Design and Test of Intersection Collision Avoidance Systems for Automobiles

by

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Submitted to the Department of Aeronautics and Astronautics
In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Aeronautics and Astronautics

At the

Massachusetts Institute of Technology

June 2003

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ABSTRACT

Much research effort has been put into the development of rear-end collision avoidance systems. However due to the complexities involved in intersection collisions, much still has to be done in the development of Intersection Collision Avoidance Systems (ICAS). The aim of this thesis was to develop a prototype ICAS algorithm and test its utility and impact on driving behavior. The problem of intersection collisions is analyzed and different modes of configuration are identified. It is also found that the order in which a given vehicle enters an intersection has significant consequences.

A mathematically rigorous algorithm is developed based on the analysis. The algorithm consists of two modules, one is responsible for straight trajectory collisions using alerts, and the other is responsible for left turn collisions by providing advisories to the driver. Numerical analysis is performed to assess the algorithm and the effects of different parameters. It is also demonstrated that the algorithm's assumptions on the type of information that is available is valid.

The algorithm was implemented on a driving simulator and human-in-the-loop experiments were performed with young and old drivers. Both young and old drivers drove more aggressively when ICAS was present, as determined by average miss distance. Older drivers in particular drove faster on average when ICAS was present. A trend suggests that the left turn aid assisted drivers in turning across traffic with a smaller gap between cars. In general the results highlight potential concerns over trust or risk homeostasis with the addition of ICAS.

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Title: Associate Professor of Aeronautics and Astronautics

Acknowledgments

Firstly, I gratefully acknowledge the support and resources made available to me from the Ford Motor Company. This work was supported by Ford Motor Company under contract 6892098.

I would like to thank my advisor James Kuchar, for his fantastic mentorship, superb advice and support. I thank the subjects for their time in taking the experiments. Ted Rosenthal, and David Smith from Systems Technology, Inc. also deserve recognition for their inputs in setting up the simulations and the driving simulator.

Back in Hong Kong, I am grateful that I had met a bunch of "brothers" who would always stand by me whenever I need them. They deserve many thanks for giving me support during the lonely hours of research.

I am indebted to my girl friend, for taking care of my life, for keeping my world stable whenever I lost my equilibrium.

Finally, I would like to acknowledge my parents, and the rest of my family. Their love has sustained me throughout my life. Thank you.

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Chapter 1 Introduction

1.1Motivation

Auto accidents account for roughly $200 billion lost annually in the United Sates alone [5], 40,000 individuals are killed, and another 5 million injured each year [6]. According to the National Highway Traffic Safety Administration (NHTSA) database [7], 6,323,000 crashes occurred in year 2001, among them 37795 fatal. Among these crashes, 2,721,000 (43%) were intersection and intersection related crashes, with 8490 fatal ones among them. These statistics are shown in Fig. 1.1. The need to derive technologies to improve automobile safety is therefore imminent, as they can reduce casualties and can lead to huge economic payoff.

Technologies to make driving safer are needed particularly for two types of people. First are people with degraded cognitive, sensory or motor ability, such as elderly people. Second are young people who don't have much driving experience or who may drive too aggressively. Fig 1.2 shows that the crash involvement rate for these two groups of people are significantly higher than other age groups.

Over the years, automakers have been developing a range of safety measures, which can be divided into two categories. One is called active safety systems, examples are seat belt pretension, airbag deployment, and nose dipping. These systems are all autonomous, in the sense that they are deployed without the involvement of the drivers. The other one is called passive safety systems. This kind of safety system functions by the interaction between the automobiles and the drivers. Alerting and decision-aiding systems belong to the passive safety systems.

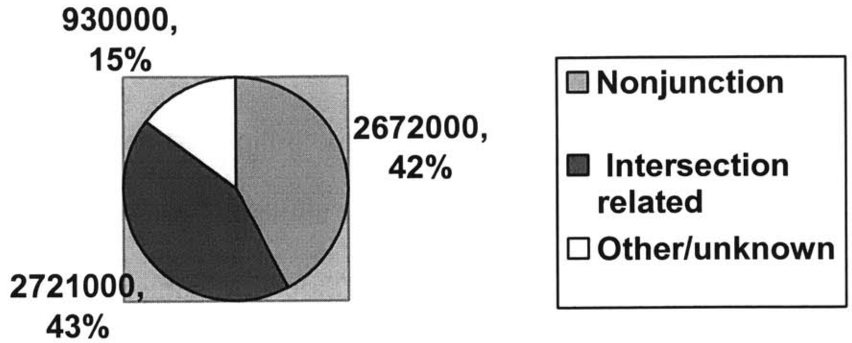


Fig 1.1 Collisions divided by type

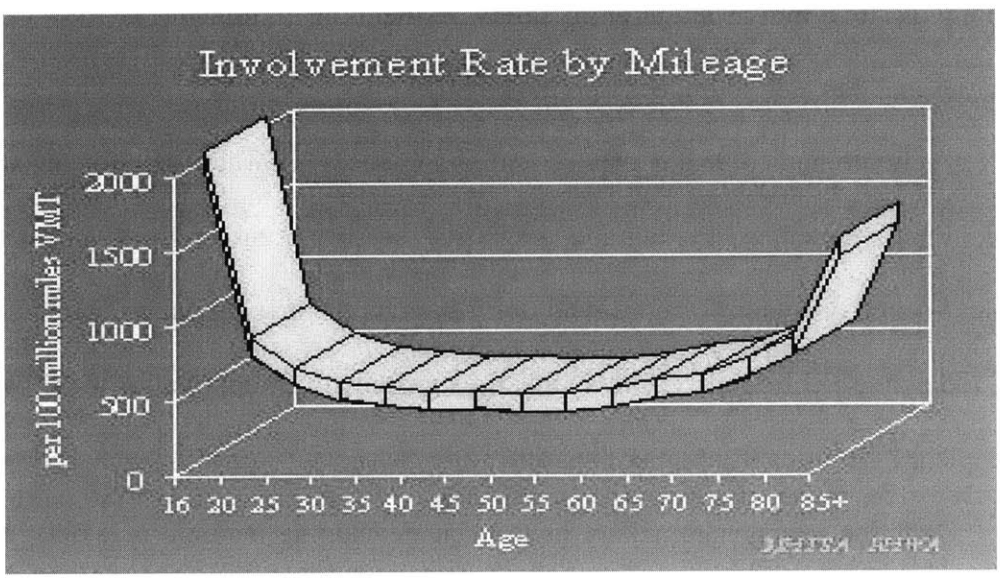


Fig 1.2 Collision involvement rate and age (adapted from [8])

Alerting systems are used to give an alarm to the operator of human-controlled vehicle, so that undesirable events can be avoided. In the general sense, human-controlled vehicles can be an aircraft, an automobile, or even a chemical plant. For instance, in the case of automobiles and aircraft, collisions between vehicles should be avoided [1]. To date, alerting systems have been widely used in the aerospace industry, every commercial aircraft flying in the United Sates is already equipped with TCAS (Traffic Alert and Collision Avoidance System). With recent advances in sensors, communication, and computing technologies, interests in automating or aiding the operation of automobiles have grown in the last decade. Along this trend is the incorporation of alerting systems into automobiles, which transfers the experience in aerospace industry to the automobile industry [2]. Examples of alerting systems are collision avoidance systems, lane-following systems, or even systems that monitor the drowsiness of the driver and give out alerts accordingly.

In contrast to conventional belief, alerting system design is far more complicated for automobiles than for aircraft. This can be attributed to several factors. First, accidents in automobiles generally occur much more quickly than that of aircraft, which gives less time for the automobile drivers to respond. Second, drivers are less trained and more diverse than pilots, which makes it harder to design a system that suits everybody. Third, drivers may not know what to do upon an alert, because they are less trained. Fourth, due to the fact that the automobiles reside in a two-dimensional space and are constrained by the roads, the options for avoidance maneuvers are considerably less than for aircraft. For instance, the driver should not drive the car onto the sidewalk to avoid a collision. Though nowadays aircraft are also being constrained by a fixed airspace, this constraint is not as harsh as that of automobiles. Lastly, automobiles are less well maintained as compared to aircraft, which results a higher chance that the alerting system or sensors are not functioning as supposed.

It is clear that human factors play a crucial role in the development of an alerting system. Unlike a completely automated system, an alerting system is just aiding a human operator to make his decisions. The interaction between the system and human is then important. Different human responses-for example the response time to an alert,-can lead to varying system performance. This may raise the question of why not develop completely autonomous collision avoidance systems. Indeed efforts are underway to build unmanned vehicles, be it ground vehicles or aerial vehicles, but there are two issues to be concerned about. First is that driving is not just a person commuting from one point to another point, but also involves the pleasure to drive. Second is that there is no auto maker that can build a completely autonomous vehicle with perfect confidence that every collision can be avoided. In case a collision does occur, the automaker will be liable for the losses. Therefore automakers are more interested in building alerting and decision aiding systems to help the drivers to make their own decisions. In addition, the development cost of an autonomous system is so high that the average drivers cannot afford the cost of such a vehicle. In light of this fact, this project aims at building alerting and decision aiding systems to aid the driver to avoid a potential threat. The payoff of such a system is enormous, as human casualties and financial losses due to automobile collisions are huge.

Development of rear-end collision avoidance systems have drawn efforts from various researchers [2, 3] and have been implemented in some car models already [3]. Due to the varying nature of intersection geometries, the interaction between vehicles approaching an intersection is more complicated than the rear-end cases. Incidentally, an avoidance maneuver can even lead to a more severe collision threat in some cases. Intersection collision avoidance systems are therefore still a hot topic of research. An extensive survey of the problem was performed and a prototype system was proposed by [4]. The emphasis of their research is on building the hardware such as sensors, necessary to avoid an intersection collision. One of the goals of this thesis is to propose a prototype alerting and decision aiding system to avoid intersection collisions between automobiles. The emphasis of this project is on the algorithm side of such a system.

A review of rear-end collision avoidance systems is given to form the cornerstone of the intersection collision avoidance systems proposed. The Intersection collision avoidance systems are composed of two modules, one is an alerting module and the other is a decision-aiding module. Roughly speaking, an alerting system tells the driver to deviate from a nominal trajectory which may be dangerous, while a decision-aiding system gives advice on what trajectory to follow. In the proposed system, an alerting module is used for the case of passing the intersection without turning, while a decision-aiding system is used for the case of making a left turn at an intersection. With the presentation of the rear-end and intersection collision avoidance systems, we hope that a more unified view of collision avoidance systems for automobiles can be obtained.

Also the focus of this research is the analysis of the proposed system. The analysis was performed analytically, numerically, and experimentally through human-in-the-loop driving simulations. These analyses enable us to find out the utility of the proposed system, the benefits it gives in enhancing safety, and also its limits. By exposing the limits of alerting and decision-aiding systems, we will realize under what situations completely autonomous systems are preferred, which will lead to future research.

1.2 Overview of the Thesis

This thesis gives an overview of the problem; outlining its significance to people with lower sensory, cognitive, or motor ability, who might have difficulty avoiding collisions both efficiently and independently. A review of existing research is performed and a prototype system is proposed and analyzed. Analyses to verify the utility of the system are given and discussed.

In Chapter 2 related research that has been accomplished is reviewed. The review includes both rear-end collision avoidance systems and intersection collision avoidance systems. The review is the foundation of the proposed system in next chapter. A high level qualitative description of alerting systems is given.

Chapter 3 provides the details of the prototype systems. Intersection collisions are defined and categorized in this chapter. We point out which cases could be solved by the proposed system and the reasons. The details of an alerting system and decision aiding system are described respectively. A graphical approach is employed to illustrate the alerting logic and the limits of the system. Possible modes of autonomous systems are considered and their related problems are addressed. Human factors issues in designing the system are also covered.

In Chapter 4 the evaluation of the performance of the alerting system is discussed. The trade-offs and factors involved in designing the alerting system are mentioned. Numerical analysis was used to examine the performance of the system.

Chapter 5 addresses a human-in-the-loop driving simulation study that was performed. This chapter discusses the setup of the experiments, and what was obtained from the experiments. The aim of the experiments is to illustrate the effect of an alerting and decision-aiding system in enhancing safety. Results of the experiments are discussed.

Chapter 6 provides the final summary of the contributions introduced in this thesis and possibilities of future research.

Chapter 2 Alerting Systems and Rear-End Collision Avoidance Systems

2.1 Generic Representation of Alerting systems

Collision Avoidance Systems (CAS) can be composed of an alerting system, an autonomous system or a hybrid system with both alerting and autonomous systems. Due to the difficulties of autonomous systems suggested earlier, the focus of this thesis will be on how alerting systems are exploited to avoid collisions. A brief introduction to the generic representation of an alerting system [1] is given here and the terminology defined is used in later chapters.

A block diagram of the generic representation of CAS is shown in Fig. 2.1

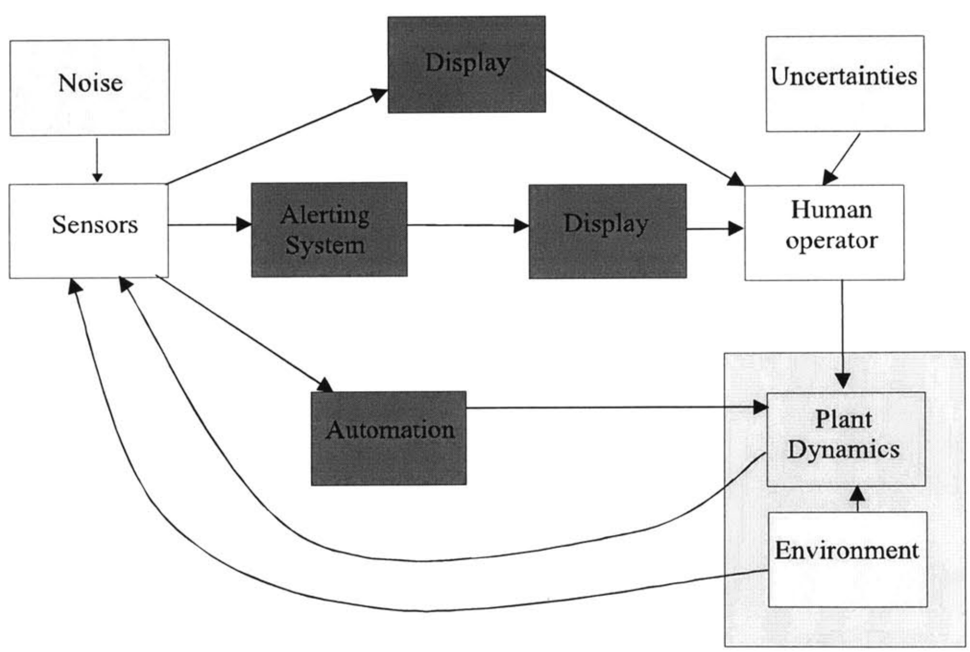


Fig 2.1 CAS structure

The *Plant Dynamics* block is what the human operator interacts with. The Plant could be an aircraft, an automobile or a chemical plant. The Plant is situated in an *Environment*. The Environment and Plant dynamics are represented by *states*. For a chemical plant, the states could be the temperature, humidity or pressure of a certain chemical process. For automobiles, the Plant states could be the position, speed and acceleration of the subject vehicle, while the Environment states could be the position, speed and acceleration of an Intruder vehicle. $\mathbf{x}(t)$ is the state trajectory, which represents how the states evolve in time, t.

Fig 2.2 shows an example of how $\mathbf{x}(t)$ evolves in time.

