



Human-like car-following model for autonomous vehicles considering the cut-in behavior of other vehicles in mixed traffic

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ABSTRACT

Car-following is a common driving behavior which has a significant effect on driver safety and comfort. Although a large number of studies have focused on car-following models for autonomous vehicles (AV) and connected vehicles (CV), car-following models for AV and CV which consider cut-ins in mixed traffic have not been investigated. In this study, a human-like car-following model for AV and CV was developed by examining the effect of cut-in vehicles on car-following behavior and the expectations of drivers. The cut-in position, reaction time, acceleration, and desired distance were investigated on a real freeway in an instrumented vehicle. Corresponding to results from previous studies, the cut-in vehicles maintain a safe distance from the preceding vehicle and a larger distance from the following vehicle to avoid conflict. Analysis of the behavior of the following driver illustrates that in the keeping stages, the reaction time after the cut-in is 0.85 s for the acceleration stimulus and 0.70 s for the deceleration stimulus. These times are shorter than the response time before the cut-in for the acceleration (1.95 s) and deceleration stimuli (1.66 s). The acceleration, rate of increase in the acceleration with the relative speed, and the desired distance are lower after than before the cut-in events. In this paper, a human-like car-following model for cut-in situations is proposed, which is designed for autonomous vehicles. Unlike previous car-following models, the proposed model has a shorter response time and lower deceleration in cut-in situations. The proposed model may help to improve car-following safety, driver comfort, and trust in AVs and CVs.

1. Introduction

Car-following is a common driving behavior and has been widely researched by numerous scholars. The development of car-following models has become an important topic in many fields, including driving safety, vehicle congestion, and car emissions (Seiler et al., 1998; Zhao and Gao, 2006; Tang et al. 2015).

In the field of traffic safety studies, Reuschel (1950) and Pipes (1953) first proposed a car-following model called the stimulus-response model. This model regarded the action of the following vehicle as directly related to the action of the preceding vehicle, and proposed that the driver always attempts to maintain the same speed as the preceding vehicle. The model also included the reaction delay of the driver during this speed adjustment. Based on the stimulus-response model, Chandler et al. (1958) determined the relationship between the acceleration of the following vehicle and the relative speed, and calibrated and verified the parameters according to field test. This procedure is the prototype of the General Motors (GM) model. Gazis et al. (1961) proposed a general formulation of GM model. Following these

works, a number of studies (Hoefs, 1972; Aron, 1988; Ozaki, 1993) focused on the calibration of the sensitivity parameters of the GM model by using a large dataset of driving behavior. Aron (1988) split car-following behavior into three phrases, namely acceleration, deceleration, and steady-state driving.

A new stimulus-response model was proposed by Treiber et al. (2000), called the intelligent driver model (IDM). This framework determined that the acceleration behavior of the following vehicle was affected by the gap, speed, and relative speed, and has been widely used in adaptive cruise control (ACC) and connected adaptive cruise control (CACC). Kesting et al. (2008) applied IDM in ACC, finding that using ACC with IDM can alleviate traffic congestion. Rahman et al. (2018, 2019) used IDM in the simulation of CACC, pointing out that IDM is the simplest model and can provide the most realistic acceleration and deceleration behavior during car-following.

In addition to the stimulus-response model, Kometani and Sasaki (1958) proposed the safety distance model which considered that the following vehicle should keep a safe distance from the preceding vehicle when the driver cannot estimate the driving behavior of the

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preceding vehicle. Based on the hypothesis that the following vehicle always attempts to maintain a constant distance from the preceding vehicle, Bullen (1982) improved the safety distance model using simulation. At the same time, Gipps (1981) developed a new safety distance model which divided the car-following process into three stages depending on the drivers' desired speed: keeping desired speed, accelerating, and decelerating to the desired speed. Subsequently, numerous scholars have calibrated the Gipps model (Punzo et al., 2012; Vasconcelos et al., 2014; Papathanasopoulou and Antoniou, 2015). The most common safety distance model is the Mazda model (Manjunath and Jaisankar, 2013; Xiang et al. 2014), which takes into consideration the speed of the leading vehicle and the subject vehicle (S), as well as the reaction times of the vehicle and driver.

With the development of the driving-assistant system and vehicle-to-vehicle wireless communication techniques, car-following safety for connected vehicles (CV) and autonomous vehicles (AV) has become an important issue. Many studies have focused on the car-following of CVs and AVs without consideration of mixed traffic (Li et al., 2017; Papadoulis et al., 2019; Latrech et al., 2018). In real traffic situations, the surrounding vehicles can influence car-following behavior. A typical event is the cut-in, which results in considerable fluctuations in the cooperative adaptive cruise control queue (Wu et al., 2016). Based on vehicle-to-vehicle communications, AVs can easily maintain a constant car-following model when following the cut-in vehicle (C) (Zhou et al., 2017; Milanés et al., 2014). However, these intelligent systems have a single control mode. To keep a constant distance in the single car-following model, the AV may decelerate rapidly, which will negatively affect driver comfort (Yi and Do Kwon, 2001; Zheng and McDonald, 2005).

The future traffic environment will consist of a mixture of AVs and conventional vehicles, and their interactions will influence the performance of the AV (Bhavsar et al., 2017; Zhu and Zhang, 2018). Compared with full market penetration of CVs, car-following safety will be impaired in mixed traffic (Rahman and Abdel-Aty, 2018). In mixed traffic situations, irregular driving behavior such as cut-ins of conventional vehicles will significantly influence the car-following behavior of the CV and AV. In various cut-in situations, the constant car-following model will result in uneven car-following behavior, degrading the car-following safety of CVs, impairing the comfort of passengers, and decreasing driver trust and acceptance of AVs (Hartwich et al., 2018). To improve the safety and acceptance of CVs and AVs, many researchers have suggested that such vehicles should drive according to human driving behavior (Waytz et al., 2014; Lee et al., 2015). Thus, it is necessary to understand driver behavior and expectation in different driving situations.

