Intelligent Vehicle Collision Risk Modeling and Comprehensive Evaluation Method

Jiaxiang Qin, Weiwen Deng and Rui He

October 19, 2019

Intelligent Vehicle Collision Risk Modeling and Comprehensive Evaluation Method

Qin JiaXiang
State Key Laboratory of Automobile Simulation and Control
Jilin University
ChangChun, China
qinjiaxiang_jlu@qq.com

Deng WeiWen
School of Transportation Science and Engineering
Beihang University
BeiJing, China
kdeng @jlu.edu.cn

He Rui
State Key Laboratory of Automobile Simulation and Control
Jilin University
ChangChun, China
herui@jlu.edu.cn

***Abstract*—Collision risk assessment is one of the key technologies of intelligent driving. At present, there are many studies on vehicle collision risk and its evaluation methods, but there are still some problems, such as multiple evaluation methods, inconsistent standards, and huge numerical range. Various evaluation methods make the quantitative description of the collision risk in the same scene different, and there are great differences in the description of the collision risk in different scenarios. It is not convenient to compare the collision risk degree in different dangerous scenarios horizontally. Based on the analysis of the mechanism and kinematics model of vehicle longitudinal and lateral collision, and the idea of time-distance model and motion model, this paper puts forward an evaluation method of vehicle longitudinal and lateral collision risk, and then puts forward a comprehensive evaluation method of vehicle collision risk during driving. This method takes into account both the simplicity of time-distance model calculation and the accuracy of motion model modeling. It can describe the collision risk in dangerous scenarios without dimension normalization. It is of great significance for the development and testing of intelligent vehicles.**

Keywords—intelligent vehicle, collision, risk assessment

I. INTRODUCTION

In recent years, China's car ownership has increased rapidly, and the incidence of traffic accidents has also increased. The statistics of vehicle traffic accidents show that the rear-end accidents caused by front collision account for about 35.71%[1] of the longitudinal dangerous accidents, and the proportion of side collision accidents is as high as 24.82%[2]. Therefore, how to reduce the incidence of traffic accidents and economic losses and casualties caused by traffic is an urgent problem to be solved.

Longitudinal collision and lateral collision are the main manifestations of traffic accidents during vehicle driving. Scholars at home and abroad have conducted extensive research on both aspects. In the field of longitudinal collision, many longitudinal hazard assessment indicators are proposed, such as TTC (Time to Collision)[3], which uses the relative distance between the vehicle and the front vehicle divided by the relative speed to evaluate, but cannot describe the collision hazard when the two vehicles are relatively stationary. MTC (Margin to Collision)[4] uses the ratio of braking distance to relative distance and braking distance to evaluate the possibility of collision when the vehicle and the front vehicle simultaneously decelerate sharply (0.7G), but there is a problem that the numerical value changes greatly and cannot be normalized. KdB [5] perceives the approach and distance of the target vehicle through the change of the driver's visual area, and so on. This evaluation method has a large amount of calculation and low real-time performance, so it is difficult to be applied in actual vehicles. In the research of lateral collision, the paper [6] analyzed the process of lateral collision, and carried out a research on the early warning method of lateral collision. Literature [7-8] designed the lateral collision avoidance system by setting the startup conditions of the control system, using I_{limit} and I_{elimit} as the threshold values of system warning or collision avoidance trigger. Paper [9] analyses the mechanism of lateral collision and establishes the mathematical model of lateral safe distance. However, the above-mentioned research on the risk of lateral collision is insufficient to evaluate the mechanism of collision and the risk of lateral collision in the course of vehicle lateral movement [10-12], which leads to the difficulty of guaranteeing the effect in actual working conditions and vehicle applications. Therefore, how to establish a reasonable and standardized description of vehicle longitudinal and lateral collision risk and a comprehensive evaluation of vehicle collision risk need to be further studied.

