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DSRC-Based Rear-End Collision Warning System - An Error-component Safety Distance Model and Field Test

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Abstract: Dedicated short-range communication (DSRC) technology can provide drivers with information about other vehicles that are beyond the normal range of vision and enables the development of driving support systems such as the rear-end collision warning system (ReCWS). However, technology constraints such as communication delays and GPS error affect the accuracy of a DSRC-based ReCWS. This paper proposes a ReCWS design that explicitly represents functional specifications of DSRC technology, including transmission delay specifications that describe the information transmission process and an error-component safety distance specification used to represent the effect of GPS error and the information propagation delay. We propose three collision warning strategies each with different deceleration requirements. The system is assembled with off-the-shelf DSRC and mobile technology that can be readily installed into test vehicles. To test the effectiveness of the proposed ReCWS, we ran a variety of controlled scenarios on a test track. The results show a high degree of warning accuracy. These field test results also provide calibrated system parameter values for future studies and designs of DSRC-based ReCWSs.

Keywords: Dedicated short-range communication (DSRC); Rear-end collision warning; Transmission delay; Safety distance model; Warning strategy; V2V.

1. Introduction

Although the number of traffic accidents has been decreasing year by year, casualties and economic losses are still significant. There were 35485 motor vehicle traffic fatalities where the

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rear-end collision accidents account for more than 30% (NHTSA, 2015). Analysis of these traffic accidents suggests that they happen when drivers of following vehicles do not pay enough attention to the leading vehicle's deceleration and when following vehicles travel too closely behind (Dingus

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et al., 1997). Therefore, a system that can detect and warn drivers how to decelerate to avoid the potential rear-end collisions could significantly reduce the number of accidents (Jamson et al., 2008).

There are two general approaches to developing a rear-end collision warning system (ReCWS). A traditional ReCWS uses ranging sensors (e.g. radar and camera) to detect vehicles in front of the equipped vehicle (Abdel-Aty et al., 2012; Alpar et al., 2016; Yang et al., 2015). These systems are expensive and their performance is limited because conditions such as darkness, fog and rain interfere with the detection (Rasshofer et al., 2011). The second approach uses vehicle to vehicle (V2V) communication technology which allows vehicles to exchange movement and trajectory information within their communication ranges (Hafeez et al., 2013). V2V technology can withstand adverse conditions and ensures the applicability of the system. As a result, research on ReCWSs in recent years have largely been focused on their compatibility with V2V technology.

Li et al. (2013) proposed a V2V-based ReCWS based on risk perception to identify danger. When the system detects an unsafe driving speed, it warns the driver to decelerate. Wang et al. (2015, 2016) developed a model based on the concept of driving safety field theory that considers driver-vehicle-road interactions to determine the safety field strength in detail. A study by Huang et al. (2014) analyzed a cooperative vehicle collision warning system under a variety of speeds, road conditions and GPS delays. The results show that the system has a low warning rate at intersections. Benedettoa et al. (2015) applied telecommunication methodologies for detecting hazardous driving conditions in order to avoid rear-end collisions. These experiments showed that the system had a high degree of detection with regard to small distances. With the development of communication technology, Cellular-V2X has drawn increasing attention. Vukadinovic et al. (2018) compared two families of radio technology: IEEE 802.11p and 3GPP Cellular-V2X in highway platooning scenarios. Simulation results show that C-V2X in both modes allows for shorter distances than IEEE 802.11p due to increased reliability of communication performance under increasing congestion on the wireless channel. However, there are few studies about C-V2X –based safety applications or real-life tests.

There has also been research that employs intelligent vehicle to infrastructure (V2I) communication technology for collision avoidance. Khan (2007) proposed a queue-end warning system for highway work zones that automatically predicts the location of a queue-end and alerts drivers based on intelligent infrastructure. Wang et al. (2011) proposed a vehicle trajectory collision warning system based on V2I that employed the method of Kalman Filter to predict the vehicle trajectory. The system predicts collisions using models of time to collision (TTC) which respectively considers vehicles as particles, circles and rectangles. The above systems are good at different scenarios, but none of them takes into account the influence of information delays and GPS errors.

A critical safety distance model based on V2V communication (Chen et al., 2013) considered information transmission delay, but the method requires dividing the radio ranges into different communication zones and controls the beacon frequency according to the required message propagation. DSRC-based systems communicate by broadcasting so the emissive frequency cannot change frequently. As a result DSRC system cannot use the critical safety distance model. Xiang et al. (2014) analyzed the advantages of DSRC and established a multi-level warning system based on vehicle kinematic models and neural networks. Simulation experiments showed that the number of correct warning rates ranges from 80% to 95%. This system did not model the information transmission process, so the experiment only provided a maximum delay to compensate. A maximum delay was probably reasonable anyway because the neural network model require a lot of data training. Another aspect of a ReCWS is the warning strategy. Zardosht et al. (2013) proposed a decision making algorithm for accident situations based on V2V and advised drivers based on different scenarios. Tang and Yip (2010) found that warning strategies for collision avoidance are constrained by the length of events such as DSRC communication latency and detection rage.

Although studies have proposed several ReCWSs and algorithms recently, three challenges remain for DSRC-based ReCWS developments. Firstly, studies have yet to consider information transmission delays that exist in the process from data acquisition to warning decisions. Secondly, the impact of intrinsic system reliability/variability such as information delay and GPS error on safety distance should be considered. Finally, given the constraints of safety distances and driver reaction times, the system should offer the best warning and mitigation mechanisms for drivers.

The purpose of this paper is to improve the accuracy of DSRC-based rear-end warning system, and to calibrate and validate the parameters in DSRC-based systems in real life. In order to precisely compute the information transmission delay in the system, we map out the exact information transmission processes in the system and present them in an information transmission delay model. To analyze the impacts of GPS error and information transmission delays on safety distance, an error-component safety distance model is proposed based on a traditional kinematic model. In addition, the system contains a warning strategy that suggests one of three different levels of braking force depending on the scenario.

