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Test Method and Risk Factor Definition of Forward Collision Warning System

JIAN WANG[1,2], XING ZHANG[1,2], HUI KANG[1,2], AND LINGYUE DENG[3]

[1]College of Computer Science and Technology, Jilin University, Changchun 130012, China
[2]Key Laboratory of Symbolic Computation and Knowledge Engineering of Ministry of Education, Jilin University, Changchun 130012, China
[3]Technology Development Department, Datang Mobile Communication Equipment Company, Ltd., Beijing 100083, China

Corresponding author: Hui Kang (kanghui@jlu.edu.cn)

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ABSTRACT In this paper, a test method of the forward collision warning (FCW) function is proposed and the forward collision risk factor is defined. Firstly, the concept of the minimum alarm distance is given according to the road scene and vehicle movement state, and then the calculation equation of the minimum alarm distance is derived by combining kinematics equation and driver's response time. We compare the actual vehicle distance and the minimum alarm distance to determine whether the FCW test is successful. The actual vehicle distance and the minimum alarm distance are used as the parameters to derive the calculation method of the vehicle's FCW risk factor. Finally, the test scenario is deployed in simulation software, and multiple test cases of FCW are established. By observing the simulation process and analyzing the experimental data, we found that the motion rule of the tested vehicle conforms to our theoretical analysis, and the experimental result is similar to the predicted result, so the conclusion is drawn: The FCW test method based on minimum alarm distance has confidence. At the same time, we conduct a comparative experiment on the hazard factor. The hazard factor we propose is applicable to more automatic driving conditions, and can be continuously output in the test process, which is more conducive to analysis.

INDEX TERMS Forward collision warning, risk factor, safe distance, simulation scenario test.

I. INTRODUCTION

A forward collision warning system is a mature vehicle warning system. The system can send an alarm signal in time before a car is about to crash, so as to remind the driver to take measures to avoid the impact. It is reported that a forward anti-collision system may prevent or reduce 70% of rear-end collisions and 20% of collision accidents [1]. In HLDI's study, FCW reduced the liability claim rate for property damage caused by traffic accidents by 7%-22%, including losses caused by negligent vehicles to other vehicles and property. At the same time, the rate of personal injury liability claim is reduced by 4-25%, which includes medical expenses incurred by malperforming vehicles for injuries to other drivers or passers-by [2]. It can be seen that the probability of rear-end collision of vehicles equipped with an FCW system is lower, and the loss caused by the accident is smaller. Therefore, the FCW system is of great significance to the driving safety of vehicles. At the same time, as one of the auxiliary driving functions, FCW needs strict test to ensure its reliability and safety.

We considered three traffic safety indicators: time-to-collision, time headway and safety distance.

Time-to-collision(TTC): TTC refers to the time that is required for a collision between front and rear vehicles that are driving at the same relative speed [3]. The general calculation method of TTC is:

$$TTC(i) = \frac{D}{v_i - v_{i-1}} \quad (v_i > v_{i-1}) \tag{1}$$

D is the distance between two cars, v_i is the speed of the car behind, v_{i-1} is the speed of the car in front. In research TTC has often been considered as a safety indicator, inversely related to accident risk (smaller TTC values indicate higher accident risks and vice versa) [4], [5]. To estimate the propriety of rear-end collisions, car followings model often use TTC as a surrogate measurement [6]. Based on the collision time, some studies propose an inverse collision time model that can be used in FCW [7]. In terms of calculation method, TTC involves few parameters, only speed and distance are required. As a safety index in safety analysis, TTC has

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been widely used, but there are still some limitations:(a)TTC only works for longitudinal scenarios. Longitudinal scenarios refers to the scene where only the longitudinal speed of the car changes. (b)The fixed threshold of TTC may not apply to all driving situations.

Time Headway(TH): TH is one of the indicators that is used to estimate the criticality of a certain traffic situation. It has been defined as the elapsed time between the front of the lead vehicle passing a point on the roadway and the front of the following vehicle passing the same point [8]. The comparison of headway distributions at a cross-section gives an indication about the positive or negative shifts in traffic safety [9]. The general calculation method of time headway is:

$$TH(i) = T_i - T_{i-1} \tag{2}$$

T_{i-1} is the moment when the car ahead passes a certain position, T_i is the moment when the vehicle behind passes through the same position. In the calculation method, the time headway involves the least parameters, which is easy to record and measure the data. For different road environment and driver state, TH will have significant difference [10], [11]. Different regions have different regulations on TH. Therefore, time headway is more suitable for execution purposes than as an evaluation indicator for safety testing [12].

Safety Distance: Safe vehicle distance refers to the necessary distance between the rear vehicle and the front vehicle in order to avoid accidental collision with the front vehicle. The general calculation method of safety distance is:

$$S = vT + \frac{v^2}{2a} - \frac{v_0^2}{2a_0} \tag{3}$$

v is the speed of the car behind, T stands for the driver's reaction time(Here we ignore the braking response time determined by the vehicle performance, which is generally very small), a is the deceleration of the car behind, v_0 stands for the speed of the car ahead, a_0 stands for its deceleration. By contrast, the formula for the safe distance model is the most complex, but it also takes into account more comprehensive factors. As an important part of a vehicle's active collision avoidance system, the safe distance model determines vehicle safety and road utilization [13]. In recent years, there have been more and more studies on safe distance and FCW (introduced in related work). In safety testing, distance can also be used as a safety criterion (for example, the likelihood of collision can be measured by comparing the actual distance between the car behind and the car in front with the safe distance of the car behind). Therefore, it is reasonable to take safety distance as the basic safety index.

Our test method includes two vehicles: the main vehicle and the target vehicle. Vehicle data is the basis of the test. In reality, can-bus can read the driving parameters of two vehicles, MV can obtain vehicle information of TV through V2I or V2V Technology (based on DSRC or lte-v2x communication technology) [14]–[17]. If it is V2I technology, MV can get TV information (such as speed, latitude and longitude, heading angle, etc.) by communicating with road side unit. If it is through V2V technology, both MV and TV are connected to the Internet and interact with each other through V2V. In the simulation environment, we can read the driving information of MV and TV (both simulation vehicles) in real time through the secondary development of simulation software. It is worth noting that no matter in the real or simulation environment, our assumption is that the MV is equipped with FCW function, while the TV is just a common vehicle to assist in the test, and does not have the ability of path planning, collision prediction, etc. Our method is to test the FCW function of MV on the premise that we can get the basic information of two vehicles.

According to different roads, we divided the test conditions into three types: straight road, curved road and intersection. On straight roads, MV is at a constant speed, and TV's state can be divided into static, decelerating and uniform speeds. In curves, the MV drives at a constant speed, and the TV state can be divided into static, decelerating and uniform speeds. For the condition of intersection, the speed direction of two vehicles is at a certain angle and they move in a straight line at a constant speed. In the process of two vehicles running, we calculate the actual distance between the two vehicles and the minimum alarm distance of MV. At the beginning of the test, the actual distance greater than the minimum alarm distance (the actual distance is gradually decreasing). If the main car issues an alarm during this period of time(when the actual distance is greater), the test is successful; otherwise, the test is failed.