Based on the vehicle kinematics model, this paper establishes the evaluation methods of vehicle longitudinal and lateral collision hazards by analyzing the mechanism and braking process of vehicle collision, puts forward the corresponding dimensionless normalized index formula, and further establishes the longitudinal and lateral coupling collision hazard evaluation method under general driving conditions. The collision risk description method can standardize the description of the collision risk in different dangerous scenarios, and facilitate the horizontal comparison of the risk levels in different driving scenarios. It is of great significance for the collision risk assessment and the generation of dangerous scenarios in the field of intelligent driving.

II. COLLISION MECHANISM ANALYSIS

This section firstly analyses the mechanism and types of vehicle collision, and simplifies the research scenarios based on the analysis of collision scenarios. It provides the basis for the third section of longitudinal collision risk assessment, the fourth section of lateral collision risk assessment and the fifth section of comprehensive evaluation of collision risk.

The mechanism of vehicle longitudinal collision is as follows: Vehicles generally run in the lanes corresponding to structured roads. Drivers tend to drive at higher speeds, resulting in the relative distance between front and rear vehicles being less than the minimum safe distance. When the driver behind the car is distracted, or when the front car suddenly brakes, it is easy to cause the rear driver's reaction is not timely enough, which leads to the longitudinal collision of vehicles. The mechanism of vehicle lateral collision is as follows: as shown in Fig. 1 below, when a vehicle is driving on the road, it will inevitably have lateral movement due to the influence of lane change, turning or driver distraction. If the vehicle moves too early or too late when lateral displacement occurs, it may collide laterally with the front or rear vehicle. The types of laterally collision include corner collision, side collision, rubbing collision and so on, and may also occur

Subsidized by the National Natural Science Foundation U1564211.

friction collision between road guardrails. Therefore, vehicles should keep a certain distance from other vehicles and road guardrails in the course of driving.

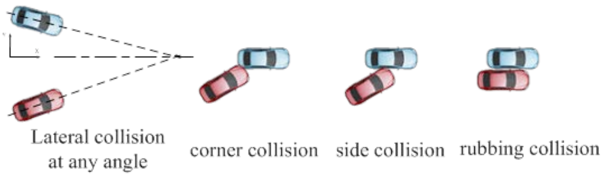

Fig. 1. Side impact diagram

III. Modeling of Longitudinal Collision Process

Longitudinal hazard degree of vehicle driving process is mainly established by the vehicle in the lane and the front and rear vehicles involved in the traffic. For the convenience of the study, this vehicle(HV: host vehicle) and the front vehicle (TV: target vehicle) are selected as the main participants in the longitudinal driving process, and only the longitudinal motion is studied, while the lateral motion of the vehicle is neglected. Simplified vertical traffic scenarios are shown in Figure 2 below.

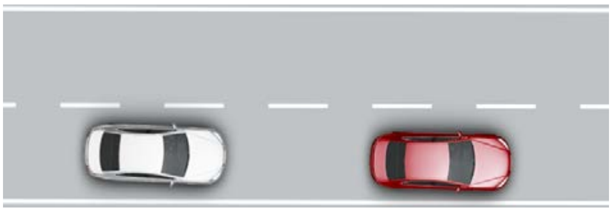

Fig. 2. Simplified Longitudinal Traffic Scene

One of the basic starting points of modeling is to consider the completeness of choosing motion parameters. In the existing studies, $TTCi$ and THW are often used to describe the longitudinal hazards. $TTCi$ includes relative distance and relative speed of two cars, THW includes relative distance and speed of the car. It is incomplete to select only one of $TTCi$ or THW for describing dangerous scenarios. Therefore, the above two evaluation indexes include three independent parameters: the longitudinal speed of HV, the longitudinal speed of TV and the relative distance, which are complete for describing the longitudinal danger degree. These two indicators are also used in the longitudinal risk assessment method proposed in this paper.

Assuming that the state information of relative motion of two vehicles is as follows, the sketch diagram of relative motion is shown in Fig. 3. The length of two vehicles is l, the speed of HV and TV is v_h and v_t, the real-time relative distance is d, the adhesion coefficient of the road surface is μ, the slope of the road surface is α, and the curvature of the road is neglected.