This paper contains seven sections. In Section 2 we set up the rear-end collision warning system infrastructure. Section 3 analyzes the information transmission process and proposes the delay model of the system. In Section 4 we present the proposed safety distance model based on V2V communication. Section 5 develops a warning strategy. In Section 6 we present experiment results. In Sections 7 conclusions are presented.

2. System architecture

The DSRC device based on the proposed IEEE 802.11p standard has a bandwidth in the 5.9 GHz range (IEEE Task Group p). V2V and V2I communication uses these DSRC devices. Based on the information received from other vehicles, the proposed warning system uses information from the DSRC BasicSafetyMessage (BSM) to compute whether there is any potential danger of collision. The BSM is the core data transmitted through V2V and V2I applications and includes information about the vehicle including its unique MAC address, its position (latitude, longitude, elevation and position accuracy), motion (speed, acceleration, direction, control brake) and size (Liu and Khattak, 2016). The system uses CAN-BUS (Controller Area Network Bus) to transmit data between the controller and the actuator on the vehicle and includes basic data from the vehicle speedometer. However, manufacturers normally encrypt the CAN data and different manufacturers use different encryption methods. It is difficult to get data directly from the CAN and other sensors have to be used to collect the data to encode as the BSM message. We describe how we gather relevant vehicle information in our proposed system blow.

Our DSRC-based ReCWS is developed with three units (shown in Fig. 1): the data acquisition module, the DSRC equipment, and the vehicle terminal (the control and display module). The data acquisition module is responsible for collecting information such as speed and acceleration. The module uses an on-board diagnostic (OBD) system integrated with the acceleration sensor to collect the acceleration and speed information. A moving average filter filters data from the sensors. The DSRC device, which has an integrated GNSS module, is responsible for collecting GPS information, along with broadcasting and receiving BSM messages. The vehicle terminal is responsible for computing the rear-end collision warning safety distance and for raising the rear-end collision alarm when appropriate. We use the smartphone as the vehicle terminal and develop the rear-end collision warning application based on an Android system. The vehicle terminal transmits data with DSRC via USB and receives data from the OBD via Bluetooth.

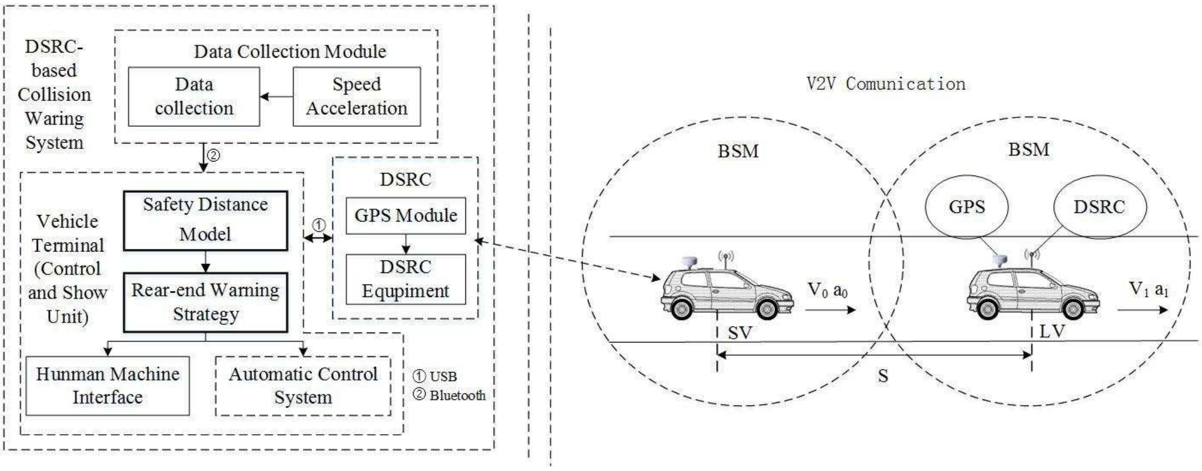


Fig. 1. Overall structure of the DSRC-based rear-end collision warning system

3. Analysis of system delays

Fig. 2 illustrates the information transmission processes in a ReCWS based on DSRC communication. The data acquisition module for the lead vehicle transmits information about the lead vehicle to the subject (following) vehicle via DSRC equipment. The vehicle terminal on the subject vehicle processes the information and sends any rear-end collision warning message to the on-board display unit. This transmission process contains three time delays: the lead vehicle's information collection, the information transmission from the front to the subject vehicle, and information processing once the subject vehicle has received.

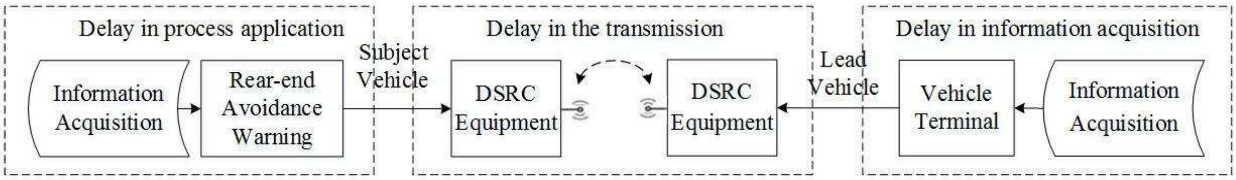


Fig. 2. The process of information transmission

It is important for warning systems to accurately account for these information delays. In the following discussions, we present how we modelled the three delay components and where we acquired the data sources in our proposed ReCWS.

(1) Delay in information acquisition

The information collection delay refers to the time it takes for the DSRC to generate information and send the information. The data collection unit collects speed and acceleration information at each cycle of T (ms) and transmits this information to the vehicle terminal. The terminal then integrates and encodes the information using multi-thread processing to form the BSM and sends the BSM at each cycle time T_d (ms). The collection cycle T is always less than the cycle T_d. Therefore, we take the delay T_c of information acquisition as

$$T_c = T_d - T \tag{1}$$

(2) Delay in information transmission

The information transmission delay is the average travel time for data packets transmitted in the air media. DSRC radio is a single hop network, and its information transmission delay includes a network delay T_s (due to an accumulation of factors including backoff, busy channels, frame spacing, transmission delays and propagation delays) and an interface queuing delay T_w where messages wait to be sent (Ghadimi et al., 2011). We formulate the total information transmission delay T_{tr} as:

$$T_{tr} = T_s + T_w \tag{2}$$

In our proposed ReCWS, we calibrated the delay parameters for information transmission using field experimental data, described in Section 6.

