ELSEVIER

Volume 42, issue 1
January 2010
ISSN 0001-4575

ACCIDENT ANALYSIS & PREVENTION

Editors: Rune Elvik & Karl Kim

- EPIDEMIOLOGY OF TRAUMA
- HUMAN FACTORS
- SAFETY MANAGEMENT & POLICY
- OCCUPATIONAL SAFETY
- RISK ANALYSIS
- TRAFFIC ACCIDENT STUDIES
- EVALUATION OF COUNTERMEASURES
- SAFETY ENGINEERING
- INJURY REDUCTION RESEARCH
- APPLIED BIOMECHANICS

Affiliated with the Association for
the Advancement of Automotive Medicine

Available online at www.sciencedirect.com
ScienceDirect

Accident Analysis and Prevention 42 (2010) 182–195

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Collision avoidance timing analysis of DSRC-based vehicles

Antony Tang*, Alice Yip

Centre for Software Analysis and Testing, Swinburne University of Technology, John Street, Hawthorn, Melbourne, Vic 3122, Australia

ARTICLE INFO

Article history:
Received 22 May 2009
Received in revised form 22 July 2009
Accepted 25 July 2009

Keywords:
Timing analysis
Software-based collision avoidance system
Dedicated short-range communication

ABSTRACT

Dedicated short-range communication (DSRC) has been used in prototyped vehicles to test vehicle-to-vehicle communication for collision avoidance. However, there is little study on how collision avoidance software should behave to best mitigate accident collisions. In this paper, we analyse the timing of events and how they influence software-based collision avoidance strategies. We have found that the warning strategies for collision avoidance are constrained by the timing of events such as DSRC communication latency, detection range, road condition, driver reaction and deceleration rate. With these events, we define two collision avoidance timings: critical time to avoid collision and preferred time to avoid collision, and they dictate the design of software-based collision avoidance systems.

1. Introduction

Vehicle and road safety has been a key issue for the communities and governments. With emerging new technologies and knowledge, different approaches have been proposed to reduce road accidents. The National Highway Traffic Safety Administration sponsors developed an Integrated Vehicle-Based Safety System to monitor traffic environment with an aim to reducing crashes (University of Michigan Transportation Research Institute, 2007). A similar project sponsored by the European Union develops a precrash sensorial system (Fuerstenberg et al., 2002). Both systems employ radars and vision sensors in a vehicle to detect potential collisions and trigger different mechanisms to mitigate or avoid the collisions. The development and application of dedicated short-range communications (DSRCs) for vehicle-to-vehicle communications is a recent development that could help reduce vehicle collisions. The DSRC device uses a bandwidth around the 5.9 GHz range and it is based on the proposed IEEE 802.11p standard (IEEE Task Group p). The National Highway Traffic Safety Administration has commissioned a study in 2006 to assess the effectiveness of such technology on road safety (U.S. Department of Transportation, 2006b). In this study, DSRC tests were performed to evaluate the safety benefits. It was found that DSRC provides an effective communication between two vehicles in a range of 250 m in a vehicle following scenario, and slightly poorer performance in an intersection scenario. Another study has found the probability of successful message reception is around 90% at a 300 m and drops off significantly with longer distances (Jiang et al., 2006). This technology is being developed and tested for vehicle-to-vehicle communication in many projects, examples are IVI in USA, Safespot and WILLWARN in Europe, and AVS in Japan (Strandén et al., 2008).

DSRC is an enabling technology that allows vehicles to communicate with each other so that advance notice or warning can be given to the driver and or the vehicle to mitigate potential collisions. Ideally the DSRC device could detect potential danger before the driver can perceive them, such as intersection collision or sudden braking of a leading vehicle. However, many issues are not well understood for the successful deployment of such a technology. Firstly, we need to understand the relationship between looking ahead for potential collision detection and when to deploy collision mitigation strategies. Secondly, within the constraint of the time that is allowed for the driver and the vehicle to react given the accident scenario, determine the best warning and mitigation mechanisms to interact with the driver. These two considerations have scarcely been studied.

In this paper, we use information from a prototyped DSRC-based collision detection system, and we take into account different timing factors that affect collision avoidance, factors such as driver reaction time, braking time and road conditions. With this information, we study how they can be used in a collision avoidance warning system, employing a DSRC device that could detect surrounding vehicles for computing vehicle trajectories. The results of this study illustrate the critical timing zones when advanced warnings must be given to effectively avoid collision in different accident scenarios. From these critical timing zones, we have devised collision detection and mitigation strategies for developing on-board computer software.

---

* Corresponding author. Tel.: +61 3 92145198; fax: +61 3 92140823.
E-mail address: atang@swin.edu.au (A. Tang).

0001-4575/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.aap.2009.07.019

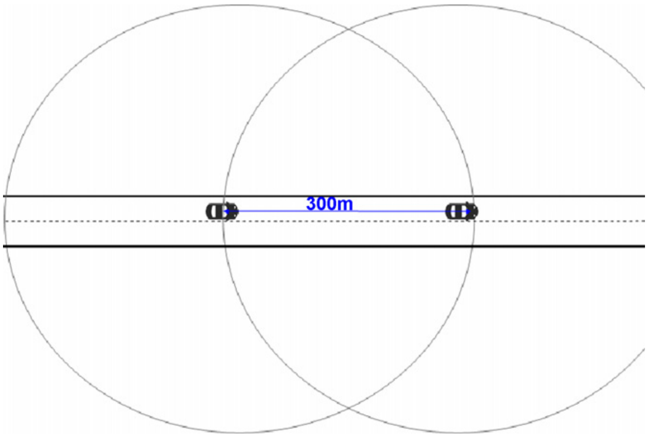

Fig. 1. Vehicle-to-vehicle communication.

2. Background

General Motors (GM) has developed a prototype Vehicle-to-Vehicle (V2V) communication device that is intended to detect potential collisions and gives drivers early warnings as well as providing automated collision avoidance measures (see Fig. 1). The device is based on a dedicated short-range communication (DSRC) using the IEEE 802.11p standard, a specialised Wi-Fi standard and DSRC message set protocol (SAE International, 2007). Vehicles that are in the vicinity of 300 m can communicate with each other of their positioning, course, speed traffic information and vehicle size. From this information, the on-board computer can compute the trajectories and if they are in danger of colliding. In case of any potential dangers, the system then alert drivers through chimes, visual icons or seat vibrations and, in cars fitted with automated braking systems (as with many modern cruise controls), can even bring the car to a safe stop and avoid a crash if the driver does not respond fully in time. For example, in an emergency stop when the car registers it is in danger of being rear-ended, it flashes its taillights rapidly. At the same time, the driver of the approaching car will get alerts in time to perform a braking or avoidance manoeuvre.

Under different traffic accident scenarios, the application of a software-based intelligent accident avoidance strategy using a V2V device relies on the contextual information gathered in real-time. For instance, in a given accident scenario, the software must compute the time to potential collision, and compares that with the timing events such as drivers' reaction time, vehicle braking performance, traffic scenarios and road conditions. These timing events are dynamic and can differ between vehicles, road conditions and drivers. In order to design the behaviour of a collision-avoidance device based on V2V communication and the dynamic timing events, we must first analyse the key factors that influence the time from when a warning is given to the time when a collision can be avoided. We call this timing zone a *collision timing avoidance zone*.

Consider a simple scenario, a V2V device in a subject vehicle continuously scans the surrounding road environment for any potential collisions. When a subject vehicle finds another vehicle, it computes the potential collision by using their trajectories and speed. If the collision potential is high, knowing when to warn the users to avoid this collision would depend on knowing a few more things. For instances, the time to decelerate the vehicle (or braking), the time for the driver to react to the warning, the time for the V2V device to detect the danger, etc. Each of these factors has certain variability, braking depends on the road condition—slippery or dry, driver reaction depends on alertness and age, V2V communication time depends of the density of the communication and the geography. These variables can significantly affect the performance and the reliability of a warning system. There has been no study on how such variations affect the strategies and the design of an early warning system and such is the purpose of this paper.

3. Timing components

Innovative traffic treatments have been difficult to assess because there is a lack of good predictive models of crash potentials and a lack of consensus on what constitutes a safe or unsafe facility. A research project has investigated into the different surrogate safety measures on the basis of an occurrence of a collision event (Gettman and Head, 2003). The proposed measures that are considered to be most useful include time to collision (TTC), post-encroachment time[1] (PET), deceleration rate, maximum speed and speed differential.

In order to assess the effectiveness of a V2V device, we study the time availability for advanced warnings and investigate the events that occur before a potential collision for selected accident scenarios that are described in Section 4. The investigation would make use of computer models to compute the collision avoidance time using different parameters. The purpose of having such a model is to assist the software design of a V2V-based collision avoidance system. We recognized that the parameters used in the computer model will vary depending on the driving conditions. For instance, braking performance can vary between vehicle models, road conditions and driver's age can change. Therefore, an intelligent warning system should take these factors into consideration in order to provide appropriate warnings. We posit that in an implementation, some of these key factors such as deceleration performance should be calibrated statically and other parameters such as V2V latency can be computed dynamically.