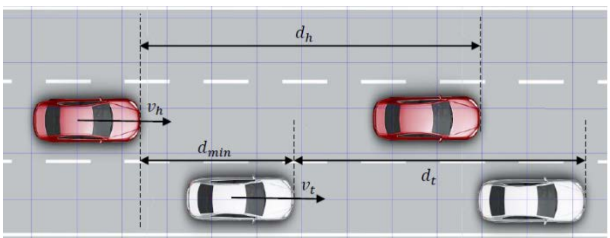

Fig. 3. Diagram of Braking Process of HV and TV

Assuming that HV and TV are braked as shown in the figure, and after braking, the head of HV is close to the rear of TV, and the following equation exists in the braking process.

$$d_{min} + d_t = d_h + l \tag{1}$$

The braking process of the vehicle in the studied scenario [13-14] is shown in Figure 4 below.

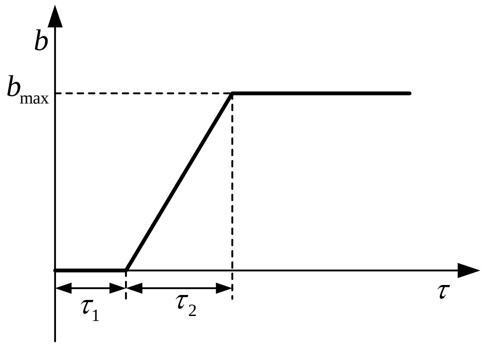

Fig. 4. Braking process of vehicle

In the above research scenario, when TV starts braking, HV will also take braking measures when it detects the TV braking. Assuming that the two vehicles are identical (braking, driving, steering and other characteristics and parameters are the same), the change of braking process is the same. τ_1 and τ_2 is the time corresponding to the two stages of braking process. Because τ_1 and τ_2 are very small in the braking process, the braking deceleration of TV is difficult to detect. Therefore, it is assumed that the braking of TV is braked with the maximum braking deceleration b_{tmax} after the braking system has worked $\tau_1 + \tau_2$ seconds, so the braking distance d_t of TV is

$$d_t = \frac{v_t^2}{2b_{tmax}} \tag{2}$$

The braking distance d_h of the car is

$$d_h = \left(\tau_1 + \frac{\tau_2}{2}\right) v_h + \frac{v_h^2}{2b_{hmax}} - \frac{b_{hmax}\tau_2^2}{24} \tag{3}$$

a_{hmax} represents the maximum deceleration of the HV,τ_2 is very small, $\frac{a_{hmax}\tau_2^2}{24}$ is neglected. a_{fmax} represents the maximum braking acceleration of a vehicle, which is

$$a_{fmax} = (\mu + sin\alpha)\mathrm{g} \tag{4}$$

Assuming that the two vehicles are identical (braking, driving, steering, etc.), the road conditions in the scenarios studied are the same, so the braking process is as follows:

$$a_{hmax} = b_{tmax} \tag{5}$$

Therefore

$$d_{min} = \left(\tau_1 + \frac{\tau_2}{2}\right) v_h + \frac{v_h^2 - v_t^2}{2b_{hmax}} + l \tag{6}$$

Considering the safety in the actual process, it is necessary to retain a certain margin of safety distance Δd

$$D_{min} = d_{min} + \Delta d \tag{7}$$

According to the above analysis, the smallest driving safety distance represents the most dangerous rear-end collision accident. When the relative distance increases, the dangerous degree decreases gradually. Therefore, the formulas for calculating $TTCi_{max}$ and THW_{min} are as follows:

$$TTCi_{max} = \frac{v_r}{D_{min}} \tag{8}$$

$$THW_{min} = \frac{D_{min}}{v_h} \tag{9}$$

In order to normalize the two methods without dimension, a comprehensive risk formula describing the degree of longitudinal hazard is proposed.

$$SRF_{long} = (w_1 \times f_{(TTCi,TTCi_{max})} + w_2 \times f_{(THW,THW_{min})}) \times \varepsilon_{(TTCi,THW)} \tag{10}$$

SRF_{long} (Synthetic Longitudinal Risk Feeling) in the formula denotes the longitudinal comprehensive risk degree, $f_{(TTCi,TTCi_{max})}$, $f_{(THW,THW_{min})}$ respectively denotes the relative motion risk factors and relative static risk factors established by $TTCi$ and THW, w_1 and w_2 are weights of $TTCi$ and THW, $TTCi_{max}$ denotes the maximum value of $TTCi$, THW_{min} denotes the minimum value of THW, and $\varepsilon_{(TTCi,THW)}$ is the function to be optimized.