(3) Delay in the application

The rear-end collision warning application, installed on the subject vehicle terminal, sends and receives messages, handles information, establishes safety distance models and provides warning commands. The different computer programming codes developed to execute the calculations have different structures and functions, so they all have different computing times. The system computes the warning result after it updates all the required data. Assume that the program receives the broadcast message at time T_r, and generates the warning result at time T_e. The main information delay T_{ap} of the system is therefore

$$T_{ap} = T_e - T_r \tag{3}$$

where T_r and T_e is recorded by a time stamp during application, so that T_{ap} can be measured in the ReCWS.

Taking all three delay components described above, the overall information transmission delay of a ReCWS is

$$T_d = T_c + T_{tr} + T_{ap} \tag{4}$$

4. An error-component safety distance

Typically, there are two components to collision avoidance: safety distance and time to collision (TTC) (Bella et al., 2011; Ward et al., 2015). The safety distance algorithm calculates a safety distance based on vehicle kinematics (speed, acceleration) and delays in human response. Examples of safety distance algorithms include the National Highway Traffic Safety Administration (NHTSA) algorithm (Brunson et al., 2002), the CAMP algorithm (Kiefer et al., 2003) and the Mazda algorithm (Ararat et al. 2006). The TTC algorithm is used to measure the risk of collision. It is defined as the time until a collision between two vehicles would have occurred if the collision course and speed difference were maintained (Minderhoud and Bovy, 2001; Mohebbi et al, 2009). The two algorithms can be converted to each other. This paper uses the safety distance to determine the danger of collision. We propose an error compensation safety distance method (EC-SDM) based on vehicle kinematics.

A rear-end collision avoidance scenario occurs if the lead vehicle is either stationary or moves slower than the subject vehicle. We made the following assumptions during the development of our safety distance method: (a) the lead vehicle will maintain constant deceleration until it stops; (b) the subject vehicle will maintain its current speed and acceleration during a fixed reaction time and then decelerate at a prescribed level; and (c) when the system warns to brake, the braking deceleration of subject vehicle is always greater than or equal to that of the lead vehicle. As shown in Fig. 3, we use LV to mark the lead vehicle and SV to mark the subject vehicle. Assume that at initial time t_0, the distance gap between vehicles LV and SV is d_m. Let the initial speed and acceleration of the LV be notated as V_{l0} and a_{l0}, and let the initial speed and acceleration of the SV be V_{s0} and a_{s0}, where $V_{l0} < V_{s0}$. The total safety distance can be divided into three parts. First, the distance d_i that the SV travels after it receives the warning and begins to decelerate. Second, the relative moving distance d_r when the SV uses desired deceleration a_s to slow down until the relative speed is zero. Third, the minimum headway distance d_f that the lead vehicle and the SV need to keep when the relative speed is zero. Therefore, we express the safety distance S for rear-end collision avoidance as:

$$S = d_i + d_r + d_f \tag{5}$$

where $d_r = d_{es} - d_{el}$, d_{es} is the traveling distance for when the SV keeps deceleration a_{sd} until the speed is consistent with the lead vehicle. d_{el} is the distance that the LV travels over time T_{sr}. The headway distance is $d_f = (L_s + L_l)/2 + d_0$, where L_s and L_l denote the length of the two vehicles, and d_0 is the final minimum distance kept between the two vehicles.

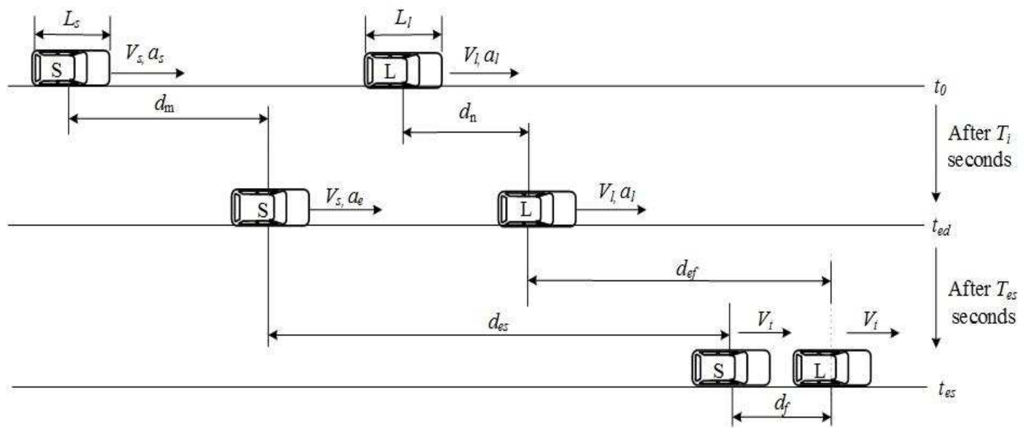


Fig. 3. Time series analysis of braking for rear-end collision avoidance

Time T_{sr} is the reaction time of the subject vehicle which is the time from when it receives the warning to when it activates braking (driver reaction time and mechanical brake delay). During time T_{sr}, the SV maintains its state of motion so

$$d_i = d_s - d_l = (v_s - v_l) * T_{sr} + \frac{1}{2}(a_s - a_l) * T_{sr}^{\ 2} \tag{6}$$

