The Effect of Communication Imperfections on Collision Warning and Avoidance Strategies

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Abstract

Vehicle-to-vehicle (V2V) communication technology has brought new developments for collision warning and avoidance system due to its broader environment information and perception range. Yet it also has limitations: packet loss, time delay and limited communication distance. This paper focuses on the effect of communication imperfections on collision warning and avoidance strategies. To better understand the avoidance behaviors, we propose two typical scenarios: vehicle following scenario and intersection scenario. In former scenario, a classical collision warning strategy, i.e., distance-base crash alert and avoidance algorithm is proposed; and in the latter scenario, a priority of vehicles using V2V communication is analyzed. Then the numerical experiments are carried out, which reveal the performance of warning and avoidance in different communication imperfections such as pack loss, time delay, limited communication distance. The results further demonstrate our model can be used to help avoid collisions and relieve traffic congestion.

Keywords: Collision warning and avoidance strategy, Advanced driver assistance systems, Communication imperfection, Time to collision

1 Introduction

With the rapid increase in traffic density, vehicle safety has become an important factor in modern intelligent transportation system. The Collision Warning and Avoidance System (CWAS) has gained more and more attentions due to its great potential of safety improvement. Indeed, CWAS are designed to predict an imminent crash, provide warnings to drivers, avoid vehicle crashes and minimize the impact of accidents [1-2]. The CWAS can be divided two classes dependent on whether or not to communicate to each other, i.e., Non-DSRC-equipped vehicles and DSRC-equipped vehicles. The former only uses the sensed data from multiple adjacent vehicles, and the latter not only applies the range data but considers the communication message from other vehicles. Both the two vehicles are able to adopts automatic braking mechanism to avoid collision when emergency occurs [3]. With the application of the vehicular wireless technologies, DSRC-equipped vehicles will become a hot topic in near future. In this paper, we focus on the collision warning and avoidance strategies of DSRC-equipped vehicles at following and intersection situations. However, sensors such as radar and camera used for environment information collection may bring about some imperfections such as pack loss, time delay and limited sensing range. Hence, we further investigate the effect of communication imperfections on collision warning and avoidance strategies in this paper.

Early works on collision warning and avoidance strategies date back to the 1970s [4-6]. Since then, many different algorithms and strategies on collision warning and avoidance strategies have been reported in the following literature. Ararat et al. [7] and Jamson et al. [8] calculate a threshold distance based on vehicle motion and the variables related to human characteristics, once the distance is smaller than the limit value calculated according to the type of system used, an alarm is activated. Then, Ward et al. [9] adopt Time to Collision (TTC) that represents the time required for two vehicles to collide if they continue at their present speed and on the same path and calculate Time to Collision for unconstrained vehicle motion. Many studies evaluated these CWAS models. Four forward collision-avoidance distance models, MAZDA, HONDA, JHU and JAGUAR, are evaluated against the identified “threatening” and “safe” data sets by Lee and Peng [10].

Recently, more and more studies focus on applying V2V technology in CWAS. For example, Zhang et al. [11] pointed that host vehicle (HV) can send or receive the basic safety message (BSM) from the remote vehicles (RVs). The collision warning predicted framework they proposed can provides connected

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automated vehicle and alert driver when car is in danger zone. After pre-processor RV BSM data, transforms the RV position and calculates the relative position, distance and speed. Then, vehicle collision can be detected in real time and the vehicle can prevent the potential conflict accordingly by using this information.

On the other hand, intersection is another critical scenario of high collision risk. For intersection scenario, Hafner *et al.* [12-13] proposed cooperative control algorithms taking system uncertainty and delay into consideration for collision avoidance at intersections; and Liu *et al.* [8] developed a collision warning strategy by applying a time model comparing TTC with time threshold and proposed two predictor feedback control strategies that overcome the destabilizing effect of the time delay caused by the packet losses. With V2V communications technology, Azimi *et al.* [14-15] developed the vehicular protocols that can be used to avoid conflict during intersection crossing and concluded from simulations that compared with traditional intersections with traffic lights and stop signs, intersections with communication protocols bear higher traffic efficiency. Furthermore, to identify the role of human factors in the timing of collision alerting in car following or intersections scenario, many existing papers indicate that V2V communications exert positive influence in crash alarm and avoidance [16-20].

However, owing to the communication limitation such as pack loss, time delay and communication distance, the collision warning and avoidance messages are influenced. Generally, DSRC is under 802.11p standard and issued by Institute of Electrical and Electronics Engineers (IEEE), it only works in the distance of 300 m between two cars in following scenario, but for intersection communication distance required is slightly shorter [21]. Message reception can be completed when the distance between two cars is in the vicinity of 300m, while its success rate decreases from approximately 80% at 0m to about 50% at 250m [22]. Another study found that when sensing range reaches 1000m, the rate of successful message reception is only 14% as WAVE typically delays 50ms [23]. Tang and Yip [21] set the delay of V2V communication at 25-300ms. The updating interval of DSRC is typically 100-1000ms. Some researchers examined the stability of control system when communication uncertainties, such as packet loss, stochastic delay [24-25] is caused by adopting zero-order hold. Tang and Yip explored the collision avoidance timing of DSRC-based vehicles and procedures in collision avoidance system with V2V communications.

Due to these defects in vehicle communication technology, it may result in a great impact on the collision warning and avoidance methods. Nevertheless, there is little study on the topic of V2V communication played in crash alerting and avoidance coping (CITE). This research aims to address how these communication imperfections exert influence on the effect of collision warning and avoidance methods in the following and intersection scenarios. Then we describe an implementation of Intersection Collision Avoidance to cover a wider range of intersection collision scenarios and study the effects of stochastic delays on the dynamics of connected vehicles by using both the mean and covariance dynamics. Finally, we also obtain requirements for the sampling frequency and reliability of DSRC devices.

The rest of this paper is structured as follows. Section 2 illustrates the definition of key concepts of crash alerting and avoidance coping in cars following and intersection situations. Section 3 presents scenarios and parameters for simulation. The results of simulation and analysis will be displayed in Section 4. At the end, Section 5 concludes this paper.

2 Collision Warning and Avoidance Strategies

In this Section, we proposed two scenarios, i.e., vehicle following and intersection to explore the effect of collision waring and avoidance strategies. We first introduce mathematical models of the two scenarios and then discuss the theoretical results in detail.

2.1 Vehicle Following Scenario

Suppose that one car is following its nearest preceding car in a single lane, the collision alert algorithm supports the driver of the rear car by issuing early warnings when the speed of leading car begins to decelerate. An accident can also be avoided through automatic braking carried out by collision avoidance system under the condition that the driver fails to take actions. Referring to Wu *et al.* [26], a warning algorithm that uses a conservative warning distance and a non-conservative braking distance is introduced as follows:

$$d_w = \frac{1}{2}\left(\frac{v^2}{a} - \frac{(v - v_{rel})^2}{a}\right) + v \times t + d_0, \tag{1}$$

where v is the velocity of the rear car, v_{rel} is the relative velocity $v_{rel} = v - v_{preceding}$ α is the maximum deceleration of both cars, τ is the system and driver delay, and d_0 is the headway offset. Note among many following models, the non-conservative braking distance can reduce brake control intrusion on normal driving maneuvers, and the algorithm was modified to include scaling functions which is suitable to account for the variation in tire road friction and driving styles.