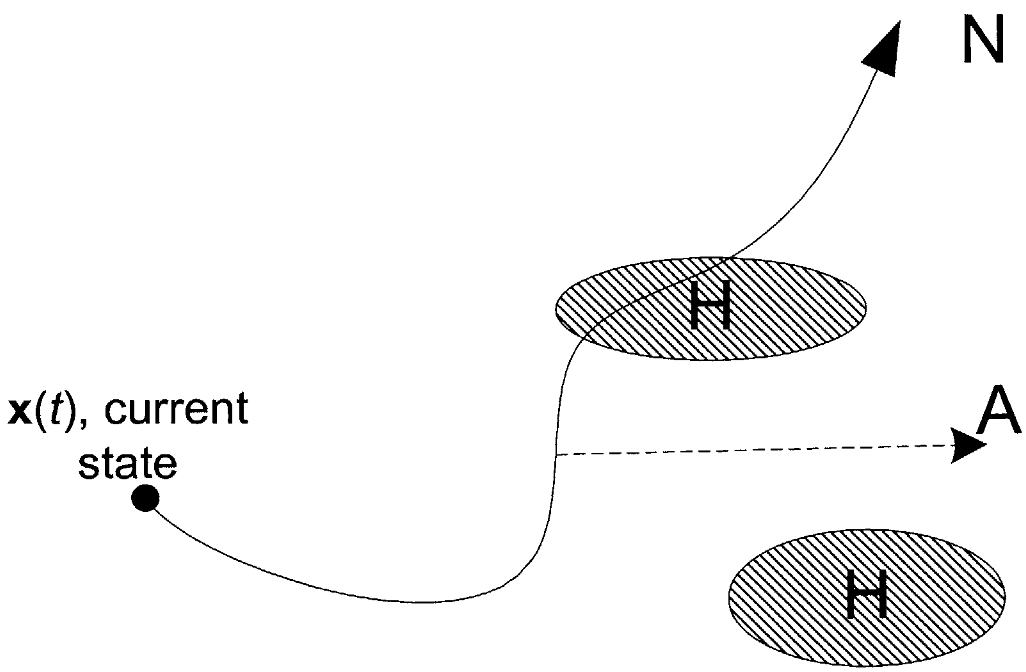


Fig 2.2 State space and trajectory evolution

In Fig 2.2, **H** denotes the *Hazard Space*. It is a collection of the states in the state space that are undesirable and have to be avoided. For instance, the hazard space of a chemical plant would be the temperature or pressure combination that might lead to explosion; the hazard space for automobiles would be where the positions of two cars are the same at the same time. **N** denotes the *Nominal trajectory*, while **A** denotes the *Avoidance trajectory*. The nominal trajectory is also called the projected trajectory and is the trajectory that the CAS thinks would be followed if no alert is issued. The CAS possesses an internal projection model to project this nominal trajectory. For example, it is reasonable for the CAS to assume that a car travels at constant speed given that the traffic light ahead is green. If the nominal trajectory overlaps the hazard space, it means that there is a potential threat along the nominal trajectory and something has to be done to remedy the situation. Of course, the system can only estimate the actual intent of the human operator, and therefore discrepancies are often found between the actual trajectory the human operator would take and the projected nominal trajectory that is assumed by the model. The effect of uncertainties in human intent on the system performance is discussed later. The avoidance trajectory is the trajectory that the human operator would take upon an alert. If the avoidance trajectory overlaps the hazard space, then the alert is an unsuccessful alert. Otherwise the alert is a successful alert. However, if both the nominal and avoidance trajectory do not overlap the hazard space, then it is a false alert.

The CAS acquires the state information through sensors. Based on the sensor readings, the CAS reconstructs the picture of the actual scenario. *Noise* is inherent in any kind of sensors. Due to the presence of noise, the reconstructed scenario is always at some degree deviated from the actual scenario. Even if there is perfect sensor information, there is no guarantee that the picture perceived by the CAS is genuine. This is because the mathematical modeling of the plant dynamics may not be genuine. The human operator can also acquire the *Nominal Information* from the sensors directly and make up his decisions on the next maneuvering input. This is usually the case when the CAS is not in place. For example, in automobiles the drivers look at the speedometer directly and decide whether to accelerate or brake. Usually this nominal information is incomplete. For instance, the visibility of a car driver at an intersection can be obstructed by a building ahead and the layout of car interior. In addition to that, distractions can also make the human driver unable to acquire the information he is supposed to acquire.

When there is a potential danger according to the internal model of the CAS, the alerting module conveys such information in the form of an alert to the human operator through a display. The display can use multiple modes, like audio, visual or even tactile. The proper way to present the alerts or other information to the human operator has been the subject of research for the last few decades [10]. Factors concerned include how much information can be conveyed in a short period of time without saturating the human operator, what kind of presenting mode is most intuitive to human and takes least time to comprehend. Once the human operator receives an alert, he can perform the *avoidance maneuver* to avoid the hazard space. The avoidance trajectory in Fig 2.2 is the avoidance maneuver taken by the human operator. For example, the pilot of an aircraft can climb to avoid a midair collision. Note that there are uncertainties in this avoidance maneuver too, such as the response time with respect to an alert and the maneuver aggressiveness. These uncertainties affect the system performance as well. The last component in Fig 2.1 is the *Automation* module. The automation module is optional to the CAS, and can come in different forms. The automation module can be completely autonomous, in which it takes complete control over the vehicle. Or it can come in as a semi-autonomous form that only constrains the human maneuver input into a certain envelope. An example of a semi-autonomous module is an auto-brake system.

2.2 Avoidance Maneuvers

In the realm of automobiles, the options of avoidance maneuvers available are much less than that of aircraft. When there is a potential threat, an aircraft can dodge by either ascent, descent, turning left, turning right, accelerating, decelerating or even a combination of more than one of these maneuvers. Some of these maneuvers are severely restricted or impossible for automobiles. As it is a two dimensional world for automobiles, ascent and descent are simply not available. The automobile driver can surely make a turn to avoid an oncoming collision, but there is potential danger to hit another car on the neighboring lane or hit a pedestrian on the sidewalk. This is a typical example of an *Induced Collision* event. Acceleration is not desirable for rear-end collision, as it only increases the chance of hitting the leading car. But acceleration may be beneficial for intersection collision avoidance in some cases, as will be shown in next chapter. Still we deem acceleration as an undesirable avoidance maneuver as it's not intuitive, and even counter intuitive to the car drivers. Suppose an alert was given out and the driver was advised to accelerate in order to avoid a collision. The driver may hesitate to accelerate, which diminishes the supposed effect of the alert. Worse still, the driver might refuse to carry out the maneuver. Therefore, deceleration is the only reasonable maneuver for automobile drivers in general. Of course some maneuvers suggested to aircraft pilots may be counter intuitive as well, but the pilots can be trained to overcome the hesitation, while such training cannot be available to all drivers. In the development of automobile collision avoidance system to come, deceleration will therefore be the only avoidance maneuver considered.

2.3 Rear-End Collision Avoidance Systems

A Collision Avoidance system for automobiles could contain at least two parts. One is rear-end collision avoidance system, and the other one is an intersection collision avoidance system. A lot of research has focused on the study of rear-end collision avoidance systems, and those systems are starting to be implemented in some car models. Rear-End Collision Avoidance systems come in two forms. First is Headway distance control, in which the systems control the speed or the distance from the leading car automatically [6]. Examples are the Intelligent Cruise Control Systems (ICC) developed by Leica and Fiat [6], and also the Adaptive Cruise Control Systems (ACC) developed by Toyota, Nissan, Mercedes-Benz and Lexus [5]. A Second kind of rear-end collision avoidance is alerting systems. Partners for Advanced Transit and Highways (PATH) [5] pointed out that an alerting system has been developed by Mazda, where an alert is issued to the driver when there is an imminent threat. If the driver ignores the alert and doesn't slow down, the system would apply the brake automatically. Collision alerting systems for trucks are already marketed in Japan by Mitsubishi, Nissan and Hino. Also, a Toyota car to be released in the near future will be able to apply the brake automatically and tighten the seatbelt when there is a potential emergency. In case of an alerting system, the computer has to be able to determine when or where to intervene by issuing an alert to the driver. In this chapter a review of some research on rear-end collision avoidance system is presented. This will be the foundation of the intersection collision avoidance system proposed in the next chapter.

2.3.1 Sensing Techniques for Rear-End Collision Avoidance

Sensing techniques have recently been a major research topic in the field of collision avoidance. The uncertainties in the state information are smaller with good sensors. In the case of rear-end collision avoidance, the system has to know the speed, position or even the width of the leading vehicle. According the [6], sensing techniques can be classified into three categories:

1. Optical Techniques: such as passive infra-red, laser radar and vision. The disadvantage of this technique is that the performance suffers from the external environment, such as rain, snow, or mud and dust accumulation on the car [5]. Laser radar can provide long range measurement.

2. Electromagnetic Techniques: such as Frequency Modulated Continuous Wave radar, impulse radar and capacitive. These perform well in a poor external environment, but the cost is relatively high. They provide short or medium range measurements.

3. Acoustic Techniques: such as ultrasonic. They provide low cost, short-term relative measurements, with high resolutions.

Another possibility is using more than one of these techniques, combining the result and computing a more accurate result. This is known as sensor fusion. Fujitsu Ten Ltd. Developed a prototype "fusion processor", which computes the distance and relative speed from the data of a millimeter-wave radar and stereo camera along with an image-processing unit [5]. If there is a communication link between vehicles, the system can fuse the data from more than one vehicle and obtain even more accurate estimate of the states.

2.3.2 Alerting Algorithms for Rear-End Collision Avoidance

The criterion to issue an alert is often either a time-to-collision criterion or a worst-case criterion. For a time-to-collision criterion, the system issues an alert if there is an imminent collision predicted in a short time. Time-to-collision is the time a car takes to crash into the leading car if both of them maintain their current speed. The CAS alerts if this time-to-collision is short. For the worst-case-criterion, the CAS computes the braking distance if the driver ahead began full braking and alerts at the required braking distance. Braking distance is the minimum distance that the car has to brake, in order to keep a desired separation from the leading car even if the leading car brakes at its full power. Another form of worst-case criterion uses braking time, which will be illustrated by an example later this chapter.

The Mazda system and the Honda system introduced by [3] will be discussed here. The Mazda system brakes automatically when the separation from the leading vehicle is less than the critical braking distance. This critical braking distance is defined based on the worst-case-criterion as [3]:

$$d_{br} = \frac{1}{2}\left(\frac{v^2}{\alpha_1} - \frac{(v - v_{rel})^2}{\alpha_2}\right) + v \cdot \tau_1 + v_{rel} \cdot \tau_2 + d_o \tag{2.1}$$

d_{br} is the critical braking distance, v is the velocity of the subject vehicle (trailing). v_{rel} is the relative velocity between the vehicles ($v_{rel} = v - v_{preceeding}$), α_1 is the maximum deceleration of the subject vehicle, α_2 is the maximum deceleration of the preceding vehicle, τ_1 and τ_2 are the delay times of subject vehicle and preceding vehicle respectively, d_o is the desired separation. Delay time is composed of the system delay (e.g. computational time and mechanical delay) and response time of the driver. As the

Mazda algorithm uses the worst-case-criterion and can avoid collisions even if the leading vehicle suddenly brakes with its full power, collisions can be avoided regardless of the intent of the leading vehicle driver. It will be shown in next chapter that the intent of the intruding vehicle has significant impact on whether a collision can be avoided in the case of intersection collision avoidance even when a worst-case criterion is used.

The Honda algorithm uses the warning distance (Unit in meters):

$$d_w = 2.2 \cdot v_{rel} + 6.2 \tag{2.2}$$

and the critical braking distance is defined by:

$$d_{br} = \begin{cases} \tau_2 v_{rel} + \tau_1 \tau_2 \alpha_1 - 0.5\alpha_1 \tau_1^2 & \dfrac{v_2}{\alpha_2} \geq \tau_2 \\ \tau_2 v - 0.5\alpha_1 (\tau_2 - \tau_1) - \dfrac{v_2^2}{2\alpha_2} & \dfrac{v_2}{\alpha_2} \prec \tau_2 \end{cases} \tag{2.3}$$

The variables in (2.2) and (2.3) are defined in the same way as (2.1), except that τ_2 is an adjustable parameter.

The Honda algorithm is defined on the driver test data collected. Honda assumes that the drivers perform steering maneuvers to avoid collisions, and asked the drivers to perform a normal steering maneuver to avoid an obstacle ahead. The warning distance is set to be less than the distance where the driver starts the normal steering maneuver, while the critical braking distance is set to be less than the distance where the driver starts the emergency maneuver by adjusting τ_2. The philosophy is that they want the driver to avoid the collisions on their own before the CAS intervenes.

Though the Mazda algorithm can avoid even the most critical cases, it may brake when it is not necessary and interfere with the normal behavior of the driver. The Mazda algorithm may therefore be considered too conservative. The Honda team designed their algorithm with the hope that it would not be too conservative. [3] Hedrick's team analyses the critical distances of these two companies and find that Honda's critical distances are less conservative [3]. Though the Honda algorithm cannot avoid all the collisions, it can nonetheless reduce the impact speed of the collisions. This is a good example of the tradeoff between safety and the fact that we don't want the drivers to be interrupted by unnecessary alerts. In a later chapter, the methodology to analyze the relationship between the tradeoffs involved and where to when the system intervene will be discussed.

Kuchar [2] developed an algorithm for a rear-end collision avoidance algorithm based on the worst-case scenario. The algorithm alerts at the alerting time t_{alert}. The algorithm assumes there is a stationary object at a distance r ahead of the subject vehicle. And the distance d taken to stop the vehicle is:

$$d = v\tau + \frac{v^2}{2a} \tag{2.4}$$

v is the velocity of the subject vehicle, τ is the delay time, a is the constant decelerating rate of the car. Though the algorithm assumes a stationary object ahead, it can be easily extended to the case of rear-end collision avoidance between vehicles by assuming that both the leading and chasing vehicles travel at constant velocity, and v is the relative velocity between the vehicles. The alerting time is defined to be:

$$t_{alert} = \frac{r}{v} - \frac{d}{v} \tag{2.5}$$

This t_{alert} is the time remaining before an alert is required to avoid a collision.

2.3.3 Performance-Based Approach

In [9], Yang proposed a performance based approach for rear-end CAS. The author argues that the state-space threshold function can be written as $f(x,a)$, and the condition to alert can be written as $f(x,a) > 0$, where x is the system states and a is the set of equation parameters. Then the boundary between alerting and not alerting is defined by the set of states x^* such that:

$$f(x^*,a) = 0 \tag{2.6}$$

The authors then pick x^* according to the performance metrics associated with it, and then solve (2.6) for a, which are the system parameters to be set in the alerting algorithm. By doing so, the system performs with the performance as specified by the performance metrics associated with the x^* chosen. Two performance metrics were used for the choice of x^*. They are the probability of successful alert, $P(SA)$ and the probability of unnecessary alert, $P(UA)$. These two probabilities were computed by:

$$P(SA(x)) = 1 - p(C \mid A(x)) \tag{2.7}$$

$$P(UA(x)) = 1 - p(C \mid N(x)) \tag{2.8}$$

where $p(C \mid A(x))$ is the probability of a collision if an alert is issued at x and $p(C \mid N(x))$ is the probability of a collision if no alert is issued. If an alert is issued early, then one would have a higher chance of preventing a collision from happening, but also a higher chance of unnecessary alert, or nuisance. On the other hand if an alert is issued late, then the nuisance rate will be lower, but comes with a cost of higher collision rate. Fig. 2.3 shows a System Operating Characteristic (SOC) curve, which can be used to visualize the tradeoff of choosing to alert at different states x.

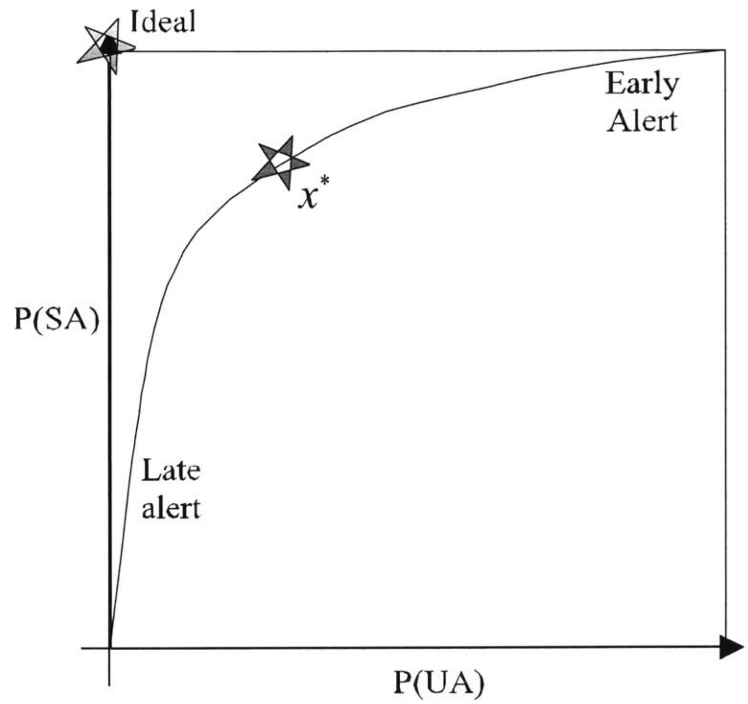


Fig. 2.3 A SOC curve

Ideally one would like to attain the upper left corner of the SOC curve, which is called an ideal point. However due to the uncertainties in an alerting system, this ideal point can never be achieved. Instead one should choose an operating point along the SOC curve to suit his own requirements (i.e. his own balance on the required P(UA) and P(SA)).