In this system we calibrate driver reaction time T_{sr} using our field experimental data, which is described later in Section 6. The expression for the relative speed between the SV and the LV after T_{sr} is

$$\Delta v = v_s - v_l + (a_s - a_l) * T_{sr} \tag{7}$$

Before the safety distance is calculated, it is necessary to assume the desired deceleration of SV. The desired deceleration a_{sd} of the SV relies on road pavement conditions and the vehicle's braking power. During calculation of the warning, the desired deceleration is an estimated value or a presupposition value. The vehicle executes the desired deceleration when the system gives the warning in order to avoid collision. Under our assumption, we expect the desired deceleration of the SV to be greater than or equal to a_l. The desired relative deceleration of the two vehicles is

$$\Delta a = a_{sd} - a_l \tag{8}$$

The relative distance d_r for two vehicles is

$$d_r(\Delta v, \Delta a) = d_{es} - d_{el} = \int_0^{\frac{\Delta v}{\Delta a}} (\Delta v - \Delta a * t) dt = \frac{\Delta v^2}{2\Delta a} \tag{9}$$

However, we cannot apply a kinematic model based on ideal conditions to actual conditions. Actual conditions present a wide variety of deviations such as GPS error and information delay T_d. The accumulation of these deviations will eventually lead to a large difference between the assumed headway distance d_f and the real headway distance d_{hd}, which we express as

$$d_{hd} = d_f + d_{Td} + \Delta E_g \tag{10}$$

where d_{Td} is the relative distance travelled during the transmission delay period. From testing done in Section 6, we found that T_d^2 <0.002s and can be ignored. Therefore

$$d_{Td} \approx \Delta v * T_d \tag{11}$$

In Eq. (10), ΔE_g denotes the difference in GPS errors between the LV and the SV, where $\Delta E_g = E_{gs} - E_{gl}$. Many factors such as the ionospheric effect and the tropospheric effect influence GPS error E_g, so it is difficult to establish an accurate error model. Some rear-end collision avoidance systems use the Gaussian distribution to compensate the error of GPS (Yang et al., 2003; Xiang et al., 2014). Other model GPS errors based on experimental test results (e.g. Liu et al., 2009; Rife and Pervan, 2012). For simplicity, we use the Gaussian distribution to represent the distribution of E_g

$$E_g \sim N(u, \sigma^2) \tag{12}$$

where u is the mean, and σ is the standard deviation. The horizontal positioning accuracy of the GPS on the DSRC equipment is 2.5m at 2DRMS (Datasheet, 2017). DRMS (Distance Root Mean

Squared) represents the square root of the average of square errors, which is defined as:

$$2\mathrm{DRMS} = 2\sqrt{\sigma_x^2 + \sigma_y^2} \tag{13}$$

We assume that the two-directional distribution has the same standard deviation, i.e. $\sigma_x = \sigma_y = \sigma$, we can get $2\sqrt{2\sigma^2}=2.5$, $\sigma^2=0.79$ (GPS Technical Support Materials, 2003). The u equals zero and generally a GPS receiver will not have a constant position bias (Xiang et al., 2014). Thus, we obtain

$$E_g \sim N\left(0, 0.79\right) \tag{14}$$

Therefore

$$\Delta E_g \sim N\left(0, 1.58\right) \tag{15}$$

The ΔE_g can be obtained by the probability density function

$$f\left(\Delta E_g\right) = \frac{1}{\sqrt{3.16\pi}} \exp\left(-\frac{\Delta E_g^2}{3.16}\right) \tag{16}$$

Through analysis of these equations, we can finally get the safety distance based on error compensation (EC-SDM)

$$S = \left(v_s - v_l\right) * T_{sr} + \frac{1}{2}\left(a_s - a_l\right) * {T_{sr}}^2 + \frac{\Delta v^2}{2\Delta a} + T_d * \Delta v + \Delta E_g + d_f \tag{17}$$

where Δv is the speed difference between the two vehicles after reaction time T_{sr} (in seconds), Δa is the acceleration difference, d_f is the required safety headway distance, T_d is the delay in information transmission, and ΔE_g is the difference in GPS error.

5. Collision warning strategy

The ReCWS is a driving assistance system that warns drivers how hard to brake if needed. The system's output is deceleration. In practice, it is difficult for drivers to perform the exact desired deceleration manually. Therefore, our ReCWS gives warnings based on ranges rather than specific deceleration rates. The designed ReCWS can provide measurement on the speed of the SV and distance between the two vehicles. The system can also receive the speed and accelerate of LV from the DSRC. We can calculate the desired deceleration of the SV by using data collected by the system.

Combining (6), (7) and (17), we get:

$$a_{sd} = \frac{\Delta v^2}{2\left(S_m - d_i - \Delta E_g - d_f\right)} + a_l \tag{18}$$

where S_m is the measured relative distance between the two vehicles. Different decelerations can cause different driving experiences. We propose three warnings levels according to different conditions as illustrated in Table 1.

Table 1 Collision avoidance warning strategy

level of warning	Condition distance	Decelerated condition	braking
I Comfortable	$S(a_c) < S_m < S_0$	$a_c < a_{sd} < 0$	light
II Uncomfortable	$S(a_{mid}) < S_m < S(a_c)$	$a_{mid} < a_{sd} < a_c$	moderate
III Emergency	$S_m < S(a_{mid})$	$a_{sd} < a_{mid}$	hard

In the table, a_c =-2m/s^2 and a_{mid} =-5.5m/s^2 are set for dry asphalt pavement given by Wu et al. (2009) and Brunson et al. (2002).

6. Field Test

In order to improve the accuracy and stability of the proposed DSRC-based ReCWS, we calibrated and tested the system repeatedly in a closed environment: Chang'an University's vehicle testing field. The testing field is a 2.4km high-speed circular runway, with a 1.1km straight section shown in Fig. 4. All experiments were performed on a single lane. We do not consider the influence of different lane vehicles in this paper, but lave-level location resolution can be solved by using the multi-sensor fusion positioning technology (Gu et al., 2016; Xu et al., 2018). Two vehicles were used (shown in Fig. 5): a BYD Automobile and a KIA-K3 Automobile, both with a length of 4.6m. The DSRC equipment used was the MK5 manufactured by Cohda Wireless. The Android application transmitted data with the DSRC via USB and received the data from the OBD via Bluetooth. The OBD module integrated the acceleration sensor and was able to read data from the interface. Fig. 6 displays the system setup. Table 2 shows the system parameter settings.