The kinematic analysis assumes the CW/CA vehicle is initially at point x_{10} and has velocity v_1. The lead vehicle has initial position x_{20} and velocity v_2. At time=0, the lead vehicle brakes with a deceleration of a_2 while the CW/CA vehicle continues at the same velocity. Under these conditions, the vehicles have the following paths as functions of time:

$$x_1(t) = x_{10} + v_1 \cdot t, \tag{2}$$

$$x_1(t) = x_{10} + v_1 \cdot t, \tag{3}$$

$$x_2(t) = x_{20} + v_2 \cdot t - 0.5 \cdot a_2 \cdot t^2. \tag{4}$$

At the time of collision t_c, this leads to:

$$x_2(t_c) - x_1(t_c) = d - v_{rel} \cdot t_c - 0.5 \cdot a_2 \cdot t^2, \tag{5}$$

where $d = x_{20} - x_{10}$ and $v_{rel} = v_1 - v_2$. In accordance with the proposition above, assume the time-to collision t_c is equal to the total warning delay $\tau_{sys} + \tau_{hum}$. The system delay is given by τ_{sys} and the human response delay is given by τ_{hum}. The braking distance (d_{br}) is defined as bellows:

$$d_{br} = v_{rel} \times (t_{sys} + t_{hum}) + 0.5 \times a_2 (t_{sys} + t_{hum})^2, \tag{6}$$

where τ_{sys} represents system delay, τ_{hum} human response time, and α_2 the supposed deceleration of the lead vehicle. Seller et al. elaborated that $\tau = \tau_{sys} + \tau_{hum}$ and $\alpha_2 = \alpha$. The suggested parameter values are: $\tau_{num} = 1\text{s}$, $\tau_{sys} = 0.2\text{s}$, $\alpha = 6\text{m/s}^2$, $d_0 = 5\text{m}$. The driver of the rear vehicle is supposed to receive warning signals when the spacing between two cars is smaller than d_w, while automatic braking is designed to avoid accidents in the case of the distance reaching d_{br}.

2.2 Intersection Scenario

At intersections, cars are crossing an intersection from different directions. Sometimes it is difficult for drivers to notice other cars coming from the crossing road due to occlusion of buildings and limitation of visual field. Therefore, a collision warning system can be applied to avoid such dangerous situations using the information gathered through V2V communications. Warning signals will be sent to drivers if other cars are likely going to collide with the host one. When the system identifies an emergency, automatic braking will be applied to avoid collisions. The concepts of priority and dangerous zone will be presented prior to introduction of collision warning and avoidance strategies adopted in this paper.

Figure 1 displays the scenario of two cars crossing an intersection. Suppose that the two cars will go straight, then the positions of potential collision are marked in Figure 1. Let l_1, l_2 stand for the lengths of vehicle A and B, w_1, w_2 the widths, and x_1, x_2 the positions of the head of vehicles A and B. The origins of both x_1 and x_2 are set at the positions of potential collision. Assume that vehicle A reaches its position of potential collision earlier than vehicle B, then collision happens if $-(l_1 + w_2) < x_1 < 0$ when $x_2 = 0$. Therefore, the dangerous zone for vehicle A is $[-(l_1 + w_2), 0]$. Likewise, the dangerous zone for vehicle B is $[-(l_2 + w_1), 0]$. For safety, the dangerous zone of vehicle A is expanded to $[-(2l_1 + w_2), 0]$ and vehicle B $[-(2l_2 + w_1), 0]$.

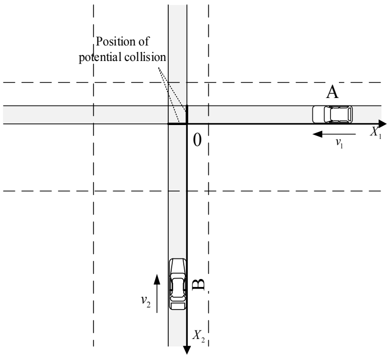

Figure 1. Intersection scenario

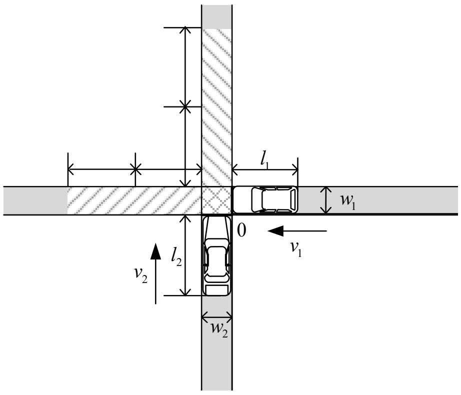

Figure 2. Illustration of dangerous zone

Priority, as defined in Eq. (7), is used to predict the vehicle which will pass the intersection first and the time interval between the two cars crossing the intersection. Priority will be measured continuously before cars reach the positions of potential collision. Assume that the cars will maintain their current speed, then if vehicle A is predicted to pass the position of potential collision earlier than vehicle B, the priorities of vehicle A and B ($priority_1$ and $priority_2$) are defined as below:

$$priority = \frac{-x_1(t_c)}{2l_1 + w_2}, \tag{7}$$

$$priority_2 = -priority_1, \qquad \textbf{(8)}$$

where $x_2(t_c) = 0$ and $x_1(t_c) < 0$.

Likewise, if vehicle B is predicted to pass the position of potential collision earlier than vehicle A at constant speed, the priorities of the two vehicles are expressed as the following equations:

$$priority_2 = \frac{-x_2(t_c)}{2l_2 + w_1}, \qquad \textbf{(9)}$$

$$priority_1 = -priority_2, \qquad \textbf{(10)}$$

where $x_1(t_c) = 0$ and $x_2(t_c) < 0$.