To sum up, we have completed the following work:

(1) we propose the concept of minimum alarm distance for FCW;

(2) we proposed the test method of FCW according to the minimum alarm distance;

(3) we give the concept of FCW risk factor and conduct a comparative experiment with the existing coefficient –the coefficient we proposed has more advantages;

(4) we set up test scenarios, created test cases and conducted FCW tests in the simulation environment to verify our theory;

This paper analyzes and discusses the FCW function test. In the introduction, we analyze three common safety indicators, and select distance as the index of this paper. Then we discuss how to obtain the vehicle data in the simulation environment and the real environment, and explained our testing ideas. Finally, we list our work and contributions. In related work, we mainly analyze some studies related to FCW and safety distance, and find that distance is one of the factors often considered in FCW research. In methods, we define the minimum alarm distance under different road conditions and give the corresponding algorithm. Then, the definition of the risk factor is proposed and theoretically compared with the existing risk factor. In the results part, we analyze the simulation results based on the minimum alarm distance and explain the advantages of the risk factor that is defined in this paper. It is also shown that our test method is feasible. In conclusion part, we explained the practical implications of our testing methods and risk factors and proposed ideas for future research.

II. RELATED WORK

So far, there have been many researches on FCW. Some studies use calibrated micro-simulation models to evaluate six FCW algorithms at the network level [18]. Some researchers find that some vehicle warnings could not be triggered at lower speeds [2], so we focus our tests on low-speed conditions. In addition, by analyzing the equation of safe distance, some researchers give a liability sensitive safety model for self-driving cars [19]. The University of California has proposed three reference standards for the development of a front collision warning system and defined the collision risk factor [20]. We improved the coefficient and proposed a new risk factor, which is suitable for more FCW conditions.

In terms of the safe distance, Hanyang University of Korea considered the variation of the tire-road adhesion coefficient, offered a calculation equation for determining the safe distance, and proposed the tire adhesion calibration function [21]. Some researches have proposed a method for accurately measuring the distance of a vehicle in an FCW system using a monocular camera and found that the method can improve the performance of the FCW system [22]. Some scholars have proposed a hierarchical safe distance algorithm, and combined FCW with ACC (Adaptive Cruise Control) to provide a stable vehicle control strategy [23]. Mazda proposed a safe braking distance algorithm based on speed, acceleration, system delay and head offset. This method can theoretically avoid collisions during all dangerous conditions, but this method is somewhat conservative and may cause the drivers to ignore the brake warnings [24]. Honda gives a braking critical distance algorithm [25]. This algorithm to some extent reduces the influence of the system on the normal driving of the driver. One study introduced the safe distance into the car-following model and found that the new model is superior to the existing FVD model [26]. Some researchers have analyzed the impact of the safe distance on the traffic flow and traffic safety from a macro perspective [27].

III. METHODS

Before we begin our research, we propose some hypotheses: a) The measure to avoid collision is braking. Steering and braking are often used by drivers to avoid collision [28]–[31]. Considering some special circumstances, the vehicle can't turn (for example, when the front vehicle is in emergency braking, there are vehicles in the left and right lanes of the rear vehicle). So the vehicle brake is considered in this paper; b) Driver response time (T) is a fixed value in simulation. In fact, different drivers have different reaction time [32]–[34], but they can fall in a range (for example, in case of an emergency, T is about 0.5s-1.5s [35]). In the real car test, the T that conforms to the driver's habit can be selected; c)MV and TV brake at maximum deceleration(In our experiment is 6m/s^2). This deceleration is the maximum deceleration the driver can achieve [36]. The TV is an active brake, so the deceleration is controlled;Since MV is a passive brake, its deceleration is related to the specific driver [37], the deceleration will also fall into an interval usually. The value of deceleration can be adjusted according to the specific situation during the real vehicle test.

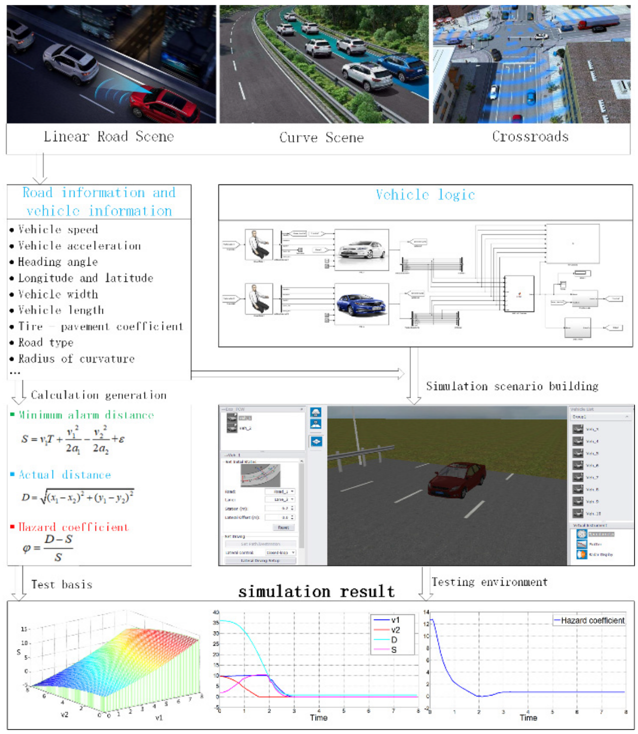

FIGURE 1. The whole process of this paper from theory to experiment.

As shown in Fig.1, we first summarized the basic parameters needed for FCW test according to road conditions and vehicle conditions. Based on the parameters, we deduce the equation of minimum alarm distance and hazard factor. We built three types of FCW simulation test environment based on collision avoidance logic and basic parameters of the tested vehicle. Finally, FCW test is carried out on the simulation platform. We summarizes some of the necessary parameters in Fig.2. We will describe in detail the minimum alarm distance and hazard factor.

A. MINIMUM ALARM DISTANCE

1) STRAIGHT ROAD

We define S as the minimum distance at which the vehicle issues an FCW alarm. According to the different states of MV and TV, S will have different calculation methods. We divide the straight road scene into two parts: First, MV driving speed is constant, and the TV is in a static or emergency braking state. Second, the transmission speed of MV is constant, while the transmission speed of TV is constant and slower.

As shown in Fig.3, it is assumed that when the MV issues an alarm, the two vehicle speeds are v_1 and v_2, respectively. In this case, we obtain the expression of S:

$$S = v_1 T + \frac{v_1^2}{2a_1} - \frac{v_2^2}{2a_2} + \varepsilon \tag{4}$$

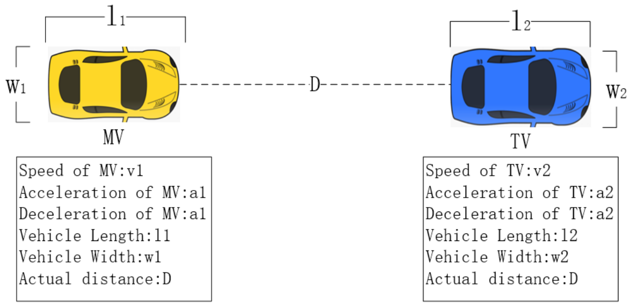

FIGURE 2. Description of some basic vehicle parameters.

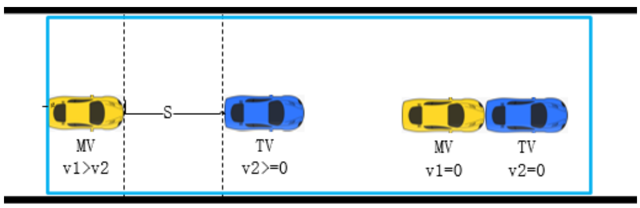

FIGURE 3. Initial and terminated state of the vehicle in a straight scene, MV is running at a constant speed, and TV is braking or stationary.