Fig. 4. Test site

Fig. 5. The test two vehicles

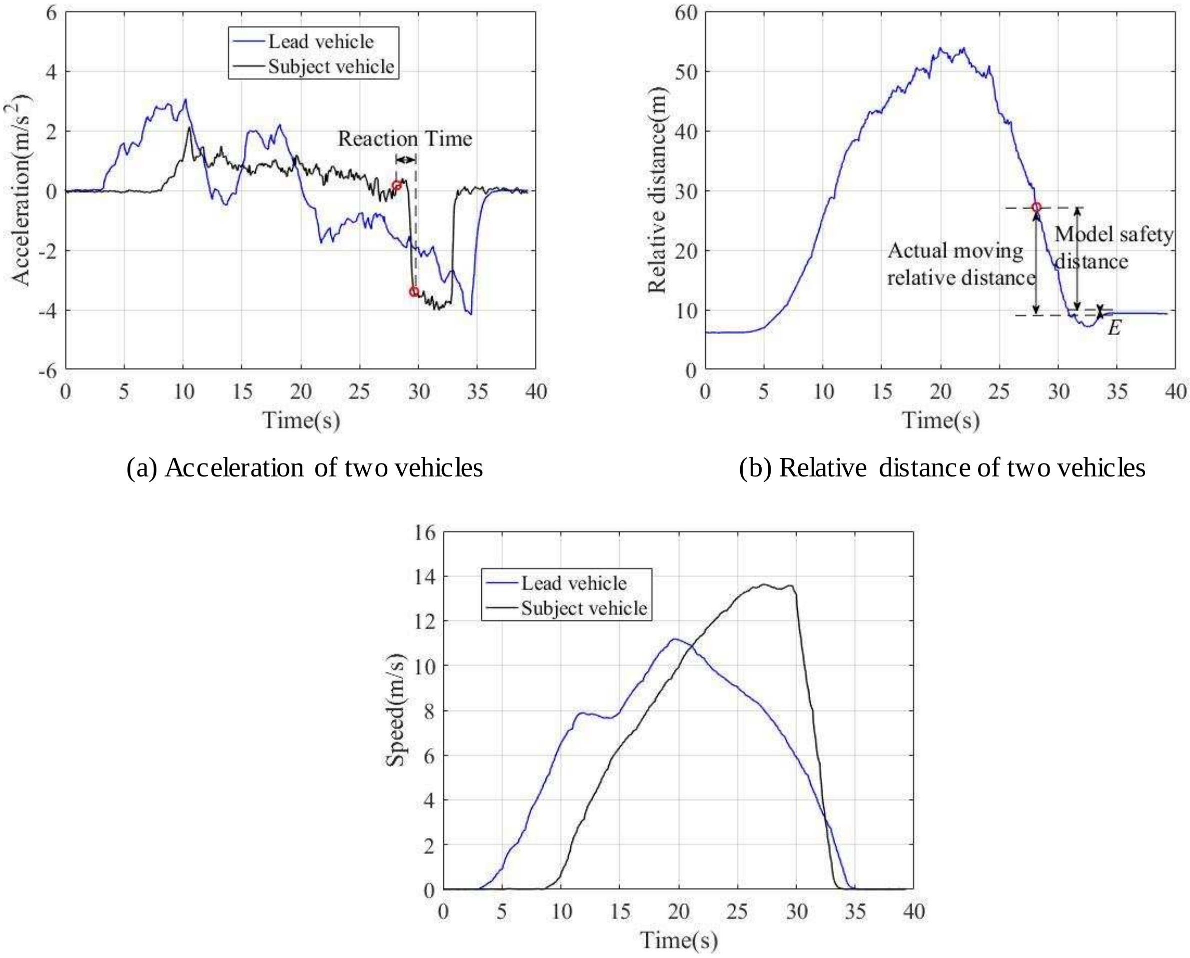
Fig. 6. The warning system

Table 2 System parameters setting

Model parameter	Setting value
The cycle of the BSM sending T_d	50ms
The cycle of the information acquisition T	40ms
Delay in the information acquisition T_c	10ms
Light brake a_c	-2m/s^2
Moderate brake a_{mid}	-5.5m/s^2
Minimum distance headway d_f	10m
Final minimum space d_0	5.4m
Length of two vehicles $L_s = L_l$	4.6m

6.1 Calibration and validation of safety distance models

In our proposed error compensation safety distance model (EC-SDM), key model parameters include the reaction time T_i, the delay in information transmission T_d and the GPS error ΔE_g. The EC-SDM used to avoid collision is a little different from the car-following models (Colombaroni and Fusco, 2014), because of the assumption that the subject vehicle's braking deceleration is always greater than or equal to that of the lead vehicle. The proposed distance indicates the traveling relative distance of the vehicles in the whole collision avoidance process. Therefore, the data collection experiments were conducted in different independent collision avoidance scenarios. We calibrated and validated the EC-SDM following the procedure of Hollander and Liu (2008). The LV travels at constant speeds or with different decelerations while the SV travels with different desirable decelerations according to the warning. The experiment software recorded the time of the warning, travelling states of both vehicles, and relative travelling distance. In order to calibrate the model, we collected 100 sets of data in two different scenarios: one where the lead vehicle is stationary and the other where lead vehicle is decelerating. Fig.7 shows one example case.



(a) Acceleration of two vehicles

(b) Relative distance of two vehicles

(c) Speed of two vehicles

Fig. 7. Exampled case: speed of lead vehicle is 40km/h, while the speed of subject vehicle is 50km/h, initial acceleration is 0m/s^2, and desired deceleration is 3.8 m/s^2.