3.1. DSRC-based V2V collision timing analysis

Punctual warning and reacting to a potential collision based on a V2V device depends on two categories of information – the space between two vehicles and their relative speed and positions; the time it takes for the driver and the vehicle to slow down or stop. Given a vehicle velocity and direction, the conversion between time and space is straight forward. However, collision avoidance involves human reaction and other timing factors. Therefore, we choose to use the time dimension in our analysis. This study compares, under different circumstances or parameters, how much warning time drivers can have when the V2V device is available, and what would be the normal and poorer condition scenarios in an intelligent software system that make decisions to mitigate potential collisions. The normal condition is defined as the average time of driver reaction and vehicle deceleration in dry road conditions. Poorer condition is when driver reacts slowly and road conditions are wet and takes longer to decelerate (see Section 3.2). A study was done by (Miller and Huang, 2002) to evaluate some timing factors but it did not provide an in-depth analysis of how timing parameters influence software-based mitigation strategies.

In Fig. 2, we outline the basic parameters that influence the timing events of an accident. The time to avoid collision (TTAC) is a function of when a potential collision is detected to the point of just avoiding the collision. With a V2V device, detection is when the device detects a potential collision at time T_i, from that time to the projected point of just avoiding the collision (time T_m) is the duration in which the V2V device can activate any mitigation strategies such as providing warnings or automatic braking, and

---

[1] Encroachment time is the time duration during which the turning vehicle infringes upon the right-of-way of through vehicle.

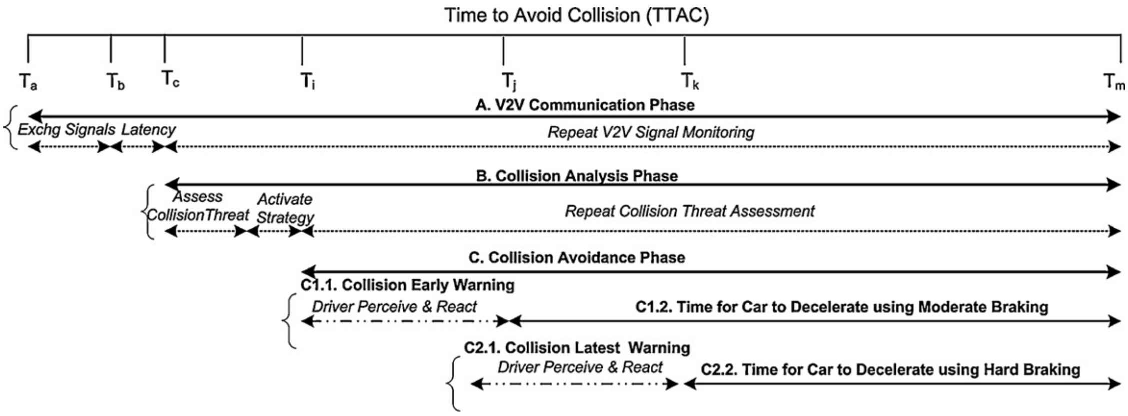

Fig. 2. Timing analysis of collision avoidance.

there is sufficient time to the driver and vehicle to react. The duration between T_i and T_m can be quite short if the vehicle does not decelerate, i.e. the driver does not brake or react to the warning. If we assume that a driver would react to a warning, the duration of the time would be longer. It can be computed based on a number of factors – including the potential collision scenario, the speed that the vehicles are travelling and the deceleration of the vehicles.

If we dissect TTAC into the timing components that are needed for mitigating the risk of a potential accident, then we observe timing related factors in three distinct phases:

1. *Phase A*: V2V Communication Phase. This is a phase in which interaction between V2V-equipped vehicles occur continuously. The timing of this phase depends on the density of the traffic and when the communication latency is high it reduces the time to react to potential collision.
2. *Phase B*: Pre-warning phase. In this phase, information is gathered by the collision avoidance software (CAS) in real-time and it continually evaluates if there is a threat of collision. If a threat is detected, it would move to Phase C. CAS also communicates the information to a driver in this phase.
3. *Phase C*: When a collision threat has been determined and the mitigation actions are computed by CAS, a mitigation strategy would be initiated. This phase depicts the time it would take to execute the actions. For instance, the time to avoid collision would depend on the deceleration rate, which is a function of vehicle speed, vehicle mass and mechanical braking.

Without the V2V device, the driver would, eventually, detect the danger of collision at a certain time. That time could be early enough or too late to avoid the accident. The CAS system is advantageous when it foresees a potential collision and warns the driver before s/he detects the danger. CAS determines how much time the V2V system can provide a warning in advance (i.e. $T_m - T_i$) to give the driver and the vehicle sufficient time to react. This modelling of collision timing enables us to evaluate the various mitigation strategies that could be implemented by the V2V device for different collision scenarios.

3.2. Timing parameters

An intelligent V2V system should compute the timing for a vehicle to stop under different circumstances. The algorithm is basically an estimation of the trajectory of a vehicle. In order to provide an early warning system for the driver to take mitigation actions, the software must, at an appropriate time, provide warnings that allow a driver to react to a collision threat. If manual actions are not carried out in time to avoid a collision, the V2V device can activate mitigation actions automatically to minimise the damage. This type of strategies requires an understanding of the timing of events. The timing events are the activities that make up the time when attempting to avoid a collision. For instance, the time, location, speed, direction and the distance of two travelling vehicles determine whether they may collide. If we dissect the time to slow down or to stop a vehicle, we have the following:

$$\begin{aligned}\text{stop or slowdown time} = {} & \text{driver perception time}\\ & + \text{driver reaction time}\\ & + \text{deceleration time}\end{aligned} \tag{1}$$

The driver perception time, the driver reaction time and the deceleration time can vary depending on the driver, the alertness of the driver, the vehicle and the road conditions. These variables can have significant influence on the stop time of a vehicle. Similarly, some vehicles are equipped with advanced features such as emergency braking support that influence the stop time. In order to deploy an effective V2V collision avoidance system, the stop time must be computed given the current conditions of the driver, the characteristics of a vehicle and the road condition.

Another set of factors that affect the timing of detection and avoidance are the communication and computation time of the devices. If the time that a V2V device takes to detect a potential threat is long, then the CAS software must compensate for the lost time to ensure that there is sufficient time for the driver/vehicle to react.

$$\text{communication time} = \text{transmission time} + \text{broadcast latency} \tag{2}$$

$$\begin{aligned}\text{collision activation time} = {} & \text{threat analysis computation time}\\ & + \text{activate mitigation strategy time}\end{aligned} \tag{3}$$

The communication time between DSRC-based devices can vary depending on the density of the traffic and the topography (U.S. Department of Transportation, 2006b). If the broadcast frequency of positioning information by a vehicle is low, the time to wait for the next update by other vehicles would be higher, i.e. higher latency. As a result, the positioning information may be out of date. A potential threat may actually become an imminent accident in between the two communication exchanges, and valuable warning time could be lost when the system waits for the next data exchange. Similarly, it would take time for the CAS to compute collision threats and activate the mitigation strategy such as displaying a warning or vibrating driver's seat.

3.2.1. V2V communication

The V2V device requires access to some positioning systems (PS) such as satellite positioning, e.g. GPS, or infrastructure-based positioning. This information is computed to determine the trajectory of the vehicle and communicated to nearby vehicles using the DSRC Message Set Dictionary (SAE International, 2007). Each vehicle equipped with a V2V device can therefore compute whether another vehicle is encroaching into its space to cause a collision. In our model, we assume that a DSRC device would have a positioning accuracy within 10 cm or 1 dm. This assumption underpins the calculation of just-in-time collision avoidance. In one scenario using precise positioning technology with a subject vehicle and a leading vehicle, the positioning of the two vehicles has a known error margin of 20 cm in the facing direction, a collision may be avoided if allowance of such an error margin is compensated for. However, using today's civilian GPS technologies, positioning can be erroneous by more than a meter and the error margin cannot be determined, making the computation of collision timing and collision distance less accurate.

The communication between the V2V devices is performed through a pre-assigned communication channel when nearby vehicles are within range. It takes approximately 20 ms to handshake. Then each vehicle would allocate a channel, out of 10 possible channels, and communication would take place through that dedicated channel. The minimum time for data exchange between two vehicles is in milliseconds. This time includes data transmission and broadcasting latency and would vary depending on the load on the communications channels.

When there is more traffic in the vicinity, this situation may change. Vehicles would compete for the bandwidth in the V2V device. Therefore, the time to receive a message is a function of the scheduling delay, which depends on the number of vehicles that are connected, and the time to physically transmit a message. In a study on DSRC-based inter-vehicular communication, it has been found that the message reception probability deteriorates from about 80% accuracy at 0 m to about 50% at around 250 m (Jiang et al., 2006). This indicates two issues. Firstly, the communication time depends on the effectiveness of a DSRC communication device. Secondly, the time taken for two vehicles to communicate their positions can increase significantly, thereby reducing the warning time to the drivers.