Some studies have demonstrated that the movement and type of surrounding vehicles can influence driving behavior, including driver reaction time and decision making (Jurecki et al., 2017; Moridpour et al., 2010). Gunay (2007) found that on a road without lane marks, the gap between the following vehicle and the preceding vehicle (P) decreased when another vehicle was driving on an adjacent lane. Wiesenthal et al. (2000) conducted a questionnaire study, finding that cut-in situations significantly influenced the driver's emotions. Most drivers dislike it when other drives cut in, and the cut-in events influenced the driver behavior and expectations. Rajaonah et al. (2006) determined that after cut-in events, the acceptance of intelligent driving systems decreased considerably, even for drivers who had a high level of trust in intelligent driving systems. To meet the driver expectations, the driver's desired distance should be considered when establishing a car-following model (Wei et al., 2013; Li et al., 2013).

The study of car-following models for AVs and CVs has been developed extensively. However, little research has focused on car-following during cut-in situations in mixed traffic. Therefore, the goal of this study is to develop a car-following model for AVs and CVs, to improve safety and comfort during cut-in situations. The main contributions of this study are outlined as follows: (1) Different car-following

behaviors in normal car-following and cut-in situations are investigated. (2) A car-following model for cut-in situations is proposed. (3) The proposed model is evaluated by comparison with the Mazda model and IDM, validating that the model can maintain car-following safety and comfort.

The remaining paper is organized as follows: In Section 2, a real driving experiment on the freeway is presented. Section 3 provides the results of car-following data analysis. In Section 4, simulations are carried out to evaluate the performance of the proposed model, and Section 5 provides a discussion of the findings.

2. Methods

A real driving experiment was conducted in this study. Driver response to cut-in events and normal car-following behavior were investigated on a real freeway when driving an instrumented vehicle. All participants were driving under normal conditions on the same freeway in the same instrumented vehicle. The car-following events and the cut-in events were manually selected based on video data.

2.1. Participants

The participants were 46 non-professional Chinese drivers (mean age = 40.55 years, standard deviation (SD) = 6.14 years; 20 females and 26 males). Each driver had normal or corrected-to-normal vision and held a valid driver's license. Their driving experiences ranged from 2 to 30 years (mean = 14.31 years, SD = 7.13 years). Each driver reported that they had not experienced a traffic accident over the past three years, and demonstrated that they could drive normally for at least 1 hour. Their driving distance per year on freeways ranged from 420 km to 1700 km (mean = 934.42 km, SD = 423.12 km), and their longest driving time on the freeway without rest ranged from 2.5 hours to 4 hours (mean = 3.23 hours, SD = 0.47 hours). In the past six months, all participants had driven at least once on the test road. Participants were recruited via an advertisement and were paid a nominal fee.

All participants signed an informed consent form after understanding the experimental procedure.

2.2. Apparatus

The test vehicle (Fig. 1) was a multi-purpose vehicle equipped with a time-synchronized data collection system that logged controller area



Fig. 1. The test vehicle

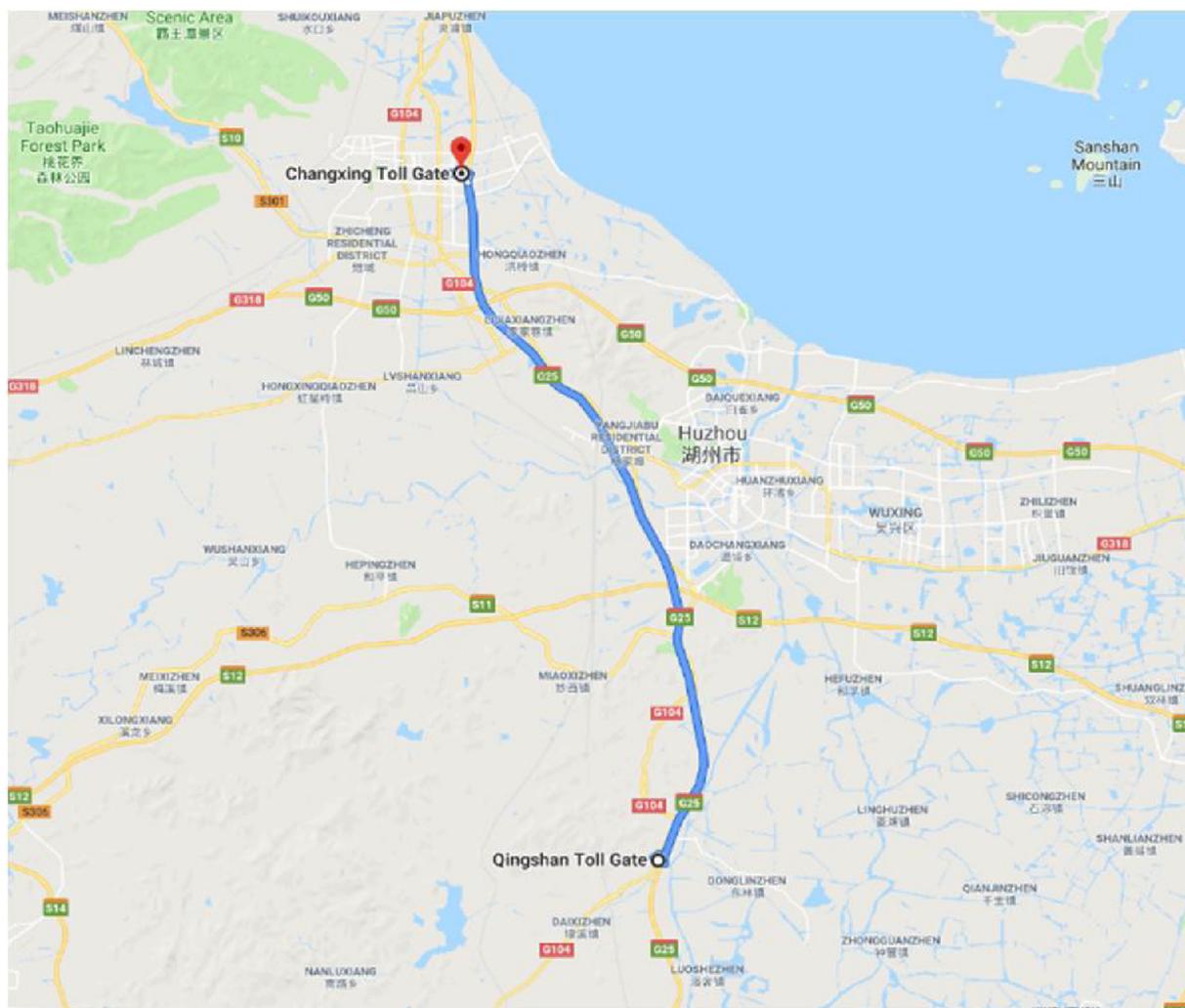


Fig. 2. Driving route

network (CAN) data. A VBOX data logger (a centimeter-resolution differential global positioning system) was used to record the test vehicle's trajectory and speed. The test vehicle was equipped with a millimeter wave radar system to measure the relative distance and speed between the S and the surrounding vehicle, and the detection frequency was 10 Hz. The front and rear traffic scene and the traffic environment were monitored in realtime by multi-high-speed cameras and vehicle acceleration data was collected using an inertial sensor with a detection frequency of 10 Hz.