At each state position x of the state space, the authors performed Monte Carlo simulations to obtain the values of $P(SA(x))$ and $P(UA(x))$ corresponding to that x, based on the trajectory model they obtained. Their trajectory model included a Gaussian distribution for reaction time, an impulse distribution for system delay, and a Gaussian distribution for braking acceleration, and also probability distributions on other uncertainties involved. Then the authors chose an operating point x^* on the SOC curve that suited their own criteria. For instance, they chose a x^* with P(SA) equal to 0.95 and

P(UA) equal to 0.21. Based on this x^*, they can compute the system parameters a based on (2.6).

2.4 Limits of Rear-End Avoidance Systems

Up to this point we have assumed that the rear-end collision avoidance system works on their own, without knowing whether the other cars on the road are equipped with rear-end collision avoidance systems or not. As pointed out earlier, with the use of a worst-case criterion, the subject vehicle is able to avoid collisions successfully even if it doesn't know the intent of the leading vehicle. In this sense, the subject vehicle doesn't have to communicate with the leading vehicle. But if the subject vehicle brakes to avoid a collision with the leading vehicle, there is a chance that it may collide with the vehicle behind if the vehicle behind is not equipped with its own rear-end collision avoidance system. Globally speaking, communication would help mitigate this problem. A worse case is when the vehicle preceding the subject vehicle decelerates, while the vehicle behind the subject vehicle accelerates. In this case a collision cannot be avoided no matter what the subject vehicle does. Therefore systems on different vehicles may need to cooperate to avoid collisions globally. Just using an alerting system is not sufficient, because the global avoidance maneuver may involve delicate balance of different vehicles' maneuvers, and human uncertainties may easily ruin the utility of the global avoidance maneuver. For this reason, a cooperative autonomous system may be the ultimate answer to prevent rear-ends collisions.

Chapter 3 Intersection Collision Avoidance

3.1 Intersection Collision Avoidance Systems

A prototype intersection collision avoidance system (ICAS) is proposed in this chapter. The algorithm is proposed and its assumptions are made. A graphical tool is developed to analyze the dynamics and interactions of vehicles approaching the intersection, and thereby to design the algorithm. This graphical tool also examines the utilities and limits of the algorithm. This thesis analyzed the problem of intersection collision and the related issues by a mathematically rigorous approach.

3.2 Interactions of Intersection Approaching Vehicles

We assume the vehicles approaching an intersection follow a straight path, namely they stay in their own lanes before and after passing the intersection. Therefore the system can project the future trajectories of the vehicles entering the intersection in the same way as shown in Fig 3.1.

There is an intersecting point of the two projected trajectories. The vehicles can travel with constant velocity, accelerate, decelerate or travel with a more complex velocity profile along their projected trajectory. Assuming a point mass for both vehicles, a collision is declared if both vehicles are within some minimum distance at the intersecting point at the same time. Otherwise there is no collision. Let d_m be the separation distance between the two vehicles when either one of them is at the intersecting point, and call it a risk metric. d_o is the *desired risk metric,* the minimum separation distance (the minimum allowed d_m) that the systems tries to keep between the vehicles when either one of them is at the intersecting point. By ensuring that one of the vehicles is at least d_o away from the intersecting point while another vehicle is at the intersecting point, the system ensures that there is no collision when the fact that the vehicles are not point mass is taken into account.

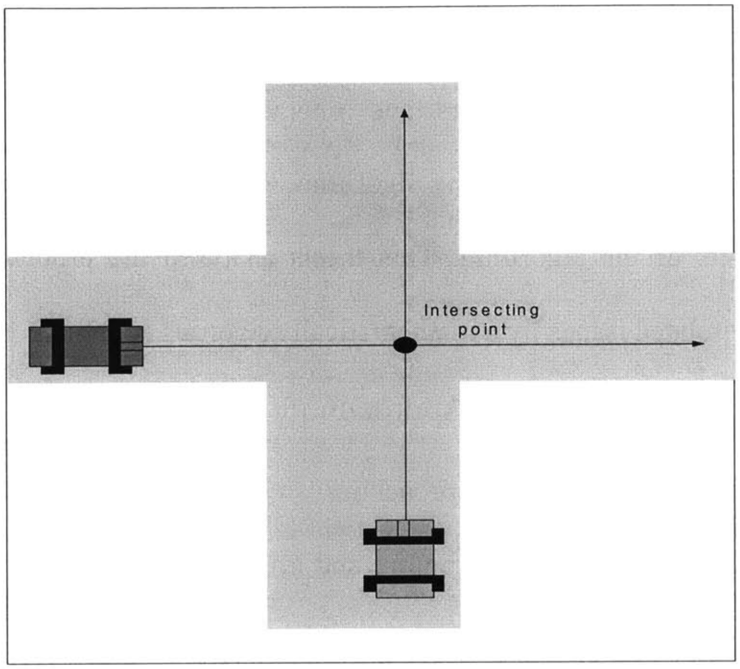


Fig.3.1 Trajectory projection of approaching vehicles

In the context of intersection collision avoidance, we argue that we can use d_m as the performance metric instead of using $d_{\min}$. Consider Fig 3.2. Without loss of generality, we assume the vehicle travels horizontally in Fig 3.1 will pass through the intersection first. We assume a coordinate frame fixed at the vehicle that travels upward in Fig 3.1, and then we can obtain the relative trajectory of the horizontal traveling vehicle with respect to the upward traveling vehicle, which is fixed at the origin of the coordinate frame. The magnitude of $d_{\min}$ and d_m are shown in the Fig 3.2. As an example, assume that initially both vehicles are 150 feet from the intersecting point, the vehicle moving to the right has velocity of 45 mph (66 feet per second), and the vehicle moving upward has velocity of 30mph (44 feet per second). Then the value of d_m is 50 feet while the value of $d_{\min}$ is 41.6 feet. We can approximate $d_{\min}$ as d_m when the two vehicles possess comparable speed. Though d_m is always larger than $d_{\min}$ and by ensuring that d_m is greater than d_o cannot ensure that $d_{\min}$ is greater than d_o, we can eliminate this problem by putting a buffer in the choice of d_o. The benefit of using this approximation is that it allows a graphical tool which enables us to visualize the complicated interplays between vehicles in an intersection collision, by taking advantage of our knowledge in the geometry of intersection collisions. This facilitates our analysis of intersection collisions and the deviation of ICAS algorithm. This will be explained in details later in this chapter.

The model proposed doesn't require information on whether it's a one-lane road, two-lane road or a road with more lanes. All the system needs is where the intersecting point is and how far each of the vehicles is from the intersecting point. This information can be obtained through GPS, an internal database of maps and a communication link or radar between the vehicles approaching the intersection. These devices are already available in some luxury cars nowadays and should be commonplace in the

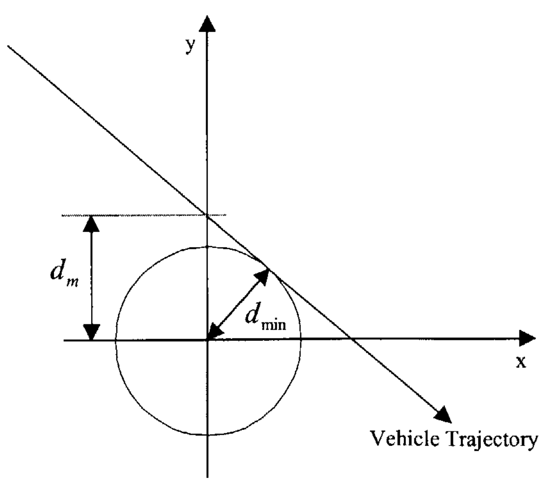


Fig 3.2 Vehicle trajectory projection in a relative frame

future. Later in this chapter, it is shown that merely having the range and range rates between the vehicles is not sufficient.

The vehicle equipped with the Collision Avoidance System (CAS) and responsible to avoid the collision is called *subject vehicle* while the vehicle that the subject vehicle tries to avoid colliding with is called an *intruder vehicle*. Suppose the subject vehicle possesses the right of way and the intruder vehicle has a red light facing it and it's required to stop before the stop line. Three situations are identified:

1. The intruder vehicle doesn't abide with the law and goes through the intersection, as shown in Fig.3.3. The subject vehicle is designated with a capital letter "S" while the intruder vehicle an "I". This is the primary case the proposed system focuses on. The intruder vehicle can travel with constant velocity, accelerate, decelerate or travel with a more complex velocity profile through the intersection. We will look at how these different intruding vehicles affect the system performance.

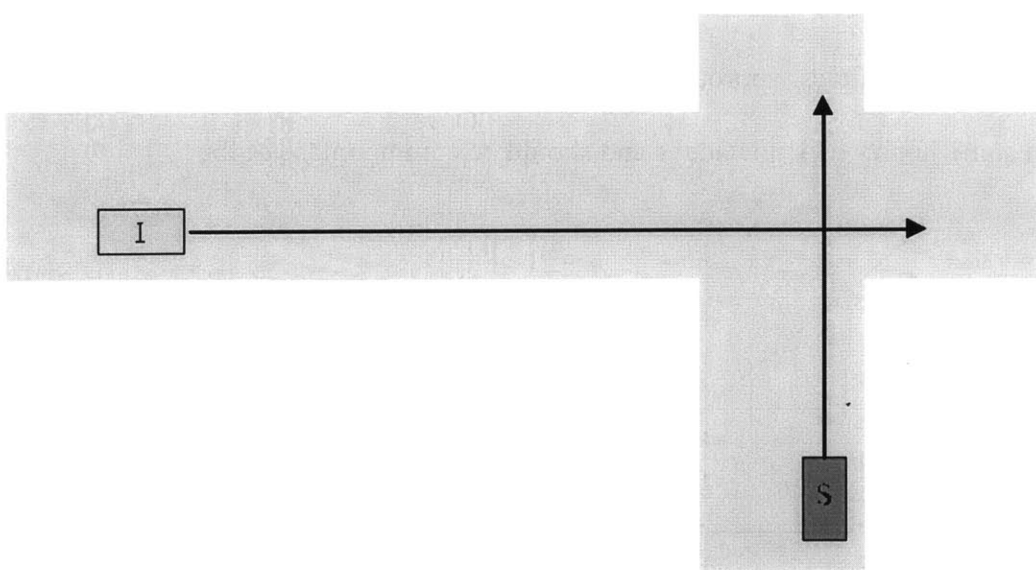


Fig 3.3 Intruding vehicle runs through a red light

2. The intruder vehicle does abide with the law and stops before the stop line, as in Fig 3.4. In this case, a collision won't occur regardless whether there is CA system or not. But the action of the intruder vehicle may trigger the CA system to issue an alert and thus generate a false alarm.

3. Initially the intruder vehicle stops before the stop line, and suddenly it accelerates and collides into the subject vehicle as in Fig 3.5.This kind of behavior is suicidal and there is almost nothing can be done with an alerting system, because the response time available to the driver is too short. Possibly an autonomous system will be able to handle this, we will analyze this situation further later.

The intersection CAS also relies on the assumption that there are only two vehicles approaching an intersection. This assumption has its own limits as in reality there are usually more than two vehicles approaching the intersection. Consider the case shown in Fig 3.6. In Fig. 3.6, the intruding vehicle doesn't abide with the law and tries to go through the intersection. The intersection CAS aboard the subject vehicle responds by alerting the driver to decelerate. When the subject vehicle S decelerates, it poses a potential threat to the vehicle behind it, which is designated with capital letter "R". If the vehicle R is equipped with the kind of rear-end CAS mentioned in Chapter 2, the danger can be alleviated as the rear-end system can handle the situation even if the car in front suddenly brakes. This example shows that how the intersection CAS and the rear-end CAS cooperate to avoid collisions involving multiple vehicles.

Another case involving multiple vehicles is illustrated in Fig 3.7. Suppose there are three intruding vehicles entering the intersection on a three-lane road, being designated as I1, I2, and I3 respectively. In the algorithm to be introduced later, criteria to decide whether