Using Eq. (2), we have a model for representing the V2V communication time. We model the transmission delay to be between 25 ms (normal condition) and 300 ms (poorer condition).[2] The broadcasting frequency of a vehicle's position depends on the time that it takes by the two vehicles to communicate their positions, which can typically be between 100 ms and 1000 ms. When that position is communicated, it may no longer be its *actual* position because of the time delay, thus creating a threat to the accuracy of the position of a vehicle and the time to collision. If the communication latency is high, then the two vehicles may be closer to collision than the reported positions, as such it is necessary to compensate for the time loss. This is adjusted in the overall CAS timing model by incorporating the Communication Time. Therefore, the communication overheads (i.e. $T_a - T_c$) must be taken into considerations in order to compensate for the V2V device latencies. In a CAS implementation, this variable can be statistically measured using the average message communication time, and dynamically adjusted in the timing model to compensate for the communication delays.

3.2.2. Collision detection and activation

Based on the information given to a vehicle by other vehicles, CAS computes if there is any potential danger of collision. The information required for such computation is encoded in the DSRC message set (i.e. MSG_BasicSafetyMessage Part I) (SAE International, 2007). It includes the following: (i) message information – MAC address for identification and security, message type; (ii) position – latitude, longitude, elevation and positional accuracy; (iii) motion – speed, heading, acceleration; (iv) control – brake, steering, throttle position and exterior lights; (v) vehicle size – weight, load and length.

Collision detection is a computation process that is made up by collision threat analysis and the activation of mitigation strategy (see Fig. 2). Threat analysis determines the trajectory and threat of collision, it typically takes about 1–105 ms. The decision process would use software algorithm to decide what to do about a threat based on time availability and mitigation strategies. The strategies could be the activation of some visual, audio or physical warning devices. The time to activate some warnings would typically take less than 100 ms. The analysis process runs continuously. The mitigation process is active until either the threat is no longer there or some actions are taken. This period is denoted by $T_c - T_i$ in Fig. 2 and computed with Eq. (3).

3.2.3. Drivers' reaction

The way a driver controls a vehicle is significant to the time that is available to avoid a potential collision. In a study on a forward warning system, the system starts giving warning at time-headway[3] of 1.7 s and the warning signal starts flashing from 1.0 s to 0.8 s (Young et al., 2007). However, when a traffic incident such as the sudden stopping of a forward vehicle happens, the reaction time of drivers may differ. According to (Triggs and Harris, 1982), most of the delay between the presentation of a stimuli and the response by a human is due to central processing time rather than to the conduction relays along neural pathways. Reaction time depends on the possible alternatives that can occur. The more alternatives that is available to a driver the longer the reaction time. It also depends on the ease of interpreting a signal or a stimulus and the association between the input stimulus and the response codes, such as interpreting an unfamiliar road sign. In the case of an in-vehicle generated warning, the braking reaction of a driver depends on a number of factors:

- *Brake reaction time* – The reaction time to braking from a stimulus is measured to be between 500 ms and 700 ms for the majority of drivers (De Silva and Forbes, 1937), or 440–640 ms in another study (Lister, 1950). The studies were not conducted in road conditions and the subjects may have an expectation and thus reacted faster.
- *Driver's age* – Reaction time depends on the age of the driver. Age group of 15–19 years has a mean reaction time of 438 ms, and range to 522 ms for 65–69-year-old group (American Automobile Association, 1958). A more recent study found that young, mid-age and older people's brake reaction time is 350 ms, 390 ms and 430 ms, respectively (Warshawsky-Livne and Shinar, 2002).
- *Movement time* – Total brake reaction time is made up of brake reaction time and movement time (Liebermann et al., 1995) and the time is influenced by the both the country of origin and the awareness of the driver (Sohn and Stepleman, 1998).

Vehicle slowdown time specified by Eq. (1) comprises the driver perception time and the driver reaction time. Driver perception

---

[2] This estimation is provided by General Motors based on their data.

[3] Time-headway is defined as the time difference between any two successive vehicles when they cross a given point.

time is the time a driver takes to perceive a warning, which depends on alertness, age and so on. Driver reaction time is the time for a driver to have perceived a danger to moving the foot to braking position. In the CAS model, we use average and age compensated perception–reaction times based on a study by (Green, 2000). The average perception–reaction time is estimated to be 1.25 s, and the age compensation is 0.3 s. Studies by (Fambro et al., 1997; Fambro et al., 2007) have suggested that a 2.5 s delay should be allowed for driver perception and reaction time, and that should cover 90–95% of the cases. In the CAS model, we have adopted a dynamic timing approach to cater for different scenarios under varying conditions. For instance, a senior driver may set his/her preference to a higher level of allowance to get more advanced warning, or the car may automatically calibrate driver response time.

3.2.4. Vehicle deceleration rate

In order to gauge the deceleration of a vehicle through braking, a number of factors such as the deceleration rate of the vehicle in different environments based on the vehicle speed, road slope, road surface and load conditions must be considered. This timing is a part of Eq. (1). Other assumptions such as the brake condition, overload condition, the temperature, brake lining condition, moisture, adjustment, and any mechanical problems should also be made to estimate the deceleration rate. In this study, we start with a simple model where we obtain the manufacturer-tested braking condition. We model the braking of a specific car-model manufactured by GM using different speed and deceleration rate. First of all, we compute the travelling distance of a vehicle from the time a warning should be issued to just avoid the collision:

$$D_s = D_b(h, i, j) + D_r(k, l) \tag{4}$$

$$D_b = hV_i + \frac{{V_i}^2 - {V_t}^2}{2R_d(i, j)}$$

$$D_r = V_i(k + l)$$

where

D_b is the braking distance of the vehicle;
D_r is the distance travelled during the perception-reaction reaction time;
h is the vehicle response time, i.e. time required to pressurise the brake system and overcome the inertia of car;
i is the braking action, i.e. moderate or hard braking;
j is the road condition, i.e. ideal or slippery;
k is the time for the driver to perceive the warning;
l is the time for the driver to react to the warning;
V_i is the initial velocity of the subject vehicle;
V_t is the target velocity of the subject vehicle, which is also the velocity of the leading vehicle;
R_d is the deceleration rate for a given braking action i and road condition j.

When a subject vehicle's target speed is 0, vehicle slowdown distance equates to vehicle stopping distance. This formula can cater for accident scenarios such as rear-end collision and intersection collision. With varying road conditions, i.e. dry or wet and other parameters such as tyre conditions, the stopping distance and time also vary. Given that CAS has detected a collision threat, the driver may or may not brake very hard. Let us say the driver brakes very hard and can just avoid a collision, we call that a *critical* time to avoid collision. It means that beyond that point in time, a braking manoeuvre alone will not avoid the collision. On the other hand, if a driver brakes moderately and is able to avoid an accident, it is a *preferred* time to avoid collision. These two scenarios represent the worst case mitigation and the preferred mitigation respectively.

4. Time to collision analysis

The purpose for modelling the timing parameters is to investigate how the variability of these parameters may influence the accident mitigation strategy of the V2V device. The timing of events that happen during an accident is not clearly understood. A study of timing events in potential accident collisions would provide information needed for V2V designers to devise better strategies using different timing scenarios. For instance, designers can estimate how much extra time a V2V device would have to warn the driver or to activate any automatic mitigation strategy in a potential collision situation. In order to achieve this, we build models to study the relevant timing events. The following are the key timing zones in the modelling:

1. Given a set of pre-defined collision scenarios, what are the minimum TTACs when two vehicles are travelling at different speeds? This is to measure the time between T_j and T_m.
2. For any scenario in (1), what is the time to detect and analyse collisions by a V2V device? This is to measure the time between T_a and T_i.
3. When we combine (1) and (2), driver reaction time and vehicle braking time together, what are the time allowances for giving collision warning and executing collision mitigation techniques? This is to study the events between time T_i and T_m.

There are many events occurring during timing zones, the variability of these timing events can be represented in a model. In this study, we provide a general model to illustrate the CAS strategies. This general model can be re-calibrated according to local and specific conditions. We study the collision scenarios under normal and poorer conditions of TTAC using different sets of data.

The computation of two vehicles colliding in a trajectory course requires the location, direction, speed and distance between two vehicles. Assuming the vehicles are heading the same way, the headway distance, HD, which is the distance between the leading and subject vehicles such that the subject vehicle can slow down to just avoid a collision, can be computed:

$$\mathrm{HD} = D_s - D_{lv} + M \tag{5}$$

$$D_{lv} = V_t T_b(h, i, j)$$

$$T_b = h + \frac{V_i - V_t}{R_d(i, j)}$$

where

D_s is the slow down distance travelled by subject vehicle computed from Eq. (4);
D_{lv} is the distance travelled by the leading vehicle;
T_b is the vehicle braking time by subject vehicle;
M is the vehicle dimensions in meters, which is (a) the length of the leading vehicle for rear-end collision scenarios, and (b) the width of the intersecting vehicle for intersection collision scenarios;
V_i is the initial velocity of the subject vehicle;
V_t is the target velocity of the subject vehicle, which is also the velocity of the leading vehicle;
h is the vehicle response time;
R_d is the deceleration rate for a given braking action i and road condition j.