When $0 \le |priority_i| \le 1 \, (i = 1, 2)$, one car will be in the dangerous zone and the other arrives at the position of potential collision, indicating a high risk of collision. There is also another parameter used in collision warning TTA [27], which means the time consumed when a car eliminates accidents:

$$TTA = t_m + t_r + t_0 + t_1 + t_b, \qquad \textbf{(11)}$$

where t_m is the time required for the software to produce, transmit and identify an alarm signal; t_r and t_0 are the time for a driver to receive messages; t_1 is the time needed for braking system to response, and $t_b = 0.12 + 0.16v_0$ the time required for cars to stop completely. As Liu *et al.* [27] suggested, t_m can be ignored, $t_r = 1.1\text{s}, t_1 = 0.09\text{s}$, and t_0 is between 0.8-2s (1.5s in this paper). TTA is to be compared with TTC for decision of warning release. TTC is defined as the time required for cars to reach the position of potential collision in this paper, i.e., $\text{TTC}_i = x_i/v_i, (i = 1 \text{ or } 2)$. Warning signals will be released if:

$$\begin{cases} 0 \le |priority_i| \le 1 \\ TTC_i < TTA_i \end{cases} (i = 1 \ or \ 2). \qquad \textbf{(12)}$$

However, if the cars do not run at constant speed, the priority would vary over time. It can therefore be observed that collision avoidance algorithm is based on adjustment of priority. This algorithm aims to lead the higher-priority car out of the dangerous zone when the lower-priority one reaches the position of potential collision. Nonetheless, only one of the two cars (host vehicle, assume it to be vehicle B) is controlled by the algorithm. Vehicle B would continuously calculate the acceleration it needs to leave the dangerous zone when vehicle A reaches the position of potential collision if $priority_2 > 0$, or the deceleration it needs to arrive at the position of potential collision after vehicle A leaves the dangerous zone if $priority_2 < 0$. The calculation holds when the host vehicle accelerates or decelerates at constant speed and vehicle A keeps its current speed. The calculation is shown in Eq. (12).

$$a_2(t) = \begin{cases} \dfrac{2(x_2(t) - v_2(t) \times t_{an})}{t_{an}^{\ 2}}, & priority_2 < 0, \\ \dfrac{2(x_2(t) + 2l_2 + w_2 - v_2(t) \times t_{bn})}{t_{bn}^{\ 2}}, & priority_2 > 0, \end{cases} \qquad \textbf{(13)}$$

where t_{an} refers to the expected time required for vehicle A to leave the dangerous zone $t_{an} = (x_1(t) + 2l_1 + w_2)/v_1(t)$, and t_{bn} the expected time required for vehicle A to reach the position of potential collision $t_{bn} = x_1(t)/v_1(t)$. The collision avoidance system will take actions when the condition $0 \le |priority_i| \le 1 \, (i = 1, 2)$ has continuously been met for more than 0.5s and $|\alpha_2| > 1\text{m/s}^2$. Before avoidance system works, potential collision and emergency should be identified to avoid unnecessary disturbance. Meanwhile, the minimum and maximum value of α_2 shall be restricted, namely $\alpha_{2\max^-} < \alpha_2(t) < \alpha_{2\max^+}$. Variable α_2 will be updated in real time.

3 Simulation Experiment

3.1 Vehicle Following Scenario

Suppose that two cars are running in a single lane of roadways toward same direction in 2-D movement, in which the distance between the host vehicle and the target one, both have the same initials speed v_0, is h. When the host vehicle is travelling at a constant speed, the target car begins to decelerate at a speed α_1 when $t = 0$. This situation will continue until accident is about to occur, then the driver of the host vehicle is expected to receive alarm signals prior to automatic braking. During the experiment, these parameters are set as: $h = 150\text{m}, v_0 = 60 \text{ or } 100\text{km/h}, \alpha_1 = 2 \text{ or } 6\text{m/s}^2$, $\alpha_{\max^-} = 6\text{m/s}^2$.

3.2 Intersection Scenario

As presented in Section 2.2, two cars are running toward an intersection. The target car moves at three speeds, namely, constant speed $v_{1,0}$, constant deceleration α_1 starting from t_1 and constant speed v_{1e} starting from t_2. The initial distance of the target car from the intersection (i.e. the position of potential collision) $x_{1,0}$ is set to ensure that the car will arrive at the position of potential collision when $t_3 = 10\text{s}$. The host car runs at constant speed $v_{2,0}$ in the absence of emergency. The initial distance of the host car from the intersection $v_{2,0}$ is set to ensure that the two cars will arrive at the position of potential collision at the same time, then Collision happens. Collision warning and avoidance actions will subsequently be taken once relevant conditions are met. The above parameters are set as: $v_{1,0}=36$, 54 or 72km/h, $v_{1e}=v_{2,0}=18$, 36 or 54km/h, $\alpha_1=1\text{m/s}^2$, $t_1=2\text{s}, t_2=7\text{s}$. Then the initial distance of the two cars from the intersection could be calculated:

$$x_{1,0}=v_{1,0}\cdot t_1+0.5\cdot(v_{1,0}+v_{1e})\cdot(t_2-t_1)+v_{1e}\cdot(t_3-t_2) \\ =72.5\text{ , }122.5\text{ or }172.5\text{m}, \tag{14}$$

$$x_{2,0}=v_{2,0}\cdot t=50,\ 100\text{ or }150\text{m}. \tag{15}$$

3.3 Parameters Concerning V2V Communications

V2V communication can be used to collect cars' speed and location information required by collision warning and avoidance system. Therefore, in order to investigate how the deteriorating communication will exert influence on crash alerting and avoidance algorithms, more attention should be given to two factors: time delay and packet drop rate. we investigate the effect of both the data rate and transmission power in different scenarios. The simulation results show that transmission power and data rate can be tailored to increase the reliability of the communication for the collision avoidance system. In the following simulations, suppose that time delay is 0.1s-1s, packet drop rate 20%-80%, communication distance 50m-300m, and message updating rate 10Hz, then V2V communication begins to sample information concerning the position and speed of relevant vehicles. of which location is added noise subject to normal distribution with standard deviation of 0.5m, and speed the noise subject to normal distribution with standard deviation of 0.5m/s.

4 Simulation Results

4.1 Vehicle Following Scenario

In order to obtain more accurate statistics, four groups of dynamic conditions: ① $v_0=60\text{km/h}$, $\alpha_1=2\text{m/s}^2$; ② $v_0=60\text{km/h}$, $\alpha_1=6\text{m/s}^2$; ③ $v_0=100\text{km/h}$, $\alpha_1=2\text{m/s}^2$; ④ $v_0=100\text{km/h}$, $\alpha_1=6\text{m/s}^2$, are expected to simulate for 200 times in all simulations. After the calculation and analysis of collected statistics, the following bar chart gives information on the change of time and distance when warning and avoidance actions are reacted under ideal conditions in vehicle following scenario: the first dark bar blue of each group shows the alerting time and the second the automatic braking time, and the two light blue bars of each group stand for the spacing between the lead vehicle and the driver's vehicle when alerting signals (the first bar) and automatic braking (the second bar) are carried out respectively.

According to this chart, time delay, packet loss and limited sensing range will not affect the accuracy of the information concerning vehicle location and speed. Figure 3 is a reference for communication imperfections.