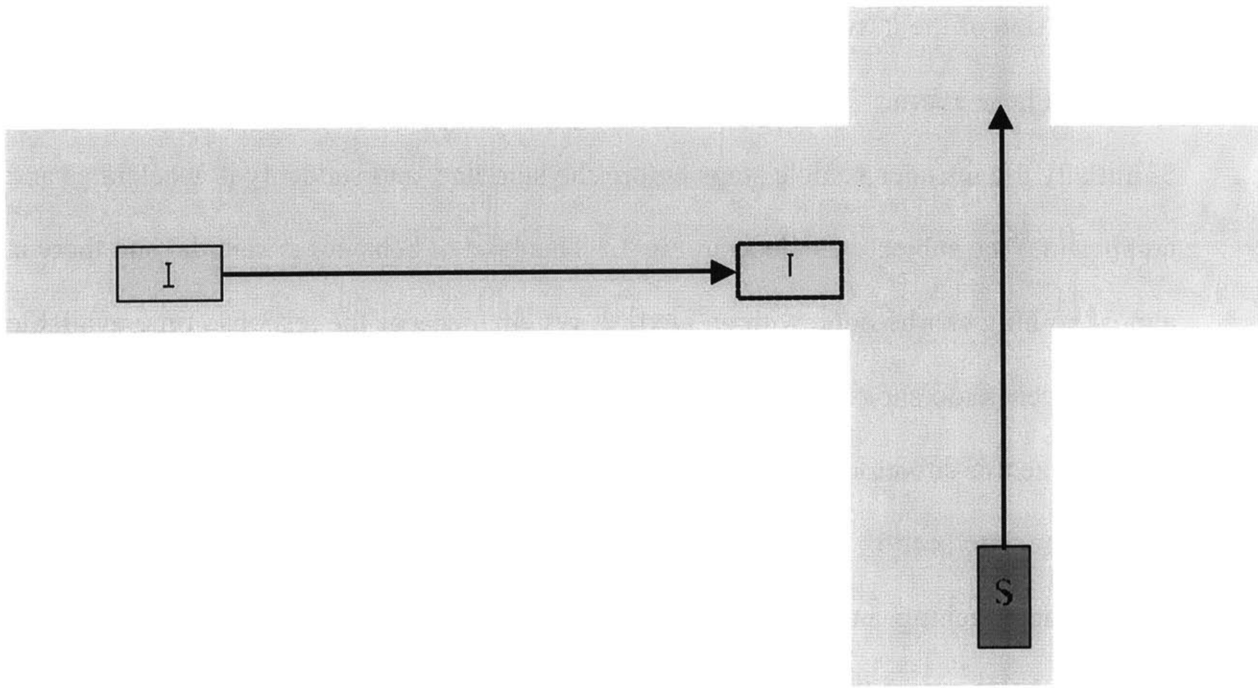


Fig 3.4 Intruding vehicle abides with the law and stops before a stop line

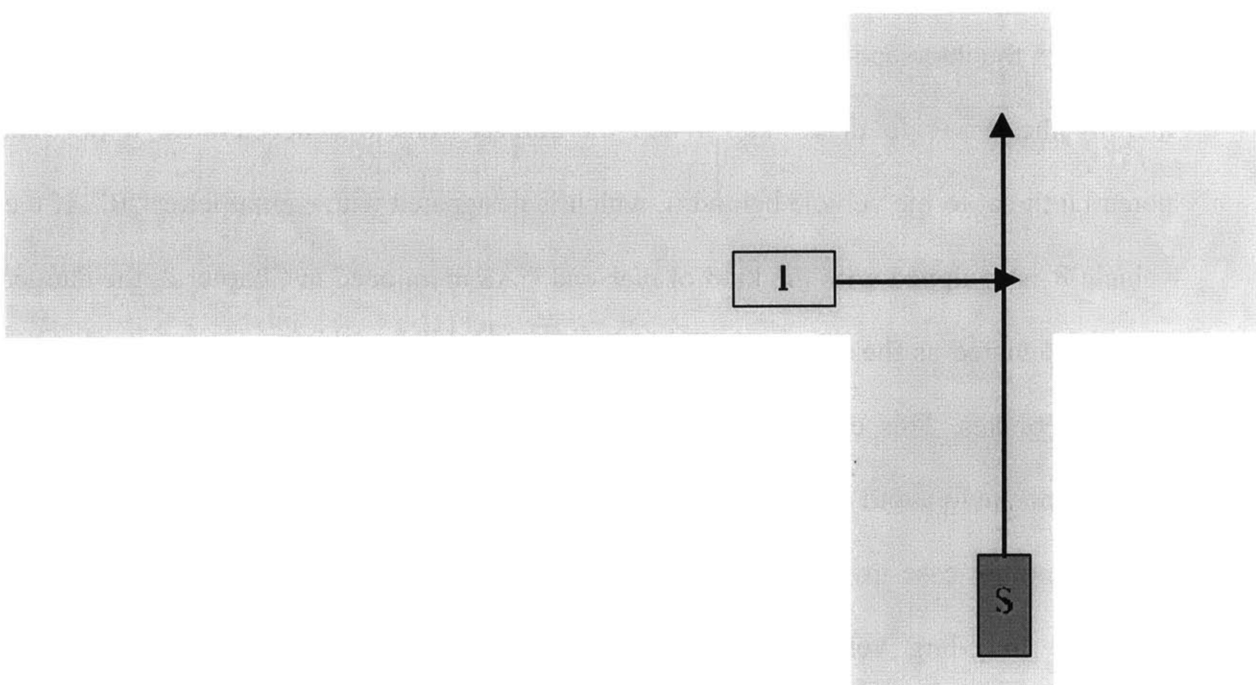


Fig. 3.5 Intruding vehicle accelerates suddenly

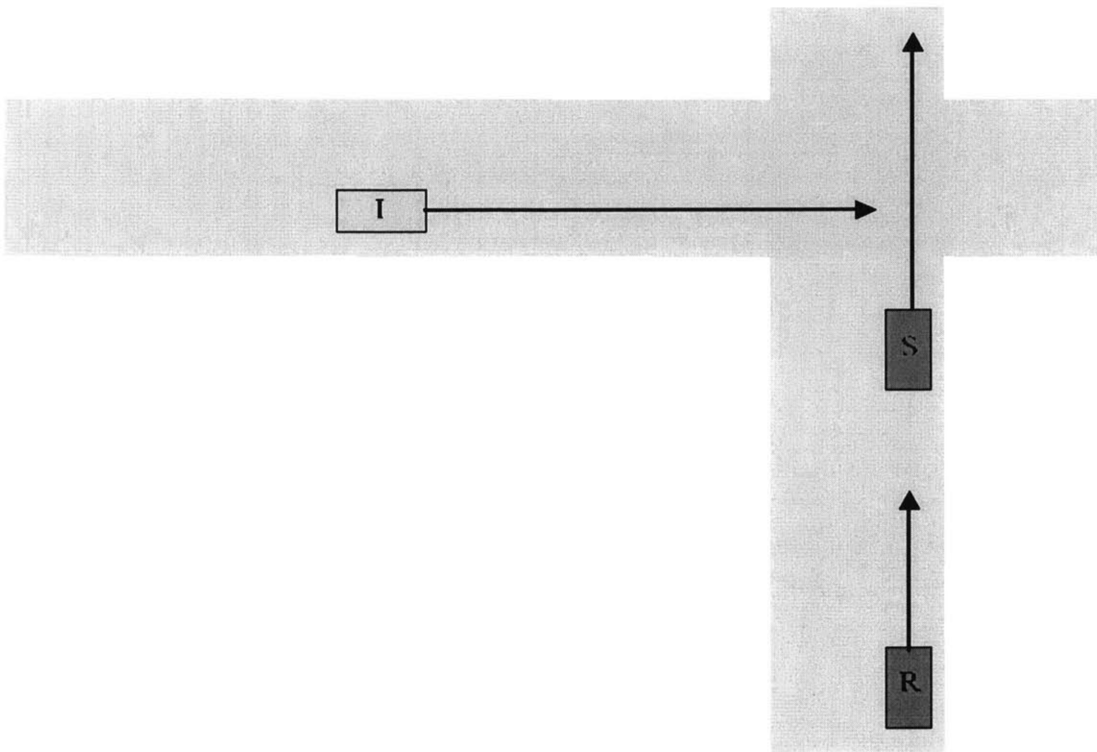


Fig. 3.6 The intersection CAS and rear-end CAS complement each other

there is collision threat will be introduced. Chances are all three vehicles pose collision threats. If so, the CAS would pick the intruder vehicle that poses the most imminent danger to avoid. I1 does not necessarily pose most imminent danger though it is the closest vehicle, because it also depends on the relative velocity of the vehicles. But now we assume that I1 pose most imminent danger, and the driver of the subject vehicle decelerates to avoid a collision with I1. By doing do, it may run into collision threats with I2 and I3, given that the subject vehicle passes the intersection before I2 and I3 if it doesn't decelerate. The moral is that the avoidance maneuver to avoid collision with a certain vehicle may induce collisions with other vehicles. One solution to this problem is to use a cooperative autonomous system, in which the vehicles communicate with each other and figure out a collective avoidance maneuver to avoid collisions globally. With only an alerting system in place, we can still assume the assumption of a 2-vehicle

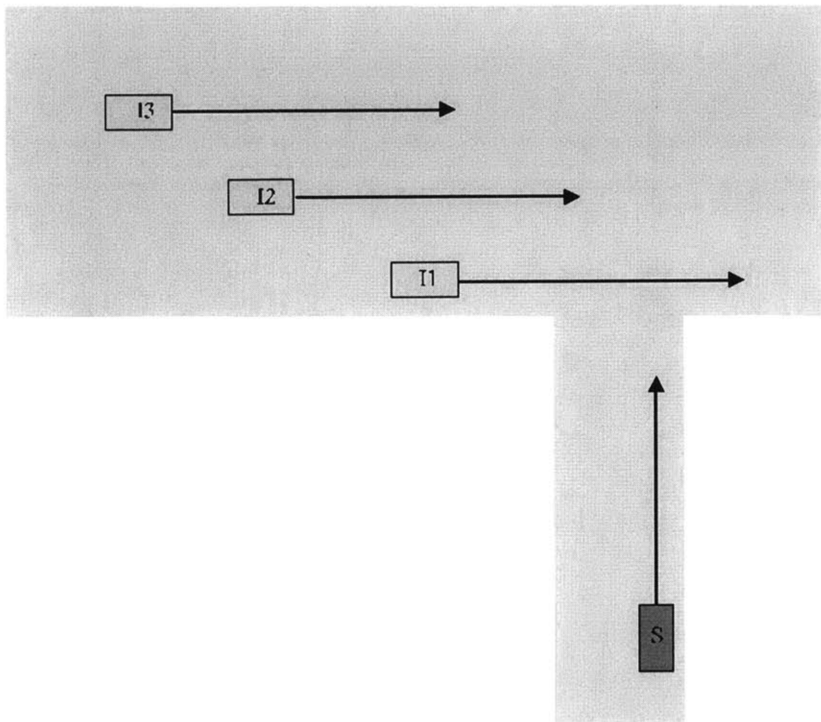


Fig 3.7 A multi vehicle case that cause potential problems to CAS

scenario to be sufficient. This is because in reality, most vehicles abide by the law and stop before the stop line. Avoidance maneuvers do not induce collisions with other intruding vehicles in almost all but the most extreme cases that there are more than one intruding vehicles violate the law.

3.3 ICAS Algorithms

3.3.1 The Graphical Tool to Analyze Intersection Collisions

Some of the rear-end CA systems mentioned in Chapter 1 use the worst-case criterion, that is the subject vehicle is able to maintain a desired distance from the front vehicle by applying brake, even if the front vehicle brakes with its full power suddenly. In developing the ICAS, a similar approach is adopted. The CA system makes sure that the subject vehicle is at a desired separation from the intruding vehicle when the intruding vehicle is at the intersection. But it is not perfectly appropriate to call this criterion the worst-case criterion in the context of intersection collisions, because there is no *absolute worst* case. For rear-end collision, the worst case is that the front vehicle suddenly brakes to its corresponding full power. In the case of intersection collision, whether the situation is a good one or a bad one depends on the interaction of the two vehicles approaching the intersection. For a certain velocity of the subject vehicle, the worst intruding vehicle velocity profile may be a constant one. While for another subject vehicle velocity, the worst intruding vehicle velocity profile could be an accelerating one. By worst we mean the velocity profile that minimizes the risk metric d_m. The risk metric d_m is the distance between the two vehicles when one of them is at the intersecting point, as shown at Fig. 3.8. Note that the intruding vehicle doesn't necessarily enter the intersection first. As there is a well defined worst case for the rear-end case and the CAS can be designed accordingly, intent of the front vehicle doesn't affect the performance of the CAS because the CAS is able to deal with the worst front vehicle intent. In contrast, intent pays a crucial part in the intersection case and can have a significant impact on the CAS performance, as the interaction between the two vehicles is very important. A further analysis on the effect of intruding vehicle intent is provided later in this chapter.

The terminologies used to describe the algorithm are given here. R is the *range*, the distance of each of the vehicles from the intersecting point. This is different from the conventional definition of range as distance between two vehicles. Both the subject vehicle and the intruding vehicle have their own range. Range is a function of time t. $\dot{R}$ is the *range rate* and is the 1st derivative of R with respect to time t:

$$\dot{R} = \frac{dR}{dt} \tag{3.1}$$

The range R decreases when a vehicle approaches the intersection point. $\dot{R}$ is thus negative if the vehicle approaches the intersecting point and it's negative of the vehicle

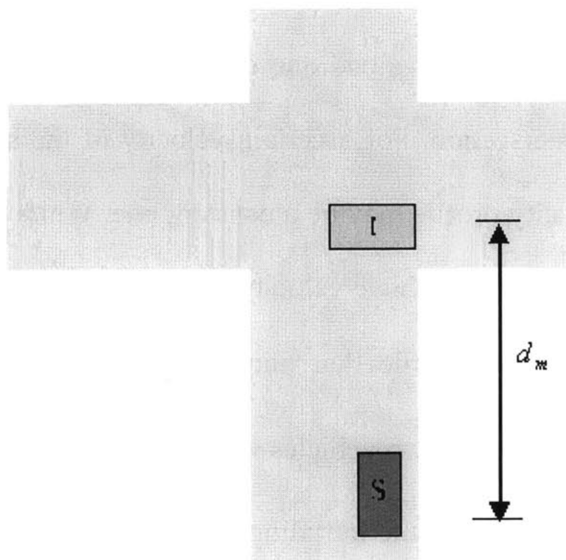


Fig. 3.8 Definition of d_m

velocity. $\ddot{R}$ is the rate of range rate and it's the 2nd derivative of R with respect to time t:

$$\ddot{R} = \frac{d\dot{R}}{dt} = \frac{d^2R}{dt^2} \tag{3.2}$$

As a vehicle approaches the intersection, a positive $\ddot{R}$ means that the vehicle decelerates while a negative $\ddot{R}$ means that the vehicle accelerates. The negative of $\ddot{R}$ is the actual acceleration of the vehicle. By the same token, both vehicles possess their own $\dot{R}$ and $\ddot{R}$ profile. At each time step, the current state information is acquired by the CAS and then the CAS projects the state information in time to make a decision of whether to alert or not. From the perspective of the CAS, every time step when the state information comes in is the *initial time,* the time *t=0.* $R_I(0)$ and $\dot{R}_I(0)$ are the *initial range* and *initial range rate* of the intruder vehicle respectively, that is the range and range rate of the intruder vehicle at *t=0.* $R_S(0)$ and $\dot{R}_S(0)$ are the initial range and initial range rate of the subject vehicle. The negative value of $\ddot{R}_S$ is the assumed deceleration of the subject vehicle. The alerting system assumes that the subject vehicle driver brakes at this rate upon receiving an alert. τ is the *assumed response time.* The CAS assumes that the subject vehicle driver waits for a time τ after an alert before starting to brake. The value of $\ddot{R}_S$ and τ can be obtained experimentally through collecting human performance data. The problem is that the value of $\ddot{R}_S$ and τ varies from driver to driver. There are three ways to select the values of $\ddot{R}_S$ and τ. First is to set the value so that it suits as many people as it can. The problem with this approach is that the people whose driving habit largely deviates from average habits cannot benefit from the CAS, and can even worse off with the presence of the CAS. An alerting system is therefore inherently a probabilistic system, as the system performance is probabilistic in nature. The second way is give the driver the option to select the values himself. A third approach is to use machine-learning techniques to let the CAS learn the driving habit of the driver and set the values accordingly. Two problems come with this approach however. First problem is it takes time for the CAS to learn the driving habits of a certain driver. In the midst of the learning process, the CAS may be unable to improve the safety while the driver thinks he is being protected, this could be potentially dangerous. Second problem is that once the CAS adapts itself to a certain driver, problems will probably arise when the driver offers somebody who has a different driving habit to take the wheel of the car. This shows that human uncertainties are the source of problem of human-in-the-loop control system and there is no easy solution to it. The problems mentioned here are not serious in the realm of aerospace, because pilots are well trained and are more or less homogeneous.

d_o is the *desired minimum* d_m. This is the minimum separation distance between the two vehicles that the CAS strives to maintain when either one of them is at the intersecting point. t_I is the time required for the intruding vehicle to arrive at the intersecting point, counting from *t=0*. t_S is the time required for the subject vehicle to enter the intersecting point. We define a risk metric to be the separation between two vehicles when either one of them is at the intersection point. d_m^N is the *nominal risk metric when* the first car arrives at the intersection point. This is a metric of risk expected by the CAS if no alert is issued. It is only an estimate of the CAS according to its internal projection model, not the actual one in reality. The actual risk metric is usually different as actually driver behavior is usually different from that of the projection model. d_m^A is the *risk metric upon avoidance*. This is the expected risk metric resulted if an alert is issued.

A graph of *R* versus *t* is used as a graphical tool to analyze the intersection vehicles' dynamics and used to derive the alerting logic. See Fig 3.9.

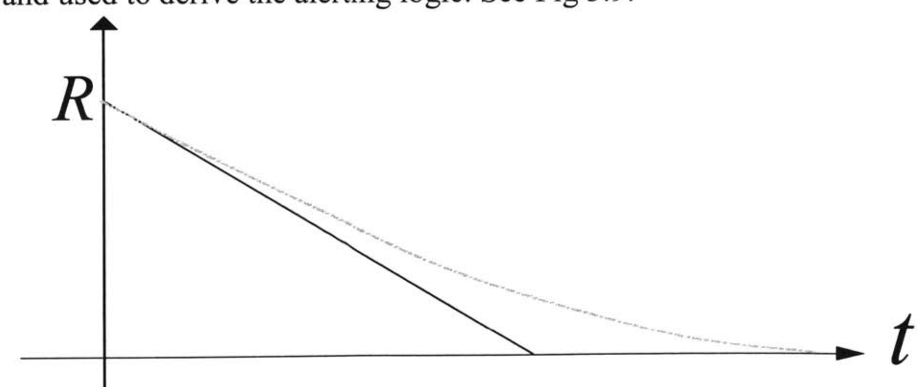


Fig 3.9 Example R-t graphs

In Fig. 3.9, the straight line and the curve represent two potential trajectories a vehicle could take. The value of R at $t=0$ is the initial range, and the value of t where $R=0$ is the time taken for the vehicle to enter the intersection, t_I if it's an intruder vehicle and t_S if it's a subject vehicle. The straight line represents a vehicle entering the intersecting point with constant velocity and the curve (a quadratic curve) represents a vehicle entering the intersecting point while it decelerates. It is very clear from this simple graph that it takes a longer time for the decelerating vehicle to enter the intersecting point. The use of this graphical tool makes the analysis of the interaction between engaging vehicles easier, as we will see later. However this graphical tool can only be used under the condition that the trajectories of the engaging vehicles intersect and the engaging vehicles are constrained in a certain trajectory channel. This is exactly the case for automobile intersection collisions, as both of the vehicles are constrained on the road structure unless they drive off the road. This is generally not the case for aircraft. Though the aircraft are constrained by certain airspace, usually the pilot has the ability to deviate from the trajectory channel on a short-term basis. However the trajectories do not necessarily intersect at right angle or necessarily in straight lines. All the algorithm has to know is the vehicles' distances from the intersecting point along the trajectory channels, and the magnitude of the speeds. Fig 3.10 shows a general case that the proposed algorithm is capable of handling.