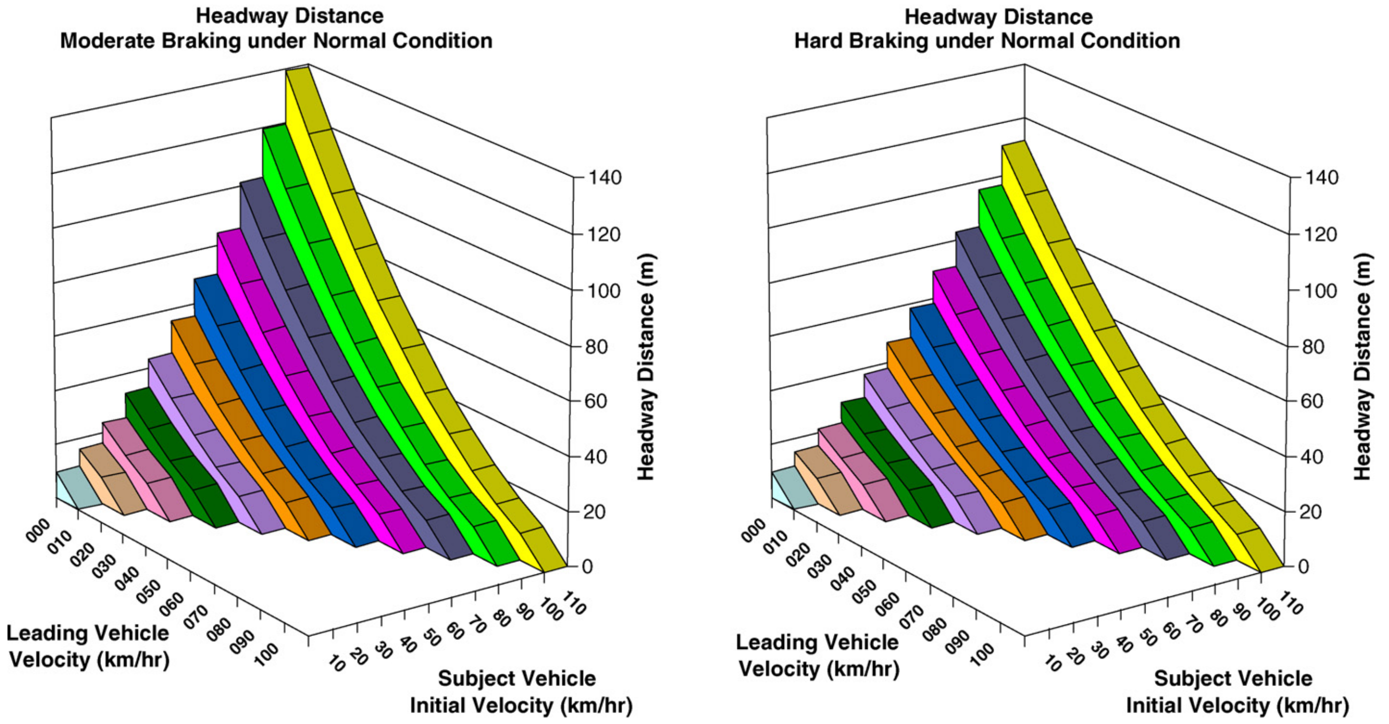

Fig. 3. (a) Headway distance with moderate braking. (b) Headway distance with hard braking.

Once we know the headway distance between the two vehicles, we can work out the time to avoid collision:

$$\mathrm{CT} = \frac{\mathrm{HD}}{V_{\mathrm{i}}} \tag{6}$$

Furthermore, the time it takes for the subject vehicle to slow down, i.e. T_{s}, to target velocity is a sum of the vehicle braking time T_{b} (computed from Eq. (5)), and the time for the driver to perceive k, and react l, to the warning.

$$T_{\mathrm{s}} = T_{\mathrm{b}}(h, i, j) + k + l \tag{7}$$

As reported in the IVBSS program, rear-end collisions, road departure and lane-change crashes account for 60% of all police-reported light-vehicle and heavy-vehicle crashes, and 50% of all crash fatalities (Kloeden et al., 1997). According to (U.S. Department of Transportation, 2006a), 70% of crashes with fatalities and 89% of on road crashes in the U.S. involve multiple vehicles. Additionally, 21% of fatalities and 45% of crash injuries are intersection related. The potential for reducing crashes on road could be significant if vehicles could communicate and coordinate amongst themselves to assess and prevent the threat of on-road accidents. Using the results of the Vehicle Safety Communications Project (U.S. Department of Transportation, 2006b), we have selected to study four V2V accident scenarios:

- collision with a forward stationary vehicle;
- collision with a forward moving vehicle;
- collision with a vehicle at an intersection;
- head-on collision.

The crash scenarios in this study involve only two vehicles. We have not considered accidents that involve a single vehicle or multiple vehicles. The model can be extended to cater for these additional crash scenarios in a CAS system.

4.1. Collision with a forward vehicle – stationary or moving

Rear-end collision basically involves a subject vehicle that is travelling faster than a leading vehicle in-front. The leading vehicle can be stationary or moving. In this study, we illustrate the model with a leading vehicle that has a constant speed. The software model can be adapted for a leading vehicle that decelerates. The deceleration of the subject vehicle to a certain speed to avoid a collision is computed based on a common braking distance formula. Firstly, we measure the headway distance and the time to avoid a collision using Eqs. (5) and (6) in the computation. It means that we compute the distance and the time to avoid collision for two scenarios: the subject vehicle brakes moderately and brakes hard. Fig. 3a and b illustrates these two scenarios. If we take the instance of a subject vehicle travelling at 110 km/h and the leading vehicle is stationery (0 km/h), then moderate braking requires 140 m of headway and hard braking requires about 110 m of headway. According to Eq. (5), the calculation is on the basis of: (a) normal road conditions; (b) average driver response time. Under these ideal conditions, a subject vehicle would be able to avoid the collision given there is a minimum of 110 m headway between it and the leading vehicle with hard braking.

If a vehicle encroaches into the 110 m zone, even hard braking could not avoid a collision. We call this point the *critical distance to avoid collision* and the *critical time to avoid collision*. The critical distance relationship is shown in Fig. 3b. Therefore, this critical point, in time or space, becomes the last possible chance the driver must react to avoid a collision. It means that if a warning is to be given to the driver, it must be given before this point (before T_j in Fig. 2). Ideally CAS should provide an earlier detection so that the driver can brake moderately to avoid the accident. We call this point the *preferred distance to avoid collision* and *preferred time to avoid collision*. The preferred time to avoid collision should be before T_i, as shown in Fig. 2. Preferred headway distance with moderate braking distance relationship is shown in Fig. 3a.

The deceleration of a vehicle to avoid accident very much depends on the road condition. Let us assume that a subject vehi-

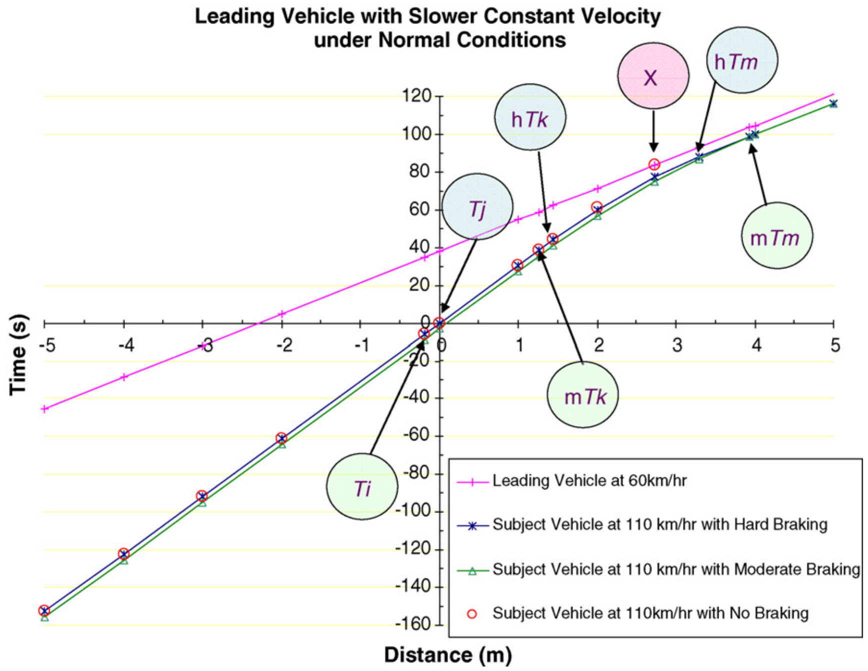

Fig. 4. Subject vehicle deceleration under normal condition.

cle is travelling at 110 km/h and the leading vehicle is travelling at 60 km/h. Under the normal condition, the distance to slow down the subject vehicle to avoid the accident would be 107 m/88 m for moderate/hard braking respectively, and the distance to slow the subject vehicle under the poorer condition would be 148 m/119 m respectively (see Appendix A). As mentioned earlier, there are other variables such as driver reaction and V2V communication latency that affect the timing of warning drivers. Using Eqs. (5) and (6), we compute, under normal condition and poorer condition, the preferred distance/time to avoid collision and the critical distance/time to avoid collision.

