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Analysis of Driver Brake Behavior Under Critical Cut-in Scenarios*

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***Abstract*— Analysis of driver brake behavior parameters under critical cui-in scenarios is conducted based on naturalistic driving data collected in Shanghai, China. Time headway (THW) when brake initiation is chosen to evaluate driver's timing of brake initiation. Average brake pressure change rate and maximum brake jerk are to evaluate driver brake response speed, average deceleration is to evaluate the effect of driver brake maneuver, maximum deceleration is to evaluate driver's maximum brake strength. Effects of different factors on driver brake behavior parameters are analyzed by using one-way analysis of variance and linear regression analysis. Driver brake behavior parameters in this study are important for the development of longitudinal control systems of automated vehicles which are suitable for Chinese people.**

I. Introduction

Research has indicated that more than 90% of road accidents occurred during driving are related to factors of human driver [1]. It is considered as an effective means to improve road safety by the realization of automated driving, so as to reduce the influence of human driver factors. According to the definitions published by the society of automotive engineers (SAE), levels of vehicle automation are categorized from Level 0 to Level 5 [2]. Limited by sensors, control strategies and other reasons, no automated vehicle at present has the capabilities of automation of level 5 where all driving scenarios could be handled all by vehicle self. So engagement of driver at different degrees is still required during the driving process, which is so called co-pilot.

For automated vehicles in the co-pilot stage, driver and automated system shall make joint effort to fulfill the dynamic driving tasks during driving. Adaptive cooperation between driver and automated system is required so as to ensure vehicle safety [3]. Due to the existence of two driving subjects during driving, the difference between driver's and automated system's cognition of driving scenarios, especially the cognitive differences of the critical scenarios, may in turn lead to the different choices of driving maneuver. This may affect the driving experience of driver, thereby affecting the user acceptance of automated vehicles. Situations even terrible are that the scramble for driving rights between driver and automated system may lead to serious road safety problems. Braking as one of the main maneuvers to avoid the danger of collision, driver's brake behavior reflects his cognition of danger in the corresponding driving scenario. And driver's timing of brake initiation and brake response process after brake initiation may give great insights and guidance for the development of longitudinal control systems of automated vehicles. Li et al. proposed the control strategy of automatic emergency brake system by analyzing driver's brake behavior in critical car-following scenarios [4]. Chen et al. provided references for the development of crash avoidance system by analyzing the brake parameters when driver facing the rider [5].

Cut-in as one of the more common driving scenarios in real traffic, driver's cognition of danger in this scenario will help guide the development of corresponding control strategies for automated vehicles. There are relatively few studies on this aspect at present. Kim et al. used driving simulator to study driver's behavior under cut-in scenarios on the highway [6]. However, results in this study are not so rich and comprehensive limited by the experimental conditions. And results in this study can not truly and completely reflect the driver's cognition of danger in cut-in scenarios as well for the difference of driving experience between driving on driving simulator and driving in real traffic.

In this paper, Analysis of driver brake behavior parameters under critical cui-in scenarios is conducted based on naturalistic driving data collected in Shanghai, China. Effects of different factors on driver brake behavior parameters are analyzed by using one-way analysis of variance (one-way ANOVA) and linear regression analysis. Driver brake behavior parameters in this study are important for the development of longitudinal control systems of automated vehicles which are suitable for Chinese people.

II. Materials and Methods

A. Naturalistic Driving Data Collection

As shown in table I, a naturalistic driving test was conducted. There were 4 cameras on each test vehicle to record the driving scenarios and driver behavior during the trips. Parameters of vehicle state were recorded through CAN-bus and were time synchronized with the data of cameras by data logger systems.