The very first thing the CAS looks at is obvious, that is whether the subject vehicle is moving at all. If not, then there is no collision threat unless the other vehicle deliberately crashes into it. If the subject vehicle is moving, the CAS has to determine whether there is a potential collision threat. Upon receiving the state information, the CAS projects the trajectories of both vehicles with its internal model. As

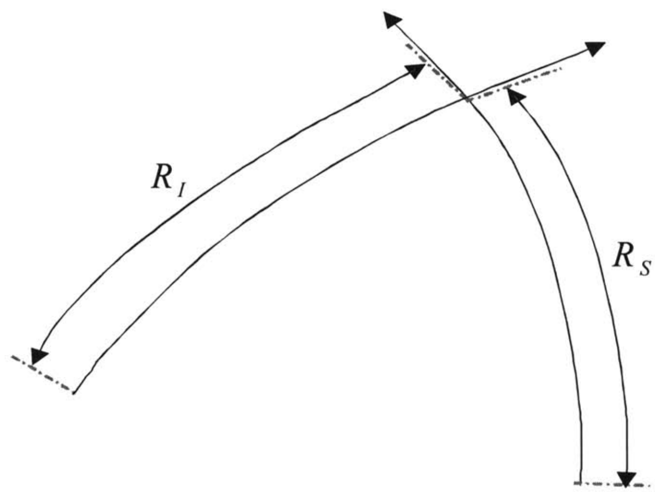


Fig 3.10 A general case for the proposed algorithm

the intent of drivers on both vehicles is largely unknown, the best estimate is that both vehicles travel with a constant velocity. The analysis lead to the algorithm is still applicable once there is some way to obtain a more accurate projection model. The effect on system performance if the vehicles do not travel with constant velocity will be discussed. In Fig 3.11 there are two trajectories. From now on we will use the thicker one to represent the subject vehicle trajectory and the lighter one to represent the intruder vehicle trajectory. From the graph we can obtain much information.

We can see that both vehicles enter the intersection point with constant velocity, the time to intersection point for both vehicles, and the nominal risk metric. As intruder vehicle enters the intersection point first in this example, the nominal risk metric d_m^N is R_S when $R_I = 0$. If $d_m^N \geq d_o$, it means that the risk metric is more than the desired value, and the safety requirement is satisfied even if no alert is issued. For the case that the intruding vehicle enters the intersection point first, d_m^N is computed by:

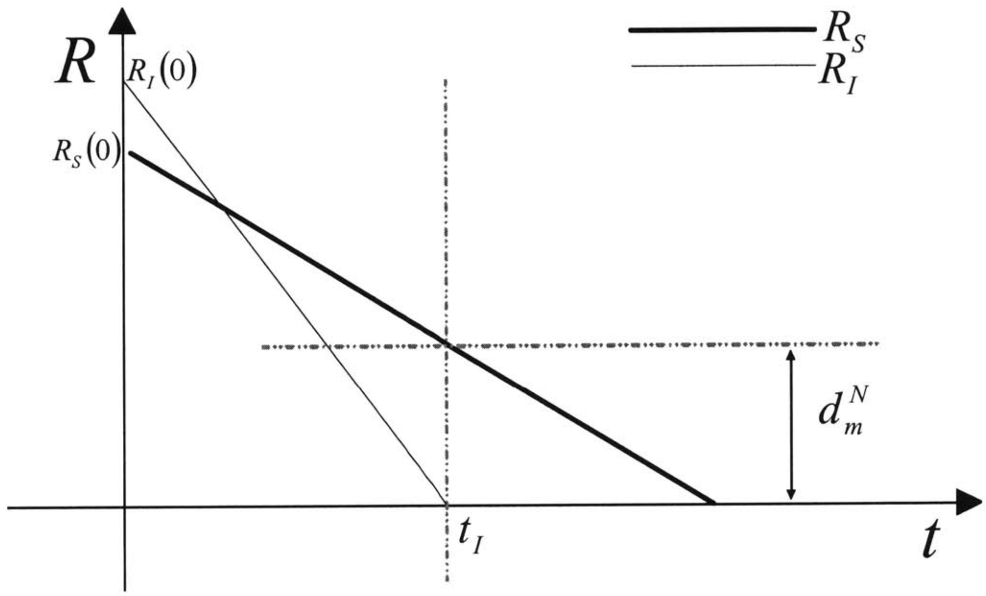


Fig 3.11 R-t graph for both vehicles with constant velocities

$$d_m^N = R_S(0) + \dot{R}_S \cdot t_I \tag{3.3}$$

If instead the subject vehicle enters the intersection point first:

$$d_m^N = R_I(0) + \dot{R}_I \cdot t_S \tag{3.4}$$

As the vehicles are assumed to travel at constant velocity, t_S and t_I are computed by:

$$t_S = \frac{R_S(0)}{-\dot{R}_S} \tag{3.5}$$

$$t_I = \frac{R_I(0)}{-\dot{R}_I} \tag{3.6}$$

If $d_m^N < d_O$, then the CAS has to issue an alert to change the situation. As pointed out earlier, the only reasonable avoidance maneuver is deceleration. Suppose an alert is issued at time $t=0$, and it takes the driver τ seconds before braking, then R_S^A, the range of the subject vehicle along the avoidance trajectory can be expressed as a function of t by:

$$R_S^A(t) = R_S(0) + \dot{R}_S t \qquad \text{for} \qquad t \prec \tau$$
$$R_S^A(t) = R_S(0) + \dot{R}_S\tau + \dot{R}_S(t-\tau) + \frac{1}{2}\ddot{R}_S(t-\tau)^2 \qquad t \geq \tau \qquad (3.7)$$

It can be seen from (3.7) that the curve for the avoidance trajectory shown in Fig 3.12 is quadratic. From now on, an avoidance trajectory will be represented by a thick dotted line in the *R-t* graph. In Fig 3.12, d_m^A is greater than d_m^N, and it means that the subject vehicle increases the risk metric by deceleration. It is also evident from Fig 3.12 that if the intruder vehicle enters the intersection point first, d_m^A is always greater than d_m^N if the subject vehicle decelerates. Therefore benefit in safety is always gained by deceleration if the intruding vehicle enters first.

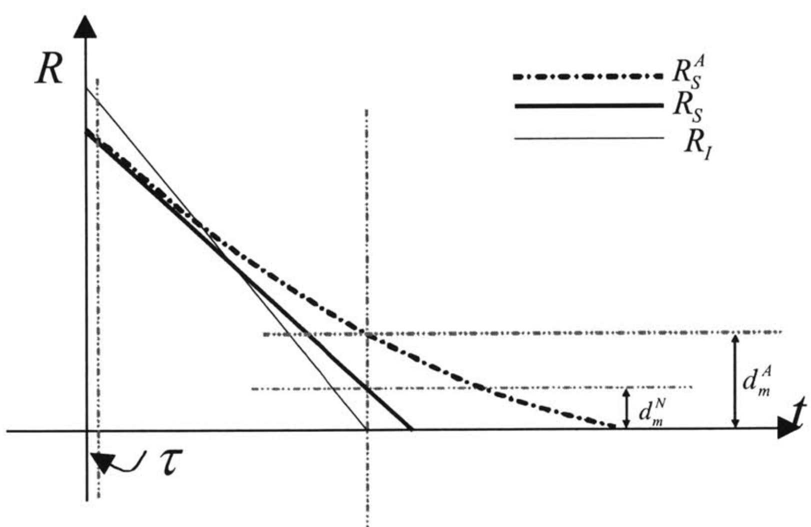


Fig 3.12 R-t curve: effects of **I** enters first and **S** decelerates

On the other hand, if the subject vehicle enters the intersection point first, deceleration may decrease the risk metric, that is $d_m^A < d_m^N$. This is shown in Fig 3.13. In

Fig 3.13, the R value of the subject vehicle reaches zero first, which means the subject vehicle enters first. It can be seen that $d_m^A < d_m^N$ as the subject vehicle decelerates. In other words, deceleration is generally undesirable if the subject vehicle enters the intersection point first.

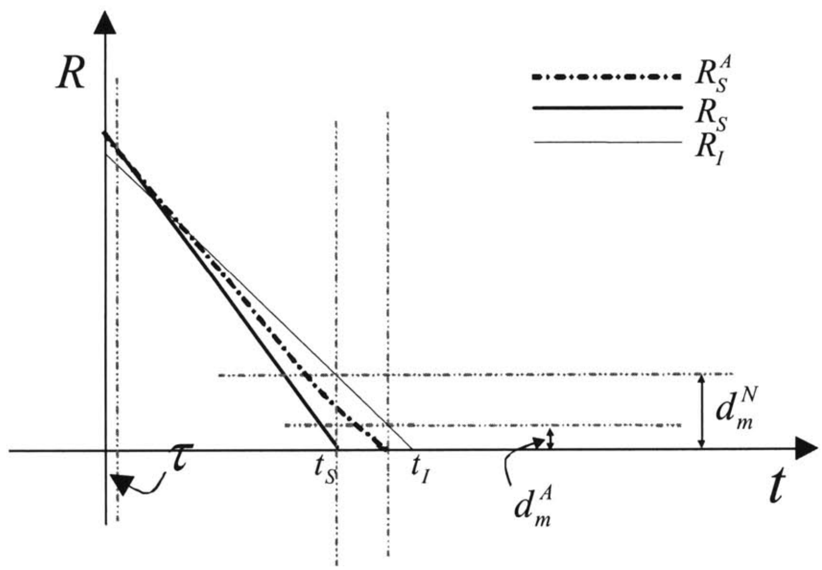


Fig. 3.13 R-t curve: effects of **S** enters first and **S** decelerates

In the case that the subject vehicle enters the intersection first, the avoidance maneuver that can increase the risk metric and thus the safety is acceleration. In Fig 3.14, the subject vehicle enters the intersection first and the avoidance maneuver adopted is acceleration. As the subject vehicle accelerates instead of decelerates, the $\ddot{R}_S$ in (3.7) will be negative instead of positive. The avoidance curve in the R-t graph will be concave instead of convex in Fig 3.13. With a concave avoidance curve instead of a convex one, d_m^A is always greater than d_m^N in the case that subject vehicle enters first. It means that for the case where subject vehicle enters first, it is desirable for the subject vehicle to accelerate. As mentioned earlier, acceleration is counterintuitive and it's not practical to ask the average untrained driver to accelerate when there is a collision threat. When the subject vehicle enters first, the best thing to do is to accelerate and an autonomous system

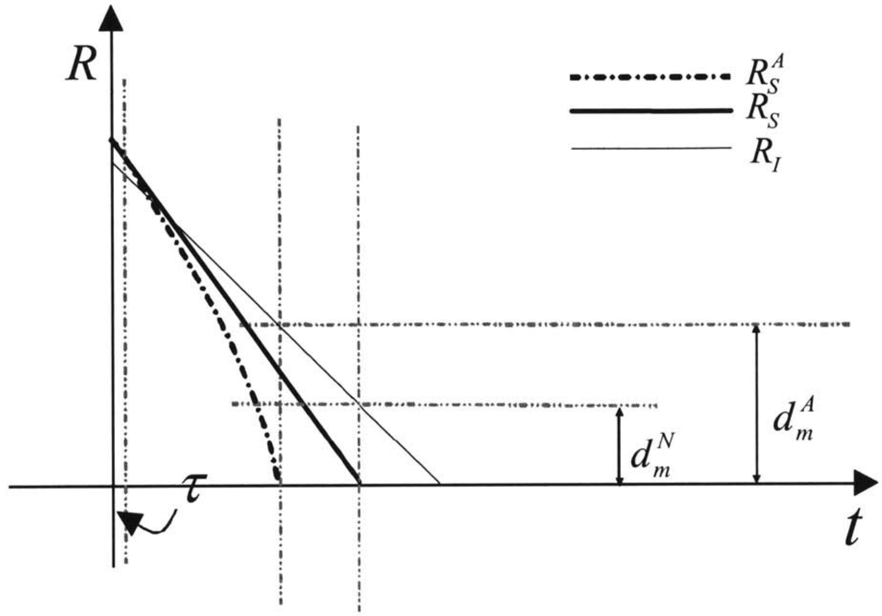


Fig. 3.14 R-t curve: effects of **S** enters first and **S** accelerates

can perform such a maneuver without hesitation. With just an alerting system in place, we can only count on the human to perform deceleration maneuvers. It will be shown later in this chapter that even if the subject vehicle enters first, it can be desirable to decelerate under some conditions. One example of these conditions is shown in Fig 3.15, in which d_m^A is greater than d_m^N by deceleration even when the subject vehicle nominally enters the intersection first. We will quantitatively define what are those conditions, when it is acceptable to decelerate and when it is not.

3.3.2 Three Configurations of ICAS

When a subject vehicle enters the intersection, there are three configurations of CAS interactions. First is both of the engaging vehicles are equipped with CAS and there is communication link between the CAS on the two vehicles. Second is only one vehicle is equipped with the CAS. Third is both of the engaging vehicles are equipped with CAS, but there is no communication link in between them.

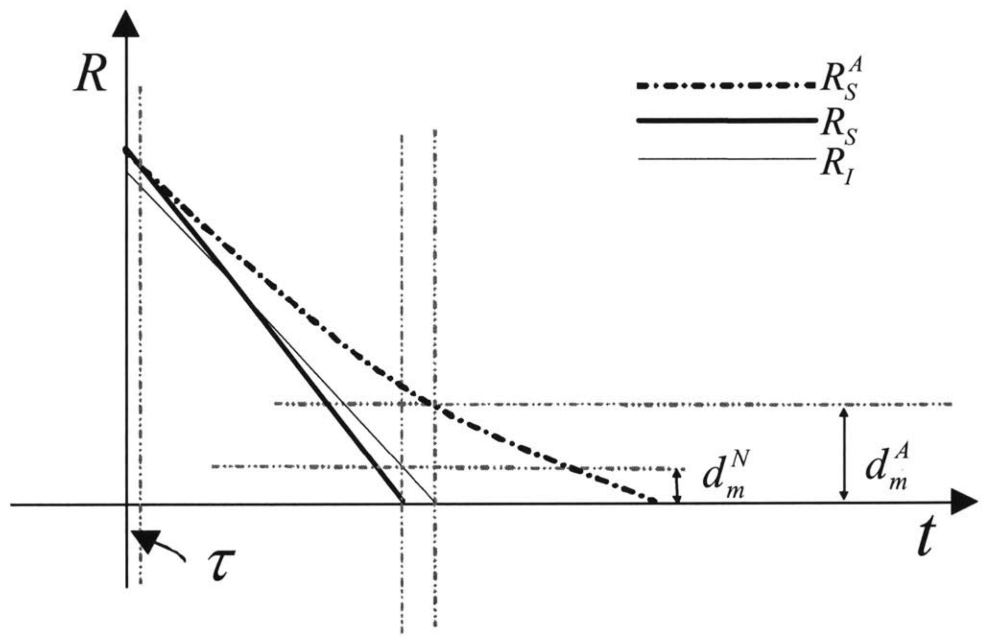


Fig. 3.15 R-t curve: case of **S** enters first, and **S** decelerates to improve safety

Let's call the vehicle that enters first the lead vehicle and the vehicle that enters that later the lag vehicle. The first configuration is the ideal case. As the lead vehicle is insufficient to avoid all the collisions when it enters the intersection first, if the CAS onboard consists of only an alerting system, the CAS on the two vehicles can figure out which vehicle is the lag vehicle and assign that vehicle to be the vehicle responsible for the avoidance maneuver (subject vehicle) through the communication link. The first configuration will not be commonplace, at least in the near future. In the near future, we cannot expect all the vehicles on the road to be equipped with CAS due to the high cost and various policy issues. Therefore it is expected that the second configuration will be the most common case. The third one is potentially dangerous as two CAS without communications can sacrifice the benefits obtained in safety and may even induce collisions, as we will see later in this chapter. In developing CAS, the essential requirement is that CAS on different vehicles can communicate each other. When a vehicle approaches an intersection, it should try to establish communications with the other engaging vehicle. If communications can be established, the first configuration is in place and collisions should be able to be avoided. If communications cannot be established, the vehicle assumes that it is that there is no CAS on the other vehicle and the second configuration is in place. The third configuration should never occur and auto developers should avoid this from occurring. One potential problem is that if the communication link is unstable and communication is lost, the CAS would assume it to be the second configuration while it is the third configuration. The problem in communication can therefore raise potential dangers. An algorithm based on the assumption of first configuration is proposed, and then an algorithm for the second configuration, which is built on top of the first algorithm, is proposed.