When we compute vehicle deceleration under different road conditions, we relate time and space with the collision avoidance events in normal condition (Fig. 4) and poorer condition (Fig. 5). In these two figures, the y-axis depicts the distance between the subject vehicle and the leading vehicle, the x-axis depicts the time between the events that occur during any collision avoidance manoeuvre. The origin (0,0) or T_j, is defined as the critical distance/time that a driver must act to avoid collision. The graph that crosses the origin is defined as the time–distance relationship of the latest reaction time to avoid collision with hard braking. There are three graphs in each diagram. The bottom graph depicts the timing

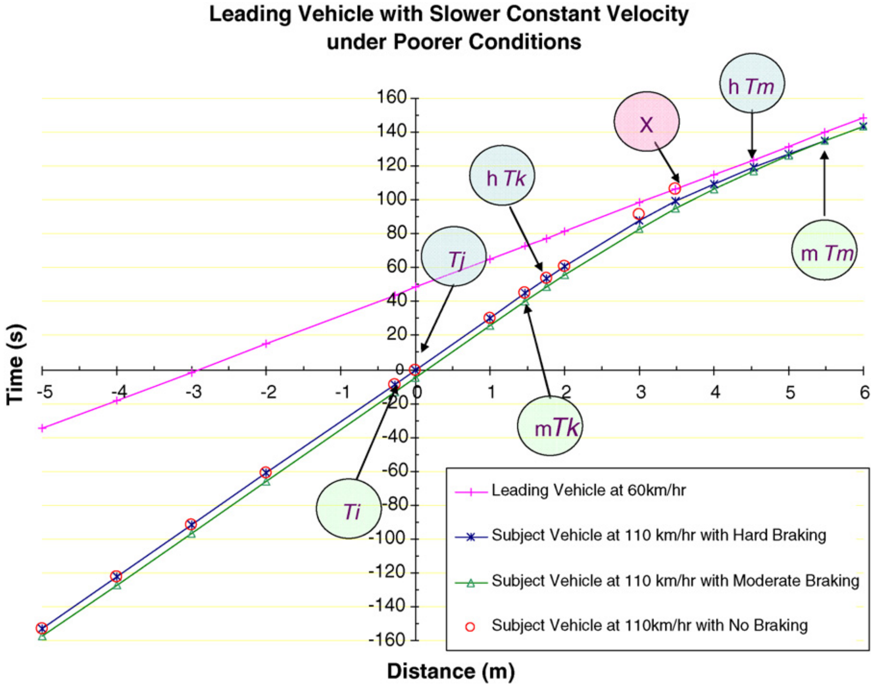

Fig. 5. Subject vehicle deceleration under poorer condition.

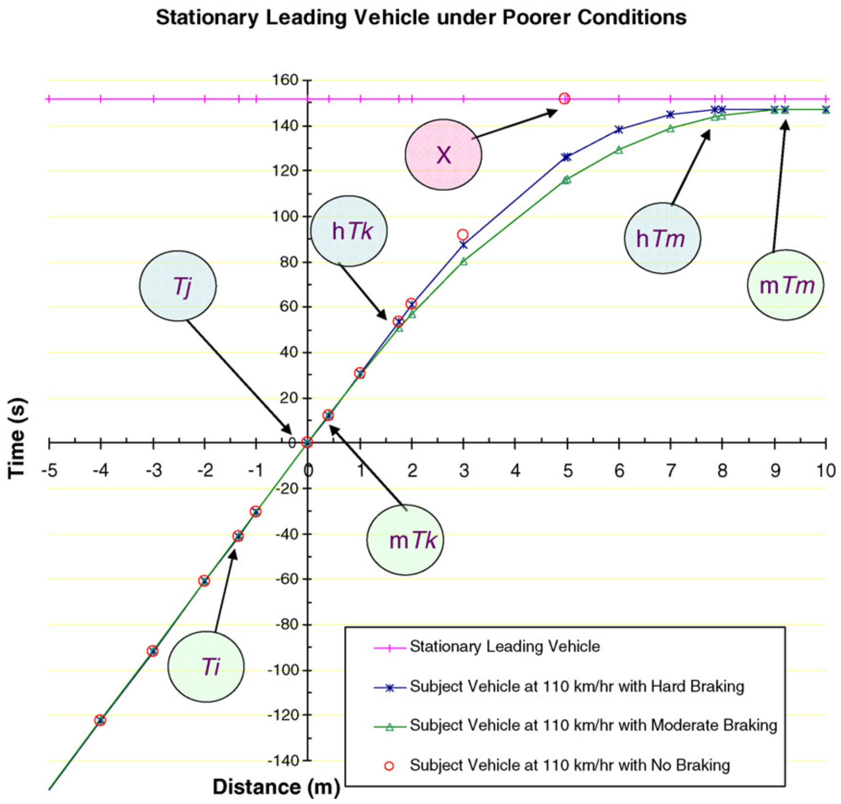

Fig. 6. Stationary leading vehicle under the poorer condition.

events to avoid collision with moderate braking. The middle graph crosses the origin and depicts the timing events to avoid collision with hard braking. The top graph depicts the time to collision if no actions are taken by the driver in the subject vehicle. The labels on the graphs identify the timing and the distance of the events that happen:

- T_j – The origin (0,0) is the point in time when the driver is alerted and hard braking must be made immediately to avoid a collision, this point defines the critical time to avoid collision.
- T_i – Time when driver is alerted by early collision warning.
- T_j to hT_k and T_i to mT_k – time periods for driver to perceive and react in hard braking or moderate braking scenarios, respectively.
- hT_k to hT_m and mT_k to mT_m – time periods when a subject vehicle avoid colliding with the leading vehicle after decelerating using hard braking or moderate braking scenarios, respectively.
- T_j to X – time period when subject vehicle collide with leading vehicle if driver takes no action.

Figs. 4 and 5 both show a scenario when a subject vehicle travelling at 110 km/h is fast catching up on a vehicle travelling at 60 km/h. Fig. 4 shows this scenario under the normal condition, approximately 80 m and 2.8 s is the distance/time to collision if the driver and vehicle do not react to the warning, i.e. $T_j - X$. However, if CAS sounds a warning just before T_j, and the driver brakes hard to avoid a collision, the point when the two vehicles barely miss the accident is at hT_m where the distance/time is 88m/3.3 s. If CAS warns earlier at point T_i, the driver gets an earlier warning by 0.2 s and an extra distance of about 6 m, allowing the driver to brake moderately to avoid the collision. Note that mT_m is later than hT_m because the leading vehicle is travelling further away. Fig. 5 shows the same scenario under poorer condition, i.e. wet road surface. Approximately 120 m and 4.5 s are the minimum distance/time required to avoid the collision with an earlier warning (T_i) of 0.3 s.

Fig. 6 shows a scenario where the subject vehicle is travelling at 110 km/h and the leading vehicle is stationary under the poorer road condition, say a vehicle breaks down in the rain on a highway. In this case, a warning to the subject vehicle must be at least 152 m away, and preferably 193 m away (see X and the distance between T_i and X). For the same scenario under the normal condition, the latest warning given to the subject vehicle must be at least 111 m away, and preferably 139 m away.

From Figs. 4–6, we observe the following:

- The time and distance between preferred early warning for moderate braking (T_i) and latest warning for hard braking (T_j) is relatively small. In this case, it is 0.19 s under normal condition and 0.28 s under poorer condition. This will have implications on when the CAS should sound warnings with regards to the time that a driver has to react before more severe warnings and actions are taken by a vehicle.
- The time difference between the normal condition and the poorer condition can significantly affect when the warning should be given. In the stationary leading vehicle scenario, there is about 1.8 s or 54 m difference to avoid collision under the two conditions. Therefore, in CAS design, current road conditions must be taken into account.
- The distance in which collision can be avoided is a minimum of 152 m if the relative velocity is 110 km/h under the poorer condition. This is still within the effective range of the DSRC device using (U.S. Department of Transportation, 2006b) as a guideline.