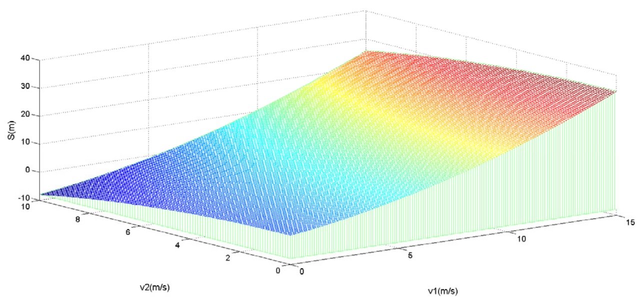

FIGURE 4. Relationship between S, v_1, and v_2.

In equation (4), the MV issues an FCW alarm when the MV is located behind the TV, the longitudinal distance between the two vehicles is S, and the lateral distance is less than $(w_1 + w_2)/2$. After the time interval T, the MV decelerates at the maximum deceleration of a_1. If the TV is braking at this time, when both the MV and the TV decelerate to a standstill, the distance between the guiding surface of the MV and the trailing surface of the TV is less than or equal to a small positive number ε. If the TV is at rest, the expression for S is as follows:

$$S = v_1 T + \frac{v_1^2}{2a_1} + \varepsilon \tag{5}$$

According to (4), S is affected by v_1 and v_2, as shown in Fig. 4. The range of v_1 is [0, 15] m/s, and the range of v_2 is [0, 10] m/s. The value of T is 1s. $a_1 = a_2 = 6\text{m/s}^2$. The value of ε is 0.5m. It can be seen that the change of S is relatively flat. As v_1 and v_2 decrease, S gradually approaches 0.

In another case (shown in fig.5), the expression of S is:

$$S = (v_1 - v_2)T + \frac{(v_1 - v_2)^2}{2a_1} + \varepsilon \tag{6}$$

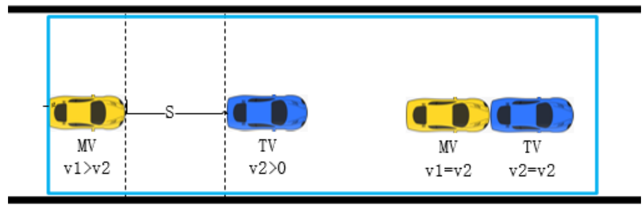

FIGURE 5. Initial and terminated state of the vehicle in a straight scene, MV runs at a constant speed, TV travels at a lower constant speed.

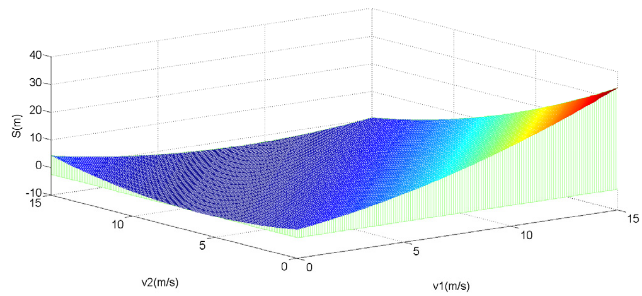

FIGURE 6. Relationship between S, v_1 and v_2.

In equation (6), $v_1 > v_2$, assuming that the MV issues an FCW alarm. after time T the MV decelerates, and the TV maintains a constant speed. When v_1 is reduced to be equal to v_2, the distance between MV and TV is less than or equal to a small positive number ε.

Fig.6 shows the change of S when the initial state of the two cars is constant. The range of v_1 is [5,15] m/s, and the value of v_2 is 5 m/s. The value of T is 1s. $a_1 = 6\text{m/s}^2$. The value of ε is 0.5 m. As seen from Fig.6, when the vehicle speed is reduced to 5 m/s, S is close to 0.

For the above two cases, if the MV sends an FCW alarm when $D > S$ is satisfied, the test is successful; otherwise, the test fails.

2) CURVED ROAD

Similar to straight road, D represents the actual distance between MV and TV on the curve road. The ground sliding friction coefficient is μ. We divide the curve scene into two categories according to the vehicle state. The first is that the MV travels at a constant speed, and the TV is stationary or conducting emergency braking. The second is that the MV travels at a constant speed, and the TV is traveling at a lower speed. We stipulate that the vehicle under test can always travel smoothly according to the curvature radius of the road. (keep a fixed transverse distance from the lane line during driving).

For curved roads, we cannot directly use the kinematics equation to calculate the distance. When the vehicle emergency braking, the deceleration speed is provided by ground friction, so the kinetic energy theorem is used to calculate the alarm distance.

The movement of the car on the curve is nonuniform motion during the deceleration of the car. We can use the microelement method to infinitely subdivide the curve into n segments. Each segment can be regarded as a uniform deceleration linear motion. We use W_i for work done by external forces. E_i represents the energy that is generated by each segment of the vehicle due to motion. Therefore, we have the following:

$$\begin{aligned} W_1 &= E1 - E0 \\ W_2 &= E2 - E1 \\ &\dots \\ W_n &= En - E(n-1) \end{aligned} \tag{7}$$

Summing the above equation, we can get:

$$W = \sum_{i=1}^{n} Wi = W1 + W2 + \ldots + Wn = En - E0 \tag{8}$$

From the kinetic energy theorem and the definition of Ei, the expression of Ei can be obtained as follows:

$$Ei = \frac{1}{2} mvi^2 \tag{9}$$

m represents the quality of the car, and vi represents the speed of the car on each segment.

The expressions obtained by (8) and (9) are:

$$W = En - E0 = \frac{1}{2} m(vn^2 - v0^2) \tag{10}$$

The car can always follow the radius of the curvature of the curve. Therefore, when the car starts to brake, the sliding friction of the car goes backwards along the tangential direction of the curve, which is recorded as F. The driving distance S' of the car is infinitely subdivided into n segments, and each segment has a length of S_i'(i = 1, 2…n), then the work done by the friction force on each section is:

$$W_i = FS_i' \tag{11}$$

For n segments:

$$\begin{aligned} W_1 &= FS_1' \\ W_2 &= FS_2' \\ &\dots \\ W_n &= FS_n' \end{aligned} \tag{12}$$

Available from (12):

$$W = F \sum_{i=1}^{n} S_i' \tag{13}$$

Known by the definition of S_i:

$$S' = \sum_{i=1}^{n} S_i' \tag{14}$$

According to the definition of sliding friction:

$$F = -\mu mg \tag{15}$$

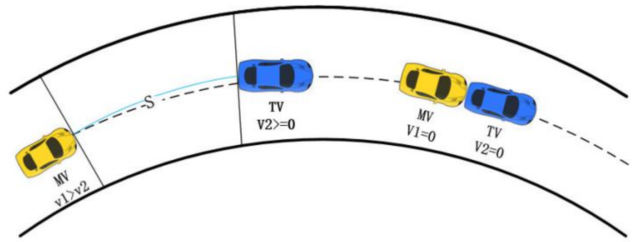

FIGURE 7. Initial and terminated state of the vehicle in the corner scene, MV travels at a constant rate, TV is braking or stationary.