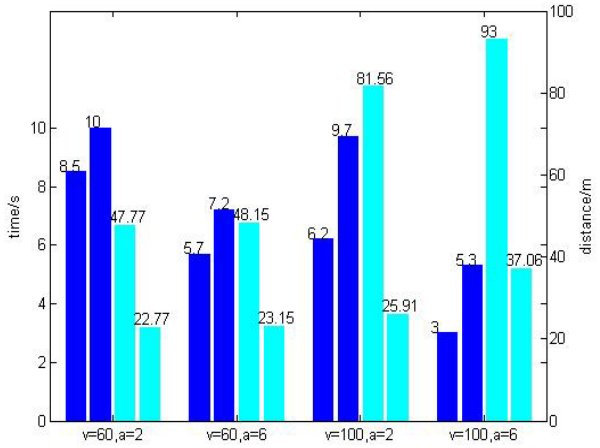

Figure 3. Time & distance of warning and braking under ideal conditions

4.1.1 Influencing Factors

(1) Pack loss. Given that packet loss affects the accuracy of evaluating surrounding cars' state, the time of warning or braking is different as packet drop rate varies, as graphically shows in Figure 4. Figures about the mean time of warning and braking can be overlooked as packet drop rate bears little relevance to it. According to the following charts, when the packet drop rate is 0.8, the standard deviations of alerting and braking also reach their largest 0.13s and 0.16s respectively. Assuming a normal distribution applied to the standard deviation, the time of warning and braking will deviate from the ideal value at its largest number, about 0.4s-0.5s. Under such circumstances, the deviation will dramatically influence the outcome of crash avoidance. Nevertheless, if the packet drop rate is less than 0.4, the accuracy of collision avoidance result will not be affected.

(2) Time delay. Warning or braking time is barely correlated with time delay, yet the mean time shifts slightly first under condition ③ and then under condition ④. As shown in Figure 5, the time stays steady under condition ① and ②. Once the start time of warning and braking is affected by time delay, the following situations will happen: (1) the observing distance between the target car and the host one becomes closer, allowing easier starting of collision warning and avoidance actions; (2) the relative velocity of the host car is reduced as the observing speed of the target car, which is decelerating, is faster than its real speed, making the distance between two cars required for triggering alerting or braking, in accordance with Eq. (1) and Eq. (2), become

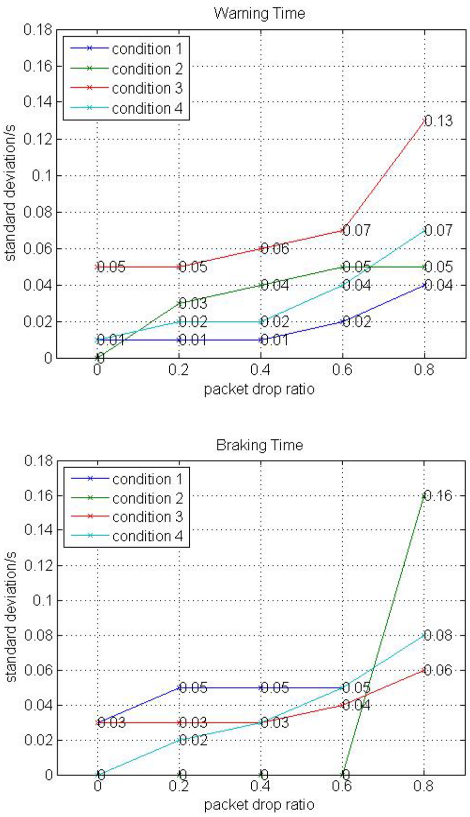

Figure 4. Standard deviations of alerting and braking time at different packet drop rate

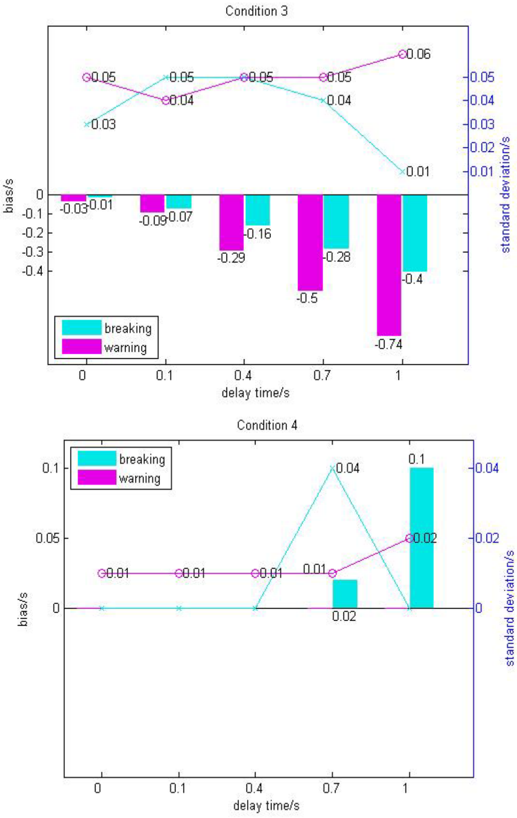

Figure 5. Mean variation (bars) and standard deviation (lines) of warning and braking time under conditions ③ and ④ during V2V communications when time delay occurs

shorter. As a result, the start time of alerting and automatic braking will be deferred. It should be noted that factor (1) and (2) also interact with each other. For example, supposed that the distance between the host car and the target one is same under condition ③ and ④, and that the target car under condition ③ is decelerating at a speed slower than that under condition ④, crash alerting and avoidance actions will be easier reacted under condition ③ than under condition ④.Therefore, it can be concluded that condition ③ is prone to be affected by increasing time delay than condition ④.Moreover, time delay exerts no influence under conditions ① and ②, for the target car has already stopped when warning or avoidance actions are about to be launched.

(3) Limited communicated distance. Conditions ① and ②, ③ and ④ represent two different trends concerning braking time and distance. Under low-speed conditions ① and ②, the mean and variance of warning and braking time are barely not be affected by changing communication distance that starts from 50m. However, the situation are opposite under high-speed conditions ③ and ④, in which the warning time is significantly deferred, a result of original warning distance beyond the limitation of communication distance, as communication distance reduces (the left part of Figure 6). The right part of Figure 6, a chart describing the distance between the target vehicle and the host vehicle when warning and braking are carried out, has proved the above situation. In this chart, the differences of warning distance and corresponding communication distance are roughly equal to each other. However, the braking distance is shorter than the warning distance, and the distances of braking and warning under low-speed conditions are shorter than that under high-speed conditions.

4.1.2 Combination of Influencing Factors

As the basic broadcasting and transmission as well as packet loss both contribute to the time delay during V2V communication process, an analysis taking into account time delay and packet loss will better reflect the real situations. Therefore, an exponential model (Eq.15) is employed to emulate the variability of packet drop rate, which is different as the communication distance between two cars changes

$$PDR(x) = 1 - \left(e^{\frac{\ln 0.05}{CD}} \right)^{x}, \qquad (16)$$

where PDR(x) represents the packet drop rate at certain distance (see Figure 7), CD the communication distance when packet drop rate reaches 0.95, and x the real distance between the two cars. In this simulation, all three factors discussed in Section 4.1.1 can be included through changing delay time and communicated Distance.

