its derivative form is $\dot{e}$; t_c is the expected headway; k_p and k_d is the control parameter of 0.45 and 0.25 respectively.

2.2 Safety surrogate measures

To evaluate the safety of mixed traffic flow, TTC(time to collision), TET, and TIT are selected for safety analysis in this study.

1) TTC

TTC indicates the time required for vehicles occupying the same lane to collide if two consecutive vehicles are traveling at the current speed when the vehicle is traveling faster than the vehicle in front. The smaller the TTC is, the more dangerous the traffic is. The larger the TTC is, the safer the traffic is[11]

$$TTC_i(k) = \begin{cases} \frac{x_{i-1}(k) - x_i(k) - L_{i-1}}{v_i(k) - v_{i-1}(k)}, if\ v_i(k) > v_{i-1}(k) \\ \infty, if\ \ v_i(k) \le v_{i-1}(k) \end{cases} \tag{4}$$

2) TET

TET is the sum of all moments when the driver approaches the vehicle ahead when the TTC value is lower than the critical threshold. Therefore, a lower TET value indicates a safer situation[11]

$$\mathrm{TET}(k) = \sum_{i=1}^{n} \delta_k \cdot \Delta k, \delta_k = \begin{cases} 1\ \forall 0 < TTC_i(k) \le TTC^* \\ 0 \quad else \end{cases} \tag{5}$$

$$\mathrm{TET} = \sum_{k=1}^{T} TET(k) \tag{6}$$

3) TIT

The TTC entity below the threshold is calculated by TIT, which allows indicating the severity related to the safety-critical situation. The bigger the TIT, the more dangerous the situation is[11]

$$\mathrm{TIT}(k) = \sum_{i=1}^{n} [TTC_i(t) - TTC^*] \cdot \Delta k, \forall 0 < TTC_i(t) \le TTC^* \tag{7}$$

3. Simulation Experiment

The joint simulation platform of SUMO and PYTHON is mainly used in this paper. In SUMO, the simulation scene is mainly built, including a straight single lane and a single lane with two ramps, and the number of cars, departure time, maximum speed, and vehicle shape parameters are set. Through the TRACI interface provided by SUMO, not only the speed, acceleration, number, and others in the platoon of the car can be obtained in PYTHON, but also the platoon of the car in front of the car. SUMO is an open-source traffic simulation software that can complete the tasks of building simulation scenes and generating cars; PYTHON is mainly the upper control. The algorithm is completed in PYTHON and the simulation results are visualized; As an interface of SUMO software, TRACI connects PYTHON and SUMO.

3.1 Build a simulation scene

This paper does not consider lane change behavior. To facilitate the study of the safety of mixed traffic flow, a section of single-lane road with a total length of 8.5 km is built based on SUMO software, and the entrance and exit ramps are set at 4 km and 4.5 km, in which the speed limit of the entrance and exit ramp area is 40 km/h. In the simulation test, 100 vehicles are randomly generated according to the penetration rates of CATP. By judging the type of vehicles in front, we can determine whether the vehicles in the rear will degenerate into ACC trucks. The simulation step is 1s. Fig. 1 is a schematic diagram of the road in the simulation scenario.

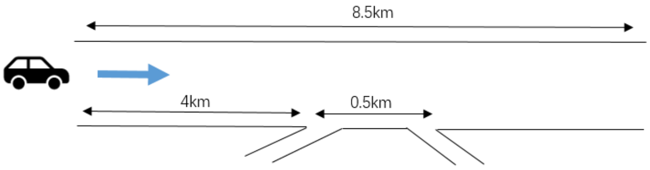


Figure 1. Schematic diagram of simulated road

To facilitate the display of the results and simplify the conditions, this paper sets the platoon form as a small platoon of three trucks of the same type. Trucks in the platoon are marked as 1, 2, and 3 from the beginning to the end in sequence. Truck 1 is the first truck. Three types of vehicles (HDV, CACC truck, and ACC truck) are set in the rou file in SUMO. Fig.2 is the schematic diagram of the mix of the CATP and HDV. It can be seen that the gap between the traditional manned trucks is large, while the CATP is small, which greatly improves the traffic capacity of the road.