TABLE I. Naturalistic Driving Test

Area	Shanghai, China
Equipment	8 cars of which each was equipped with 4 cameras and a data logger system
Participant	32 licensed drivers with a mean age of 32.06 years(SD 2.73 years)
Distance traveled	about 130,000 kilometers
Duration	8 months consist of four 2-month stages with 8 drivers driving in each stage
Data collected	camera data ： videos of four camera perspectives(12.5fps) CAN-bus data：vehicle state parameters e.g. velocity, acceleration, brake pressure(10Hz)

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Figure 1. Camera data of naturalistic driving data collection

B. Extraction of Critical Cut-in Scenarios

To extract critical driving situations (CDS) from the naturalistic driving database, an automated CDS detection algorithm was developed where parameters of vehicle dynamics (velocity, longitudinal acceleration, lateral acceleration and yaw rate) and driver maneuver (e.g. average brake pressure change rate) were chosen to setup the criteria for CDS [7]. 2275 CDS cases were detected and 780 cases were proved true after the verification by reviewing camera data. And 80 cases in critical cut-in scenarios were extracted from these CDS cases, where braking is the primary evasive maneuver. Absolute values of maximum deceleration in these 80 cases have all exceeded 0.4g.

C. Driver Brake Behavior Parameters Extraction

To study the brake response process of driver in naturalistic driving condition, driver brake behavior parameters of two phases (when brake initiation and after brake initiation) were extracted. In phase 1, parameters were extracted to evaluate driver's timing of brake initiation. By reviewing the pedal-position camera data, the initial brake time of driver was determined, and then the corresponding parameters at this time, which were time to collision (TTC) and time headway (THW) relative to the cut-in vehicle, were extracted and analyzed. TTC is defined as the time required for two vehicles to collide if they continue at their present speed. It equals the range between two vehicles divided by the range rate. THW is defined as the range between two vehicles divided by the velocity of the following vehicle. Because of the very large range of distribution of TTC values (some are even negative), THW was chosen to be the parameter in phase 1 to evaluate driver's timing of brake initiation for its compact and regular distribution characteristics. Larger THW values when brake initiation mean that driver brakes earlier. In the total 80 critical cut-in cases, 77 effective THW values were extracted (3 cases in which driver brake behavior was influenced by brake maneuver of other leading vehicles).

In phase 2, parameters were extracted to evaluate the brake response process after brake initiation, where average brake pressure change rate (BPCR) and maximum brake jerk are to evaluate driver brake response speed, average deceleration is to evaluate the effect of driver brake maneuver, maximum deceleration is to evaluate the maximum brake strength of driver.

Average BPCR is defined as the average brake pressure change rate between the initial brake time of driver and the maximum brake pressure time. Maximum brake jerk is defined as the absolute value of the maximum derivative of deceleration during the braking process. Average deceleration and maximum deceleration are defined as the absolute value of the average deceleration and the maximum deceleration during the braking process.

D. Factors Considered in the Analysis

Data analysis was conducted for the evaluation of different factors' effects on driver brake behavior parameters. For THW when brake initiation, factors include the cut-in direction, lateral relative position, turning indicator state, vehicle type, lighting condition, velocity, relative velocity as shown in table II.

For driver brake behavior parameters after brake initiation, their relationships with velocity, THW and TTC are of great importance in developing longitudinal control systems for automated vehicles. Here we mainly take them as the focus.

TABLE II. FACTORS CONSIDERED IN THE ANALYSIS

Factor	Category	Category description	Type of factor variable
Cut-in direction	left	the direction from which the target vehicle (the leading vehicle which cuts in) cuts in	nominal
	right		
Lateral relative position	y0	lateral relative position between subject vehicle (SV) and target vehicle (TV) at the initial brake time	ordinal
	y1		
	y2		
	y3		
	y4		
Turning indicator state	on	turning indicator state of TV before the initial brake time	nominal
	off		
Vehicle type	type Ⅰ	sedan of different classes and SUV of class A and B	ordinal
	type Ⅱ	SUV of class C and above and MPV	
	type Ⅲ	bus and truck	
Lighting condition	good	lighting condition in clear and bright weather	nominal
	other	other lighting conditions (such as darkness and rain)	
Velocity	--	velocity of SV when collision threat appears, substituted by velocity at the initial brake time	scale
Relative velocity	--	relative velocity between SV and TV when collision threat appears, substituted by relative velocity at the initial brake time. It equals the velocity of SV substracting that of TV	scale
THW	--	THW at the initial brake time	scale
TTC	--	TTC at the initial brake time	scale

Lateral relative position refers to the lateral relative position between SV and TV at the initial brake time. Because it is difficult to get the accurate lateral relative position between SV and TV in naturalistic driving condition, a quasi-quantitative method is adopted to describe lateral relative position in an approximate way. For position of SV, because braking is the primary evasive maneuver in all 77 effective cases, SV was supposed to at the central of the lane.