The mean difference between the model safety distance and the real measured relative distance quantifies the Measures of effectiveness (MOE). The model calibration adopts the following objective optimization model:

$$\min\ E\quad S.T.\{\mathbf{P}_{EC-SDM} \in \mathbf{R}_{EC-SDM}\} \tag{19}$$

where $E = \frac{1}{N}\sum_{i}^{N}\left|\hat{S}_{sim} - S_{real}\right|$, $\hat{S}_{sim}$ denotes the simulated safety distance, S_{real} denotes the real measured relative distance, P denotes the calibrated model parameters and R contains the parameter upper and lower bounds.

We used the Genetic Algorithm (GA) (Miettinen, 2012) to search for optimal parameters that enable the minimum MOE. The GA iteratively executes the EC-SDM and computes the MOEs at various parameter levels.

E_g is a series of discrete data which is measured and calibrated via a static measurement method. Let the lead vehicle remain static and the subject vehicle move gradually. We calibrate the GPS by comparing the distance measured by the GPS with the distance measured by a ruler. The ΔE_g is obtained by the probability density function in formula (16).

The reaction time T_i is the time from when the SV first receives the warning to when it activates braking. The program recorded the warning times and the reaction times for each case as shown in the Fig.7. As a result, the T_i threshold boundary is

$$T_i^* \in \left[0.6s, 1.6s\right] \tag{20}$$

System delays have three parts. Field test results directly influence the calibration the delay in information transmission, while the system specifications directly affect the calculation of delays in information. In our experiment, two vehicles travelled a safe distance apart from each other using on-board DSRC devices to broadcast BSMs in single-hop mode. We recorded the time spent sending each a BSM packet (256 bytes) and the time spent receiving each packet at different driving speeds. Fig.8 displays the average and maximum transmission delays at different speeds. From the figure, the T_{tr} threshold boundary is

$$T_{tr}{}^* \in [0, 33ms] \tag{21}$$

The calibrated parameters are reaction time T_i and delay T_{tr}. Table 3 shows their value.

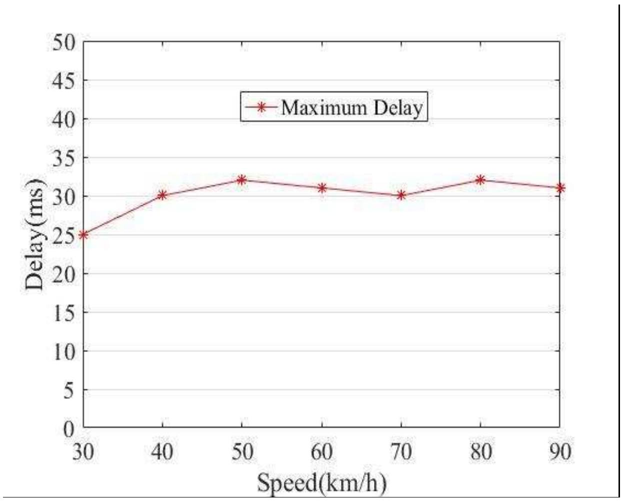


Fig. 8. Delay in the information transmission

Table 3 Calibrated parameters

Model parameter	Optimal value
Delay in the information transmission(DIT) T_{tr}	19ms
Reaction time T_i	0.85s

After obtaining the optimal system parameters, we tested the EC-SDM in further experiments to validate them. The lead vehicle travels at a constant speed or at different decelerations while the subject vehicle decelerates with different desirable decelerations according to the calibrated EC-SDM. We collected ten sets of data. The error between the simulated safety distance and the real relative travelling distance reflects the performance of the system. The data used in the evaluation applies separate measurements at each time-space point rather than at all measurements jointly. Therefore, the mean error (ME), and the mean percent error (MPE) help evaluate the system. These indicate systematic under or overproduction in the simulated measurements (Toledo and Koutsopoulos, 2012), and are given by

$$ME = \frac{1}{N}\sum_{n=1}^{N}\left(S_n^{sim} - S_n^{real}\right) \tag{22}$$

$$MPE = \frac{1}{N}\sum_{n=1}^{N}\frac{S_n^{sim} - S_n^{real}}{S_n^{real}} \tag{23}$$

where S_n^{sim} denotes the simulated safety distance and S_n^{real} denotes the real measured relative distance. ME =0.66 and MPE =0.084 are obtained in the validation. Theil's inequality coefficient shows the relative error between the simulation value and the measured value (Toledo and Koutsopoulos, 2012), which is given by

$$U = \frac{\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(S_n^{sim} - S_n^{real}\right)^2}}{\sqrt{\frac{1}{N}\sum_{n=1}^{N}(S_n^{sim})^2} + \sqrt{\frac{1}{N}\sum_{n=1}^{N}(S_n^{real})^2}} \tag{24}$$

where U is bound, $0 \le U \le 1$. $U = 0$ implies a perfect fit between the simulation and measurement. $U = 1$ implies the worst fit. Table 4 shows the validation results.

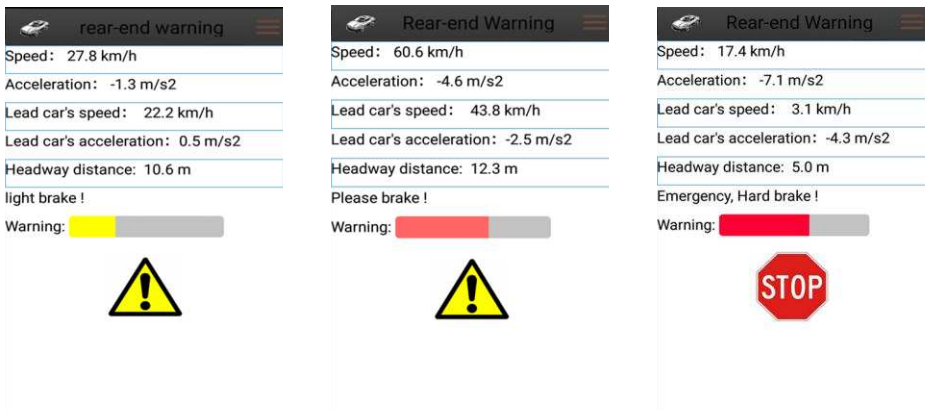
Table 4 Safety distance model validation results