The simulation results (Figure 7) of the combined factors are consistent with previous findings. It can be concluded from Figure 8, which describes the mean and standard deviations of the alerting and braking time, that the standard deviations are affected by CD, communication distance, will shorten the warning time under conditions ③ and ④.

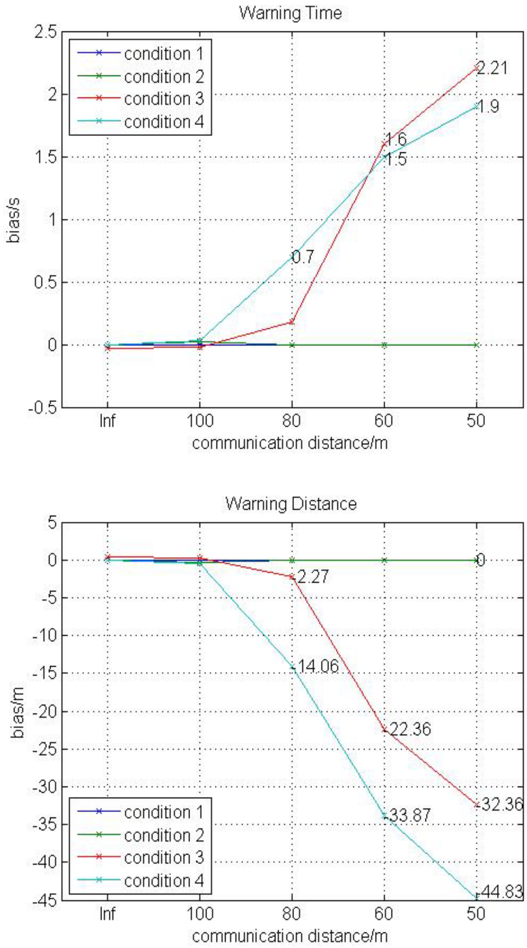

Figure 6. Mean variation of warning time and distance as the limitation of communication distance changes

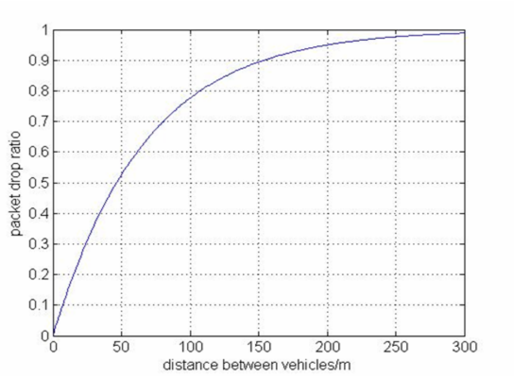

Figure 7. Packet drop ratio when CD=200m

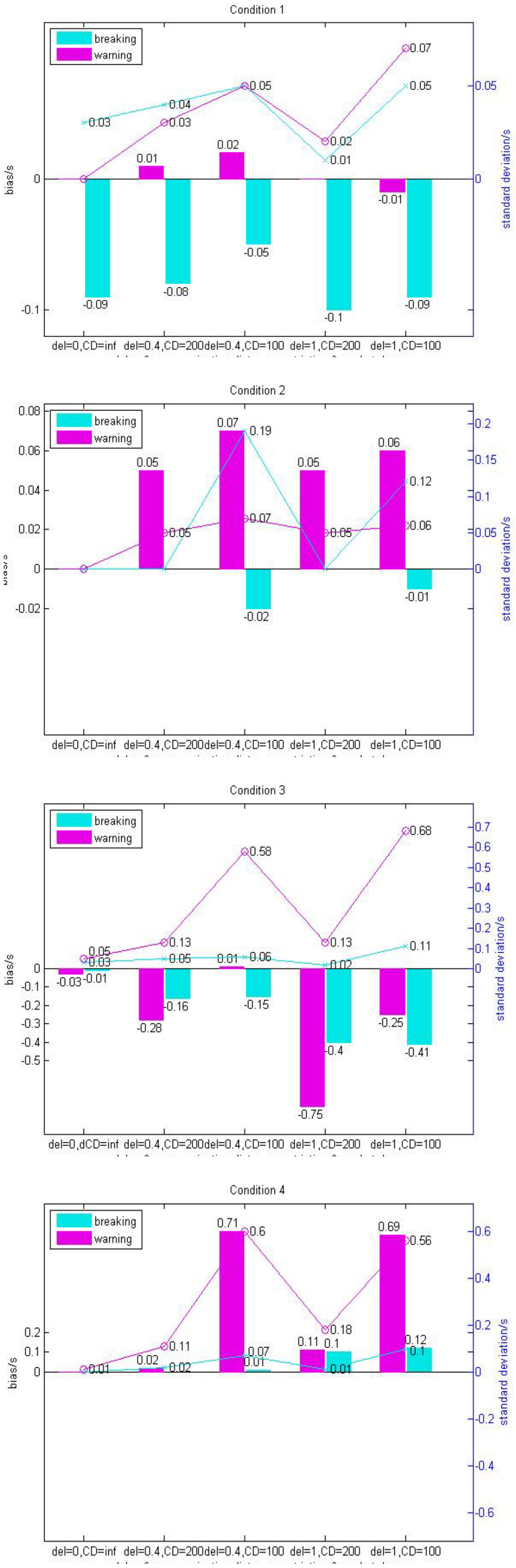

Figure 8. Mean variation (bars) and standard deviation (lines) of warning and braking time affecting by contributory factors

4.2 Intersection Scenario

In order to confirm whether time delay, packet drop and limited sensing range will affect the accuracy of information about vehicle velocity and position, a series of simulations are conducted under three groups of dynamic conditions: ① $v_{1,0} = 36\text{km/h}$, $v_{1e} = v_{2,0} = 18\text{km/h}$; ② $v_{1,0} = 54\text{km/h}$, $v_{1e} = v_{2,0} = 36\text{km/h}$; ③ $v_{1,0} = 72\text{km/h}$, $v_{1e} = v_{2,0} = 54\text{km/h}$; in which each group of conditions are simulated for 200 times.

Figure 9 is in accordance with above simulations, in which the first dark blue bar of each group represents the alerting time and the second the automatic braking time, and the light blue bars stand for the distance between the host car and the intersection when alerting signals (first bar) and automatic braking (second bar) are carried out. According to the chart, it can be concluded that communication imperfections will not affect the accuracy of vehicle velocity and location information.