μ is the sliding friction coefficient, g is the local gravity acceleration. We combine (10), (13), (14) and (15) to derive the kinetic energy theorem of the whole system:

$$-\mu mgS = \frac{m}{2}(v_n^2 - v_0^2) \tag{16}$$

We get the expression of S:

$$S = -\frac{v_n^2 - v_0^2}{2\mu g} \tag{17}$$

As shown in Fig.7, since the speed of the MV does not change, the kinetic energy theorem cannot be used to calculate the curve distance of the MV at time T. Therefore, we use calculus to derive the distance that is traveled by the MV during the time T.

The curve is wirelessly subdivided into n segments, and each segment is labeled as Δs. Divide T into n time periods, and record each period as Δt. Because the direction of v_1 at each moment is the tangent direction of the curve and the size does not change, we have the following equation:

$$v = \frac{\Delta s}{\Delta t} \tag{18}$$

From the above equation, we can get:

$$s = v \int dt = vt \tag{19}$$

Therefore, the curve distance of the MV is $S1 = v1T$.

Suppose that when the FCW alarm is issued from the MV until it stops completely, the moving distance of MV is $D1$ and the moving distance of TV is D_2. According to the definition of the minimum alarm distance, the expression of S can be:

$$S = D_1 - D_2 + \varepsilon = v_1 T + \frac{v_1^2 - v_2^2}{2\mu g} + \varepsilon \tag{20}$$

When the distance between MV and TV is S, MV gives an alarm and then starts to slow down. When the velocities of MV and TV are both 0, the distance between MV and TV is less than or equal to a small positive number ε. As shown in Fig.8, the range of v_1 is [0,15] m/s, the value of v_2 is 0 m/s, the value of T is 1s, and $\varepsilon = 0.5$m. It can be seen that the distance changes smoothly on the curve road. When the velocity of MV is reduced to 0, S is also close to 0. For the above two cases, if the MV issues an FCW alarm when $D >= S$ is met, the test passes; otherwise, the test fails.

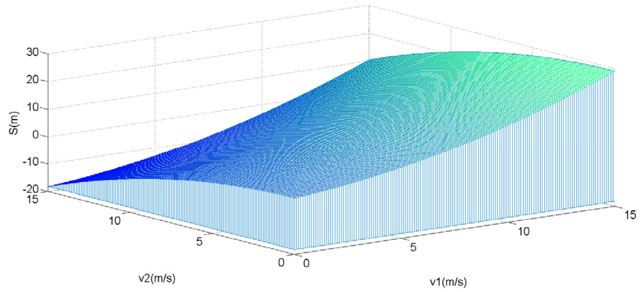

FIGURE 8. Relationship between S, v_1 and v_2 in a curve.

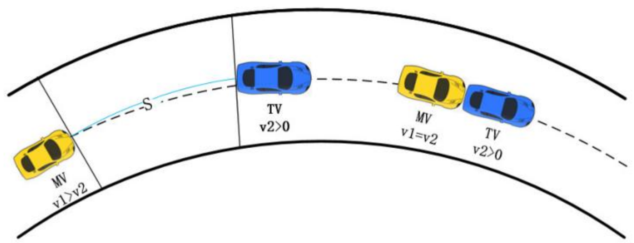

FIGURE 9. Initial and terminated state of the vehicle in the corner scene, MV travels at a constant rate, and the TV travels at a lower speed.

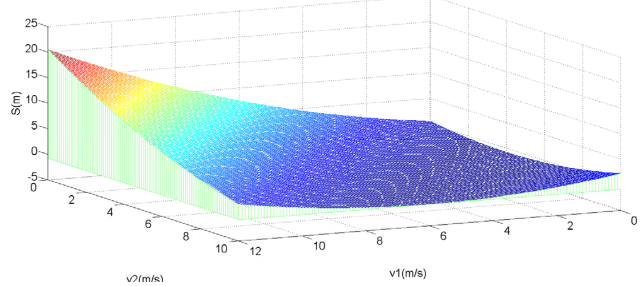

FIGURE 10. Relationship between S, v_1, and v_2 in a curve.

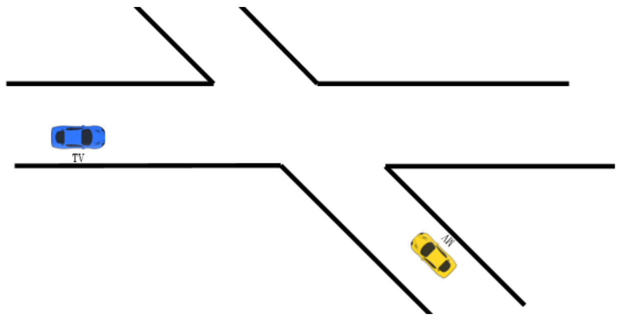

FIGURE 11. Intersection scenario.

As shown in Fig.9, in this scenario, the speed of the TV has never changed. The MV is decelerating along the curve. Since the direction of sliding friction is opposite to the direction of velocity, and the magnitude of friction is fixed (determined by sliding friction coefficient), the change of velocity is actually the integration of deceleration and time, as shown below:

$$\Delta v = -\mu g \int dt = -\mu g t \tag{21}$$

For MV:

$$\Delta v = v_2 - v_1 \tag{22}$$

According to (21) and (22), t can be calculated:

$$t = \frac{v_1 - v_2}{\mu g} \tag{23}$$

Suppose that when the speed of MV decreases to the same as that of TV, MV will give an alarm. At this time, the moving distance of MV is D_1, and the moving distance of TV is D_2. According to (23) and the kinetic energy theorem, the expression of S is as follows:

$$S = D_1 - D_2 + \varepsilon = (v_1 - v_2)T + \frac{(v_1 - v_2)^2}{2\mu g} + \varepsilon \tag{24}$$

S is defined as follows: when the MV issues an FCW alarm, the curve distance between the MV and the TV is S, and the driver starts to slow down after receiving the alarm. When $v_1 = v_2$, the distance between MV and TV is less than a smaller positive number ε.

In Fig.10, the initial size of v_1 is 12 m/s, and the initial size of v_2 is 10 m/s. The value of T is 1s. $\varepsilon = 0.5$m. When v_1 is reduced to 10 m/s, S is a positive number close to 0. For this case, if the vehicle issues an FCW alarm when $D >= S$ is satisfied, the test passes; otherwise, the test fails.

3) INTERSECTION

There is an angle between the two vehicles at an intersection (see Fig.11), so it is necessary to determine whether the two vehicles will collide. For this, we analyze the relative position of the vehicles.

The angle is defined using an obtuse angle or an acute angle. In Fig.12, the distance between the center of the MV and the TV is a. The angle between the driving direction of the two vehicles and the connecting line of the center of the two vehicles is r_1 and r_2 respectively. Z is a possible collision point of the two cars. The distances from the center of the two cars to Z are c and b. Both cars are in uniform motion. The coordinates of MV and TV are (x_1, y_1) and (x_2, y_2), then we get:

$$a = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \tag{25}$$

$$b = \frac{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \sin r1}{\sin(180 - r_1 - r_2)} \tag{26}$$

$$c = \frac{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \sin r2}{\sin(180 - r_1 - r_2)} \tag{27}$$

We approximate the car as a rectangle. The critical conditions for the collision of the two vehicles are discussed under the conditions that the angle is obtuse or the angle is acute.