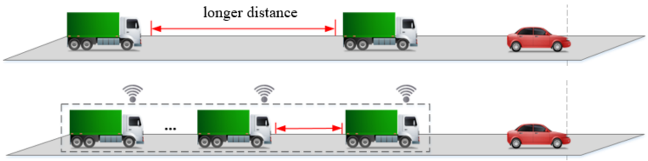
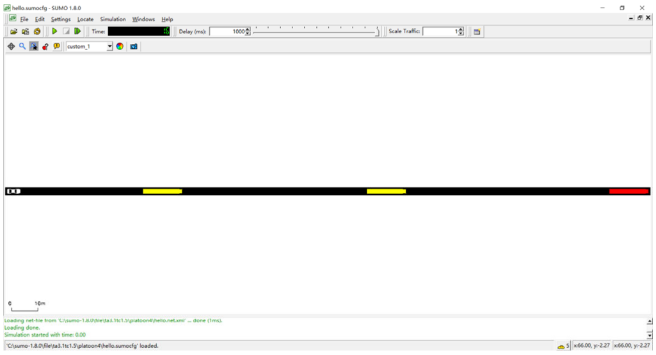


Figure 2. Schematic diagram of the simulation scene

Fig.3 is a screenshot of the simulation scene in SUMO after building the simulation scene. The white vehicle is HDV, the red truck is an ACC truck, and the yellow truck is a CACC truck.