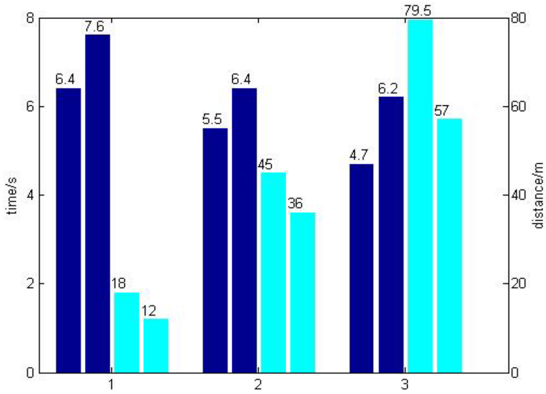

Figure 9. Time and distance of warning and barking under ideal conditions

4.2.1 Influencing Factors

(1) Packet loss. There is the positive correlation between the initial standard deviations of warning and braking time and packet drop rate. (see Figure 10). More packet loss means less information of the car coming to the intersection, the host car will therefore immediately predict other cars' state by filter when measurement information is not available. Another finding is that the standard deviation of warning time is much less than that of braking time. This can be explained by warning or braking algorithms. The warning algorithm (Eq. 11) relies largely on information of the host car, while the automatic braking algorithm (Eq. 12) reckons more on information of other cars. Packet loss merely disturbs the estimation of the other cars' state. Assume that the uncertainty of braking time is subjected to normal distribution, packet loss will lead to up to 0.52*3+0.73=2.29s ahead of normal braking, an annoying disruption for drivers.

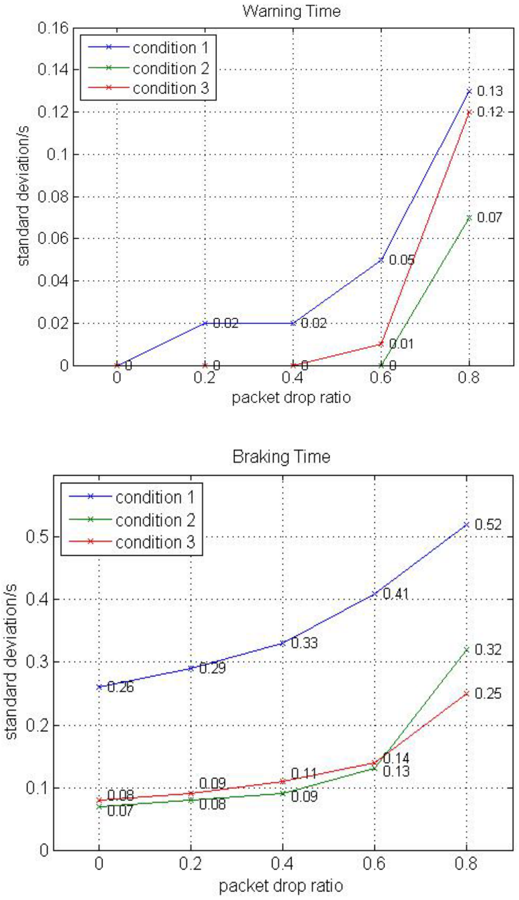

Figure 10. Mean variation of warning and braking time under packet loss

(2) Time delay. It can be observed from the left part of Figure 11 that time delay during V2V communication has significant impact on the performance of collision avoidance. The target and host cars are running vertically. Time delay will affect observation of the target car's location, directly undermining judgment on potential collision, *priority* and pre-acceleration. Substantial delay may lead to total failure of the entire system. The faster the target car is, the more vulnerable the algorithm is to communication latency.

The right part of Figure 11 displays the mean variation of braking time. Due to wrong perceived position of the target car, the braking time is apparently inconsistent with the ideal value, entailing failure of collision avoidance.

(3) Limited communication distance. Figure 12 depicts the distance of the host car to the intersection when warning and braking is triggered under limited communication distance. Delay was observed when communication distance was no more than 50m under condition ② and 100m under ③. Limited communication distance exerts slight influence on warning and braking time unless CD is shorter than warning or braking distance. Communication distance refers to the linear distance between two cars, thus the physical distance to the intersection does not equal to communication distance. Even so, the delay does not necessarily cause

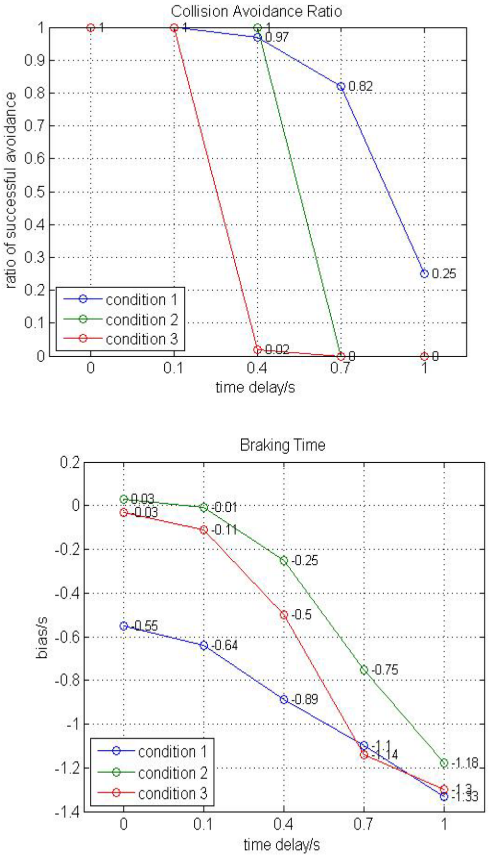

Figure 11. Ratio of successful collision avoidance and mean variation of braking time with time delay during V2V communications

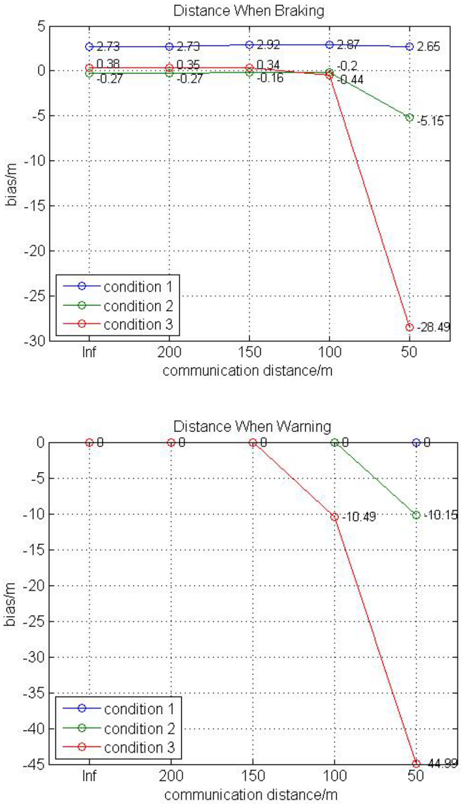

Figure 12. Mean variation of warning and braking distance under limited communication distance

a collision. It is shown in the simulation that the ratio of successful collision avoidance did not suffer a decline under all three conditions even if the communication distance is restricted to 50m, for the collision avoidance at intersection is designed to be started with moderate acceleration. When the start time of warning or braking is delayed, greater acceleration can be adopted for compensation.

4.2.2 Combination of Influencing Factors

The model of changing packet drop ratio could also be applied to the intersection scenario. Communication parameters are time delay and communication distance when packet drop ratio is 0.95. The simulations were also conducted under the above three conditions.