Scenarios					S_{real} (m)	S_{sim} (m)	ME	MPE	U
a_{sd} (m/s^2)	v_l (m/s)	a_l (m/s^2)	v_s (m/s)	a_s (m/s^2)					
-2	0	0	5.2	0.6	22.9	23.3	0.682	0.025	0.019
-1.8	0	0	4.3	0	18.5	18.5			
-3.5	0	0	4.9	0.7	18.7	18.9			
-2	0	0	5.7	0.3	23.3	24.5			
-2.5	0	0	6.3	0.4	26.4	26.0			
-5	7.2	-1.8	13.4	0.2	25.3	26.4			
-6.5	5.1	-2.6	14.1	-0.4	34.1	34.0			
-6	6.3	-2.1	14.4	0	33.8	34.3			
-5.5	4.9	-2.8	12.2	-0.2	27.9	29.8			
-5.5	5.7	-1.5	15.2	-0.1	29.3	31.2			

6.2 Test of rear-end collision warning system

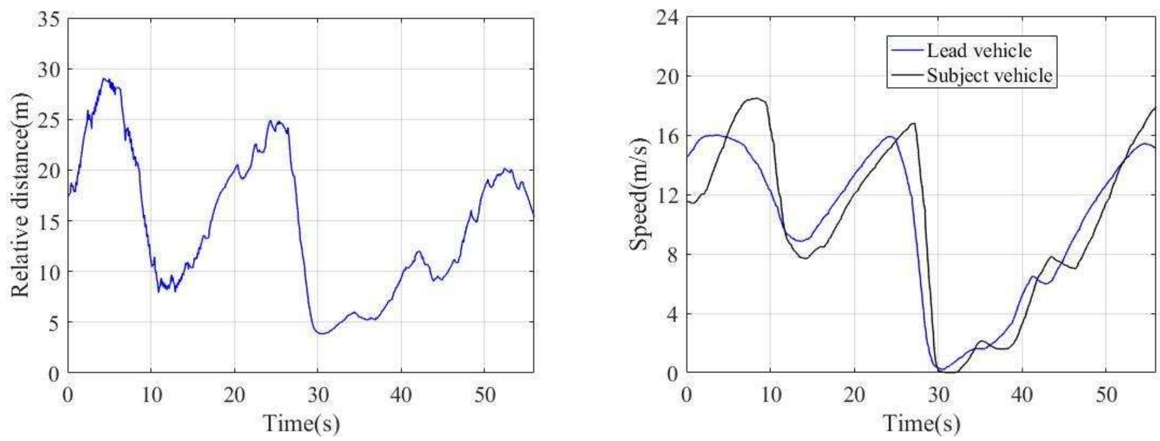
The system proposes three levels of break warning strategy comfortable, uncomfortable and emergency. Different traveling states of the lead vehicle cause different influences on collision warnings. In this section, we present field experiments conducted under car-following scenarios to test the warning system. Fig. 9 shows the different warning interfaces displayed on smartphones. Fig. 10 shows the speed, acceleration and measured headway distance recorded by the experiment software.

The risk of collision will increase when the distance between the two vehicles is smaller than the safety distance. The warning level choice relies on the state of the lead vehicle and the gap between the two vehicles. Fig. 10 presents the deceleration profiles of both vehicles, where we can clearly see that the subject vehicle's speed decreases when the lead vehicle decelerates. The values of deceleration and spacing change more for warning level III than for level I. This analysis shows that the rear-end collision warning system has the ability to adjust the speed of the subject vehicle in order to improve its safety.