Thus

$$w_1 + w_2 = 1 \tag{11}$$

In order to describe the non-linear change of dangerous degree in longitudinal driving process, an exponential description [15-16] is introduced.

$$f_{(TTCi,TTCi_{max})} = e^{\varsigma_1(\frac{TTCi}{TTCi_{max}}-1)} \tag{12}$$

$$f_{(THW,THW_{min})} = e^{\varsigma_2(\frac{THW_{min}}{THW}-1)} \tag{13}$$

Therefore, a comprehensive hazard formula describing the degree of longitudinal hazard is presented.

$$SRF_{long} = (w_1 \times e^{\varsigma_1\left(\frac{TTCi}{TTCi_{max}}-1\right)} + w_2 \times e^{\varsigma_2\left(\frac{THW_{min}}{THW}-1\right)}) \times \varepsilon_{(TTCi,THW)} \tag{14}$$

In the above formulas, $w_1, w_2, \varsigma_1, \varsigma_2$ are coefficients, and $TTCi_{max}$ and THW_{min} are obtained by analyzing the braking process of vehicles.

IV. Modeling of Lateral Collision Process

The simplified Research scenario in this paper is shown in Fig. 5 below. Because the corner collision and rubbing collision between vehicles can be regarded as a special case of side collision, the main research object of this paper is the side collision of vehicles in this scenario, in which host vehicle (HV) and the target vehicle (TV) are traffic participants. The side impact here is limited to the side body of the side car collided with the front of the car at a certain angle ($0° < \theta < 90°$). So, suppose that one side of the lateral conflict is straight, and the angle between the direction of motion and the direction of the road is 0 degrees [2]. Suppose that the geometry of the two vehicles is approximately the same and they move at a uniform speed. The speed $v_h cos\theta$ of the HV on the direction of the road is greater than the speed v_t of the TV.

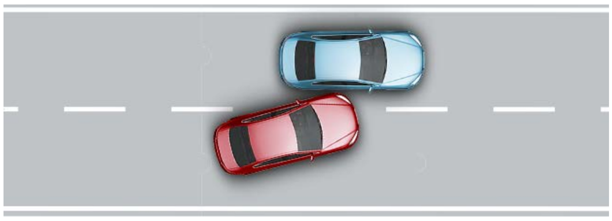

Fig. 5. Research scenario simplification

Because of the existence of vehicle body length, vehicle side collision may theoretically occur at any position from the front to the rear of the side body. Therefore, in the research scenario of this paper, the time of lateral collision is determined, but the change of the longitudinal speed of the vehicle in the lane direction will lead to side collision occurring at different locations of the side body of the TV, as shown in Fig. 6 below.

Fig. 6. A sketch of the lateral collision range

There are two extreme scenarios in the above-mentioned side collision scenarios: side collision occurs at the side head of the TV, and side impact occurs at the side tail of the TV. Two kinds of limit conditions for lateral collision and their sketches are shown in Fig. 6a and Fig. 6C. Assuming that the time of lateral collision is TTC_y and the time of longitudinal collision is TTC_x, the above analysis shows that the time interval of longitudinal collision exists $(TTC_{x_{min}}, TTC_{x_{max}})$. In order to be able to occur lateral collision, it is necessary to meet the corresponding requirements of the longitudinal relative position, while the lateral distance is zero.

$$TTC_y \in \left(TTC_{x_{min}}, TTC_{x_{max}}\right) \tag{15}$$

In the course of driving, the geometric relationships of the longitudinal and transverse distances d_x , d_y and the longitudinal and transverse distances D_x and D_y of the center of mass of the two vehicles are shown in Fig. 7.