3.3.3 First Configuration: Both Vehicles Possess CAS and Communication Link Exist

As mentioned, the lag vehicle is designated as the subject vehicle in the first configuration, ensuring that $t_S \geq t_I$. After the CAS determined that $d_m^N < d_o$, it has to determine whether it has to intervene. Even though there is a projected collision such that $d_m^N < d_o$, the subject vehicle may still be very far away from the intersection and there could still be plenty of time for the driver to change its course. For instance if the driver is a thousand feet away and $d_m^N < d_o$, the alert is unnecessary and annoying if he plans to slow down the car to a stop at five hundred feet. In Fig 3.16, an alert is issued right away and the resulting risk metric is greater than the desired distance. The alert in

Fig 3.16 is issued too early. In order not to be too conservative, the CAS alerts at the point that the driver cannot maintains a safety separation ($d_m^A \geq d_o$) through an avoidance maneuver if it alerts later than this point.

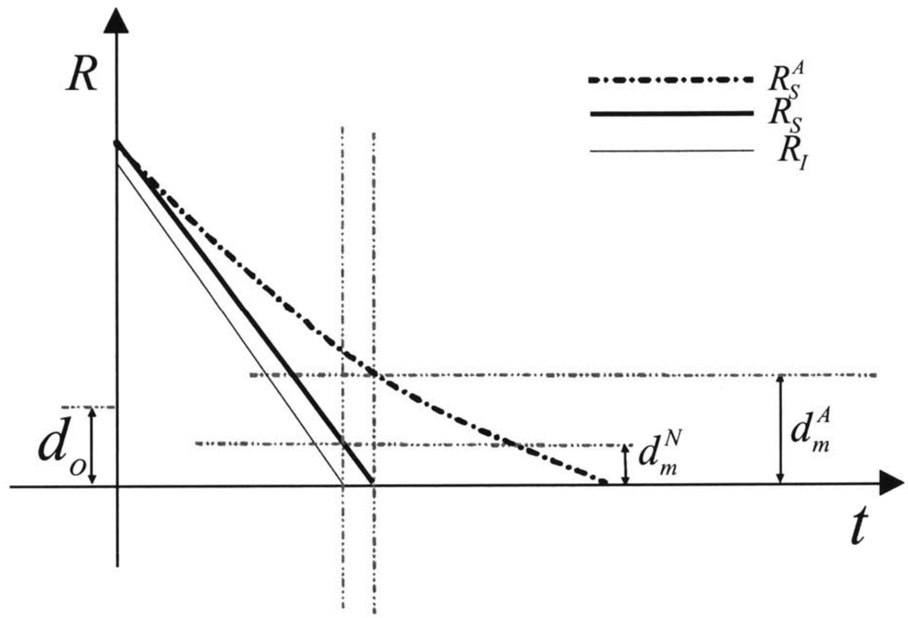


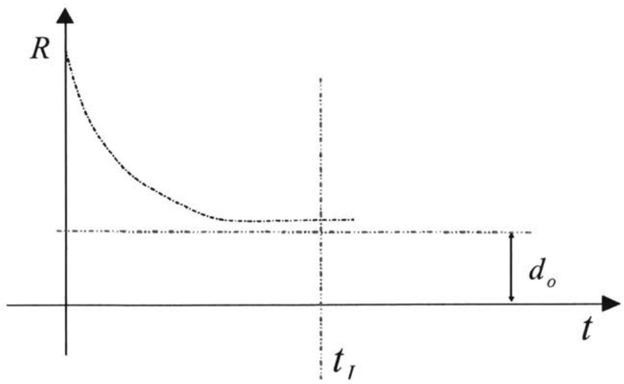
Fig.3.16 An alert issued too early

The philosophy of alerting is that alerts are given at the point that d_m^A is barely bigger than d_O. Therefore alerts are given whenever $d_m^A < d_o$. Due to uncertainties in human behavior, this choice of alerting philosophy cannot guarantee that everyone can achieve $d_m^A < d_o$. Therefore in choosing d_o, one has to make sure that there is a safety buffer included in the d_o. For example, if there is a crash when the separation between two vehicles is smaller than ten feet, then we can choose d_o to be 20 feet. The choice of d_o is not arbitrary, it should be chosen based on the knowledge of the uncertainties involved. An additional buffer due to the difference between d_m and $d_{\min}$ (see Fig. 3.2) should also be included. In later chapters we will explore the effect of the choice of d_o.

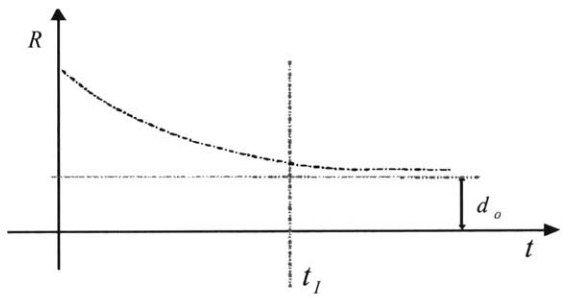
Six possibilities exist for the avoidance maneuver for the first configuration, as shown in Fig 3.17 (a) to (f). Only the avoidance maneuvers' *R-t* curves are shown in the diagram. The vertical dotted line indicating t_1, the horizontal dotted line indicating d_o, and the *t*-axis divide the *R-t* plane into six regions. The six possibilities for avoidance maneuver correspond to where in these six regions the minimum point of the avoidance maneuver *R-t* curve lies. The minimum point corresponds to the point in range and time, which the subject vehicle comes to a complete stop.

Fig 3.17 (a) shows the case where the subject vehicle is able to stop before the intruding vehicle enters the intersecting point, and its range from the intersecting point is greater than d_o when it is fully stopped. Fig 3.17 (b) shows the case where the subject vehicle is unable to stop before the intruding vehicle enters the intersecting point, but its range from the intersecting point is greater than d_o when it is fully stopped. Clearly it is safe for both vehicles if the subject vehicle stops at a distance greater than d_o, therefore these cases are safe cases and an alert is too early. The alerting algorithm decides that there will be no alerts if the expected range of the subject vehicle from the intersecting point is greater than d_o when the subject vehicle comes to full stop. With t_{stop} denoting the time when the subject vehicle comes to a full stop, then by (3.7), the range of subject vehicle at t_{stop} is given by:

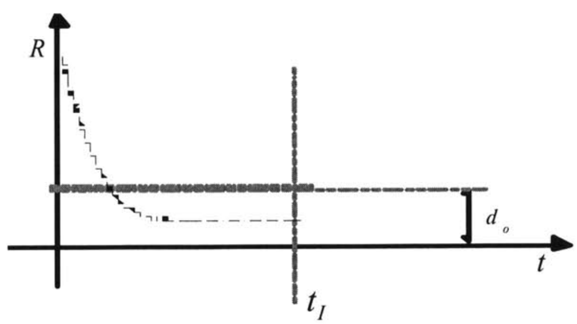
$$R_S^A(t_{stop}) = R_S(0) + \dot{R}_S \cdot t_{stop} + \frac{1}{2}\ddot{R}_S(t_{stop} - \tau)^2 \tag{3.8}$$



(a)

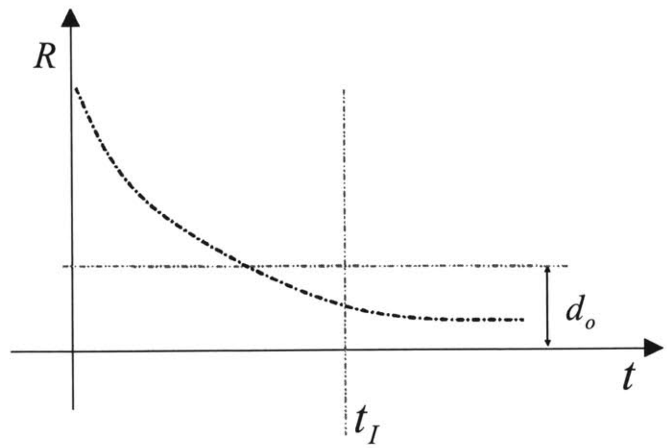


(b)

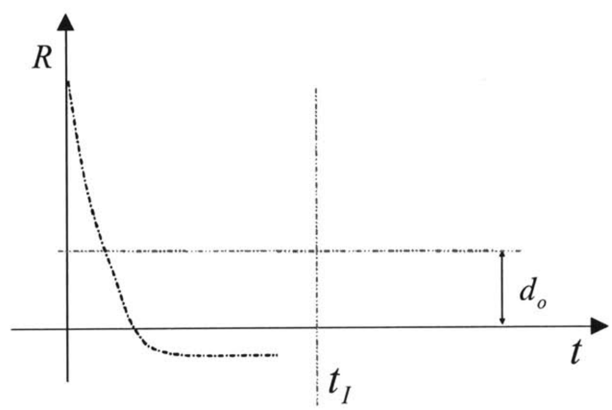


(c)

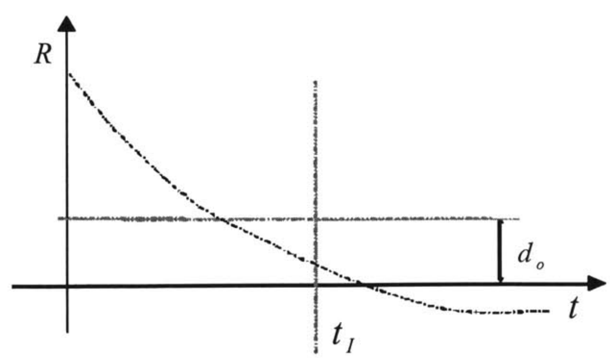
Fig 3.17



(d)



(e)



(f)

Fig. 3.17 Six possibilities for the avoidance maneuvers

Then there is no alert if (3.9) is satisfied:

$$R_S^A(t_{stop}) \geq d_O \tag{3.9}$$

t_{stop} is computed by (3.10), here a driver model with a reaction time delay followed by a step response input to the brake is assumed.

$$t_{stop} = \frac{-\dot{R}_S}{\ddot{R}_S} + \tau \tag{3.10}$$

Fig 3.17(c) indicates the case where the subject vehicle stops before the intruding vehicle enters the intersecting point, while its range from the intersecting point is positive but smaller than d_O. This means that the subject vehicle is able to stop before entering the intersecting point at a moment earlier than when the intruding vehicle enters, but the range is less than desired. In this case, an alert is issued. The reason is that if the subject vehicle stops and stays there, the avoidance risk metric d_m^A will be smaller than d_O when the intruding vehicle is at the intersecting point. If it accelerates and travels towards the intersecting point, the resulting d_m^A will be smaller than the d_m^A of staying at where it stops. This is because the *R-t* curve decreases as *t* increases if the vehicle travels towards the intersection. Travel backward is the only way that the resulting d_m^A will be improved, but this is unlikely. Even if the subject vehicle driver acknowledges the situation and is willing to take the backward maneuver, a potential rear-end collision with vehicle behind might be induced as the rear-end CAS is designed to be capable of handling the scenario that the preceding vehicle fully brakes suddenly only, not the case that the preceding vehicle moves backward. Therefore the algorithm issues an alert when it figures that it is the case as shown in Fig 3.17 (c), for which (3.11) and (3.12) is satisfied:

$$R_S^A(t_{stop}) < d_O \tag{3.11}$$

$$t_{stop} < t_I \tag{3.12}$$

where $R_S^A(t_{stop})$ is computed by (3.8), t_{stop} is computed by (3.10) and t_I is computed by (3.6).

Fig 3.17(d) corresponds to the case where the subject stops after the intruding vehicle enters the intersecting point. The subject vehicle is able to stop before entering the intersecting point, but at a range smaller than d_O. Fig 3.17(f) corresponds to the case where the subject stops after the intruding vehicle enters the intersecting point as well, but it is only able to stop after traveling through the intersecting point. In both cases, it is not important where the subject vehicle stops. Instead it is important to make sure that the subject vehicle's range is greater than d_O at the moment the intruding vehicle is at the intersecting point, that is t_I. In the diagrams of Fig 3.17(d) and (f), the ranges $R_S^A(t_I)$ are both smaller than d_O. This is not necessarily the case though. If $R_S^A(t_I)$ is greater than d_O, it means that it's still too early to give an alert, and it can afford to give an alert later. In simpler words, the CAS issues an alert at the very first moment when $R_S^A(t_I)$ is smaller than d_O. It is either case in Fig3.17 (d) or (f) if both (3.11) and (3.13) are satisfied:

$$t_{stop} \geq t_I \tag{3.13}$$

Then an alert is given when (3.14) is satisfied:

$$R_S^A(t_I) < d_O \tag{3.14}$$

where $R_S^A(t_I)$ is computed by (3.15)

$$R_S^A(t_I) = R_S(0) + \dot{R}_S \cdot t_I + \frac{1}{2}\ddot{R}_S(t_I - \tau)^2 \tag{3.15}$$

When the subject vehicle enters later, the case in Fig 3.17(e) never occurs. This is because a deceleration maneuver only delays the time when it enters the intersecting point. Therefore a deceleration maneuver makes the avoidance t_S bigger than the nominal one, while the nominal t_S is already greater than t_I. Fig 3.17(e) shows a case where the avoidance t_S smaller than t_I, therefore it never occurs.

This completes the discussion of the first configuration, namely both vehicles possess CAS, they communicate and assign the vehicle that enters later to be the subject vehicle. The algorithm is summarized in the flowchart shown in Fig. 3.18.

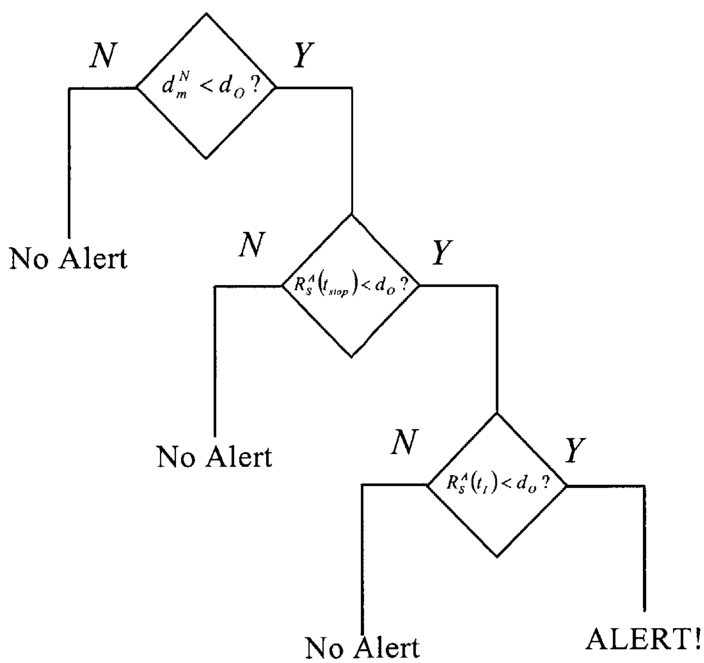


Fig 3.18 Flowchart for the algorithm of first configuration

3.3.4 Second Configuration: Only One of the Vehicles Possesses CAS

Now we turn to the second configuration that is where only one vehicle possesses CAS and is primarily responsible to avoid collisions. This vehicle is therefore designated as the subject vehicle. As mentioned earlier, the third configuration that the both vehicles possess CAS but do not communication each other should be avoided. Therefore when the subject vehicle successfully establishes communication with another vehicle, it is in the first configuration and the analysis given earlier follows. Otherwise if communication cannot be successfully established, it assumes that it is under the second configuration. Under the second configuration, the subject vehicle firstly tries to figure out whether it enters the intersection point before or after the intruder. By utilizing (3.5) and (3.6), if (3.16) is satisfied, the subject vehicle enters the intersection first:

$$t_S < t_I \tag{3.16}$$

Otherwise if (3.16) is not satisfied, the subject vehicle enters later. Notice that a constant velocity projection model is used. Indeed for the first configuration, the CAS on each vehicle uses (3.5) to compute its own time to enter intersection, and compare the corresponding result with the counterpart vehicle to decide which vehicle is the lag vehicle, and therefore the vehicle responsible to avoid the collision (subject vehicle). In the second configuration, if (3.16) is not satisfied and the subject vehicle enters the intersection later, it is then at the same setup as the first configuration. The analysis for the first configuration therefore can be used for the case that the subject vehicle enters the intersection later in the second configuration. But if the subject vehicle enters first, we have shown that it is potentially harmful to decelerate. We will analyze the case that the subject vehicle enters first in the second configuration as follows.