For position of TV, first the point of TV which is closest to SV in the lateral direction is determined by reviewing the forward looking camera data. And then 5 reference lines are defined as shown in Figure 2, where y0 and y2, y3, y4 are the quadripartite lines of lane of TV and lane of SV, and y1 is the central line of the lane line. The position of TV is defined as the line label of the reference line which the point determined before is close to. For example, the position of TV in Figure 2 is y1. Lateral relative position could be represented by the value of position of TV.

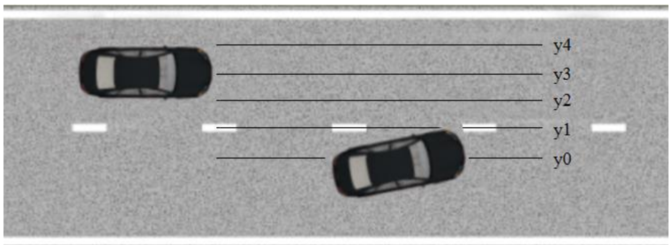

Figure 2. Definition of lateral relative position of subject vehicle and target vehicle

Velocity refers to the velocity of SV when collision threat appears. However, the determination of the right time when collision threat appears in cut-in scenarios is not easy. The only thing for sure is that it is before the initial brake time of driver. Driver brake reaction time is defined as the time interval from the moment when a collision threat appears to the moment that the driver actually initiates brake to avoid the collision [8]. According to research results in [9] [10] [11], there is little driver brake reaction time which is longer than 2s. So velocity of SV when collision threat appears is substituted by velocity at the initial brake time. And the same substitution is applied in the determination of relative velocity between SV and TV when collision threat appears.

E. Statistical Methods in the Analysis

For nominal and ordinal factor variables, One-way ANOVA is chosen to test whether factors' effects on THW when brake initiation are significant. Kolmogorov-Smirnov test (KS test) is to test whether data samples follow normal distributions. Variance homogeneity of data samples is tested by using Levene's test. Before one-way ANOVA, data samples will be tested with KS test and Levene's test to verify if they have satisfied the assumption of using this method.

For scale factor variable, linear regression is used to test the relationships between different factors and driver brake behavior parameters of phase 1 and phase 2. T test is used to test the significance of the regression coefficients.

III. Results

A. Statistical Characteristics of THW When Brake Initiation

Values of THW when brake initiation range from 0.14s to 2.73s. Mean value is 0.93s with standard deviation of 0.60s. And the 25th percentile, the median, and the 75th percentile are 0.42s, 0.77s, 1.34s respectively. Frequency distribution histogram of THW and lognormal fitting curve are shown in Figure 3. THW when brake initiation obeys lognormal probability distribution (KS test: p=0.472>0.05).

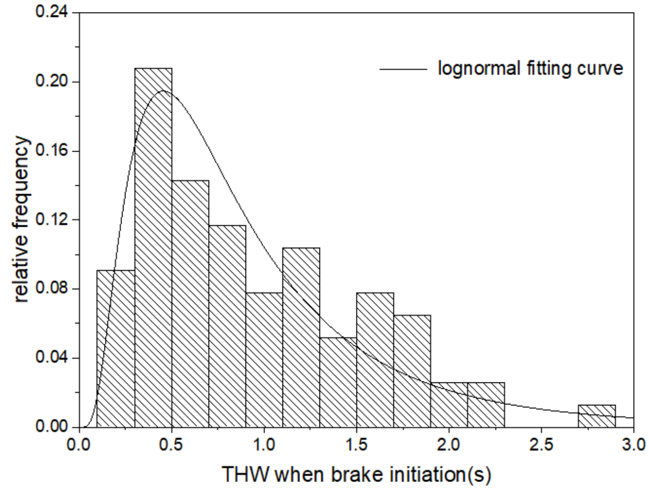

Figure 3. Frequency distribution histogram of THW when brake initiation and lognormal fitting curve

B. Influence of Different Factors on THW When Brake Initiation

For factors of nominal and ordinal types, data samples have all satisfied the assumption of using one-way ANOVA. And the test results are in table III. THW when brake initiation for different factors are shown in Figure 4 and Figure 5.