2.3. Driving route

The driving route was the G25 freeway section from Qingshan to Changxing, which is a two-way four-lane road with a median barrier and maximum speed limit of 120 km/h (Fig. 2). The test road was approximately 42 km, and each driver required about 35 minutes to complete the trial. The width of the lanes, left shoulders, right shoulders and medians of the test road was 3.75 m, 0.75 m, 3.50 m and 2.00 m, respectively. The minimum horizontal curve radius of the test road was 900 m, the tangents were longer than 800 m, and the maximum longitudinal gradient of the test road was 1%. There were overhead signs on the test road, and the lane marking was a single broken white line. To preclude the negative effects of weather on driving safety, the test was carried out in clear weather. In order to encounter a sufficient number of cut-in events, the test was conducted during peak hours (7:30 am to 9:30 am and 5:00 pm to 7:00 pm). This experiment was carried out

from 2011 to 2019.

2.4. Procedure

Following the informed consent procedure, participants were given a period of time to adapt to the instrumented vehicle until they felt that the vehicle could be driven normally. Participants were required to inform the staff when they wanted to discontinue the experiment before they arrived at the destination for any reason. During the experiment, the staff did not control the driving behavior of the drivers, who chose their own driving style. When the participants were ready for the test, the test began.

During the driving experiment, one staff representative remained in the back seat in order to ensure the equipment was running normally, and this person did not talk to the drivers.

2.5. Data collection

The car-following events were documented using video data and millimeter microwave radar data while considering the definition of car-following (Saifuzzaman and Zheng, 2014). In order to select stable car-following processes (Tang et al., 2005), car-following events in which the duration of car-following was longer than 10 s were selected. All car-following events occurred on non-congested sections to ensure that the S was at high speed and the drivers maintained the high-speed car-following behavior. If the P changed lanes, the S also changed lanes

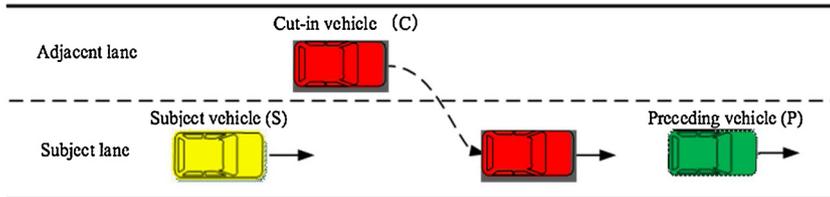


Fig. 3. Diagrammatic sketch of the traffic scene during a cut-in event

or the car-following process ended if the P exceeded the radar monitoring range. Fig. 3 shows a sketch of the traffic scene during a cut-in event.

The cut-in events were obtained using car-following data. According to the definition of lane departure in *Road/Lane Departure Warning Systems* (2007), the start of the cut-in event was determined as the moment when the front tire of the C contacted the lane marking. The video was manually processed frame by frame to select the start of the cut-in event. The motion of the C was detected by the millimeter microwave radar of the S. As most cut-in events occur with cars and the type of C has an impact on the driving behavior (Sayer et al., 2003; Tordeux et al., 2010), only the cut-in events of cars were selected. A cut-in event is illustrated in Fig. 4.

2.6. Driving performance metrics

In this experiment, the gap, speed of the S, speed of the P, speed of the C, relative speed between the S and the P, relative speed between the S and the C, reaction time, acceleration of the S, and the desired distance were used as driving performance metrics.

Various definitions of the gap exist (Green, 2010), along with different calculation methods for the reaction time. In this study, the distance between the rear of the leading vehicle (the P or the C) and the front of the S are used as the gap, following the *International Standards Organization* (2007). The reaction time was calculated based on the speed trends between the S and the leading vehicle (Ozaki, 1993).

2.7. Car-following structure

Prior to the cut-in events, the S followed the P, which was in the same lane as the S. After the cut-in events, a new car-following event began, i.e., the S would follow the C. In this study, this type of car-following event is called C following.

Many researchers have divided the driving behavior of the S in car-following events into three stages (Aron, 1988; Yeo, 2008; Koutsopoulos and Farah, 2012). In this study, prior to cut-in events,

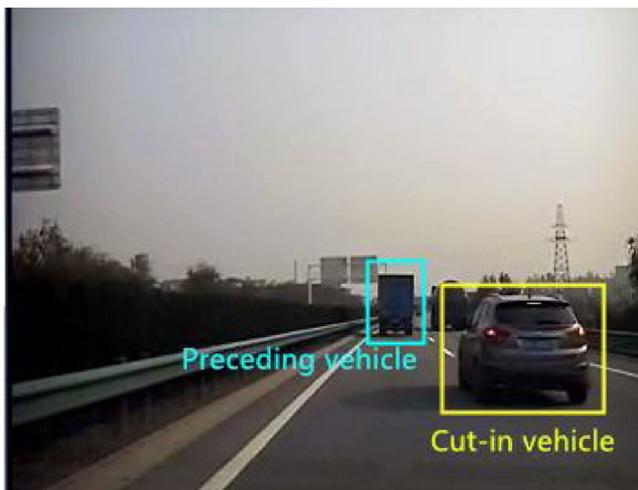


Fig. 4. A cut-in event

that is, under normal conditions, car-following was divided into three stages: acceleration (AN), keeping (KN), and deceleration (DN). During KN, there are two maneuvers, namely acceleration (AKN) and deceleration (DKN). After the C following event has occurred, the driving behavior of the S was also divided into three stages (Fig. 5): acceleration (AC), keeping (KC), and deceleration (DC). During KC, there are two maneuvers, namely acceleration (AKC) and deceleration (DKC). The car-following structure includes normal car-following and C following, as shown in Fig. 5. The AN stage and DN stage depend on the desired distance of the driver and the gap. The AKN and DKN are caused by the driver slightly adjusting to the speed of the car. The KN stage begins when the desired distance is close to the gap and the relative speed between the S and the leading vehicle fluctuates within a small range. Similar to previous studies (Sayer et al., 2003; Sultan et al., 2004), the driving stage was considered as the KN stage when the relative speed between the S and the leading vehicle ranged from -1.5 m/s to 1.5 m/s.