Delay (ms): 1000

Scale Traffic: 1

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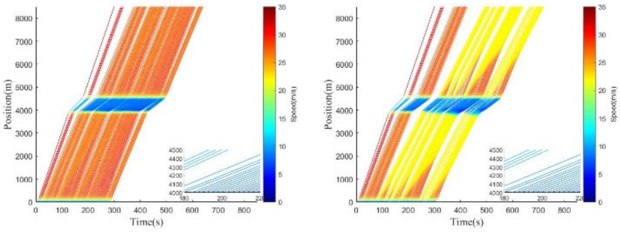
Loading net-file from 'C:\sumo-1.8.0\file\ta3.1tc1.5\platoon4\hello.net.xml' ... done (1ms).
Loading done.
Simulation started with time: 0.00
'C:\sumo-1.8.0\file\ta3.1tc1.5\platoon4\hello.sumocfg' loaded.
```

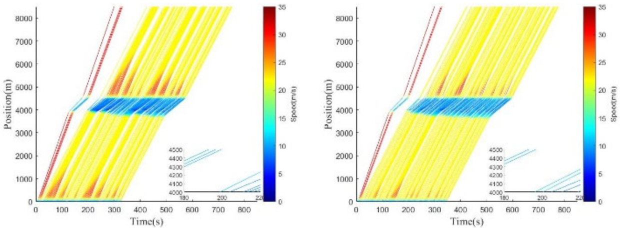
Figure 3. SUMO simulation scene

3.2 Output of track data

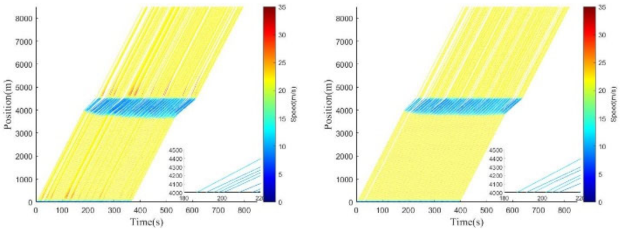
After the simulation of SUMO software is completed, each data of the simulation can be output. Fig.4 shows the space-time trajectory, the abscissa axis represents time, the ordinate axis represents position, and the color represents speed. It describes the mixed traffic of vehicle trajectory flow of CATP at 0%, 20%, 40%, 60%, 80%, and 100% penetration rates respectively.



(a)P=0 (b)P=0.2



(c)P=0.4 (d)P=0.6



(e)P=0.8 (f)P=1.0

Figure 4. The Vehicle trajectory of mixed traffic flow under different penetration rates of CATPs

When P=0, that is, when there are only human-driven vehicles on the road, the speed is distributed within the speed limit of 33.3m/s for human-driven vehicles. With the increase of CATP penetration rates, the speed of vehicles is closer to the speed limit of 22.2m/s for freight cars. Until P=1, the speed is completely within the speed limit. With the increase in penetration rates, the speed of vehicles is also more and more uniform. When P=0 and P=1, the trajectory is relatively uniform and smooth, and the stability of homogeneous traffic flow is better. With the increase in CATP penetration rates, the trajectory is also more uniform.

4. Safety analysis

4.1 Calculation of each safety evaluation index

In the simulation experiment, t_a=3.1s, t_c=1.5s as an example. Based on the output of trajectory data, the safety substitution metric TTC can be calculated according to the above (4). Because the mass of human-driven vehicles and trucks is different, the braking capacity is also different, so the TTC threshold setting varies from 1 second to 3 seconds [11].

When P=0, there are only human-driven vehicles on the road, so the TTC threshold is set to 1.5s; When P is not equal to 0, that is, when trucks appear on the road, the TTC threshold becomes 3s. According to the TTC scatter distribution in Figure 4, with the increase of P, the number of times when the TTC is below the threshold will increase, and the traffic conditions will become more dangerous. When P=0 and P=1, there are only buses or trucks on the road, which is a homogeneous traffic flow. There is no TTC less than 1.5s, which means the most stable and the best traffic conditions.

1) TET

TET is the sum of all moments when the driver approaches the vehicle ahead when the TTC value is lower than the critical threshold. Therefore, a lower TET value indicates a safer situation. The value of TET can be calculated according to the value of TTC. Fig.5 describes the mixed traffic flow of TET of CATP at 0%, 20%, 40%, 60%, 80%, and 100% penetration rates respectively.

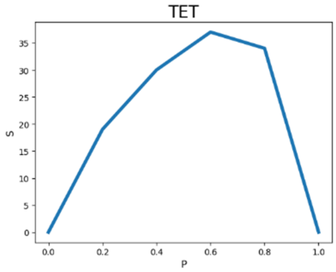


Figure 5. The TET of mixed traffic flow under different penetration rates of CATPs

2) TIT

TIT is a TTC entity that calculates below the threshold and allows it to represent the severity related to safety-critical situations. The bigger the TIT, the more dangerous the situation is. The value of TIT can be calculated according to the value of TTC. Fig.6 describes the mixed traffic flow of TIT of CATP at 0%, 20%, 40%, 60%, 80%, and 100% penetration rates respectively.

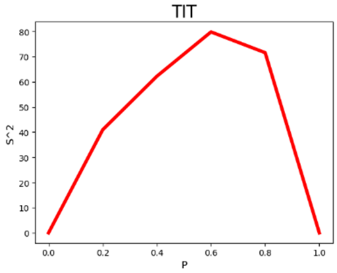


Figure 6. The TIT of mixed traffic flow under different penetration rates of CATPs

Table 2. The mixed traffic flow of Percentage reduction of safety indicators under different penetration rates of CATPs

P	TET	TIT
0	-	-
0.2	51.4	51.3
0.4	29.7	26.6
0.6	18.9	22.1
0.8	-8.1	-10.3
1.0	-91.9	-89.7

4.2 Analysis