In Fig.13(a), MV and TV are the actual positions of the two vehicles, MV1 and TV1 are the critical positions. After reaching the critical positions, the two cars will not collide again. When in the critical state that is shown in Fig.13(a),

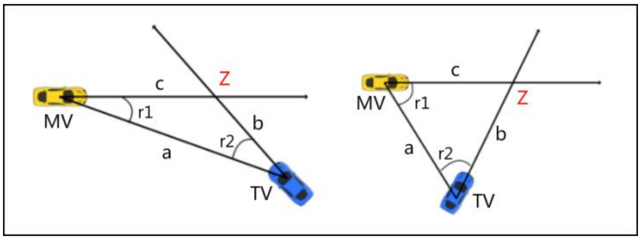

FIGURE 12. Relative position of the vehicle.

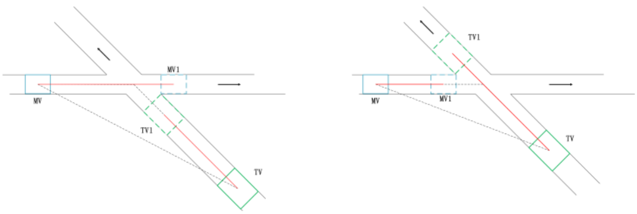

FIGURE 13. Critical position of obtuse angle. (a) and (b) are two collision critical cases.

the distance between actual position and critical position of the two vehicles is as follows:

$$D_1 = c + \frac{l_1}{2} + \frac{w_2}{2\sin(r_1 + r_2)} + \frac{w_1}{2\tan(r_1 + r_2)} \quad (28)$$

$$D_2 = b - \frac{w_1}{2\sin(r_1 + r_2)} - \frac{w_2}{2\tan(r_1 + r_2)} - \frac{l_2}{2} \quad (29)$$

When the TV reaches the position of TV1, we compare D and D_1 (D is the actual distance of the MV at this time). If $D >= D_1$, there is no risk of collision. If $D < D_1$, we consider the situation in Fig.13(b). Fig. 13(b) is another critical state in which the two cars collide. The distance between the actual position of the two vehicles and the critical position is calculated as follows:

$$D'_1 = c - \frac{w_1}{2\tan(r_1 + r_2)} - \frac{w_2}{2\sin(r_1 + r_2)} - \frac{l_1}{2} \quad (30)$$

$$D'_2 = b + \frac{w2}{2\tan(r_1 + r_2)} + \frac{w1}{2\sin(r_1 + r_2)} + \frac{l_2}{2} \quad (31)$$

When the angle between the two vehicles is an obtuse angle and the driving distance of the TV is D_2, if $D >= D_1$, there is no risk of collision. Other way, when the driving distance of the TV is D'_2, if $D <= D'_1$, there is no risk of collision. Similar to the obtuse angle case, we calculate the distance between vehicles at an acute angle. For Fig.14(a), there are:

$$D_1 = c + \frac{w_1}{2\tan(180 - r_3)} + \frac{w_2}{2\sin(180 - r_3)} + \frac{l_1}{2} \quad (32)$$

$$D_2 = b - \frac{w_2}{2\tan(180 - r_3)} - \frac{w_1}{2\sin(180 - r_3)} - \frac{l_2}{2} \quad (33)$$

For Fig.14(b):

$$D'_1 = c - \frac{w_1}{2\tan(180 - r_3)} - \frac{w_2}{2\sin(180 - r_3)} - \frac{l_1}{2} \quad (34)$$

$$D'_2 = b + \frac{w2}{2\tan(180 - r_3)} + \frac{w_1}{2\sin(180 - r_3)} + \frac{l_2}{2} \quad (35)$$

In the above equations: $r_3 = r_1 + r_2$.

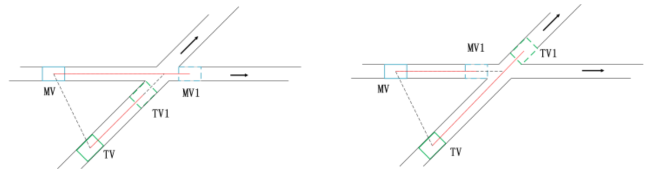

FIGURE 14. Critical position with acute angle. (a) and (b) are two collision critical cases.

Therefore, when the driving distance of the TV is D_2, if $D >= D_1$, there is no risk of collision. Other way, when the driving distance of the TV is D'_2, if $D <= D'_1$, there is no risk of collision. When it is determined that a collision will occur, if the MV issues an alarm when $S < D'_1$ is satisfied, the test is successful, otherwise the test fails.

B. RISK FACTOR

Based on alarm distance and actual distance, we propose a method for grading the risk of FCW. Prior to this, we analyze the existing collision risk factor k[20].

$$k = \frac{d - d_{br}}{d_w - d_{br}} \quad (36)$$

$$d_{br} = (v_c - v_p)tr + f(u)\frac{v_c^2 - v_p^2}{2a} \quad (37)$$

In the above equations, dw is a warning safety distance, $dw = d_{br} + v_c t_{\min}$. d_{br} is the brake safety distance. d is the actual distance. v_c is the speed of the main car (v_1 in this article), v_p is the speed of the target car (v_2 in this article). tr is the delay time of the collision avoidance system, $f(\mu)$ is the tire-ground friction coefficient influence factor, where $f(\mu) = 1$. $t_{\min}$ is the minimum time allowed by the driver (corresponding to T in this paper).

So there is $k = \frac{d - d_{br}}{v_c t_{\min}}$.

There are two problems with this model. First, the minimum distance between the front and rear vehicles is not taken into account when calculating the safe braking distance. This will result in the critical distance being too low when the two vehicles are stopped, and there is the possibility of a collision. Second, when v = 0 or is very close to 0, there will be a case where the denominator approaches 0, which affects the computational continuity of k. We propose the definition of the FCW risk factor as follows:

$$\varphi = \frac{D - S}{S} \quad (38)$$

where φ is the risk factor, D is the distance of the MV from the collision point, and S is the minimum alarm distance of the MV. When $\varphi >= 0.5$, the vehicle is in a safe state; When $0 < \varphi < 0.5$, the vehicle does not need to issue FCW warning in theory, but the closer φ is to 0, the higher the urgency of the vehicle alarm, which can be graded to give different levels of safety reminders(Such as voice prompts, tactile vibrations, etc [38,39]). When $\varphi = 0$, it is at the critical point of the risk factor, the vehicle must give an FCW alarm. When the

FIGURE 15. **Simulation process for a straight scene.**

system detects $\varphi < 0$, it should trigger the active braking of the vehicle.

By comparing k and φ, we can find that the risk grading methods are similar, and both can realize the vehicle collision warnings. For k, there may be a case where the denominator is 0, and the value of k is undefined, which will affect the analysis of the risk factor. For φ, there will be no undefined situation, because the denominator can be controlled by parameter ε to be positive. We can continuously output the risk factor during the experiment, thus reflecting the danger of the forward collision warning of the main car during the whole driving process. Furthermore, ε can make the two cars have a relative distance at the end of the real vehicle test, which ensures the safety of the test.

IV. RESULTS

According to the above ideas, we build a test scene using the car driving simulation software Panosim. Simulations are critical for the automated driving tests of modern vehicles, which can significantly reduce costs and time and improve efficiency and safety compared to real vehicle test [40]. Therefore, we verify the function of FCW in the simulation scene.