2.8. Experimental Results

A statistical analysis of the driving data of the 46 drivers was conducted. A total of 519 car-following events were selected and the driving time was more than 400 min. A total of 215 cut-in events occurred, accounting for 37.77% of the total number of car-following events, and the driving time was about 150 min. In 196 cut-in events, the S followed the C and still drove in the subject's lane, i.e., C following occurred. In 15 cut-in events, the S changed to the adjacent lane, and in the remaining events, the C failed to cut-in, and remained driving in the adjacent lane. In this study, the driving behavior was investigated based on the 196 C following events.

Linear regression was used to investigate the distance between C and S and the distance between P and C. The reaction time for different stages was examined using a one-way analysis of variance (ANOVA). A linear regression was used to investigate the relationship between acceleration and relative speed, and regression curve estimation was employed to examine the relationship between the speed of S and the desired distance.

2.9. Cut-in position

According to the definition of cut-in events (*Road/Lane Departure Warning Systems*, 2007), the start time of a cut-in event is the moment that one of the front tires of C contacts the lane marking. At the start time of the cut-in event, the gap between the S and C, the gap between the S and P, and the gap between the S and P were analyzed.

Fig. 6(a) shows the relationship of the gaps between the S and C and the gaps between the S and P at the start of the cut-in event. In the experiment, 68% of cut-in events occurred when the gap between the S and P was 40–80 m. A linear regression was used to analyze the relationship between these gaps. The gap between the S and C was found to increase linearly with the gap between the S and P ($F(1,194) = 1360.952$, $p < 0.001$, $R^2 = .875$, standardized coefficients of Beta = .936).

Fig. 6(b) shows the relationship of the gaps between the C and P and the gaps between the S and P at the start of the cut-in event. More than 92% of the cut-in events occurred when the gap between C and P

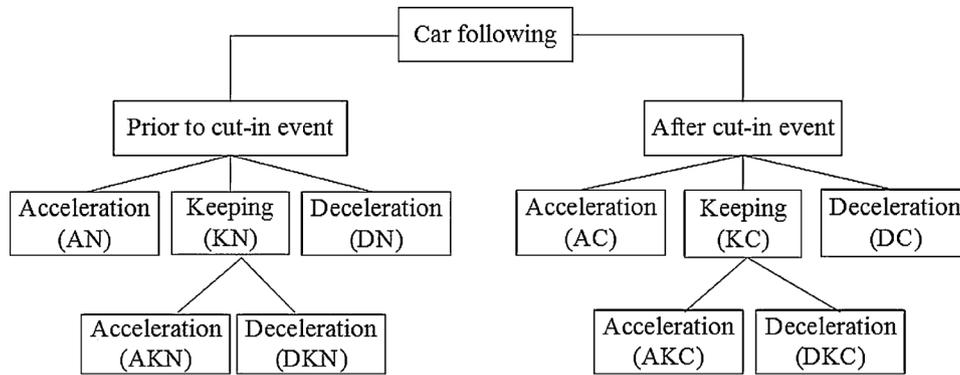


Fig. 5. Car-following structure

ranged from 10 to 30 m (mean = 15.1 m, SD = 0.56 m). Linear regression was used to analyze the relationship between these gaps. The gap between S and C increased linearly with the gap between S and P ($F(1,194) = 27.988, p < 0.001, R^2 = .126$, standardized coefficients of Beta = .355).

As the gap between the S and P increased, the cut-in position of the C was farther from the S, but the rate of increase in the gap between C and P was lower.

2.10. Reaction time

The reaction time for the four keeping stages (AKN, DKN, AKC, and DKC) was analyzed using ANOVA. The mean, minimum, and maximum reaction time and the standard error and standard deviation of the means are shown in Fig. 7 and Table 1.

The ANOVA result shows the significant effect of the stages on the mean reaction time ($F(3, 780) = 333.451, p < 0.001$). Post-hoc comparisons indicate that the reaction time was highest for AKN, followed by DKN, AKC, and DKC ($p < 0.001, p < 0.001, p < 0.001$, respectively).

The reaction time for the four acceleration and deceleration stages (AN, DN, AC, and DC) was analyzed using an ANOVA. The mean, minimum, and maximum reaction time and the standard error and standard deviation of the means are shown in Fig. 8 and Table 2.

The ANOVA result illustrates the significant effect of the stages on the mean reaction time ($F(3, 780) = 122.036, p < 0.001$). Post-hoc comparisons indicate that the reaction time was highest for AN, followed by DN, AC, and DC ($p < 0.001, p < 0.001, p < 0.001$,

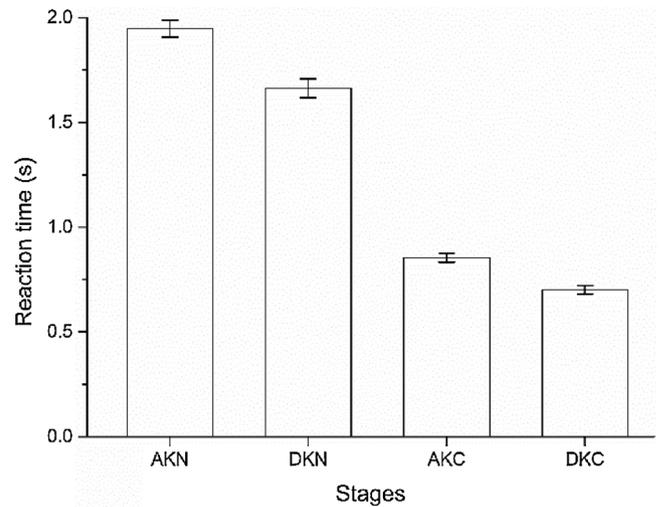
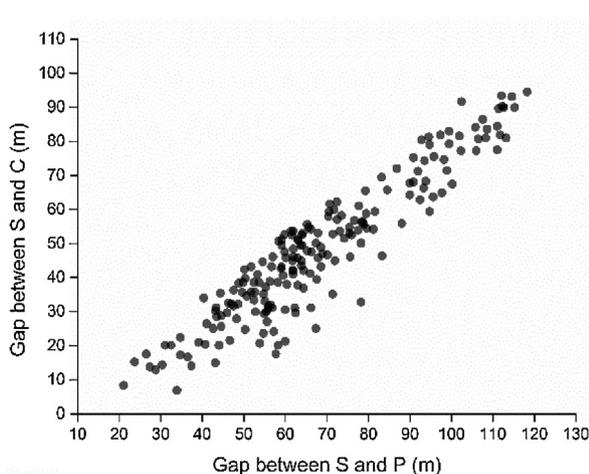