From Figure 13 and Figure 14, it is clear that time delay exerts considerable influence on braking time, leading to direct failure of collision avoidance. In addition, uncertainty of warning and breaking time rises as CD (indirectly affecting packet drop ratio) shortens. Another interesting result is that both warning and braking time suffered a significant delay when CD was 100m. The reason is that the initial distance of warning and braking is set to the upper limit under condition ③, and ideally CD=100m is not enough to start warning or braking.

5 Conclusion

This paper investigates how the crash alerting is affected by communication imperfections, that is, packet drop, time delay and communication distance, through theoretical method and numerical experiments. In detail, two typical scenarios related to high collision risk are presented: vehicle following scenario and intersection scenario.

The algorithms in this article analyzed three kinds of influence factors and the combination of Influencing factors in the case of control variables more comprehensively. Compared with other articles, the chart visually shows the trend in warning and braking distance and time. The detection probability of the method is evaluated versus several driving conditions.

As the results shown, for both scenarios, increasing packet drop ratio will lead to uncertainties of warning and braking time. As the result shows, the above three communication imperfections affect the performance of warning and braking time in both scenarios. Firstly, the varying packet drop and its filter’s properties contribute to the uncertainties of warning and braking time. Secondly, time delay may shorten the observing distance or quicken the observing velocity of the target car, making the actions of warning and braking are activated earlier or later. Thirdly, when distance between two cars is smaller than original warning or braking distance, alerting or braking time will be

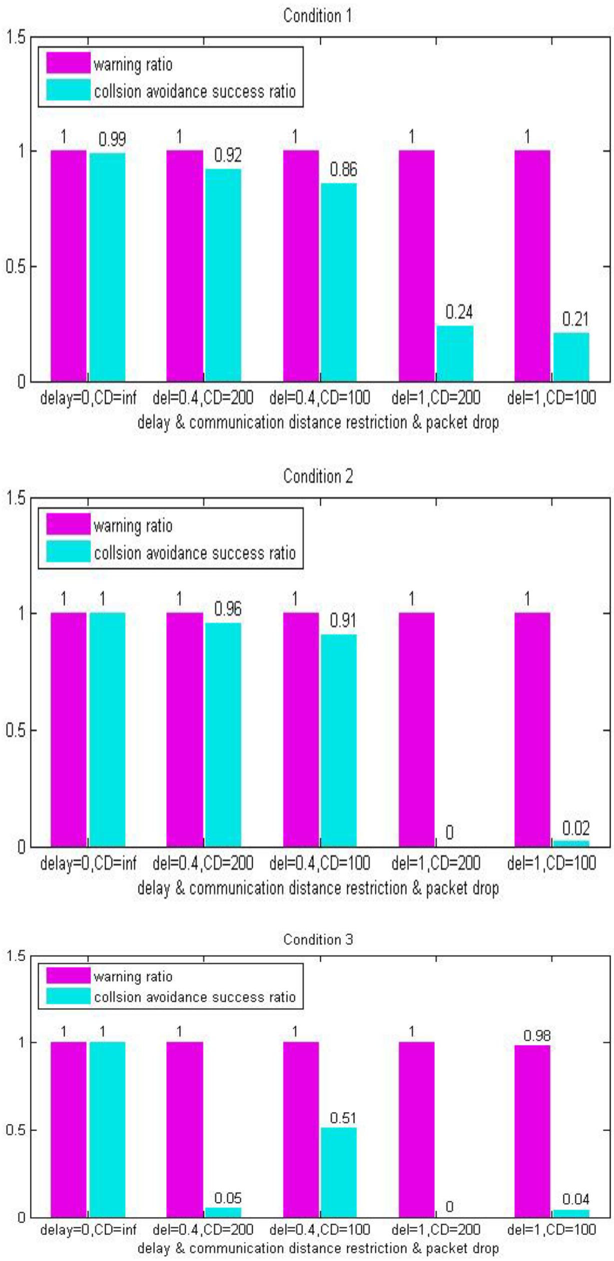

Figure 13. Warning ratio and ratio of successful collision avoidance under multiple influencing factors

affected significantly. Moreover, the starts point of observation and filtering varies in accordance with changing communication distance, resulting in differences in the filtered value and deviation of alerting and braking time.

As the outcome of analysis on multiple communication parameters is consistent with that of each parameter in both scenarios, it can serve as a reference to for crash alerting and avoidance algorithm to deal with communication imperfections so as to ensure the accuracy of alerting and braking time. Meanwhile, a better communication quality and operation of crash alerting and avoidance system is expected to be achieved through quantitative analysis in our follow-up studies.

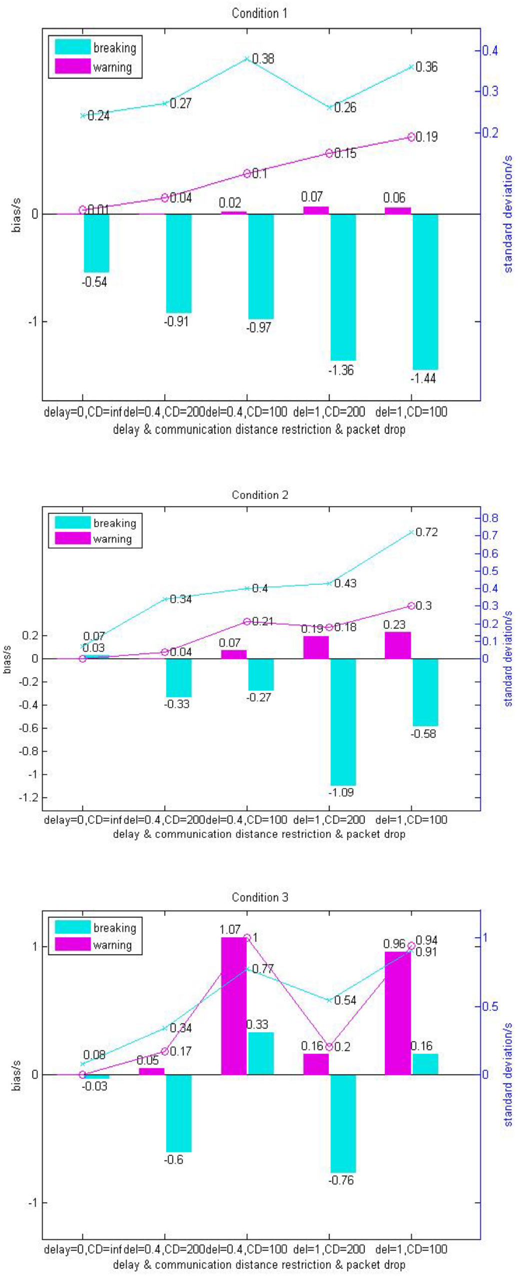

Figure 14. Mean variation (bars) and standard deviation (lines) of warning and braking time under different contributing factors

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References

[1] J. Ji, A. Khajepour, W. W. Melek, Y. Huang, Path Planning and Tracking for Vehicle Collision Avoidance Based on Model Predictive Control with Multiconstraints, *IEEE Transactions on Vehicular Technology*, Vol. 66, No. 2, pp. 952-964, February, 2017.