TABLE III. Influence of Different Factors on THW When Brake Initiation

Factor	Assumption of using ANOVA		One-way ANOVA test results	
	Normally distributed (KS test)	***p value of Levene's Test***	***F value***	***p value of F test***
Cut-in direction	yes	0.676>0.05	F(1,42)=0.172	0.681>0.05
Lateral relative position	yes	0.657>0.05	F(2,72)=0.107	0.898>0.05
Turning indicator state	yes	0.791>0.05	F(1,75)=0.021	0.885>0.05
Vehicle type	yes	0.079>0.05	F(2,74)=3.108	0.051>0.05
Lighting condition	yes	0.189>0.05	F(1,75)=0.507	0.478>0.05

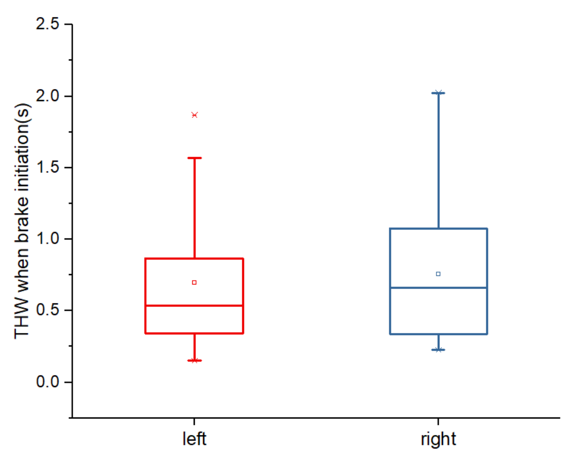

Figure 4. THW when brake initiation for cut-in direction after data preprocessing

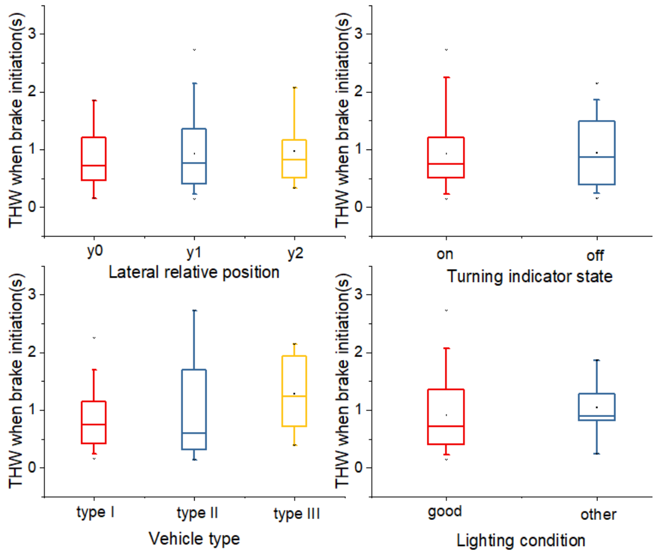

Figure 5. THW when brake initiation for different factors

For one-way ANOVA test result of cut-in direction without data preprocessing, it shows that driver initiates brake significantly earlier in right cut-in cases than in left ones ($F(1,75)=5.176$, $p=0.026<0.05$). However, further analysis shows that the correlation between cut-in direction and relative velocity can not be ignored. Values of relative velocity in right cut-in cases are significantly bigger than that in left ones with mean values of 17.72km/h and 10.98km/h. Then data preprocessing is conducted to minimize the disturbance of relative velocity in analysis for cut-in direction. 22 cases are extracted from 55 right cut-in cases to work as the counterparts of 22 left cut-in cases based on the relative velocity value. That is, to select a right cut-in case with a relative velocity value closest to that of a left cut-in case as its counterpart. And then result shows that cut-in direction does not have significant influence on THW when brake initiation.