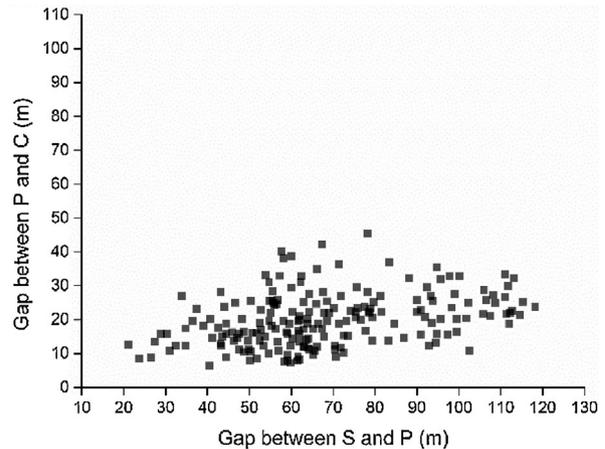
Fig. 7. Reaction time for the keeping stages

Table 1
Reaction time for the keeping stages.

	Mean (s)	Standard deviation (s)	Maximum (s)	Minimum (s)
AKN	1.93	0.58	3.24	0.63
DKN	1.67	0.63	3.08	0.51
AKC	0.85	0.32	1.64	0.23
DKC	0.70	0.33	1.53	0.17



(a) Gap between S and C



(b) Gap between P and C

Fig. 6. Cut-in position

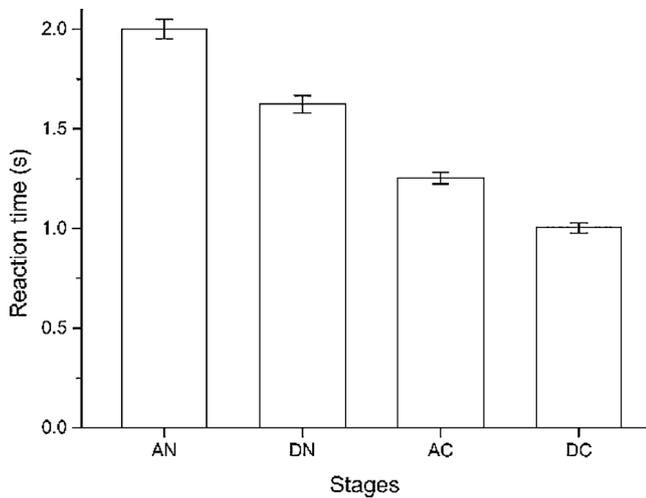


Fig. 8. Reaction time for the acceleration and deceleration stages

Table 2
Reaction time for the acceleration and deceleration stages.

	Mean (s)	Standard deviation (s)	Maximum (s)	Minimum (s)
AN	2.00	0.70	3.32	0.66
DN	1.62	0.65	2.98	0.37
AC	1.25	0.42	2.19	0.42
DC	1.00	0.41	2.01	0.25

respectively).

2.11. Acceleration

To compare the acceleration behavior of the subjects in the keeping stages before and after the cut-in events, the relative speed between the S and P (before the cut-in event), the relative speed between the S and C (after the cut-in event), and the acceleration of the S at the 3rd second of the keeping stage were determined. When investigating the relationship between the relative speed and acceleration, the reaction time was taken into consideration. Based on the mean reaction times, 1.8 s was used as the reaction time for KN and 0.8 s was used as the reaction time for KC (Sun et al., 2016; Koutsopoulos and Farah, 2012).

The Pearson correlation coefficient of the relative speed between the S and P and the acceleration of the S was also determined. The

relative speed between the S and P was significantly correlated with the acceleration of the S ($r = 0.91, p < 0.001$; Fig. 9(a)). A linear regression was used to determine the effect of the relative speed between the S and P on the acceleration of S. The linear regression model for the relative speed between the S and P was significant ($F(1, 194) = 935.475, p < 0.001, R^2 = 0.83$). The linear regression function used is as follows:

$$a(t + T) = 0.5763v_p(t) + 0.1719 \tag{1}$$

where T is the reaction time, $T = 1.8\text{ s}$, and $v_p(t)$ is the relative speed between the S and P.

The Pearson correlation coefficient between the relative speed between the S and C and the acceleration of the S was then determined. The relative speed between the S and C was significantly correlated with the acceleration of the S ($r = 0.92, p < 0.001$; Fig. 9(b)). A linear regression was used to observe the effect of the relative speed between the S and P on the acceleration of S. The linear regression model for the relative speed between the S and P was significant ($F(1, 194) = 1038.177, p < 0.001, R^2 = 0.84$). The linear regression function used is as follows:

$$a(t + T) = 0.4603v_c(t) + 0.2615 \tag{2}$$

where T is the reaction time, $T = 0.8\text{ s}$, and $v_c(t)$ is the relative speed between the S and C.

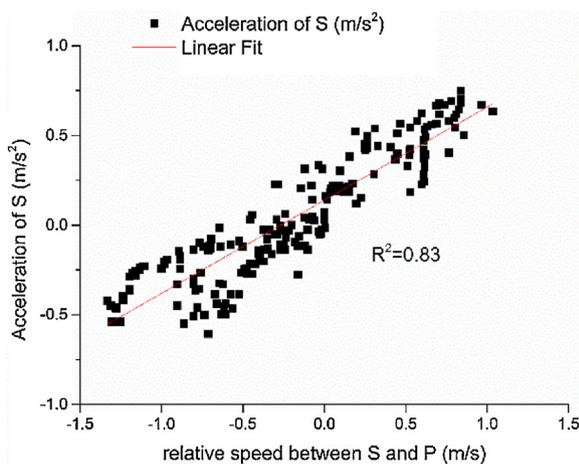
A linear regression was used to analyze the effect of the relative speed between the S and C and the relative speed between the S and P on the acceleration of the S. The results illustrate that there was a significant difference between the coefficient of the relative speed between the S and C and the relative speed between the S and P.