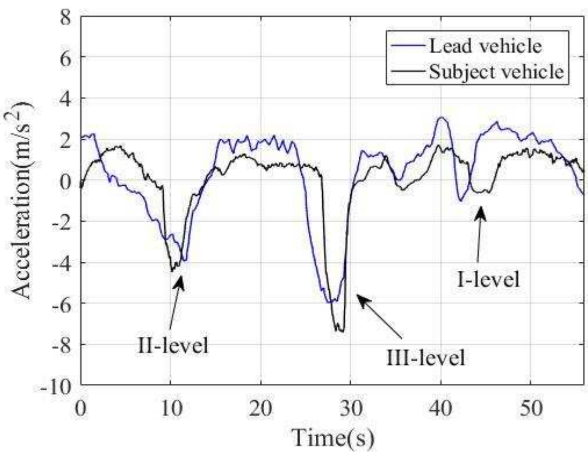


(a) I-level warning (b) II-level warning (c) III-level warning

Fig. 9. Different warning levels



(a) Relative distance of two vehicles (b) Speed of two vehicles



(c) Acceleration of two vehicles

Fig. 10. The states of two vehicles

6.3 Performance evaluation of the whole system

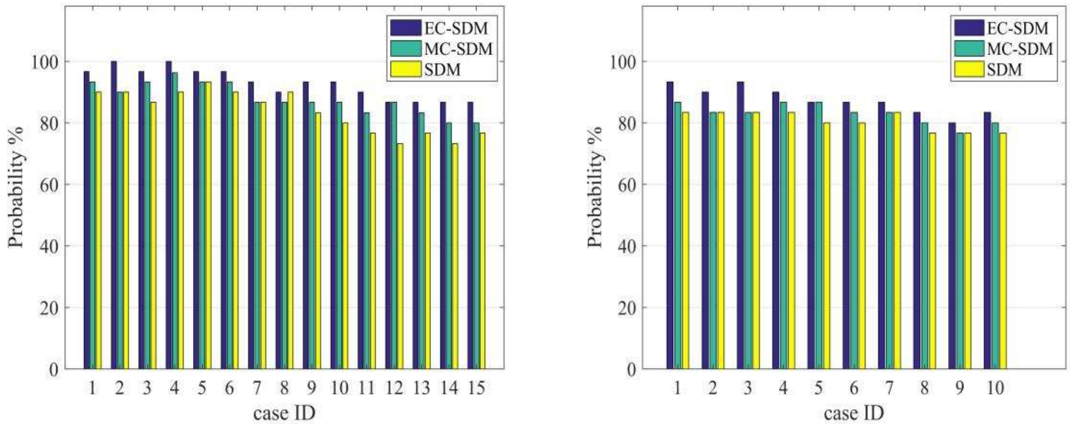
Performance evaluation focuses on the accuracy of the warning system. One performance indicator is the timing of the warning signal. The system will not be effective if it gives the warning too late or too early. There is also one other metric used to evaluate performance: probability of correct warning $P(c)$. We define this systematic error as the difference R_m between the measured spacing d_{fm} and the system-specified spacing d_0 after the collision warning. When the systematic error belongs to $\{R_m | R_m = |d_{fm} - d_0| < T_h\}$, where T_h is a threshold set to 2m, the warning is the correct warning. $P(c) = (N_c / N) * 100\%$, where N_c is the number of correct warning and N is the total experiment times. To demonstrate the accuracy of the ReCWS, the proposed algorithm was compared with the safety distance model (SDM) and maximum compensation safety distance method (MC-SDM, Xiang et al., 2014). The SDM does not take communication delays and GPS error into consideration. The MC-SDM uses the maximum compensation for safety distance according to the GPS error. We have counted the correct warning rate of the system in different scenarios. Tables 5 and 6 show the fifteen test scenarios carried out as field test experiments on the straight road and ten test scenarios carried out on the slightly curvy road. Each scenario is tested 30 times for different safety model in each scenario. We recorded the spacing each time.

Table 5 Scenario description on the straight line

Scenario (ID)	V_l (km/h), a_l (m/s^2)	V_s (km/h), a_s (m/s^2)	Scenario (ID)	V_l (km/h), a_l (m/s^2)	V_s (km/h), a_s (m/s^2)
1	0, 0	20, 0	9	50, -1	50, 2
2	0, 0	30, 0	10	55, -1	60, 0
3	0, 0	40, 0	11	45, -5	50, 1
4	0, 0	50, 0	12	45, -5.5	60, 2
5	0, 0	60, 0	13	50, -6	40, 0
6	30, -1	50, 0	14	55, -5	60, 0
7	30, -1.5	50, 2	15	55, -5.5	60, 2
8	40, -2	55, 1			

Table 6 Scenario description on the slightly curvy line

Scenario (ID)	V_l (km/h), a_l (m/s^2)	V_s (km/h), a_s (m/s^2)	Scenario (ID)	V_l (km/h), a_l (m/s^2)	V_s (km/h), a_s (m/s^2)
1	0, 0	30, 0	6	40, -1	45, 0
2	0, 0	40, 0	7	45, -1.5	50, 0
3	0, 0	45, 0	8	40, -4	50, 0
4	0, 0	50, 0	9	40, -5	50, 1
5	30, -1	40, 0	10	45, -5	50, 0



(a) On the straight road (b) On the slightly curved road

Fig. 11. The correct warning rates for different methods

The number of correct warning rates of ReCWS ranges from 100% to 86.7% on the straight road and 93.3% to 80% on the curved road, as shown in Fig.11. Note that a false warning does not mean an unsafe amount of space. On the contrary, a false warning is given when the error in spacing is too large. A vehicle has a risk of collision only when the error is negative. In the system experiment, there are no missing alarms, which may be due to our compensation for safety distance and the vehicle speed. We consider both the false warning and the missing warning rates as the incorrect warning rates of the system. The proposed algorithm improves the average of correct warning rates by 4.9% compared with the MC-SDM, and 9.12% compared to the SDM on the straight road. The system improves the average of correct warning rates by 4.3% compared with the MC-SDM, and 7.6% compared to the SDM on the slightly curved road. The correct warning rates has decreased compared with the warning rates on the straight road. The main reason is that the distance measured by GPS is smaller than the actual distance on the curve. The results of the correct warning rates suggest that our proposed warning system is reliable and effective.

7. Conclusion

This paper presents a DSRC-based rear-end collision warning system. We base the system on the explicit representation of functional and technical specifications of DSRC, including various system delay components. To compensate errors from GPS vehicle positioning, we developed an error compensation safety distance model. We also propose three collision warning strategies based on different levels of braking comfort.

Our field tests implemented the proposed warning system on a closed test track environment.

The results show that the proposed DSRC-based ReCWS can effectively provide correct collision warnings to the driver. Overall, the system achieves an average correct warning rate of 90% when the systematic error is 2m. The field tests also provided calibrated system parameter values, which will be useful for future studies and designs of DSRC-based ReCWS.

Although our proposed ReCWS has considered a number of parameters, we only measured it in testing scenarios and calibrated it using limited real vehicle experimental data. The accuracy of GPS is easily influenced by the driving environment, especially in cases of shielding. Multi-sensor fusion positioning technology is a promising method to improve the accuracy of safety distance calculation and to achieve lane-level location. We will integrate high precision positioning and collision warning system in the future. The parameter that we decided from the traffic environment could have been obtained by traffic flow statistics (Hollander Liu, 2008; Park and Schneeberger. 2006). Ongoing research needs to test this system in different kinds of traffic flows in order to validate it. Although our proposed ReCWS has considered many technical and system factors, such as delays in information transmission, GPS error and driver reaction time, some aspects of driver behavior and style such as age and skill (Abe and Richardson, 2004; Adell et al., 2011; Li et al., 2017; Toledo et al., 2007) are not included in this study. Cellular-V2X is the emerging technology which will be carried out in the future. Research shows the performance of C-V2X is more reliable than have been reported in IEEE 802.11p (Hu et al., 2017; Vukadinovic et al., 2018). An important direction for future research is to develop the C-V2X-based safety applications and tests in the real-life scenarios. In the future, we will analyze the influence of these behaviors on our ReCWS performance and do further experiments in complex real-life traffic environments with multi-vehicle communication.

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