From Fig.5 and Fig.6, we can see the changing trend of the two safety indicators under different CATPs penetration rates. It can be seen that when the CATP is added to the traffic flow, the leader of CATP will degenerate into ACC trucks due to the following HDV. The increase of ACC trucks will lead to the deterioration of TET and TIT, which will increase the traffic flow safety risk. Table 3 shows the percentage reduction of safety indicators of CATP and HDV mixed traffic flow under different penetration rates of CATP. When P=0.2 and 0.4, TET and TIT increase significantly. When P=0.6, the growth rate of TET and TIT slows down and then decreases after P=0.6.

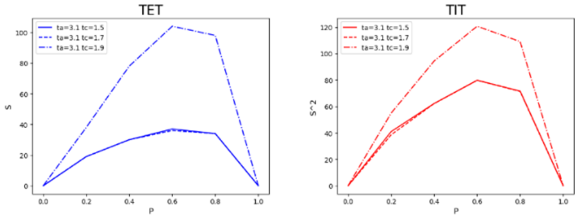
At the same time, the CATP has significant safety benefits for mixed traffic flow. With the gradual increase of the penetration rate of the CATP, the increase of CACC trucks will reduce the traffic flow safety risk, especially after P=0.6. Because when P exceeds 0.5, CACC trucks in the traffic flow reach a certain penetration rate.

5. Sensitivity Analysis

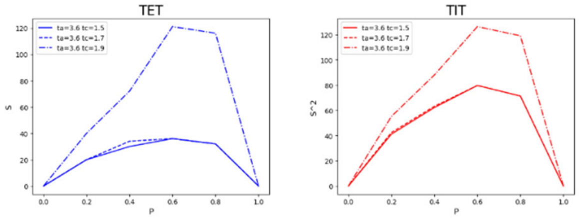
Many factors affect the safety evaluation of mixed traffic flow. This section analyzes the sensitivity of car-following model parameters, TTC threshold (TTC*), and platoon length.

5.1 Parameter sensitivity analysis of car-following model

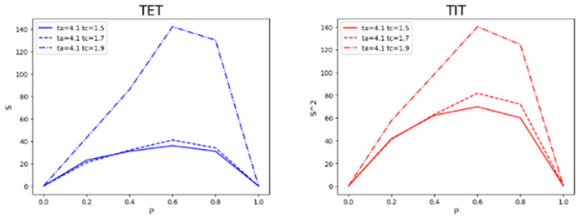
The different parameters of the car-following model will affect the safety of mixed traffic flow. Therefore, this section carries out sensitivity analysis on ACC (t_a) and CACC (t_c) parameters. The simulation results are shown in Fig.7.



(a) ta=3.1s,tc=1.5s-1.9s



(b) ta=3.6s,tc=1.5s-1.9



(c) ta=4.1s,tc=1.5s-1.9s

Figure 7. TET and TIT of different car-following model parameters

From Figure 7 (a), (b), and (c), it can be seen that:

With t_c within 0.6~1.1 s, with t_a increase in the range of 3.1 to 4.1s, the peak value of TET and TIT will increase no matter in horizontal or vertical comparison;

When ta is unchanged when t_c increases from 1.5s to 1.7s, the traffic flow safety risk changes little, when t_c increases to 1.9s, the traffic flow safety risk increases significantly;

t_a unchanged, The increase of t_c will be greater than that of t_c unchanged, and the increase of t_a will have a greater and more obvious impact on traffic flow safety.

Therefore, these results show that compared with the increase of t_a, the increase of with t_c will have a greater impact on the traffic flow safety risk; Nevertheless, in general, the smaller the t_a and t_c, the lower the traffic safety risk.

5.2 TTC threshold sensitivity analysis

Considering the impact of TTC*, the values of TTC* are 2s, 2.5s, and 3s respectively. Set the parameter of CATP to t_a =3.1s, t_c =1.5s.

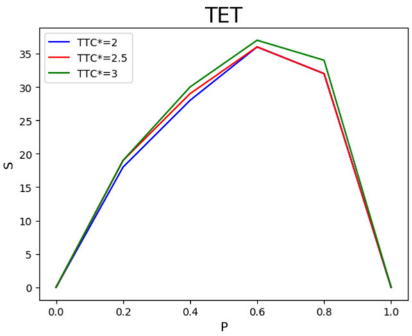


Figure 8. The TET of CATP with different TTC thresholds

As can be seen from Figure 9, taking TET as an example, it starts to show a trend of improvement and then decline, but the change degree of each indicator is the same under different thresholds (TTC*), and the overall trend is also the same. Therefore, different thresholds have little impact on traffic flow safety evaluation.

5.3 Sensitivity analysis of platoon length

To study the impact of platoon length on traffic safety risk, the platoon length is taken as 2, 3, 4, and 5 vehicles respectively. Set the parameter of CATP to t_a =3.1s, t_c =1.5s. To reduce the error, we will do many experiments and take the mean value for display.

Table 3. TET with different platoon length CATP

P	**n=2**	**n=3**	**n=4**	**n=2**
	TET	TET	TET	TET
0	0	0	0	0
0.2	38	19	15	12
0.4	41	30	27	22
0.6	52	37	30	28
0.8	34	34	29	25
1.0	0	0	0	0

Table 4. TIT with different platoon length CATP

P	**n=2**	**n=3**	**n=4**	**n=2**
	TIT	TIT	TIT	TIT
0	0	0	0	0
0.2	65	40.93	26.2	24.4
0.4	89.2	62.18	58.9	44.7
0.6	116.4	79.78	60.1	59.7
0.8	77	71.54	54	55.8
1.0	0	0	0	0

It can be seen from Table 3 and Table 4 that with the increase in platoon length, the values of TET and TIT will gradually decrease, which will reduce the traffic safety risk. Because under the same penetration rate of CATP, the longer the platoon length is, the more CACC trucks are, and the lower the traffic safety risk will be, which is consistent with the conclusions drawn in the previous section.