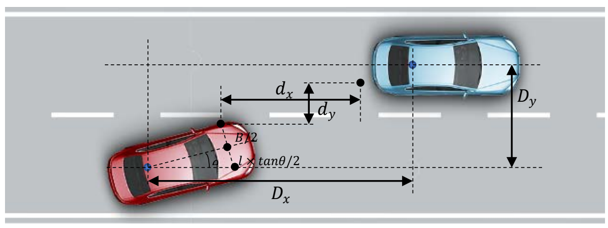

Fig. 7. Geometric relationship between edge and center of mass

Assuming the relative transverse distance between the two vehicle's center of mass is D_y, the transverse edge distance d_y between two vehicles can be approximately calculated from the geometric relations, the vehicle width B, the vehicle length l and the θ between two vehicles.

$$d_y = (D_y - \left(\frac{l}{2} \cdot tan\theta + \frac{B}{2}\right) \cdot cos\theta - \frac{B}{2} \tag{16}$$

The time of lateral collision TTC_y is

$$TTC_y = \frac{D_y - \left(\frac{l}{2} \cdot tan\theta + \frac{B}{2}\right) \cdot cos\theta - \frac{B}{2}}{v_h \cdot sin\theta} \quad (17)$$

In the formula, v_{h_y} denotes the lateral velocity of HV, which is perpendicular to the direction of the lane. When $D_y = 3.75$, the corresponding TTC_y at the time of lane change can be obtained.

The formulas for calculating the longitudinal edge distance d_x and the relative longitudinal distance D_x at the center of mass of the two vehicles are as follows.

$$d_x = D_x - \left[\frac{l}{2 \cdot cos\theta} - \left(\frac{B}{2} + \frac{l}{2} \cdot tan\theta\right) \cdot sin\theta\right] - \frac{l}{2} \quad (18)$$

Thus, the time range of longitudinal collision TTC_x can be obtained as follows:

$$TTC_{x_{min}} = \frac{D_x - \left[\frac{l}{2 \cdot cos\theta} - \left(\frac{B}{2} + \frac{l}{2} \cdot tan\theta\right) \cdot sin\theta\right] - \frac{l}{2}}{v_h \cdot cos\theta - v_t} \quad (19)$$

$$TTC_{x_{max}} = \frac{D_x - \left[\frac{l}{2 \cdot cos\theta} - \left(\frac{B}{2} + \frac{l}{2} \cdot tan\theta\right) \cdot sin\theta\right] + \frac{l}{2}}{v_h \cdot cos\theta - v_t} \quad (20)$$

According to the above analysis, the lateral collision time is:

$$TTC_y = \begin{cases} inf, while\ TTC_y > TTC_{x_{max}}\ or\ TTC_y < TTC_{x} \\ \frac{d_y}{v_{r_y}}, \quad while\ TTC_{x_{min}} < TTC_y < TTC_{x_{max}} \end{cases} \quad (21)$$

When $TTC_y \neq inf$, side collision will occur between HV and TV. According to the model of longitudinal collision process, the minimum safety distance of the center of mass in the lateral direction of HV with lateral motion is as follows.

$$D_{ymin} = D_{xmin} \cdot tan\theta \quad (22)$$

Considering the safety margin Δd, the minimum safety distance from the side of HV is

$$d_{ymin} = D_{ymin} - \left(\frac{l}{2} \cdot tan\theta + \frac{B}{2}\right) \cdot cos\theta - \frac{B}{2} + \Delta d \quad (23)$$

Lateral collision risk of vehicles is when $TTC_y \neq inf$, the vehicle will have the risk of lateral collision. In this case, the risk degree of lateral collision of vehicles will be evaluated. Once the TV is braked, there will be a great risk of collision if the minimum safe distance between the two vehicles is reached. Therefore, the lateral synthetical risk feeling ($SRF_{lateral}$) formula is established based on the minimum driving safety distance and the real-time distance between two vehicles.