A. STRAIGHT ROAD SIMULATION

We take the experimental data 1 as an example (shown in Table 1). The simulation process is shown in Fig.15. From left to right, the figure represents the changes of the vehicle position at the beginning of the experiment, during the experiment and at the end of the experiment. As shown in Fig.16(a), during the whole experiment, the TV decelerates, and v_1 remains unchanged at the beginning of the experiment.

Because $v_1 > v_2$, the distance between the two cars is decreasing. When D is close to S, the relationship between D and S affects the change of v_1. The decrease in v_1 also causes a change in S, and S begins to decrease.

B. CURVE SCENE SIMULATION

The experimental data for this scene are shown in Table 2. We use the distance equation and chord length equation of two-dimensional coordinate system to calculate the arc length. In the Panosim coordinate system, R is the radius of the curve, and the (0,0) point is the origin. The MV's coordinates are (x_1, y_1), and the TV's are (x_2, y_2). Then the distance D is calculated as follows:

$$D = 2R\arcsin(\frac{\sqrt{(x_1 - x_1)^2 + (y_1 - y_2)^2}}{2R}) \tag{39}$$

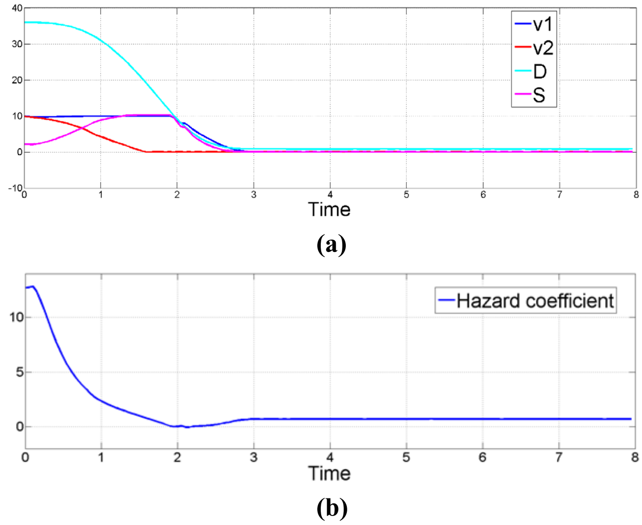

FIGURE 16. **Data analysis of experimental results.**

FIGURE 17. **Simulation process on a curve.**

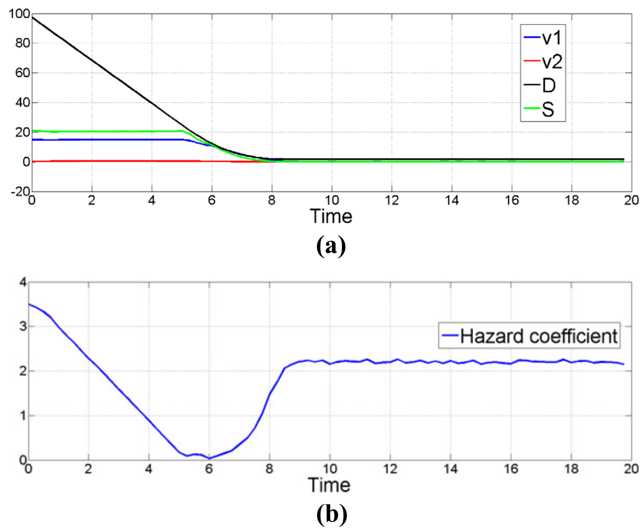

FIGURE 18. **Experimental results and data. (a) represents the change of speed (v1, v2), actual distance (D) and minimum alarm distance (S) over time. (b) represents the change of hazard coefficient.**

Taking experimental data 2 as an example, the simulation process is shown in Fig.17. The experimental results and data analysis are shown in Fig.18.

In Fig.18(a), D is linearly reduced, which indirectly proves the rationality of (19). During the experiment, the TV is always at rest, the change of S is determined by v_1. MV moves at a uniform rate at the beginning of the experiment. When D approaches S, the MV sounds an alarm and starts to decelerate. When the speed is reduced to 0, the distance between

TABLE 1. Experimental data for straight scenes.

Serial number	Initial state (MV)	Initial state (TV)	Initial speed (MV)	Initial speed (TV)	Deceleration value(MV)	Deceleration value(TV)	Vehicle distance
1	Uniform speed	Deceleration	10m/s	10m/s	6m/s²	6m/s²	40m
2	Uniform speed	Deceleration	15m/s	10m/s	6m/s²	6m/s²	50m
3	Uniform speed	Static	5m/s	0m/s	6m/s²	-	30m
4	Uniform speed	Static	10m/s	0m/s	6m/s²	-	40m
5	Uniform speed	Uniform speed	10m/s	5m/s	6m/s²	-	40m
6	Uniform speed	Uniform speed	15m/s	5m/s	6m/s²	-	50m

TABLE 2. Experimental data for corners.

Serial number	Initial state(MV)	Initial state(TV)	Initial speed(MV)	Initial speed(TV)	Deceleration value(MV)	Deceleration value(TV)	Vehicle distance
1	Uniform speed	Static	10m/s	0m/s	6m/s²	-	100m
2	Uniform speed	Static	15m/s	0m/s	6m/s²	-	100m
3	Uniform speed	Uniform speed	15m/s	10m/s	6m/s²	-	70m
4	Uniform speed	Uniform speed	12m/s	10m/s	6m/s²	-	50m

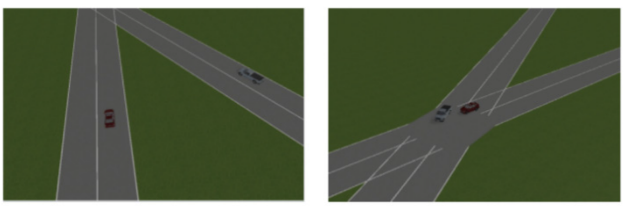

FIGURE 19. Intersection simulation process.

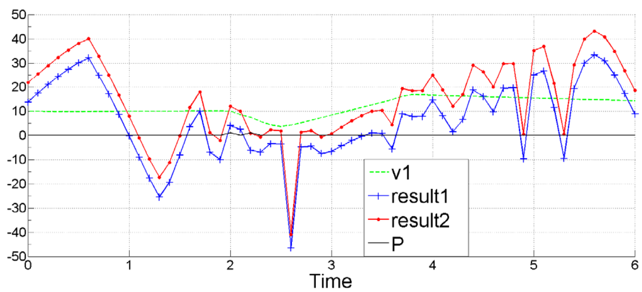

FIGURE 20. Experimental results and data analysis.

MV and TV is also close to 0. At this time, the two cars are stationary and the experiment ends.

The experimental data changes in line with the simulation process. The risk factor in Fig.18(b) is close to 0 when $t = 5s$, and the MV also starts to slow down in Fig.18(a).

C. INTERSECTION SIMULATION

We set up a simulation experiment with the angle of the speed as an acute angle. The experimental data are shown in Table 3. Taking experimental data 2 as an example, the simulation process is shown in Fig.19.

At the beginning of the simulation, the two cars are driving at the same speed. When the MV (the red car in the picture) determines that a collision will occur, the MV will sound an alarm and start to decelerate. After the TV exits the collision range, the MV continues to travel in the original direction, and the two cars do not collide.