4.2. Collision with a vehicle at an intersection

The intersection collision analysis is similar to the collision analysis of a forward vehicle except two differences. Firstly, we assume that when a potential collision is detected, the subject vehicle will come to a stop before the intersection. The stopping scenario is the

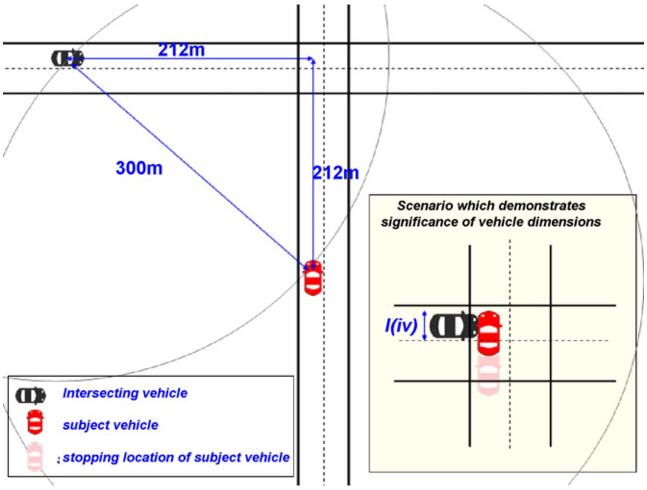

Fig. 7. DSRC intersection collision distance analysis.

safest, whereas crossing the intersection and avoiding the other vehicle depend on variables such as velocities of both vehicles, vehicle sizes and their relative positions. Secondly, there is less distance for a subject vehicle to stop because of the angle in which they approach each other (see Fig. 7). When the two vehicles detect each other at the ideal range of 300 m, there is only 212 m to stop a vehicle to avoid collision.

Assuming that there are no obstructions to hinder the DSRC communication of the two vehicles, the stopping distance is only 212 m. It provides the subject vehicle barely sufficient time/distance (i.e. 190 m, see Fig. 6) to carry out moderate braking if it is travelling at 110 km/h under the poorer road conditions. However, the reliability of DSRC communication can drop quite significantly due to distance (Jiang et al., 2006) and structures at intersections (U.S. Department of Transportation, 2006b). If the two vehicles detect each other at the range of 240 m, it is only 169 m before the collision point and insufficient time for the vehicle to stop in time to avoid the collision.

An additional issue could be the latency of communication between vehicles and the delay of the positioning broadcast. When the positioning data of a vehicle is broadcast, the accuracy and the timing are important because that vehicle could already be meters away from its original position and that would provide erroneous data for CAS computation. Additionally, we can consider the width of the intersecting vehicle in our model solution (see inset in Fig. 7). It would allow us to compute avoidance using the dimensions of a vehicle, therefore the algorithm can be applied to longer vehicles such as trucks and trains.

4.3. Head-on collision

In a highway situation where vehicles from opposite directions are travelling at high speed, a detection range of 300 m without any latency or delays can help avoid an accident. As shown in Fig. 8, at 300 m there is approximately 1.4 s before the critical time to avoid a collision T_j. This applies to both vehicles. However, in the case of both vehicles travelling at 80 km/h, the warning time can be extended to 2.6 s and the drivers will have more time to react to the situation.

The time that is available for a driver and a vehicle to react in a head-on collision scenario is a lot less. Therefore, CAS requires the maximum detection range that DSRC can provide to give as early a warning as possible. Additionally, avoidance mitigation also relies on the accuracy of the positioning system as well as the low latency of the V2V communication. As discussed in the last section, a high latency of DSRC communication would imply that the position of the vehicles can be quite different and affect the computation of the time to decelerate or stop. One second latency can imply a 30.5 m difference in distance when a vehicle is travelling at 110 km/h.

5. Findings for collision avoidance mitigation strategies

The main objective of studying the timing relationships between DSRC-based communication and accident avoidance is to understand the events that need to take place within the time constraint

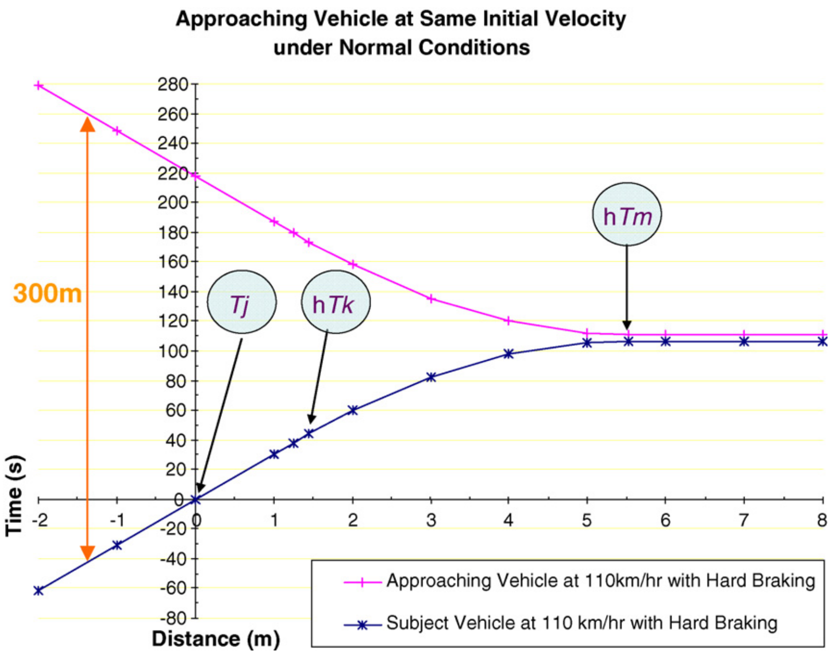

Fig. 8. Head-on collision time–space analysis.

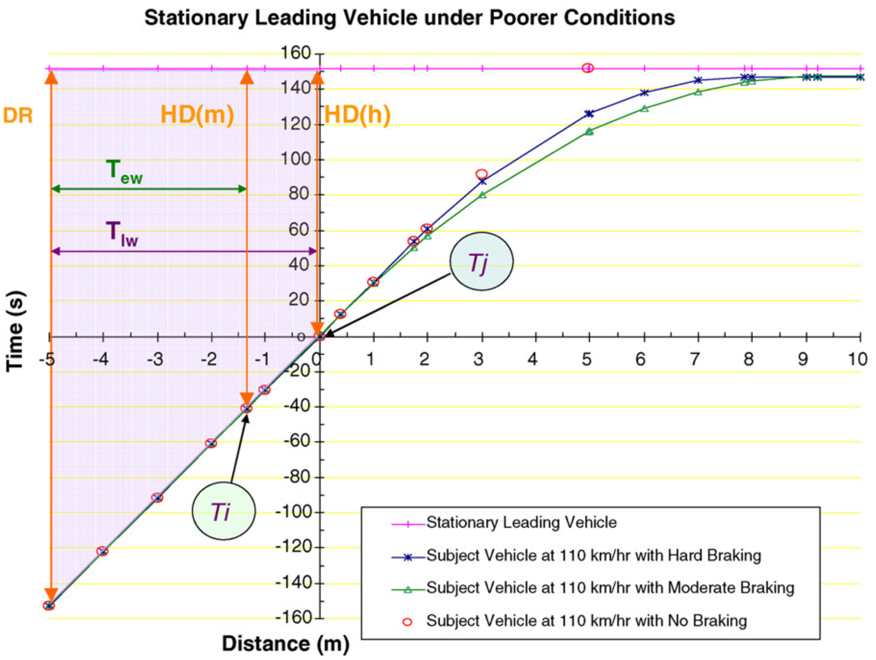

Fig. 9. Collision warning time gap analysis.

given by the forewarning of a DSRC device. Such understanding would allow better accident avoidance system to be built.

5.1. Timing components

In this study, we have shown that there are a number of variables that need to be considered in a DSRC-based CAS system. They are DSRC communication latency time, driver reaction time, road conditions and deceleration rate. These variables need to be tailored for each type of vehicle, the driver and the driving conditions. The dynamic change of these variables as conditions change is essential to accurately warn the driver. For instance, an older driver with slower response time could have the vehicle compensate for his/her slower response by adjusting a dial or having the vehicle automatically set the adjustment according to the driver's response calibration. Similarly, varying road conditions and DSRC communication latency should be compensated for in the computation of accident timing.

We define the critical time to avoid collision (CTAC) which is the last chance a driver can decelerate a vehicle with hard braking to avoid collision; we also define preferred time to avoid collision (PTAC), which is the time when a driver should be warned so that s/he can moderately brake to avoid a collision. For drivers who require early warnings to compensate for his/her slower reaction time, being able to receive an earlier warning gives more allowance to react to the situations (i.e. the times between T_i and mT_k and between T_j and hT_k shown in Figs. 4–6). Since varying road conditions affect braking distance and time, its accurate computation can determine if an accident can be avoided. For instance, the timing difference to stop from 60 km/h between normal and poor conditions is 1.2 s. If for instance, the DSRC latency is 200 ms and the driver has a 0.3 s slower reaction time, the total timing variations would add up to 1.7 s. If the driver is not aware of the potential danger with a stationary vehicle ahead and the V2V system sounds the warning 1.7 s after PTAC, instead of avoiding the collision, the vehicle would have travelled another 28.3 m and then collide with the stationary vehicle at a speed of 12.7 km/h. For CAS to work correctly, such timing variations must be dynamically adjusted according to the environment to obtain an accurate warning time.