For the case that the subject vehicle enters the intersection first, we can identify three situations. These situations are shown in Fig 3.13, and Fig 3.19 (a) and (b). In contrast to the case that deceleration always makes d_m^A greater than d_m^N, deceleration can make a d_m^A smaller than d_m^N. Therefore in this case the algorithm doesn't just consider d_O only, it also takes the relative values of d_m^A and d_m^N into its consideration.

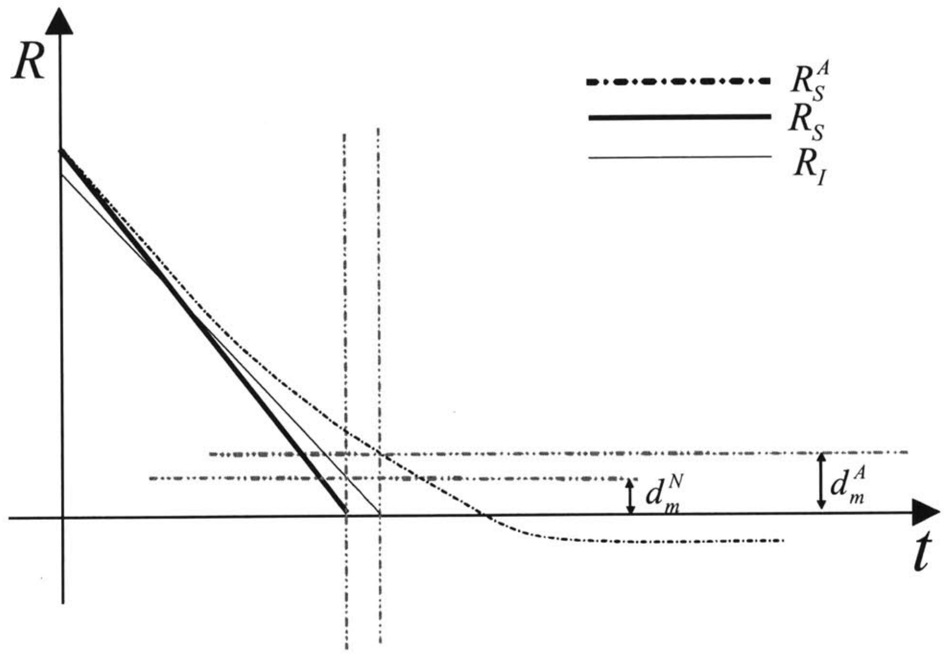
Look at Fig. 3.19 (a) and (b). Fig. 3.19 (b) shows the case where the subject vehicle is able to stop before entering the intersection point, while (a) shows the case where the subject vehicle is only able to stop itself after passing the intersection point. In (b) the R_S^A curve doesn't intersect with the t-axis, while the R_S^A curve in (a) does intersect with the t-axis. The equation for R_S^A is given by (3.7). There are no real roots for the equation (3.17) for the case in (b), while there are two real roots for equation (3.17) for the case in (a).

$$R_S(0) + \dot{R}_S\tau + \dot{R}_S(t-\tau) + \frac{1}{2}\ddot{R}_S(t-\tau)^2 = 0 \tag{3.17}$$

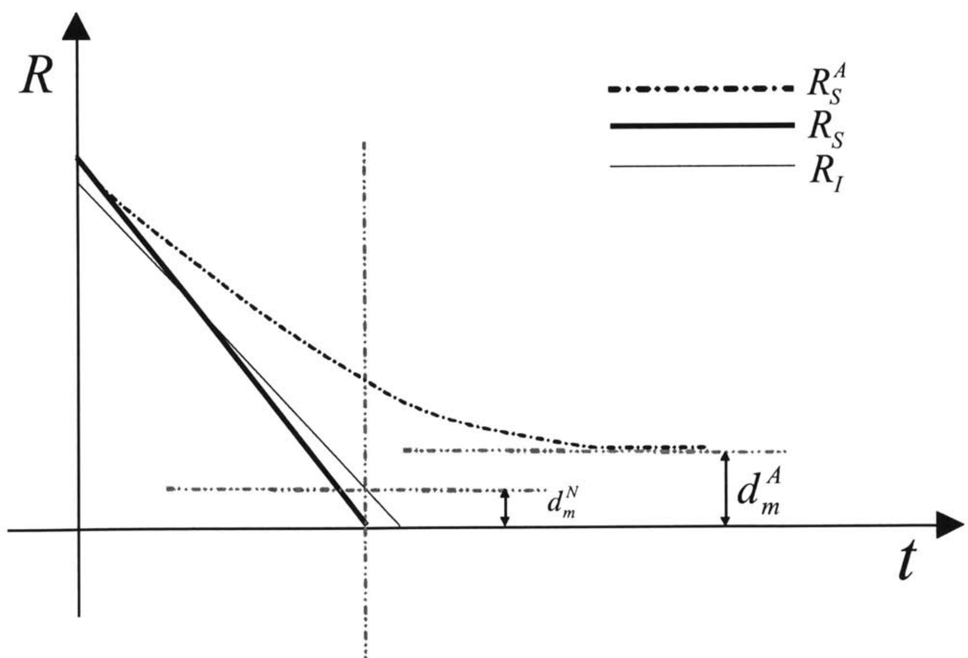
By a change of variable $t' = t - \tau$, it is case (a) if the quantity in (3.18) is greater than zero and case (b) if the quantity in (3.18) is smaller than zero.

$$\ddot{R}_S^2 - 2\ddot{R}_s\left(R_S(0) + \dot{R}_S\tau\right) \tag{3.18}$$

Notice that it corresponds to the case that the subject vehicle stops exactly at the intersection point if the quantity in (3.18) equals zero.



(a)



(b)

Fig 3.19 Avoidance maneuvers when **S** enters first

To begin with, there is no projected collision threat if d_m^N is greater than d_O. d_m^N is computed by (3.3) in this case. If there is a projected collision threat, the algorithm proceeds by computing (3.18) to decide whether it is case Fig. 3.19(a) or (b). If it is case (b), d_m^A is computed by (3.8) and (3.10). The reason to choose $R_S^A(t_{stop})$ instead of $R_S^A(t_I)$ to be the value of d_m^A is that if the subject vehicle able to stop before intruding vehicle pass intersection point, then $R_S^A(t_I)$ will be meaningless. By the same logic that the alerting system tries to avoid alerting too early, an alert is again only issued when d_m^A is smaller than d_O. One condition has to be added however. As d_m^A can be smaller than d_m^N when the subject vehicle enters first, an alert is given not only when d_m^A is smaller than d_O, but this d_m^A also has to greater than d_m^N. Otherwise if an alert is given when d_m^A is smaller than d_m^N, the driver will be worse off upon reacting to the alert. Fig 3.19(b) shows the case where d_m^A is greater than d_m^N, and an alert can be issued. But it can be easily visualized that d_m^A can also be smaller than d_m^N. One dilemma is raised under this condition. The algorithm doesn't issue an alert because an alert may increase the chance of collision, but there is a potential threat even there is no alert. The driver might be complacent with the alerting system and think that there is no danger based on the fact that there is no alert, while there is a potential collision threat. Indeed, when we think carefully, we can see that only an acceleration maneuver can save the situation under this condition. On the other hand braking can reduce collision energy. Therefore if unfortunately a collision occurred, braking can nonetheless mitigate the damage. Also it may be good to alert anyway just to let the driver know about the collision threat. We can divide the alerts into two groups of alerts, one is the braking alert, the other one could be just an awareness alert. Notice that this dilemma doesn't exist for the case when subject vehicle enters later (because d_m^A is always greater than d_m^N), which is the first configuration analyzed above.

If the quantity in (3.18) is greater than zero, then it is the case shown in Fig 3.19(a) which is the subject vehicle is only able to stop after passing the intersection point. Two situations can happen in this case. First is the subject vehicle decelerates aggressive enough so that it enters the intersection later than the intruding vehicle, as shown in Fig 3.19(a). Then d_m^A is computed as the risk metric between the two vehicles when the intruding vehicle is at the intersecting point. The other case is that the subject vehicle's deceleration is not aggressive enough, and the subject vehicle still enters the intersection first. Under this situation, the resulted d_m^A is computed as the risk metric between the two vehicles when the subject vehicle is at the intersection, and will be always smaller than d_m^N, as shown in Fig 3.13. Again an alert will therefore make it worse off for the case in Fig 3.13. Due to this reason, the alerting algorithm remains silent or just provides awareness of danger. The dilemma pointed out above shows up again in this case, but again there is nothing an alerting system can do here. The alerting system has to decide whether it is the case in Fig 3.19(a) or the case in Fig 3.13. As mentioned before, both of these cases possess two real roots for (3.17). From Fig 3.13 and Fig 3.19(a), it can be seen that t_S^A, the time for the subject vehicle to enter the intersection through the avoidance maneuver, equals the value of the smaller real root of (3.17). Therefore t_S^A is given by:

$$t_S^A = \frac{-\dot{R}_S^2 - \sqrt{\dot{R}_S^2 - 2\ddot{R}_S\left(D_S + \dot{R}_S\tau\right)}}{\ddot{R}_S} + \tau \tag{3.29}$$

If t_S^A is smaller than t_I, then it is the case in Fig 3.13 and the alerting algorithm remains silent to avoid making the situation worse. Otherwise if t_S^A is greater than t_I, it is the case in Fig 3.19(a) and the alerting algorithm proceeds to decide whether and when an alert should be given. In the case of Fig 3.19(a), as the intruding vehicle enters the intersection first due to the subject vehicle's avoidance maneuver, d_m^A can be computed as $R_S^A(t_I)$ through (3.15). If d_m^A is smaller than d_m^N, then this is a case that the situation is worse with the alerts, and so the alerting algorithm remains silent or provides a danger advisory. Otherwise if d_m^A is greater than d_m^N, it means that safety is improved with an alert and therefore an alert is acceptable. But to avoid giving the alerts too early, the alerting algorithm gives an alert at the moment d_m^A becomes smaller than d_O. In summary, the alerting algorithm can be summarized in the flowchart shown in Fig 3.20.

In Fig 3.20, 'No Alert' means that the algorithm figures that there is no need to give alert, as the collision threat is not imminent. By 'Advisory' it means that though there is an imminent danger, the algorithm chooses to provide a danger advisory rather than a brake command in order to avoid making the situation worse. $R_S^A(t_{stop})$ and $R_S^A(t_I)$ are the values of d_m^A under different conditions mentioned above. The values of t_S^A and t_I are computed according to its context as introduced earlier.

3.3.5 Third Configuration: Both Vehicles Possess CAS and Communication Link Does Not Exist

The third configuration is the one that both vehicles possess a CAS but the CAS do not communicate to each other. Imagine that both vehicles are running toward each other with constant velocity. Up to a certain point the CAS on each of the vehicle alerts the driver to

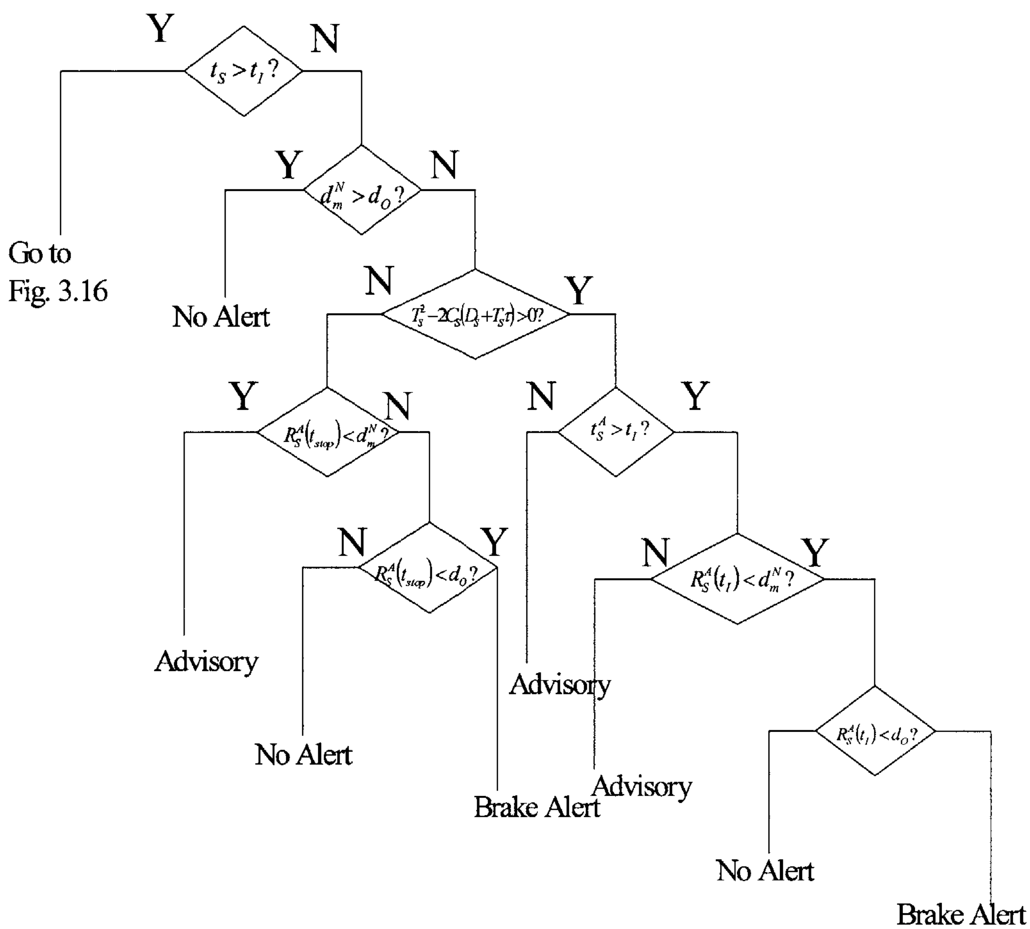


Fig.20 Flowchart for alerting algorithm in the second configuration

decelerate. If both drivers obey the alerts and decelerate, the vehicles will crash into each other while the driver thinks that he decelerates to avoid a collision. Therefore the utility gained in safety by CAS will be sacrificed if both vehicles carry out the avoidance maneuver. However this only happens at the last moment when the CAS decides to intervene with an alert. Before the CAS Intervenes, the driver can brake or even accelerate on his own will to change the situation. Therefore there is a period of exposure time in which the driver can avoid running into the crisis described above. In the next chapter we will investigate the relationship between braking distance and the velocity and range of the engaging vehicles. Braking distance is the distance where an alert is issued. The exposure time is then the time before the vehicle passes through the braking distance. One may argue that similar trouble may occur even in the first two configurations if the driver decides to brake on his own will and discard the alerting system. This is true. The moral here is that an alerting system is only a decision aid to help the driver. If the driver deliberately disregards the alerting system, there is nothing an alerting system can do. This problem occurs easier in the intersection collisions than in rear-end collisions, this is another reason why driver intent play a crucial role in the intersection collisions. Fig 3.21 shows a case where the vehicles still crash into each other with CAS as both vehicles decelerate. In the case that both approaching vehicles possess a CAS that works independently at the same time, it is meaningless to define which one is subject vehicle and which one is intruder vehicle. For the sake of convenience, we still designate one vehicle to be subject vehicle while the other one the intruder vehicle in Fig 3.21. In Fig. 3.21, R_S and R_I are the nominal range trajectory of the subject vehicle and the intruder respectively. R_S^A and R_I^A are the decelerating trajectory of the subject vehicle and the intruder upon receiving alerts respectively.