The experimental results are shown in Fig.20. In the figure, $result_1 = D - D_1$, $result_2 = D - D_1'$, v_1 is the speed of the MV. $P = 1$ means that the MV issues an FCW alarm. At $t = 2.1s$, the MV sends out the FCW alarm and starts to decelerate. At $t = 2.6s$, the distance between the two vehicles is the smallest during the whole simulation. If the two cars do not collide at this time, there will be no collision in the future. Fig.19 and Fig.20 show that the experimental MV issued an FCW alarm at the intersection in time, and the test was successful.

D. COMPARISON OF TWO RISK FACTORS

We compare the hazard coefficient k that is defined by (36) with the hazard coefficient φ that is defined by (37) on a straight road.

TABLE 3. Intersection experimental data.

Serial number	Speed(MV)	Speed(TV)	Deceleration value(TV)	Angle of direction
1	5m/s	5m/s	$6m/s^2$	<90°
2	10m/s	10m/s	$6m/s^2$	<90°
3	15m/s	15m/s	$6m/s^2$	<90°

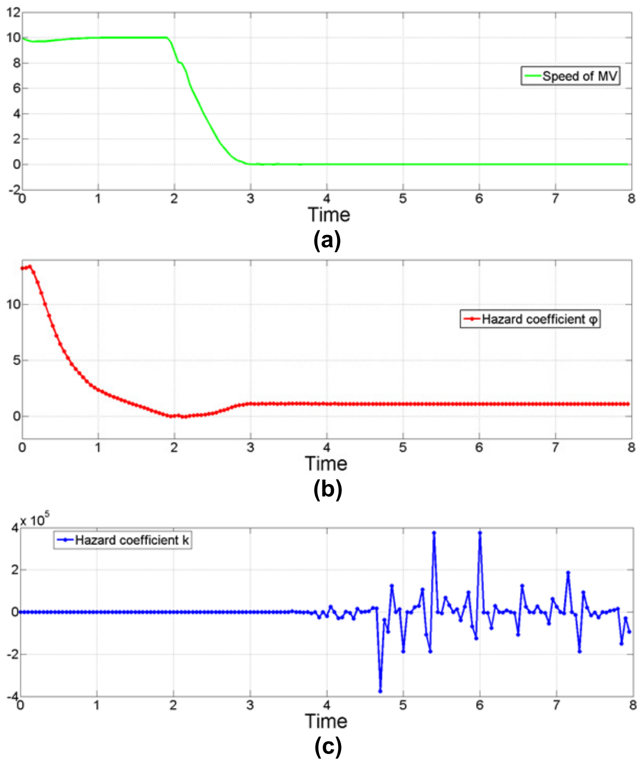

FIGURE 21. Comparison of risk factors. (a) is the change curve of MV's speed. (b) and (c) are the risk factors of two different algorithms.

As shown in Fig.21, comparing (a), (b), and (c), it is found that when the vehicle speed is not 0, the two risk coefficient curves are smoothly change. However, when the vehicle speed is reduced to 0, φ remains unchanged, but k has obvious fluctuations. In fact, the two cars have stopped, there is no danger of a collision, and k should be a fixed constant. Compared with k, φ can not only reflect the risk of forward collision, but also ensure the continuity of data recording.

V. CONCLUSION

We propose a method to test whether the FCW is a timely alarm, and propose the risk factor to describe the collision risk. In a simulation environment, the virtual vehicle with collision avoidance logic is tested multiple times, and the test data are visualized in MATLAB. It is found that our method provides good results. For the actual situation, vehicle parameters can be obtained through CAN and V2X technology, and the actual distance, minimum alarm distance and risk coefficient can be calculated in real time during driving, so as to evaluate the FCW performance of the tested vehicle. For the sake of safety, it is recommended to input parameters (initial speed, driver reaction time, maximum reduced speed, etc.) into the simulation environment for multiple tests before the actual vehicle test, so as to save costs and reduce unnecessary losses. The risk factor can be used as an observation value in the FCW test, and can also be applied to the actual situation, where the risk is graded according to the size of the coefficient (for example, it can be applied to collision avoidance algorithm based on trajectory prediction, so that drivers can know their collision risk at any time).

In our study, we assume that the driver's reaction time(T) and vehicle deceleration(a) are fixed, but in fact these parameters vary according to the specific situation. In the future work, we can use interval mathematics to improve the formula of S. S may change from a unique value to a value with a range (affected by T and a). At the same time, the packet loss rate exists in the actual vehicle communication. In the future, the influence of packet loss on our method can be considered to improve the test method.

REFERENCES

[1] J. S. Jermakian, "Crash avoidance potential of four passenger vehicle technologies," *Accident Anal. Prevention*, vol. 43, no. 3, pp. 732–740, May 2011.

[2] J. B. Cicchino, "Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates," *Accident Anal. Prevention*, vol. 99, pp. 142–152, Feb. 2017.

[3] R. van der Horst and J. Hogema, "Time-to-collision and collision avoidance systems," in *Proc. 6th ICTCT Workshop-Saf. Eval. Traffic Syst., Traffic Conflicts Other Measures*, Oct. 1993, pp. 109–121.

[4] D. Gettman, and L. Head, "Surrogate safety measures from traffic simulation Models," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 1840, no. 1, pp. 104–115, 2003.

[5] C. Oh and T. Kim, "Estimation of rear-end crash potential using vehicle trajectory data," *Accident Anal. Prevention*, vol. 42, no. 6, pp. 1888–1893, 2010.

[6] L. Hajar, R. Khadija, and M. D. Rahmani, "A modified full velocity difference model based on time to collision as a safely indicator for braking state," in *Proc. 2nd World Symposium Web Appl. Netw. (WSWAN)*, Mar. 2015, pp. 1–6.

[7] R. J. Kiefer, D. J. LeBlanc, and C. A. Flannagan, "Developing an inverse time-to-collision crash alert timing approach based on drivers' last-second braking and steering judgments," *Accident Anal. Prevention*, vol. 37, no. 2, pp. 295–303, Mar. 2005.

[8] C. A. Soderstrom, "Traffic safety and the driver," *J. Amer. Med. Assoc.*, vol. 270, no. 1, p. 99, 1993.

[9] M. M. Minderhoud and P. H. L. Bovy, "Extended time-to-collision measures for road traffic safety assessment," *Accident Anal. Prevention*, vol. 33, no. 1, pp. 89–97, Jan. 2001.

[10] M. Taieb-Maimon and D. Shinar, "Minimum and comfortable driving headways: Reality versus perception," *Hum. Factors, J. Hum. Factors Ergonom. Soc.*, vol. 43, no. 1, pp. 159–172, Mar. 2001.

[11] T. A. Ranney, "Psychological factors that influence car-following and car-following model development," *Transp. Res. F, Traffic Psychol. Behaviour*, vol. 2, no. 4, pp. 213–219, Dec. 1999.

[12] K. Vogel, "A comparison of headway and time to collision as safety indicators," *Accident Anal. Prevention*, vol. 35, no. 3, pp. 427–433, 2003.

[13] J. Dong and L. Chu, "Coupling safety distance model for vehicle active collision avoidance system," Automot. Eng. College, Jilin Univ., Changchun, China, SAE Int., Tech. Rep., Apr. 2, 2019.

[14] R. Li, C. Liu, and F. Luo, "A design for automotive CAN bus monitoring system," in *Proc. Vehicle Power Propuls. Conf.*, Sep. 2008, pp. 1–5.