5.2. DSRC communication

The analysis has shown that in some scenarios, especially in poorer road conditions and in intersections, the time to warn the drivers is limited. Communication latency (depicted by T_a–T_c zone in Fig. 2) may cause a subject vehicle to encroach into the critical time zone and miscalculate collision timing. There are two scenarios. Firstly, if the DSRC communication broadcast frequency is in seconds (Jiang et al., 2006), in cases where vehicles are travelling fast and the DSRC range is small, there may not be enough time for a driver and vehicle to avoid a collision by the time the next broadcast is made. Secondly, when the DSRC communication channels are congested, there would be delays in communicating the position and speed of vehicles. A similar observation was reported in Ito (2007).

In both scenarios, CAS must first realise that delays are occurring. One way to detect this delay is to have the CAS software examine the frequencies and the timestamps of the packets being exchanged between vehicles. Since communication delays would mean that the real position of the other vehicle is different to when it broadcasts its position, CAS must compensate for such error by computing its current position based on current time and last positions.[4] It must recompute the timing events and collision mitigation strategies based on this compensation for delays.

5.3. Time gap and warnings

We have also found that the time gap between the preferred warning and the critical warning is small (as shown in

---

[4] The messaging protocol (i.e. MSG_BasicSafetyMessage) defined in the draft DSRC standard does not contain a timestamp that could be used for computing the positional compensation. For compensation to work, vehicle clocks must be synchronised.

Tables 3a and 3b in Appendix B). Preferred warning is the warning for when a driver can avoid a collision by braking moderately, critical warning is when the driver must brake hard to avoid a collision. From when the DSRC device first detects an approaching vehicle to when the time a warning should be given, there is a window of opportunities to warn a driver. There are two especially important times: (a) duration to give early warning, T_{ew}; (b) duration to give latest warning, T_{lw}. They are defined as:

$$T_{\mathrm{ew}} = \frac{\mathrm{DR} - \mathrm{HD(m)}}{V} \tag{8}$$

and

$$T_{\mathrm{lw}} = \frac{\mathrm{DR} - \mathrm{HD(h)}}{V} \tag{9}$$

where DR is the detection range of the V2V device, HD(m) and HD(h) are the headway distance for moderate and hard braking respectively and V is the velocity of the subject vehicle. The time duration that is available to warn the driver is primarily bound by the communication range of a DSRC device. If a subject vehicle is travelling at 110 km/h towards a stationary vehicle and the DSRC detection zone is 300 m, then the total time available to warn the driver is known. As shown in Fig. 9, T_{ew} is the duration between the leading vehicle coming into range and a warning is given for a driver to brake moderately; T_{lw} is the duration between the leading vehicle coming into range and when a driver must brake hard to avoid collision. In the case of poorer road condition, CAS has at most 5 s to warn the driver (i.e. T_{lw}) and the early warning is only 1.4 s earlier (i.e. $T_{\mathrm{lw}} - T_{\mathrm{ew}}$). The questions are at which point in time CAS should warn the driver and what mitigation steps should be taken and when.

From Fig. 9, we see two different timing zones when information and warnings could be given: (a) the time zone between preferred warning T_i and last warning T_j; (b) the time zone to forewarn the driver before T_i. With (a), the time gap between T_i and T_j is small. It is not very useful to give two consecutive warnings because just as the driver has a chance to perceive and react to the first warning, the second warning is sounded. The overlap of warnings may startle the driver unnecessarily. So it is preferable to have CAS provide a warning immediately at first detection of danger at T_i. If the earliest detection is beyond T_j, then the accident is imminent, an autonomous braking system similar to Adaptive Cruise Control can be used to minimise the impacts of a collision. Autonomous braking has been demonstrated in the PreVENT project (Schulze et al., 2008). Additionally, a risk-based analysis could also be incorporated into the CAS design to compute the potential severity of collisions for deciding what mitigation strategies to deploy. For instance, if a vehicle is travelling at high speed and the collision impact is high, then the mitigation strategies should be different.

Scenario (b) is concerned with pre-warning timing (i.e. before T_i) by CAS to a driver so that s/he can decelerate and/or manoeuvre the vehicle before the danger arises. The issue is how far ahead the information should be given, and in what form. In terms of timing of the information dissemination within T_{ew}, information provided to a driver could be continuous through audio and/or video signals. If there is no risk of a collision, the information provided to a driver could be minimal. The urgency of that information could increase as the vehicles approach T_i. Further studies on human machine interface are required to determine what type of information and in what form are most useful to drivers in both cases. Considerations should be given to driver perception of information and reactions. With the right information provided to a driver pre-T_i, early and defensive driving could minimise the chance that a driver would encroach in the $T_i - T_j$ zone.

5.4. Intersection collision avoidance

We have found that the time allowed for warning in intersection collision is short, especially when vehicles are travelling in high speed. Ineffective DSRC communication exacerbates this problem. In order to address this problem, some DSRC roadside infrastructure should be considered. The installation of a roadside DSRC device at an intersection may not solve this issue entirely, installation of roadside relays to extend the range of detection could be considered. One possible application is railway level-crossing when forewarning road traffic must be further than the 300 m range that DSRC can support, and similarly for trains. Such CAS software requires enhancements to the proposed SAE J2735 message standard, and construction of intelligent CAS software to relay and compute appropriate mitigation strategies.

6. Conclusion

DSRC has been used in prototyped vehicles to test vehicle-to-vehicle communication for collision avoidance. However, there is little study on how in-vehicle software should behave to mitigate the risk of accident collision. One important aspect is the timing events that determine when collision might occur. In this study, we have analysed the timing events and their relationships with computing warnings for collision avoidance.

We have defined three timing zones: pre-warning, preferred time to avoid collision (PTAC) and critical time to avoid collision (CTAC). Pre-warning zone is defined as from when two vehicles start communicating through DSRC to PTAC; PTAC is the time when a driver is warned and s/he could brake moderately to avoid a collision; CTAC is the time when a driver is warned and s/he must brake hard to avoid a collision. Since the information and warnings that CAS provides to a driver are according to the timing zones, these timing zones help us define the events based on the amount of time available to a driver and a vehicle to avoid a collision.

In analysing the timing events, we have found that variations in road conditions, driver perception–reaction time and communication latency significantly affect the correctness of computing warning times and recommending mitigation strategies. We suggest that these timing events should be dynamically monitored and adjusted by CAS according to the current driving conditions. For instance, vehicle positions can be incorrectly reported due to DSRC communication latency, leading to incorrect computation of trajectory and collision time. Dynamic compensation for such errors by allowing for communication latency can reduce such errors. Similar adjustments should be handled by CAS for road and driver conditions. Additionally, current commercial and affordable positioning systems do not give positioning information with enough accuracy and this will add to the computational errors. These are the challenges that need to be addressed for a V2V collision avoidance system to work effectively.

Although CAS captures a lot of the surrounding real-time traffic information, not all of them would be presented to a driver because that would overload and confuse the driver. In order to understand what type of information should be presented by CAS, in which timing zone and by what means they should be presented, experiments on driver reactions over the three timing zones should be conducted. Studies in human–machine interface would be essential to implement an adaptable and accurate CAS.

Acknowledgements

This study was partially supported by the Commonwealth of Australia through the Cooperative Research Centre for Advanced

Automotive Technology under the Proactive Maintenance project (C4-01). We would like to thank Greg Lake and Don Grimm of General Motors for providing information to us and their constructive comments on our work.

Appendix A. Slowdown distance for moderate and hard braking under normal and poorer conditions

Tables 1a, 1b, 2a and 2b

Table 1a
Slowdown distance for moderate braking under normal condition (m).

Initial velocity (km/h)	Target velocity (km/h)										
	0	10	20	30	40	50	60	70	80	90	100
10	5										
20	11	10									
30	19	18	16								
40	28	27	25	21							
50	39	38	36	32	27						
60	51	50	48	44	39	32					
70	65	64	62	58	53	46	38				
80	80	79	77	73	68	61	53	43			
90	96	96	93	90	84	78	70	60	49		
100	114	114	112	108	103	96	88	78	67	54	
110	134	133	131	127	122	116	107	98	87	74	60

Table 1b
Slowdown distance for hard braking under normal condition (m).

Initial velocity (km/h)	Target velocity (km/h)										
	0	10	20	30	40	50	60	70	80	90	100
10	5										
20	10	10									
30	17	16	15								
40	24	24	22	20							
50	33	32	31	28	25						
60	43	42	41	38	34	30					
70	53	53	51	49	45	41	35				
80	65	65	63	61	57	52	47	40			
90	78	77	76	73	70	65	59	53	45		
100	92	91	90	87	83	79	73	67	59	50	
110	107	106	104	102	98	94	88	81	74	65	55

Table 2a
Slowdown distance for moderate braking under poorer condition (m).