3. Desired distance model

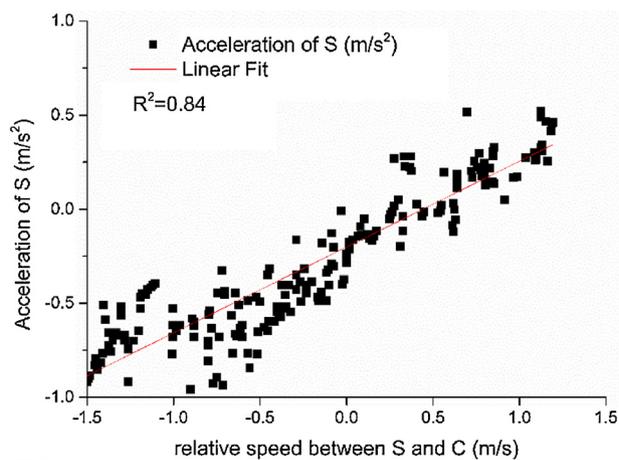
The characterization of the mean desired distance, maximum desired distance, and minimum desired distance were divided into 10 km/h speed bins for vehicle driving speeds between 60 and 120 km/h.

The mean desired distance, maximum desired distance, and minimum desired distance for KN and KC are provided in Table 3. At all six speed level, the mean desired distance, maximum desired distance, and minimum desired distance for KN were longer than those for KC.

Fig. 10 illustrates the relationship between the speed of the S and the mean, minimum, and maximum desired distances for the KC and the fitted curves. The R^2 -values for mean, maximum, and minimum desired distances were 0.99, 0.90, and 0.97, respectively. The third order polynomial equations were:



(a) Prior to the cut-in event



(b) After the cut-in event

Fig. 9. The relationship between the acceleration of S and the relative speed

Table 3
The desired distance for KN and KC.

		60-70 km/h	70-80 km/h	80-90 km/h	90-100 km/h	100-110 km/h	110-120 km/h
KN	Maximum	64	69	90	94	97	128
	Mean	35	39	51	53	56	68
	Minimum	20	20	21	23	23	31
KC	Maximum	45	57	82	85	89	117
	Mean	28	35	40	46	49	55
	Minimum	17	19	21	23	24	29

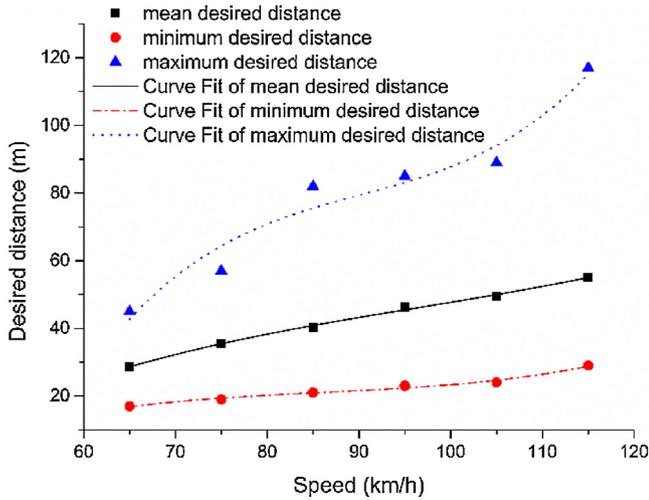


Fig. 10. Desired distance model for KC

Mean desired distance:

$$D_{mean} = 0.0001104v^3 - 0.03201v^2 + 3.539v - 96.47 \quad (3)$$

Maximum desired distance:

$$D_{max} = 0.001148v^3 - 0.3107v^2 + 28.76v - 829.3 \quad (4)$$

Minimum desired distance:

$$D_{min} = 0.0001574v^3 - 0.04054v^2 + 3.612v - 89.89 \quad (5)$$

where D_{mean} is the mean desired distance, D_{max} is the maximum desired distance, D_{min} is the minimum desired distance, and v is the speed of the S.

Fig. 11 shows the relationship between the speed of the S and the

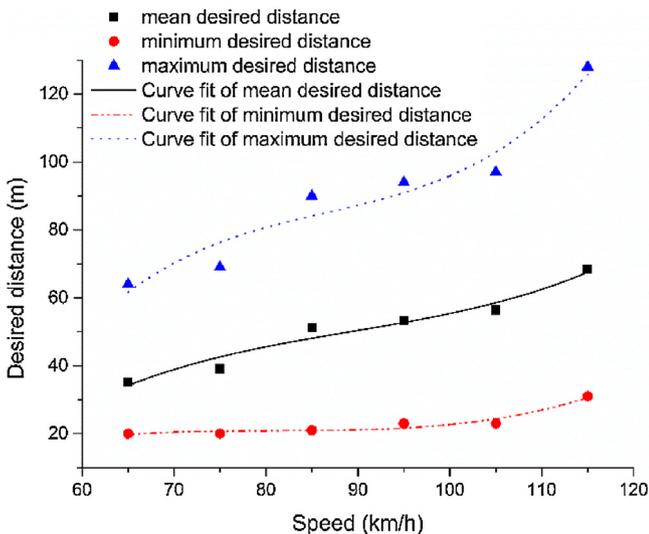


Fig. 11. Desired distance model for KN

mean, minimum, and maximum desired distances for the KN and the fitted curves. The R^2 -values for the mean, maximum, and minimum desired distances were 0.90, 0.86, and 0.87, respectively. The third order polynomial equations were determined as:

Mean desired distance:

$$D_{mean} = 0.0003382v^3 - 0.09057v^2 + 8.53977v - 231.11507 \quad (6)$$

Maximum desired distance:

$$D_{max} = 0.0001v^3 - 0.25964v^2 + 23.06929v - 617.26 \quad (7)$$

Minimum desired distance:

$$D_{min} = 0.0002407v^3 - 0.05857v^2 + 4.75985v - 108.33 \quad (8)$$

where D_{mean} is the mean desired distance, D_{max} is the maximum desired distance, D_{min} is the minimum desired distance, and v is the speed of S.

The mean, minimum, and maximum desired distances were higher after than prior to the cut-in events for all speed bins.

3.1. Summary of the C following model

The C following model is summarized in Table 4.