$$0 < SRF_{lateral} = \frac{d_{ymin}}{d_y} = f(v_h, v_t, \theta, d, \mu, \alpha) < 1 \quad (24)$$

The established $SRF_{lateral}$ formula includes vehicle geometric parameters (l, B), vehicle motion parameters (v_h, v_t), vehicle dynamics parameters $(\tau_1, \tau_2, b_{hmax}, b_{tmax})$, vehicle relative position parameters (θ, d) and road parameters (μ, α), and considers the scene parameters of lateral collision. Therefore, the $SRF_{lateral}$ formula can describe the scene of lateral collision well, and use this description method, the formula can represent and evaluate the risk degree of different lateral collision risks in different collision scenarios.

When the real-time distance d_y between two vehicles is less than the minimum safe distance d_{ymin}, collision is very easy. In this case, $SRF_{lateral} = 1$.Therefore

$$SRF_{lateral} = \begin{cases} \frac{d_{ymin}}{d_y}, & while\ d_y \geq d_{ymin} \\ 1, & while\ d_y < d_{ymin} \end{cases} \quad (25)$$

The formula $SRF_{lateral}$, which is established in this section, is complete in describing lateral collision scenarios because it takes into account the scene parameters and the state parameters of traffic participants. The formula has the characteristics of dimensionless and standardization. It can characterize and evaluate the risk degree of different lateral collision risks in different collision scenarios, and better describe the lateral collision scenarios.

V. COMPREHENSIVE EVALUATION METHOD OF COLLISION RISK

In order to describe the collision risk of vehicles under general driving conditions, a comprehensive evaluation method SRF (Synthetical Risk Feeling) is proposed for the collision risk of intelligent vehicles. Because the collision may occur in both longitudinal and lateral directions, the vehicle is in a safe state when the vehicle is in a safe state both vertically and horizontally. When one of the vehicles is in danger of collision or both are in danger, the vehicle is in a dangerous state. Whether collisions occur in the longitudinal and lateral directions of vehicles can be expressed in terms of safety and danger. The combination of longitudinal and lateral state arrangements is shown in Table 1 below.

TABLE I. LONGITUDINAL AND LATERAL SAFETY STATUS AND VEHICLE SAFETY STATUS

Safety Status	Longitudinal Safety	Longitudinal Risk
Lateral Safety	Safe	Dangerous
Lateral Risk	Dangerous	Dangerous

Set the longitudinal and lateral collision risk thresholds as $SRF_{long\_warning}$ and $SRF_{lateral\_warning}$. When the longitudinal and lateral collision risk levels SRF_{long} and $SRF_{lateral}$ are lower than the corresponding risk threshold, they are considered safe.

IF $SRF_{lateral} < SRF_{lateral\_warning}$ && $SRF_{long} < SRF_{long\_warning}$

$SRF_{safe} = 1, SRF = max\{SRF_{lateral}, SRF_{long}\}$

ELSE

$$SRF_{safe} = 0, SRF = max\{SRF_{lateral}, SRF_{long}\}$$

In the above formula, SRF_{safe} is the symbol of comprehensive collision risk safety, SRF_{safe}=1 indicates that the risk of comprehensive collision is low and the vehicle is in a safe state, SRF_{safe}= 0 indicates that the risk of comprehensive collision is high and the vehicle is in a dangerous state.

Therefore, SRF can normalize the level of collision risk in different scenarios on the basis of synthesizing longitudinal collision risk assessment formula SRF_{long} and lateral collision risk assessment formula $SRF_{lateral}$, and the calculated value of collision risk is dimensionless. Since the classical time-distance models (such as $TTCi$, THW) and vehicle braking-based kinematics models are taken into account in the process of establishing SRF_{long} and $SRF_{lateral}$, the collision hazard model established from the geometric point of view is theoretically accurate.