[2] Y. Ba, W. Zhang, Q. Wang, R. Zhou, C. Ren, Crash Prediction with Behavioral and Physiological Features for Advanced Vehicle Collision Avoidance System, *Transportation Research Part C*, Vol. 74, pp. 22-33, January, 2017.

[3] Y. Gao, X. Liu, W. Dong, A Multiple Vehicle Sensing Approach for Collision Avoidance in Progressively Deployed Vehicle Networks, *2017 IEEE 25th International Conference on Network Protocols (ICNP)*, Toronto, Canada, 2017, pp. 1-10.

[4] T. L. Vincent, E. M. Cliff, W. J. Grantham, W. Y. Peng, *A Problem of Collision Avoidance*, University of Arizona, 1972.

[5] T. Maeda, N. Irie, K. Hidaka, H. HNishimura, *Performance of driver-vehicle System in Emergency Avoidance*, SAE Technical Paper, 1977.

[6] E. H. Düll, H. J. Peters, *Collision Avoidance System for Automobiles*, SAE Technical Paper, 1978.

[7] O. Ararat, E. Kural, B. A. Guvenc, Development of a Collision Warning System for Adaptive Cruise Control Vehicles Using a Comparison Analysis of Recent Algorithms, *Intelligent Vehicles Symposium, 2006 IEEE*, Tokyo, Japan, 2006, pp. 194-199.

[8] A. H. Jamson, F. Lai, O. Carsten, Potential Benefits of an Adaptive Forward Collision Warning System, *Transportation Research Part C: Emerging Technologies*, Vol. 16, No. 4, pp. 471-484, August, 2008.

[9] J. R. Ward, G. Agamennoni, S. Worrall, A. Bender, E. Nebot, Extending Time to Collision for Probabilistic Reasoning in General Traffic Scenarios, *Transportation Research Part C: Emerging Technologies*, Vol. 51, pp. 66-82, January, 2015.

[10] K. Lee, H. Peng, Evaluation of Automotive Forward Collision Warning and Collision Avoidance Algorithms, *Vehicle System Dynamics*, Vol. 43, No. 10, pp. 735-751, October, 2005.

[11] R. Zhang, L. Cao, S. Bao, J. Tan, A Method for Connected Vehicle Trajectory Prediction and Collision Warning Algorithm Based on V2V Communication, *International Journal of Crashworthiness*, Vol. 22, No. 1, pp. 15-25, January, 2017.

[12] M. R. Hafner, D. Cunningham, L. Caminiti, D. D. Vecchio, Automated Vehicle-to-vehicle Collision Avoidance At Intersections, *Proceedings of 18th World Congress on Intelligent Transport Systems*, Orange, FL, 2011.

[13] M. R. Hafner, D. Cunningham, L. Caminiti, D. D. Vecchio, Cooperative Collision Avoidance at Intersections: Algorithms and Experiments, *IEEE Transactions on Intelligent Transportation Systems*, Vol. 14, No. 3, pp. 1162-1175, September, 2013.

[14] R. Azimi, G. Bhatia, R. R. Rajkumar, P. Mudalige, STIP: Spatio-temporal Intersection Protocols for Autonomous Vehicles, *ICCPS'14: ACM/IEEE 5th International Conference on Cyber-Physical Systems*, Berlin, Germany, 2014, pp. 1-12.

[15] S. R. Azimi, G. Bhatia, Vehicular Networks for Collision Avoidance at Intersections, *SAE International Journal of Passenger Cars-Mechanical Systems*, Vol. 4, No. 1, pp. 406-416, April, 2011.

[16] M. Burmester, E. Magkos, V. Chrissikopoulos, Secure and Privacy-preserving, Timed Vehicular Communications, *International Journal of Ad Hoc & Ubiquitous Computing*, Vol. 10, No. 4, pp. 219-229, September, 2012.

[17] J. Werneke, M. Vollrath, How to Present Collision Warnings at Intersections? —A Comparison of Different Approaches, *Accident Analysis & Prevention*, Vol. 52, pp. 91-99, January, 2013.

[18] X. Yan, Y. Zhang, L. Ma, The Influence of In-vehicle Speech Warning timing on Drivers' Collision Avoidance Performance at Signalized Intersections, *Transportation Research Part C: Emerging Technologies*, Vol. 51, pp. 231-242, February, 2015.

[19] R. Yim, F. Ye, S. Roy, P. Orlik, Effect of Transmission Parameters on Efficiency and Reliability of V2V Networks, *17th ITS World Congress*, Busan, Korea, 2010.

[20] M. Maile, Q. Chen, G. Brown, L. Delgrossi, Intersection Collision Avoidance: From Driver Alerts to Vehicle Control, *Vehicular Technology Conference (VTC Spring), 2015 IEEE 81st*, Glasgow, Scotland, 2015, pp. 1-5.

[21] A. Tang, A. Yip, Collision Avoidance Timing Analysis of DSRC-based Vehicles, *Accident Analysis & Prevention*, Vol. 42, No. 1, pp. 182-195, January, 2010.

[22] D. Jiang, V. Taliwal, A. Meier, W. Holfelder, Design of 5.9 GHz DSRC-based Vehicular Safety communication, *IEEE Wireless Communications*, Vol. 13, No. 5, pp. 36-43, November, 2006.

[23] A. S. Farahmand, L. Mili, Cooperative Decentralized Intersection Collision Avoidance Using Extended Kalman Filter, *IEEE Intelligent Vehicles Symposium*, Xian, China, 2009, pp. 977-982.

[24] W. B. Qin, M. M. Gomez, G. Orosz, Stability Analysis of Connected Cruise Control with Stochastic Delays, *American Control Conference (ACC), 2014*, Portland, OR, 2014, pp. 4624-4629.

[25] W. B. Qin, M. M. Gomez, G. Orosz, Stability and Frequency Response under Stochastic Communication Delays with Applications to Connected Cruise Control Design, *IEEE Transactions on Intelligent Transportation Systems*, Vol. 18, No. 2, pp. 388-403, February, 2017.

[26] J. S. Wu, Y. C. Cheng, S. T. Sheu, Memorised Carrier Sense Multiple Access with Collision Avoidance (MCSMA/CA) protocol for IEEE 802.11p, *International Journal of Internet Protocol Technology*, Vol. 7, No. 1, pp. 52-61, July, 2012.

[27] T. Liu, Y. Wang, E. Wenjuan, D. Tian, Vehicle Collision Warning System and Algorithm at Intersection under Internet-Connected Vehicles Environment, *The 12th COTA International Conference of Transportation Professionals*, Beijing, China, 2012, pp. 1177-1185.

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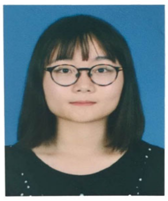

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