Considering the count of cases in each bin and the assumption of using one-way ANOVA, only cases in lateral relative position of y0, y1, y2 were analyzed. Lateral relative position is not found to significantly influence THW when brake initiation. THW when brake initiation is not significantly influenced by turning indicator state or lighting condition either. However, driver in other lighting conditions (such as darkness and rain) tends to brake earlier than in good lighting condition (mean of THW are 1.04s and 0.91s respectively). Vehicle type has a relatively significant influence on THW when brake initiation ($F(2,74)=3.108$, $0.051>0.05$) and driver brakes significantly earlier when vehicle of type Ⅲ cuts in than vehicle of type Ⅰ (Scheffé post hoc test: $p=0.018$*).

As shown in Figure 6, velocity when collision threat appears ranges from 13.12km/h to 100.12km/h and relative velocity when collision threat appears ranges from -13.21km/h to 45.61km/h. For the velocity axle, THW when brake initiation tends to increase firstly with the increase of velocity and then decrease, where the demarcation point is at about 55km/h. And for the relative velocity axle, THW when brake initiation tends to increase with the increase of relative velocity. Segmented binary linear regression is used to analyze the relationship between THW when brake initiation and velocity and relative velocity when collision threat appears. For velocity under 55km/h, there is no significant relationship between velocity and THW (t value $t=0.24$, p value $p=0.81$), and there is significant relationship between relative velocity and THW ($t=2.65$, $p=0.01$). And for velocity above 55km/h, there is significant relationship between velocity and THW ($t=-3.19$, $p=0.004$), and relationship between relative velocity and THW is still significant ($t=2.89$, $p=0.008$).

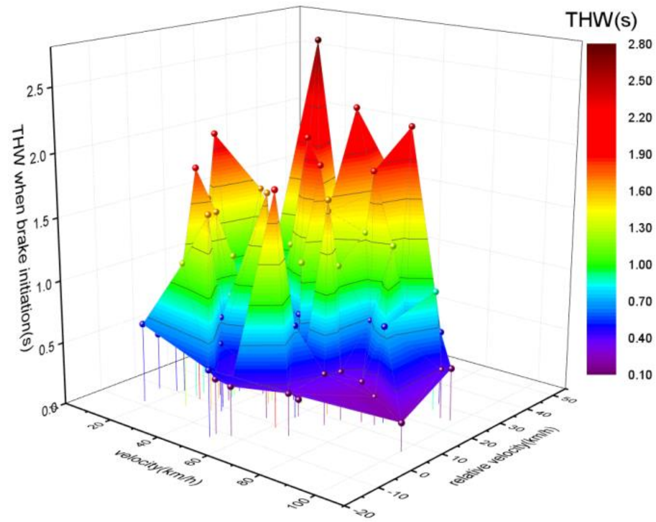

Figure 6. Relationships between THW when brake initiation and velocity and relative velocity when collision threat appears

C. *Relationships Between Different Factors and Driver Brake Behavior Parameters After Brake Initiation*

Here we mainly take factors of velocity, THW and TTC as the focus to analyze their relationships with driver brake behavior parameters after brake initiation for their crucial status in longitudinal control system developing.

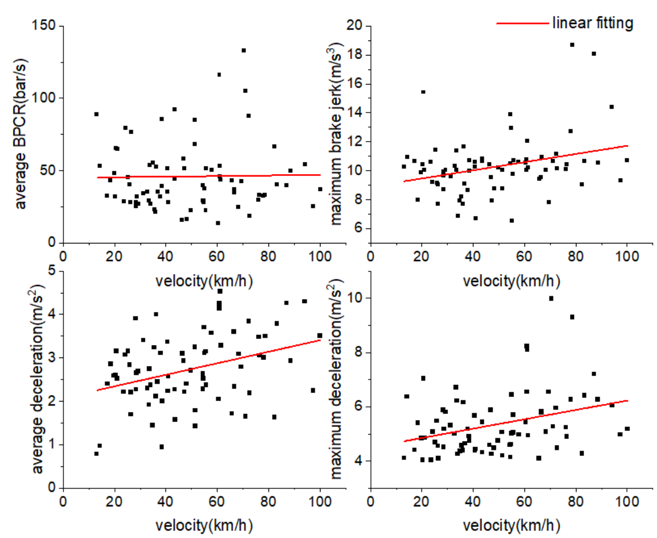

Figure 7. Relationships between velocity and driver brake behavior parameters after brake initiation