6. Conclusion

This paper builds a simulation scene based on SUMO simulation software and builds a car-following model of CATP. According to the Traci interface of SUMO and PYTHON programming language, the functions of connected automated environment configuration and real-time data acquisition are realized, and then the safety of mixed traffic flow is evaluated using multiple safety indicators such as time exposure collision time and comprehensive collision time. It is also considered that if the leader of the CATP is following HDV, it will degenerate into an ACC truck, and the following vehicle will still be a CACC truck. Based on the simulation experiment and sensitivity analysis, the following conclusions can be drawn:

When the CATP is added to the traffic flow, the CACC trucks will degenerate into ACC trucks due to the following vehicles. The increase of ACC trucks will lead to the deterioration of TET and TIT, which will increase the traffic flow safety risk. According to the graph of percentage reduction of safety indicators under different penetration rates, when P=0.2 and 0.4, TET and TIT increase significantly, when P=0.6, the growth rate of TET and TIT slows down and then decreases after P=0.6. At the same time, the CATP has significant safety benefits for mixed traffic flow. With the gradual increase of the penetration rate of the CATP, the increase of CACC trucks will reduce the traffic flow safety risk, especially after P=0.6.

In terms of sensitivity analysis, when the parameters of the car-following model are changed, the increase of t_a and t_c will lead to the increase of peak value of TET and TIT. The smaller the t_a and t_c, the lower the traffic flow safety risk; When t_a is unchanged, When t_c increases from 1.5s to 1.7s, the traffic flow safety risk changes little, when t_c increases to 1.9s, the traffic flow safety risk increase significantly; t_a unchanged, The increase of t_c will be greater than that of t_c unchanged, The increase of t_a will have a greater and more obvious impact on traffic flow safety. Therefore, these results show that compared with the increase of t_a, the increase of t_c will have a greater impact on the traffic flow safety risk; Nevertheless, on the whole, t_a and the smaller the t_c, the lower the traffic safety risk.

When the TTC threshold is changed, the change degree of each safety index under different thresholds is the same and the overall trend is the same. Therefore, different TTC thresholds have little impact on traffic flow safety risk.

With the increase in platoon length, the values of TET and TIT will gradually decrease, which will reduce the traffic safety risk. Because under the same penetration rate of CATP, the longer the platoon length is, the more CACC trucks will account for, and the lower the traffic safety risk will be. This is consistent with the previous conclusions. Of course, the platoon length is not arbitrarily set and will be affected by the efficiency of cargo transportation, energy conservation, emission reduction, road conditions, and other factors. Considering these factors, this paper studies the platoon length of 3.

In this paper, the SUMO simulation software is used to build the simulation scene and the car-following model of the CATP. According to the Traci interface of SUMO and PYTHON programming language to realize the functions of connected automated environment configuration and real-time data acquisition, to study the safety of the mixed traffic flow of CATP and human-driven vehicles. In practical application, it has reference significance for the safety and practical implementation of CATP in ports and logistics parks. However, this paper only studies the safety of single-lane car-following in the mixed traffic flow with the CATP. In the future, the lane change mechanism will be added to analyze the safety of the multi-lane scene.

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