4. Simulation experiment

To evaluate the performance of the C following model, it was compared with two widely used car-following models in a PreScan simulation environment. The two comparison models used were the Mazda model, which is a safety distance model, and IDM model, which is a stimulus-response model. PreScan is a simulation software that uses a variety of sensors and vehicle models, connects to Matlab or Simulink software, and is widely used in the design and testing of advanced driver assistance systems (ADAS) (Tideman and Janssen, 2010).

For the simulation experiment, a two-way four-lane straight road was designed as illustrated in Fig. 12. The speed of the P was 80 km/h. When the S was in the keeping stage, the cut-in event began, as shown in Fig. 12, and the vehicle speed was 72 km/h. In this experiment, three cut-in position distances were tested, when the gap between the C and the S was 30 m, 40 m, and 50 m, respectively. The three car-following algorithms for the S, namely IDM, the Mazda model, and the C following model were then compared.

The simulation results of the C following model, the Mazda model, and IDM for the cut-in position of 40 m are presented in Figs. 13–15, respectively.

The maximum deceleration, standard deviation of speed, and

Table 4
The C following model.

Types	Equations
Maximum desired distance	$D_{max} = 0.001v^3 - 0.25964v^2 + 23.06929v - 617.26$
Mean desired distance	$D_{mean} = 0.0001104v^3 - 0.03201v^2 + 3.539v - 96.47$
Minimum desired distance	$D_{min} = 0.0002407v^3 - 0.05857v^2 + 4.75985v - 108.33$
Acceleration	$a(t + T) = 0.4603v_c(t) - 0.2615$



Fig. 12. Simulation environment

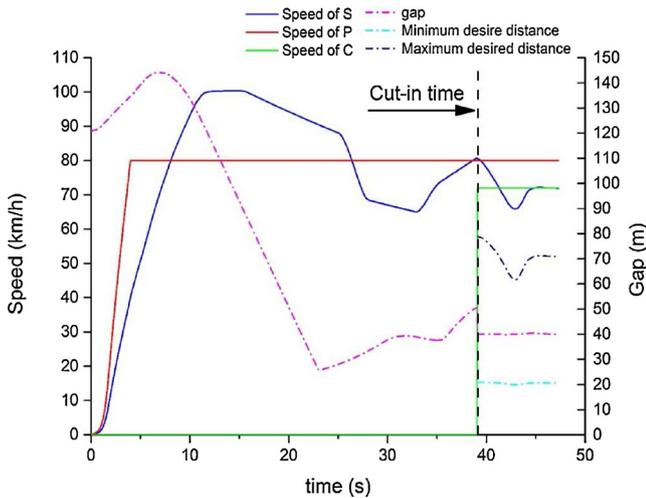


Fig. 13. Simulation result for the C following model

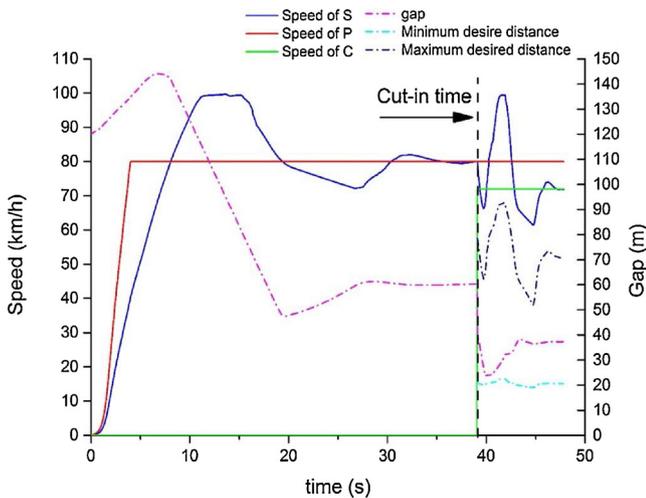


Fig. 14. Simulation result for the Mazda model

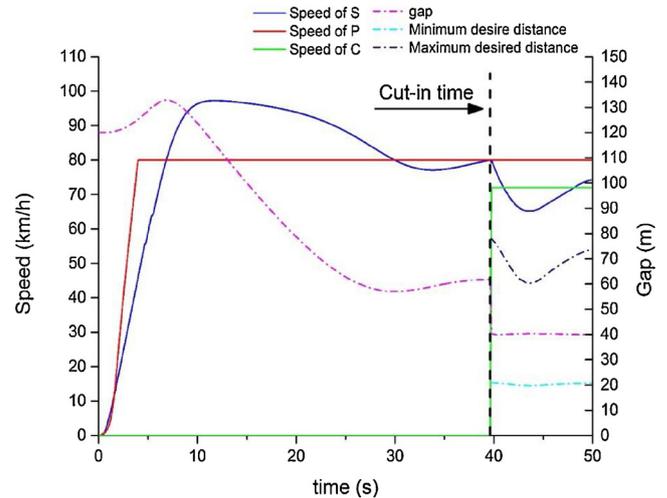


Fig. 15. Simulation result for the IDM model

Table 5

Evaluation parameters of the C following model.

Cut-in position (m)	Maximum deceleration (m/s ²)	The standard deviation of speed (km/h)	Adjusted duration (s)
50	-ss0.32	12.95	4.10
40	-0.96	5.29	4.85
30	-1.85	4.13	5.77

Table 6

Evaluation parameters of the Mazda model

Cut-in position (m)	Maximum deceleration (m/s ²)	The standard deviation of speed (km/h)	Adjusted duration (s)
50	-1.49	16.56	5.33
40	-2.12	12.58	6.17
30	-3.94	8.71	7.96

Table 7

Evaluation parameters of the IDM

Cut-in position (m)	Maximum deceleration (m/s ²)	The standard deviation of speed (km/h)	Adjusted duration (s)
50	-1.09	13.34	4.68
40	-1.83	6.18	5.11
30	-3.05	4.71	6.02

means a longer adjustment of the driving speed and the acceleration, which will affect the safety of the car-following and the comfort of the passengers.

Tables 5–7 illustrate the maximum deceleration, standard deviation of speed, and the adjusted duration for all three cut-in positions. The result shows that for the three cut-in position levels, the maximum deceleration and standard speed of the C following model was the smallest among the three models, and the adjusted duration of the C following model and the IDM were almost the same, but shorter than the Mazda model.