VI. SUMMARY

In view of the problems existing in the current risk assessment methods, such as the lack of uniformity of standards, the large variation of numerical intervals, and the inconvenience of comparing the risk levels of different dangerous scenarios horizontally, this paper carries out relevant research, including the following three parts:①Based on the classical time-distance model and vehicle braking model, a description method of vehicle longitudinal collision risk degree and its SRF_{long} formula are proposed. ②Based on the mechanism of vehicle lateral collision and vehicle kinematics model, a description method of vehicle lateral collision risk degree and its $SRF_{lateral}$ formula are proposed. ③Longitudinal and lateral collision risk based on decoupling is presented. In this paper, a comprehensive evaluation method SRF for collision risk in general collision scenarios is proposed. The established collision risk assessment formula can standardize and dimensionless describe the level of collision risk in dangerous scenarios, and can be used for horizontal comparison of the degree of collision risk in different dangerous scenarios. It is also of great significance for the development and testing of intelligent driving. According to this method, a dangerous scene with a certain degree of dangerous collision can be constructed for the development and simulation test of unmanned driving function.

There are also some shortcomings in this study: there is no calibration of the coefficients in the longitudinal collision risk assessment formula, which requires a large number of real vehicle experimental data to be calibrated accurately; there is no design of relevant simulation experiments to simulate the lateral, longitudinal and established comprehensive collision risk assessment formula; the established evaluation method still needs verification and correction of the real vehicle data. This part of the work will be carried out in the following research.

REFERENCES

[1] Sun Weifu. Analysis and Prevention Countermeasures of highway traffic accidents based on data mining [D]. Jilin University, 2018.

[2] Xu Hanqing. Study on calculation model of lateral conflict index based on collision time [J]. Urban road and bridge and flood control, 2014 (06): 268-271+23.

[3] Lee D N. A theory of visual control of braking based on information about time-to-collision. [J]. Perception, 1976, 5 (4).

[4] Sou Kitajima et al, Representation of Danger of Rear-end Collision by Drive Video Record and Verification of Driver's Brake Operation, JSAE, 2007, 38 (4): 191-196

[5] Zhang Hui, Qiu Shaobo, Li Hongjian, et al. [C]// Academic Conference on Automobile Safety Technology. 2011.

[6] Siyu Lin, Zhiyuan Liu, Songyan Wang. Receding Horizon Control for Lateral Collision Avoidance of Intelligent Vehicles[C]. CIAC, 2017.

[7] Zhao Wei, Wei Lang, Zhang Huai. Study on lateral collision avoidance control strategy under parallel overtaking condition [J]. Journal of Zhengzhou University, 2008 (01): 83-87.

[8] Zhao Wei, Wei Lang, Zhang Huai. Fuzzy-PID control simulation of vehicle lateral collision avoidance system [J]. Journal of Nanchang University, 2008(02): 159-164.

[9] Peng Xianwu, Li Baichuan, Cheyong. Handling and Analysis of Driving Dangerous Points [J]. Road Traffic and Safety, 2006 (05): 21-24.

[10] Bian MingYuan. Safety vehicle distance model for active obstacle avoidance based on emergency lane changing strategy [J]. Journal of Chongqing University of Technology (Natural Science), 2012 (04): 1-4.

[11] Cheyong. Development and Research of Vehicle Lateral Anti-collision Early Warning System [D]. Chang'an University, 2007.

[12] Hu Tiehong. Research on the model of rear-end collision and lateral collision warning system of Expressway [D]. Chang'an University, 2004. [13] Automobile Theory [M]. Machinery Industry Press, Yu Zhisheng, 2009.

[13] Automobile Theory [M]. Machinery Industry Press, Yu Zhisheng, 2009

[14] Wang Bin. Risk Assessment and Trajectory Planning for Obstacle Avoidance of Intelligent Vehicles [J]. Automotive Technology, 2018 (06): 32-37.

[15] Jiang Q, Deng W, Zhu B. Integrated Threat Assessment for Trajectory Planning of Intelligent Vehicles[R]. SAE Technical Paper, 2016.

[16] Zhu B, Jiang Y, Zhao J, He R. et al., Typical-driving-style oriented Personalized Adaptive Cruise Control design based on human driving data, Transportation Research Part C: Emerging Technologies, Volume 100,2019,Pages 27