Relationships between velocity and driver brake behavior parameters after brake initiation are shown in Figure 7. There is no significant relationship between velocity and average BPCR (t= 0.16, p= 0.87). However, relationship between velocity and maximum brake jerk indicates that driver brakes significantly faster in higher velocity when collision threat appears (t= 2.70, p= 0.009). And the higher the velocity is, the stronger effect of braking of driver becomes according to relationship between velocity and average deceleration (t=3.22, p=0.002). And driver tends to perform a harder brake in higher velocity according to the relationship between velocity and maximum deceleration (t= 2.94, p= 0.004).

Relationships between THW, TTC and driver brake behavior parameters after brake initiation in critical car-following scenarios have been research hot spots [12] [13]. However, different from critical cases in car-following scenarios, there are much more cases where TTC values are negative with small THW values in critical cut-in scenarios, which may be critical enough to initiate a hard brake in driver's eyes even though there is little chance to collide with the cut-in vehicle. Hence driver risk perception parameter (RPP) is introduced to evaluate the collective effect of THW and TTC on driver brake behavior parameters after brake initiation. RPP is defined as follows [12]:

$$RPP=1/THW+4/TTC \tag{1}$$

Relationships between RPP and driver brake behavior parameters after brake initiation are shown in Figure 8. All brake behavior parameters after brake initiation tend to increase with the increase of RPP, while their relationships with RPP are all not significant (t= 0.53, p=0.59; t= 0.35, p= 0.72; t= 0.46, p= 0.64; t= 0.03, p= 0.97).

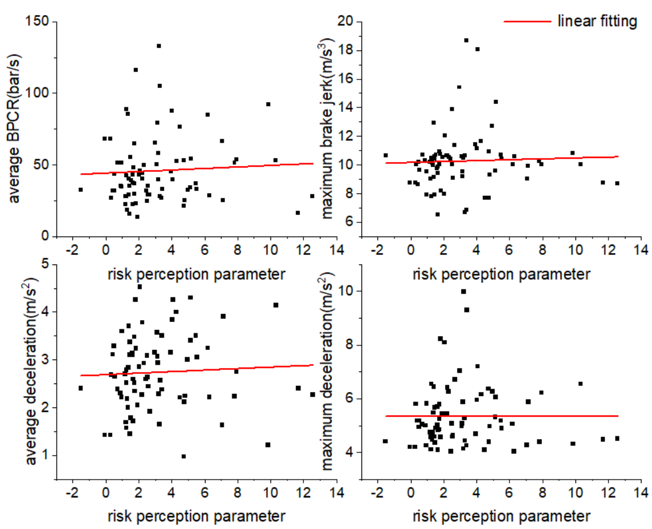

Figure 8. Relationships between risk perception parameter and driver brake behavior parameters after brake initiation

IV. DISCUSSION

A. *Statistical Characteristics of THW When Brake Initiation*

In this paper, THW when brake initiation under critical cut-in scenarios obeys lognormal probability distribution, which is consistent with Li's findings, where THW when brake initiation under critical car-following scenarios are analyzed based on naturalistic driving data [13]. In this study, mean value of THW is 0.93s, which is larger than Li's finding of 0.84s. It should be noted that in Li's research the time of brake initiation is determined by longitudinal deceleration rather than the action of driver's foot on brake pedal in this paper. The time delay of brake system may lead smaller THW values when brake initiation than the actual ones.

B. *Influence of Different Factors on THW When Brake Initiation*

Cut-in direction, lateral relative position when brake initiation, turning indicator state before brake initiation and lighting condition do not have significant influence on THW when brake initiation according to the results of one-way ANOVA analysis. And driver in other lighting conditions (such as darkness and rain) tends to brake earlier than in good lighting condition according to the mean values of THW when brake initiation. Vehicle type has a relatively significant influence on THW when brake initiation and for cut-in vehicles of bus and truck, brake initiation of driver tends to come significantly earlier. That gives the advice that factor of vehicle type of TV in cut-in scenarios shall be taken into consideration in longitudinal control strategies for automated vehicle.