Initial velocity (km/h)	Target velocity (km/h)										
	0	10	20	30	40	50	60	70	80	90	100
10	6										
20	14	13									
30	25	23	20								
40	37	36	33	27							
50	52	51	48	42	34						
60	69	68	65	59	51	41					
70	89	87	84	79	71	61	48				
80	110	109	106	100	92	82	70	56			
90	134	133	129	124	116	106	94	79	63		
100	160	159	155	150	142	132	120	105	89	70	
110	188	187	184	178	170	160	148	134	117	98	77

Table 2b
Slowdown distance for hard braking under poorer condition (m).

Initial velocity (km/h)	Target velocity (km/h)										
	0	10	20	30	40	50	60	70	80	90	100
10	6										
20	13	12									
30	22	21	18								
40	32	31	29	25							
50	44	43	41	37	31						
60	57	56	54	50	45	38					
70	72	71	69	65	59	53	44				
80	88	88	85	81	76	69	60	50			
90	106	105	103	99	94	87	78	68	57		
100	126	125	123	119	113	106	98	88	76	63	
110	147	146	144	140	134	128	119	109	97	84	70

Appendix B. Additional time required for preferred warning under normal and poorer conditions

Tables 3a and 3b

Appendix C. Time available to give latest warning with a 300 m V2V detection zone under normal and poorer conditions

Tables 4a and 4b

Table 3a
Additional time required for preferred warning under normal condition (s).

Initial velocity (km/h)	Target velocity (km/h)										
	0	10	20	30	40	50	60	70	80	90	100
10	0.08										
20	0.16	0.04									
30	0.25	0.11	0.03								
40	0.33	0.18	0.08	0.02							
50	0.41	0.26	0.15	0.07	0.02						
60	0.49	0.34	0.22	0.12	0.05	0.01					
70	0.57	0.42	0.29	0.19	0.11	0.05	0.01				
80	0.66	0.50	0.37	0.26	0.16	0.09	0.04	0.01			
90	0.74	0.58	0.45	0.33	0.23	0.15	0.08	0.04	0.01		
100	0.82	0.66	0.52	0.40	0.29	0.20	0.13	0.07	0.03	0.01	
110	0.90	0.74	0.60	0.48	0.36	0.27	0.19	0.12	0.07	0.03	0.01

Table 3b
Additional time required for preferred warning under poorer condition (s).

Initial velocity (km/h)	Target velocity (km/h)										
	0	10	20	30	40	50	60	70	80	90	100
10	0.12										
20	0.25	0.06									
30	0.37	0.16	0.04								
40	0.49	0.28	0.12	0.03							
50	0.61	0.39	0.22	0.10	0.02						
60	0.74	0.51	0.33	0.18	0.08	0.02					
70	0.86	0.63	0.44	0.28	0.16	0.07	0.02				
80	0.98	0.75	0.55	0.38	0.25	0.14	0.06	0.02			
90	1.11	0.87	0.67	0.49	0.34	0.22	0.12	0.05	0.01		
100	1.23	0.99	0.79	0.60	0.44	0.31	0.20	0.11	0.05	0.01	
110	1.35	1.12	0.90	0.71	0.55	0.40	0.28	0.18	0.10	0.04	0.01

Table 4a
Time available to give latest warning under normal condition (s).

Initial velocity (km/h)	Target velocity (km/h)										
	0	10	20	30	40	50	60	70	80	90	100
10	104.6										
20	51.3	52.3									
30	33.4	34.2	34.9								
40	24.4	25.1	25.6	26.2							
50	18.9	19.5	20.0	20.5	20.9						
60	15.1	15.7	16.2	16.7	17.1	17.4					
70	12.4	13.0	13.5	13.9	14.3	14.7	14.9				
80	10.3	10.9	11.4	11.8	12.2	12.5	12.8	13.1			
90	8.7	9.2	9.7	10.1	10.5	10.8	11.1	11.4	11.6		
100	7.3	7.8	8.3	8.7	9.1	9.4	9.7	10.0	10.3	10.5	
110	6.2	6.7	7.1	7.5	7.9	8.3	8.6	8.9	9.1	9.3	9.5

Table 4b
Time available to give latest warning under poorer condition (s).

Initial velocity (km/h)	Target velocity (km/h)										
	0	10	20	30	40	50	60	70	80	90	100
10	104.2										
20	50.8	52.1									
30	32.8	33.9	34.7								
40	23.7	24.6	25.4	26.1							
50	18.1	19.0	19.7	20.3	20.8						
60	14.3	15.1	15.8	16.4	16.9	17.4					
70	11.5	12.2	12.9	13.5	14.1	14.5	14.9				
80	9.3	10.0	10.7	11.3	11.8	12.3	12.7	13.0			
90	7.6	8.3	8.9	9.5	10.1	10.5	10.9	11.3	11.6		
100	6.1	6.8	7.4	8.0	8.6	9.1	9.5	9.8	10.2	10.4	
110	4.9	5.5	6.2	6.8	7.3	7.8	8.2	8.6	9.0	9.2	9.5

References

American Automobile Association, 1958. Reaction Time as Related to Age, Washington, DC.

De Silva, H.R., Forbes, T.W., 1937. Driver Testing Results. Harvard, Traffic Bureau, Cambridge, MA.

Fambro, D.B., Fitzpatrick, K., Koppa, R.J., 1997. Determination of Stopping Sight Distances. Transportation Research Board.

Fambro, D.B., Fitzpatrick, K., Koppa, R.J., 2007. New Stopping Sight Distance Model for Use in Highway Geometric Design, Transportation Research Record. Transportation Research Board.

Fuerstenberg, K., Baraund, P., Caporaletti, G., Citelli, S., Eitan, Z., Lages, U., Lavergne, C., 2002. Development of a Pre-Crash Sensorial System – The CHAMELEON Project, p. 23.

Gettman, D., Head, L., 2003. Surrogate safety measures from traffic simulation models, Transportation Research Record. Journal of the Transportation Research Board, 104–115.

Green, M., 2000. How long does it take to stop? Methodological analysis of driver perception-brake times. Transport Human Factors 2, 195–216.

IEEE Task Group p, IEEE 802.11p – WAVE – Wireless Access for the Vehicular Environment Draft Standard.

M. Ito, 2007. Development of INter-vehicle communication type driving support system in the ASV-3 project. Mitsubishi Motors Technical Review.

Jiang, D., Taliwal, V., Meier, A., Holfelder, W., Herrtwich, R., 2006. Design of 5.9 GHz DSRC-based vehicular safety communication. IEEE Wireless Communication, 36–43.

Kloeden, C.N., McLean, A.J., Moore, V.M., Ponte, G., 1997. Travelling Speed and the Risk of Crash Involvement. NHMRC Road Accident Research Unit, The University of Adelaide.

Liebermann, D.G., Ben-David, G., Schweitzer, N., Apter, Y., Parush, A., 1995. A field study on braking responses during driving. Ergonomics, 1894–1902.

Lister, R.D., 1950. The Reaction Time of Drivers in Moving and Stationery Vehicles. Road Research Laboratory.

Miller, R., Huang, Q., 2002. An adaptive peer-to-peer collision warning system. In: Proceedings of the IEEE 55th Vehicular Technology Conference (VTC), pp. 317–321.

SAE International, 2007. Dedicated Short Range Communications (DSRC) Message Set Dictionary, p. 30.

SAE International, 2008. Draft SAE J2735 Dedicated Short Range Communications (DSRC) Message Set Dictionary (Dsrc_rev029.ITS). SAE International, p. 303.

Schulze, M., Mäkinen, T., Irion, J., Flament, M., Kessel, T., 2008. IP_D15: Final Report, Preventive and Active Safety Applications Integrated Project.

Sohn, S.Y., Stepleman, R., 1998. Meta-analysis on total braking time. Ergonomics 41, 1129–1140.

Strandén, L., Chalmers, E.S., Uhlemann, E., 2008. Wireless Communications Vehicle-to-Vehicle and Vehicle-to-Infrastructure. SAFER Vehicle and Traffic Safety Centre.

Triggs, T., Harris, W., 1982. Reaction Time of Drivers to Road Stimuli. Monash University, p. 60.

U.S. Department of Transportation, 2006a. Traffic Safety Facts 2006. National Highway Traffic Safety Administration, Washington, DC.

U.S. Department of Transportation, 2006b. Vehicle Safety Communications Project. National Highway Traffic Safety Administration, Washington, DC.

University of Michigan Transportation Research Institute, 2007. Integrated Vehicle-Based Safety Systems First Annual Report. U.S. Department of Transportation, p. 116.

Warshawsky-Livne, L., Shinar, D., 2002. Effects of uncertainty, transmission type, driver age and gender on brake reaction and movement time. Journal of Safety Research 33, 117–128.

Young, K., Regan, M., Triggs, T., Tomasevic, N., Stephan, K., Mitsoupoulos, E., 2007. Impact on car driving performance of a following distance warning system: findings from the Australian Transport Accident Commission SafeCar Project. Journal of Intelligent Transport System 11, 121–131.