[15] Z. Zhengli, R. Shaoyun, and Y. C. Amp, "The application of CAN bus system to electric car," *Automot. Eng.*, to be published.

[16] L. C. Bento, R. Parafita, and U. Nunes, "Intelligent traffic management at intersections supported by V2V and V2I communications," in *Proc. IEEE Conf. Intell. Transp. Syst.*, Sep. 2012, pp. 1495–1502.

[17] J. Santa, A. F. Gómez-Skarmeta, and M. Sánchez-Artigas, "Architecture and evaluation of a unified V2V and V2I communication system based on cellular networks," *Comput. Commun.*, vol. 31, no. 12, pp. 2850–2861, Jul. 2008.

[18] M. H. Tawfeek and K. El-Basyouny, "Network-level comparison of various forward collision warning algorithms," *Simulation*, vol. 95, no. 4, pp. 313–325, Apr. 2019.

[19] S. Shalev-Shwartz, S. Shammah, and A. Shashua, "On a formal model of safe and scalable self-driving cars," 2017, *arXiv:1708.06374*. [Online]. Available: https://arxiv.org/abs/1708.06374

[20] P. Seiler, B. Song, and J. K. Hedrick, "Development of a collision avoidance system," *SAE Trans.*, vol. 107, no. 6, pp. 1334–1340, 1998.

[21] K. Yi, J. Hong, and Y. D. Kwon, "A vehicle control algorithm for stop-and-go cruise control," *Proc. Inst. Mech. Eng., D, J. Automobile Eng.*, vol. 215, no. 10, pp. 1099–1115, Oct. 2001.

[22] J. Han, O. Heo, M. Park, S. Kee, and M. Sunwoo, "Vehicle distance estimation using a mono-camera for FCW/AEB systems," *Int. J. Automot. Technol.*, vol. 17, no. 3, pp. 483–491, Jun. 2016.

[23] S. Duan and J. Zhao, "A model based on hierarchical safety distance algorithm for ACC control mode switching strategy," in *Proc. 2nd Int. Conf. Image, Vis. Comput. (ICIVC)*, Jun. 2017, pp. 904–908.

[24] A. Doi, "Development of a rear-end collision avoidance system with automatic brake control," *JSAE Rev.*, vol. 15, no. 4, pp. 335–340, Oct. 1994.

[25] Y. Fujita, "Radar brake system," *JSAE Rev.*, vol. 16, no. 1, p. 113, Jan. 1995.

[26] Z. Cao, D. Yang, K. Jiang, S. Xu, S. Wang, M. Zhu, and Z. Xiao, "A geometry-driven car-following distance estimation algorithm robust to road slopes," *Transp. Res. C, Emerg. Technol.*, vol. 102, pp. 274–288, May 2019.

[27] T.-Q. Tang, J. Zhang, L. Chen, and H.-Y. Shang, "Analysis of vehicle's safety envelope under car-following model," *Phys. A, Stat. Mech. Appl.*, vol. 474, pp. 127–133, May 2017.

[28] X. Xiong, M. Wang, Y. Cai, H. Farah, and M. Hagenzieker, "A forward collision avoidance algorithm based on driver braking behavior," *Accident Anal. Prevention*, vol. 129, pp. 30–43, Aug. 2019.

[29] J. Song and W. S. Che, "Comparison between braking and steering yaw moment controllers considering ABS control aspects," *Mechatronics*, vol. 19, no. 7, pp. 1126–1133, 2009.

[30] A. Eckert, B. Hartmann, M. Sevenich, and P. Rieth, "Emergency steer & brake assist: A systematic approach for system integration of two complementary driver assistance systems," in *Proc. 22nd Int. Tech. Conf. Enhanced Safety Vehicles (ESV)*, Washington, DC, USA, Jun. 2011, pp. 13–16.

[31] J. Mårtensson, M. Nybacka, J. Jerrelind, and L. Drugge, "Evaluation of safety distance in vehicle platoons by combined braking and steering," in *Proc. 11th Int. Symposium Adv. Vehicle Control*, Sep. 2012, pp. 1–7.

[32] Lerner N D, "Brake perception-reaction times of older and younger drivers," in *Proc. Human Factors Ergonom. Soc. Annu. Meeting*, vol. 1, Oct. 1993, pp. 206–210.

[33] G. Johansson and K. Rumar, "Drivers' brake reaction times," *Hum. Factors*, vol. 13, no. 1, pp. 23–27, 1971.

[34] J. Khashbat, T. Tsevegjav, J. Myagmarjav, I. Bazarragchaa, A. Erdenetuya, and N. Munkhzul, "Determining the driver's reaction time in the stationary and real-life environments (Comparative Study)," in *Proc. 7th Int. Forum Strategic Technol. (IFOST)*, Sep. 2012, pp. 1–3.

[35] M. Green, "'How long does it take to stop?' Methodological analysis of driver perception-brake times," *Transp. Hum. Factors*, vol. 2, no. 3, pp. 195–216, Sep. 2000, doi: 10.1207/STHF0203_1.

[36] G. Markkula, O. Benderius, K. Wolff and M. Wahde, "A review of near-collision driver behavior models," *Hum. Factors, J. Hum. Factors Ergonom. Soc.*, vol. 54, no. 6, pp. 1117–1143, 2012.

[37] P. Bosetti, M. D. Lio, and A. Saroldi, "On the human control of vehicles: An experimental study of acceleration," *Eur. Transp. Res. Rev.*, vol. 6, no. 2, pp. 157–170, 2013.

[38] R. Gray, C. Ho, and C. Spence, "A comparison of different informative vibrotactile forward collision warnings: Does the warning need to be linked to the collision event?" *PLoS ONE*, vol. 9, no. 1, 2014, Art. no. e87070.

[39] X. Wu, L. N. Boyle, D. Marshall, and W. O'Brien, "The effectiveness of auditory forward collision warning alerts," *Transp. Res. F, Traffic Psychol. Behaviour*, vol. 59, pp. 164–178, Nov. 2018.

[40] J. J. Eckert, E. Bertoti, E. dos Santos Costa, F. M. Santiciolli, R. Y. Yamashita, L. C. D. A. Silva, and F. G. Dedini, "Experimental Evaluation of rotational inertia and tire rolling resistance for a twin roller chassis Dynamometer," Univ. Campinas UNICAMP. Campinas, Brazil, SAE Tech. Paper 2017-36-0212, Nov. 7, 2017.

JIAN WANG received the B.S., M.S., and Ph.D. degrees from the College of Computer Science and Technology, Jilin University, in 2004, 2007, and 2011, respectively. He is currently a Professor with Jilin University, China. He has published over 50 articles on international journals. He is interested in topics related to wireless communication and vehicular networks, especially for network security and privacy protection.

XING ZHANG received the B.S. degree in software engineering from Jilin University, in 2018, where he is currently pursuing the M.S. degree in computer application technology. He is interested in the Internet of vehicles technology.

HUI KANG received the M.E. and Ph.D. degrees from Jilin University, in 1996 and 2007, respectively. She is currently an Associate Professor with the College of Computer Science and Technology, Jilin University. Her research interests include grid computing, information integration, and distributed computing.

LINGYUE DENG currently works at the Technology Development Department, Datang Mobile Communication Equipment Company, Ltd., Beijing, China. She is good at mobile device communication and vehicle communication.