As for effects of velocity and relative velocity when collision threat appears on driver's timing of brake initiation, driver tends to brake earlier when velocity goes up before about 55km/h, and then brake initiation of driver tends to come significantly later with the increase of velocity, especially when velocity above 80km/h. This may because in high speed situation, the chance of avoiding collision by steering maneuver increases once there is enough space for lane change [14]. Cases where velocity above 80km/h are all from highway cut-in scenarios, where there is enough space for lane change maneuver. And once there is steering maneuver as the backup evasive maneuver, driver may tend to postpone the brake initiation. And with the increase of relative velocity when collision threat appears, driver tends to initiate brake earlier in the entire velocity range in this paper.

C. *Relationships Between Different Factors and Driver Brake Behavior Parameters After Brake Initiation*

Driver brake significantly faster with the increase of velocity when collision threat appears according relationship between velocity and maximum brake jerk. And the higher the velocity is, the stronger effect of brake becomes. Driver tends to perform a harder brake in higher velocity.

All brake behavior parameters after brake initiation tend to increase with the increase of RPP which is derived from THW and TTC when brake initiation. However, their relationships with RPP are all not significant. This may because RPP is set up based on data under car-following scenarios and may not fit the risk perception of driver under cut-in scenarios well. So further study is required for the estimation of risk perception of driver under cut-in scenarios.

V. CONCLUSION AND FUTURE WORKS

Analysis of driver brake behavior parameters under critical cui-in scenarios is conducted based on naturalistic driving data collected in Shanghai, China. THW when brake initiation is chosen to evaluate driver's timing of brake initiation. Average brake pressure change rate and maximum brake jerk are to evaluate driver brake response speed, average deceleration is to evaluate the effect of driver brake maneuver, maximum deceleration is to evaluate the maximum brake strength of driver. Effects of different factors on driver brake behavior parameters are analyzed by using one-way ANOVA and linear regression analysis.

THW when brake initiation obeys lognormal probability distribution. Cut-in direction, lateral relative position when brake initiation, turning indicator state before brake initiation and lighting condition do not have significant influence on THW when brake initiation. Vehicle type has a relatively significant influence on THW when brake initiation and for cut-in vehicles of bus and truck, brake initiation of driver tends to come significantly earlier. Driver tends to brake earlier when velocity goes up before about 55km/h, and then brake initiation of driver tends to come significantly later with the increase of velocity. And with the increase of relative velocity when collision threat appears, driver tends to initiate brake earlier in the entire velocity range in this paper.

Driver brake significantly faster with the increase of velocity when collision threat appears. And the higher the velocity is, the stronger effect of brake becomes. Driver tends to perform a harder brake in higher velocity. Collective effect of THW and TTC when brake initiation on driver brake behavior parameters after brake initiation are analyzed by the introduction of risk perception parameter. All brake behavior parameters after brake initiation tend to increase with the increase of RPP which is derived from THW and TTC. However, their relationships with RPP are all not significant.

It's important for automated vehicles at co-pilot stage to minimize the difference between automated driving systems and human drivers on scenario cognition and maneuver performing. Because it is related to the driving experience and user acceptance of people, as well as the vehicle safety issues. Driver brake behavior in this study reflects Chinese drivers' cognition of danger under critical cut-in scenarios. The distributions of driver brake parameters and the effects of different factors on them (e.g. the effect of vehicle type on drivers' timing of brake initiation) could work as the references and guidance in developing longitudinal control systems of automated vehicles which are suitable for Chinese people.

For further research purposes, typical cut-in test scenarios are going to be extracted based on naturalistic driving data and performance of some automated vehicles will be tested in these scenarios. The comparison of driver behavior and performance of these automated vehicles will be conducted, hence insights in the conflicts between human drivers and automated systems in critical cut-in scenarios could be obtained.

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