5. Discussion

The goal of this research was to investigate driving behavior during normal car-following and cut-in events on a real freeway. A car-

adjusted duration was used to evaluate the performance of the three models. Driving comfort is affected by deceleration, and the higher the deceleration, the more discomfort. Oh et al. (2005) pointed out that the leading factor to trigger traffic accidents is the standard deviation, and many studies (Abdel-Aty et al., 2009; Rahman et al., 2018) consider the standard deviation of speed as an indicator to evaluate the safety of car-following models. The adjusted duration is the duration from the cut-in time to the start time of the keeping stage. A longer adjusted duration

following model was proposed for autonomous vehicles driving during cut-in events in mixed traffic.

The study was conducted using 46 non-professional Chinese drivers operating vehicles during normal freeway driving conditions in which 519 car-following events and 219 cut-in events were recorded. The driving behavior of the S during 196 cut-in events that met the selection principle. The driving performance metrics that were examined in this study were the gap, the speed of the S, the speed of the P, the speed of the C, the relative speed between the S and the leading vehicle, reaction time, the acceleration of the S, and the desired distance. Based on real driving behavior recorded in the experiment, a car-following model of the cut-in situations was then proposed. The proposed model was compared with the Mazda model and IDM in a simulation experiment, in which the performance of the three car-following model was evaluated by maximum deceleration, the standard deviation of speed, and adjusted duration.

Similar to the results of a previous study (Daamen et al., 2010), the results of this investigation show that at the start of the cut-in time, the gap between the C and the P is larger than the gap between the C and the following vehicle. The C selects a safe cut-in position that does not trigger collisions with the leader and the following vehicle. If the gap between the leader and the follower is sufficiently large, the C will ensure that a safe distance from the P is maintained (Chen et al., 2015). Subsequently, the largest possible gap will be maintained between the C and the following vehicle. Cut-in behavior can be understood as an attempt by the following vehicle to avoid being cut in by the surrounding vehicle while in the stable car-following stage in which it may accelerate to decrease the gap between itself and the preceding vehicle. This means that at the starting moment of cut-in events, a too short gap between the following vehicle and the C can cause a collision. Kim et al. (2017) pointed out that conflicts between the C and the following vehicle decrease with an increasing gap between two vehicles. To minimize such conflicts, the C driver will keep a larger distance to the follower.

The results show that the reaction time of the S driver is longer for acceleration than for deceleration, which is consistent with the results of research conducted by Xue et al. (2015), who found that reaction time is varied when the driver meets different types of stimuli. The reaction time was longer during acceleration of the preceding vehicle than for deceleration. Furthermore, the gathered results show that after cut-in events, the reaction time for both acceleration and deceleration were shorter than those at the normal car-following stage. The shorter reaction time implies that the drivers are becoming more cautious and paying more attention to the driving behavior of the new leading vehicle after the surrounding vehicle has cut in in front of them. Such results also correspond with those of a previous driving simulation experiment, which demonstrated that the position and movement of the surrounding vehicles have an impact on the driver's reaction time (Jurecki et al., 2017). A shorter reaction time helps the following vehicle maintain a short distance from the new leading vehicle, in which the shorter distance can reduce the occurrence of being cut-in. However, when the gap between the following vehicle and the new leading vehicle is short, the shorter gap may lead to a rear-end collision. To decrease the risk when following the cut-in vehicle, the driver must pay more attention to the driving behavior of the cut-in vehicle, which can help reduce reaction time.

The relationship between the acceleration of the S and the relative speed between the S and the leading vehicle found in this experiment was similar to that reported in previous studies (Sun et al., 2016; Ranjitkar et al., 2003), which determined that the acceleration of the S has a strong positive correlation with the relative speed between the S and the P. The effect of different driving situations (following the C and the P) on the acceleration behavior was also investigated. The result shows that while following the cut-in vehicle, the acceleration and the rate of acceleration with the relative speed are lower than those while following the P. This may be attributed to the fact that the gap between

the C and the S is smaller than the gap between the C and the P. Rapid acceleration and high acceleration will result in a smaller gap, which may cause rear-end collisions.

An interesting finding of this experiment is that the desired distance is shorter when following the C than when following the P. This is likely attributed to the fact that most drivers dislike cut-ins and believe that a large gap causes the cut-ins (Wiesenthal et al., 2000). Thus, they decrease the distance to avoid cut-ins.

Compared to the Mazda model and IDM, the maximum deceleration of the C following model was the smallest in all three levels of cut-in position. At the cut-in position of 30 m, the maximum deceleration of the Mazda model and IDM was higher than 3 m/s^2 , and will seriously impair passenger comfort (Hoberock, 1977). The standard deviation of speed of the C following model was the smallest in all three levels of cut-in position. Small standard deviation of speed indicates that the adjustment of speed of the following vehicle after the cut-in event is relatively stable, which can reduce the occurrence of collision with the vehicle behind the following vehicle. Furthermore, the adjusted duration of the C following model and IDM were very close, but higher than the Mazda model, which indicates that the C following model is an efficient model. Short adjusted duration implies that the duration of adjustment of the deceleration and speed are short, which indicate the C following model not only can improve passenger comfort, but also increases safety.

The limitations of the C following model should also be taken into consideration. This model is designed for the car-following process on a freeway, in which the driving speed of the following vehicle should range from 60 km/h to 120 km/h, in line with Chinese transportation laws of freeway speed limit. As the Chinese freeway speed limit is 120 km/h, when the follower speed is over 110 km/h, the occurrence of cut-in events is greatly decreased. When analyzing the desired distance, an insufficient number of high speed cut-in events may cause the maximum and minimum desired distance to be incorrect. To solve the problem of insufficient data, speed bins were used in this study. However, binning also reduces the accuracy of results. In future work, more attention will be devoted to supplementing the experimental data so that speed bins will not be required.

In this paper, different car-following behaviors in normal situations and in cut-in situations were investigated, and a human-like car-following model for following the C was proposed to address the car-following problem of AVs and CVs in mixed traffic. To improve the safety and acceptance of AVs and CVs, the proposed model was developed based on real car-following data. The simulation result shows the C following model both improves safety during car-following and ensures the comfort of passengers. Future studies should extend the C following model to multiple research fields. In the simulation, this realistic model can be used to measure the effectiveness of CV and AV. The model can also be applied in ACC, which will improve the acceptance of ACC and car-following safety.

Declaration of Competing Interest

None.

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