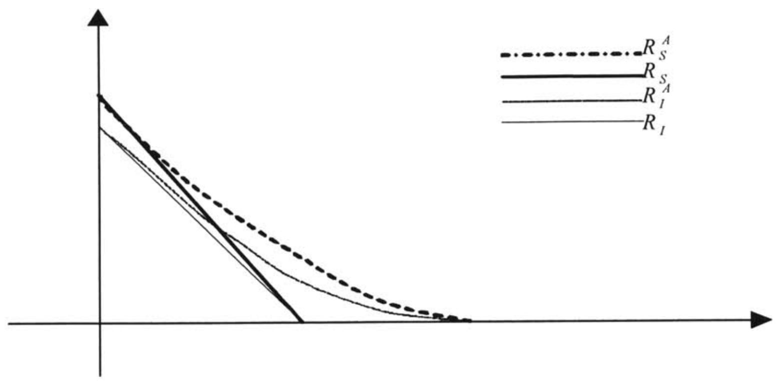


Fig 3.21 Vehicles crash into each other when both are quipped with CAS

3.4 Game Theory Point of View of ICAS

As pointed out a couple times, the rear-end CAS doesn't care what the preceding vehicle does as long if the worst-scenario criterion is used (Unless the preceding vehicle travels backward). While in the analysis given, it is evident that the design of an algorithm for intersection CAS largely depends on the interaction between the two engaging vehicles. In fact, the intent of the intruding vehicle affects the significance of the intersection CAS significantly. In light of this, we can look at the problem of intersection collision from a Game theoretic point of view.

Fig. 3.22 shows a *payoff matrix* for the approaching vehicles. A payoff matrix shows the payoff gained by each of the *players* involved in the *game* according to the action taken. The Intersection Collision problem is posed a two-player game, and the players are the subject vehicle and the intruder vehicle respectively. The payoff is defined

		Intruder vehicle		
		Accelerating	Constant	Decelerating
Subject Vehicle	Accelerating	0	1	2
	Constant	1	0	1
	Decelerating	2	1	0

Fig 3.22 Payoff matrix for intersection approaching vehicles

as the risk metric between the vehicles. The payoff increases as the risk metric increases. Assume that both vehicles are at the same initial distance from the intersection and possess same velocity. If both keep their velocity constant, they will crash into each other. The payoff value is assigned to be zero in this case. If one of them keeps its velocity constant and the other one decelerates, the collision can be avoided and the payoff value is assigned to be one. The risk metric is maximized when one of them accelerates while the other one decelerates and a payoff value of two results. From the payoff matrix, we can see that the third configuration suggested above corresponds to *(D, D)* (Subject vehicle decelerates, intruding vehicle decelerates). The third configuration should be avoided as a zero value is assigned to *(D, D)*. If the game can be posed as a cooperative game, namely the players coordinate to maximize their payoff, the either *(D, A)* and *(A, D)* should be chosen. In reality we don't see this happen because without a communication link, the problem can only be posed as a non-cooperative game. In a non-cooperative game, no matter what one player does, the payoff can still be zero, as he doesn't know what the other player would do. Even when an alerting system is in place, it still cannot be guaranteed that a payoff will be greater than zero. For example, a collision can occur if the intruding vehicle slows down when the subject vehicle driver slows down upon an alert. Later in this chapter, we will discuss why alerting system still works for most of time even it is a non-cooperative game.

If a coordinating autonomous system is in place, then either *(D, A)* or *(A, D)* will be chosen and the payoff is maximized. Indeed when there are more than two vehicles approaching the intersection, the payoff matrix will become much more complex. For instance, a three-dimensional payoff matrix is obtained when there are three vehicles approaching the intersection. In those multi vehicle cases, it is too complicated for an alerting system to figure out what are the appropriate alerts to be issued. While in reality, we often can navigate through an intersection with multiple vehicles easily. This can be explained by the fact that the degree of freedom a driver has is constrained by the existence of road structure and established driving procedures. These cues and structures also provide cues for our unconscious decision making process when driving through an intersection.

3.5 Effects of Deviated Intruder Vehicle Behavior

3.5.1 Intruding Vehicle Decelerates or Accelerates Before Alert is Issued

The alerting algorithm proposed assumes that the intruder vehicle approaches the intersection with constant velocity. It was claimed that there are no better assumptions without knowing the intent of the intruder vehicle driver. In this chapter we will investigate the effects if the intruder vehicle does not travel with constant velocity.

Here we assume that the lag vehicle is the subject vehicle, while the lead vehicle is the intruder vehicle (First configuration). Firstly we will look at the case that the intruder vehicle decelerates. Clearly if the intruder vehicle decelerates before t_{alert}, the time that alert is issued, the deceleration makes t_{alert} different from the t_{alert} corresponding to constant velocity. Consider Fig.3.23. At a certain time $(t = 0)$, the algorithm projects the velocity trajectory with the assumption that the intruder vehicle has constant velocity based on the sensor reading acquired at each time step. If the intruder vehicle is decelerating, value of velocity will be smaller at next time step $(t = \Delta t)$ when the sensor reading is acquired again. With the constant velocity projection, the algorithm projects the velocity with a smaller value at the next time step $(t = \Delta t)$. The absolute value of the slope of the *R-t* curve at $t = \Delta t$ is thus smaller than that of $t = 0$.

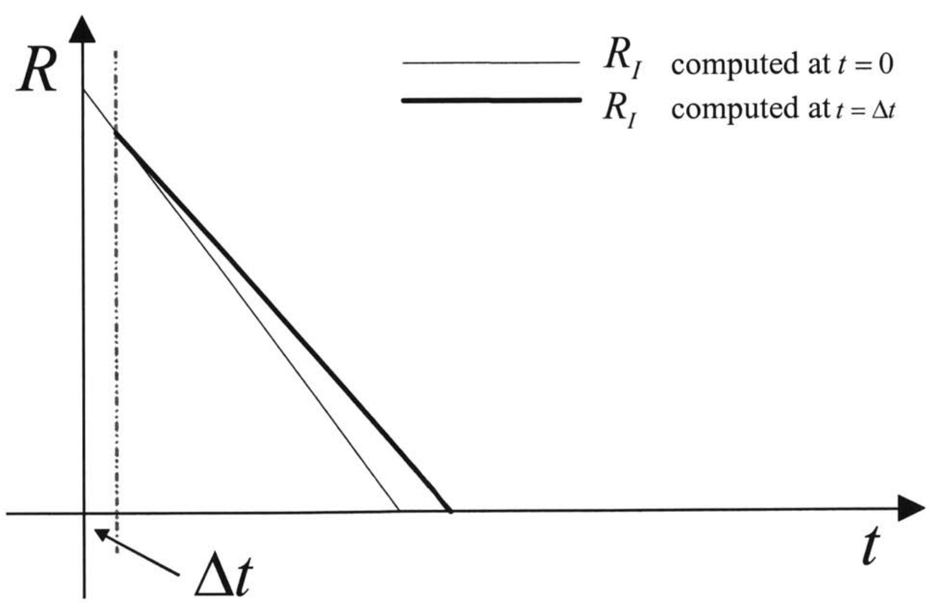


Fig 3.23 Trajectory projection at different time steps when **I** decelerates

The R-t curves for the intruder vehicle at both $t = 0$ and $t = \Delta t$ are shown in Fig 3.23 for the case that the intruding vehicle decelerates. Now we put these two R-t curves separately into Fig 3.24 and Fig 3.25. Imagine that the subject vehicle brakes immediately at each time step. The resulting d_m^A is then shown in Fig 3.24 and Fig 3.25 respectively.

The velocity projection based on sensor reading at $t = 0$ and the resulting d_m^A is shown in Fig 3.24. The velocity projection based on sensor reading at $t = \Delta t$ and the resulting d_m^A is shown in Fig 3.25. d_m^A in Fig.3.25 is smaller than that in Fig. 3.24. Recall that an alert is given at the time when d_m^A is smaller than d_O. Therefore the situation in Fig.3.25 is

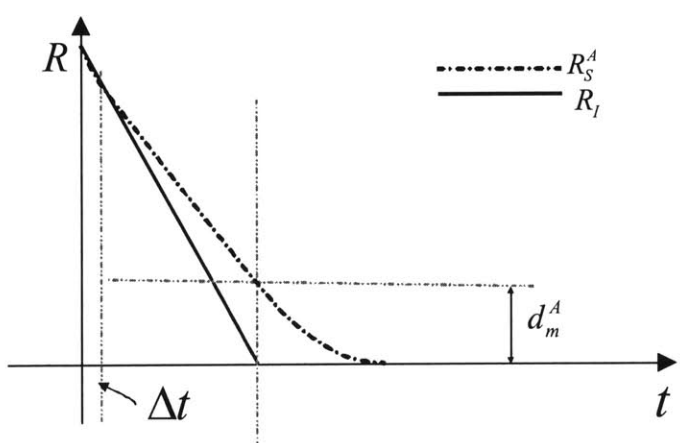


Fig 3.24 Trajectory projection based on sensor reading at $t = 0$

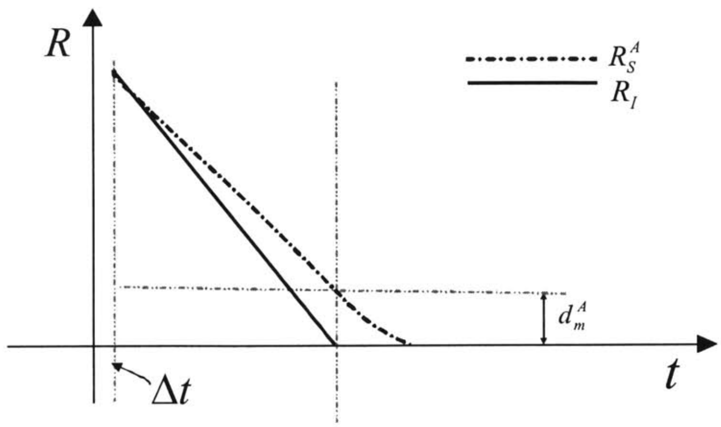


Fig 3.25 Trajectory projection based on sensor reading at $t = \Delta t$

closer to the point of alert is issued than that in Fig. 3.24. Therefore the expected alerting time t_{alert} is pushed earlier at $t = \Delta t$ than at $t = 0$. The moral here is that if the intruder vehicle decelerates instead of following constant velocity, the alerting time t_{alert} is pushed earlier.

3.5.2 Intruding Vehicle Decelerates or Accelerates After Alert is Issued

The analysis above illustrated how t_{alert} is affected if the intruding vehicle decelerates. Now we turn our attention to the affect on system performance when an alert is triggered (after t_{alert}). Again we assume that the lag vehicle is the subject vehicle, and the lead vehicle is the intruder vehicle. Here we consider a case where the intruding vehicle decelerates after the alert is triggered. d_m^A equals d_O if the intruding vehicle follows constant velocity after t_{alert} as assumed by the algorithm. Fig 3.26 illustrates the effect. The part of *R-t* curves for $t > t_{alert}$ of the avoidance maneuver of the subject vehicle, the trajectory for decelerating intruding vehicle, and the trajectory of the constant velocity-intruding vehicle are shown. d_m^A correspond to the decelerating intruding vehicle is smaller than the d_m^A correspond to the constant velocity intruding vehicle. In simpler words, safety is sacrificed if the intruding vehicle decelerates after the alert is triggered. Following analysis similar as above, it can be deduced that if the intruding vehicle accelerates instead of traveling at constant velocity, the t_{alert} will be pushed later. And once the alert is triggered, acceleration of the intruding vehicle increases the safety by increasing d_m^A. These analyses can be applied to more complicated velocity trajectory. For example, the intruding vehicle can first decelerate to push t_{alert} earlier, and then accelerates to push t_{alert} later. Or the intruding vehicle can decelerate to push t_{alert} earlier, and once the alert is triggered, it can accelerate to increase the safety.

If the subject vehicle enters first, it is generally good if the intruder decelerates. However this is not always the case. It is because if the subject vehicle is alerted by the CAS to decelerate (this could happen if subject vehicle enters first), then the benefit in safety by the intruder's deceleration is compensated by the subject vehicle's deceleration.

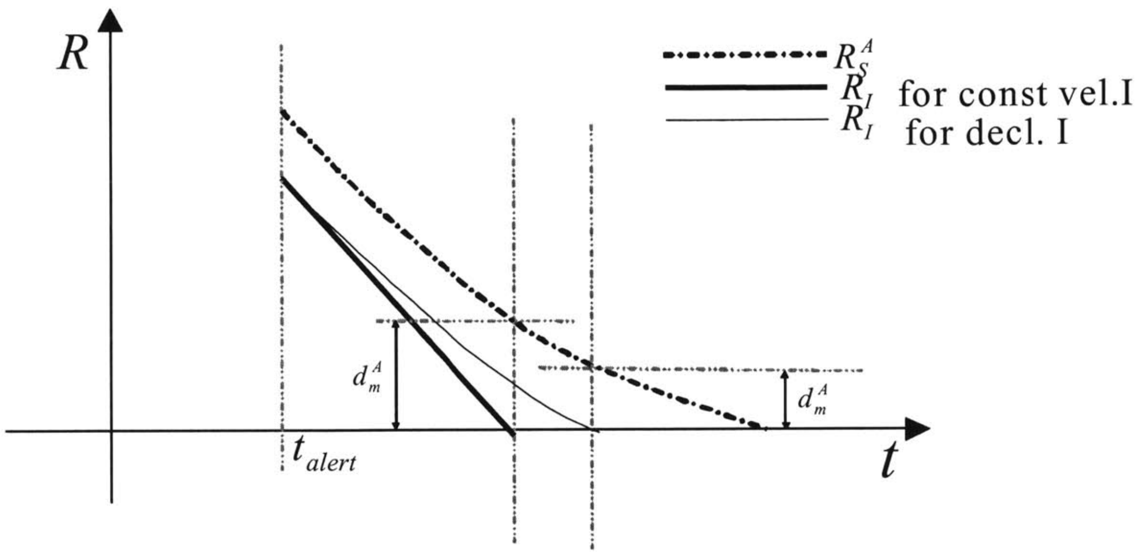


Fig. 3.26 Effect of **I** decelerates after alert is triggered

3.6 Left Turn Advisory (LTA)

3.6.1. Theoretical LTA

Because collisions that occur when vehicles turning into an intersection contribute to a significant portion of all intersection collisions, a complete ICAS should be able to avoid collisions when vehicles are turning. On top of the ICAS mentioned earlier in this chapter, a Left Turn Advisory (LTA) module is used to provide assistance in avoiding collisions when one of the vehicles is making a left turn. The LTA is an advisory system instead of an alerting system, as it works by advising the driver when it is appropriate to turn rather than issuing an alert to notify the driver to brake.

The vehicle passing straight through an intersection possesses the right of way, so the responsibility to avoid a collision is put on the vehicle that makes a left turn. Therefore the vehicle that makes a left turn is designated as the subject vehicle, on which the LTA works. See Fig. 3.27

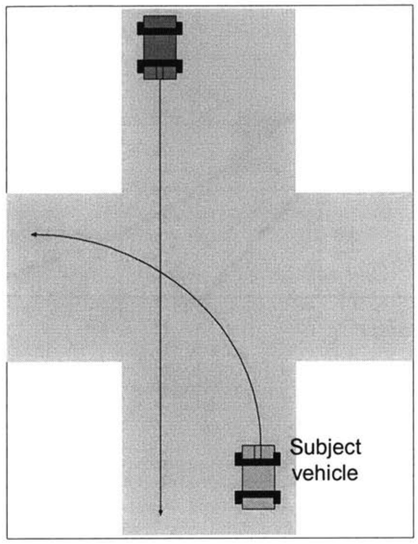


Fig. 3.27 The left turning vehicle is designated as the subject vehicle

If the intersection is divided into four quadrants, then in most cases collisions happen in the second quadrant, as shown in Fig. 3.28.

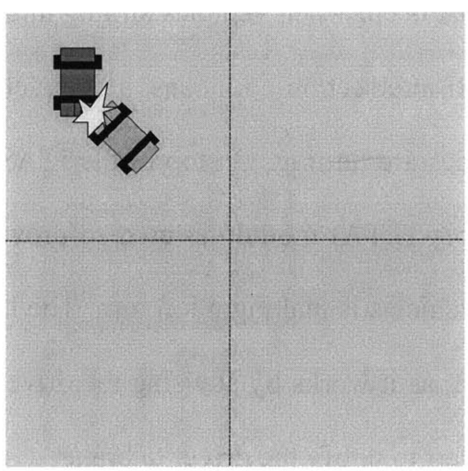


Fig. 3.28 Collisions happen in the second quadrant

When a vehicle is about to make a left turn, driver would wait and see if there is enough time for him to pass the intersection before the vehicle on the opposite side comes into the intersection. Collisions may occur when he judges that the gap is big enough while it isn't. The LTA works by advising the driver when it is appropriate to make the left turn. If the LTA determines that it is unsafe to turn, the driver would see a red color box on the display. Otherwise if the LTA determines that it's safe to make the left turn, the driver would see a green color box on the display.

The LTA algorithm works by making sure that the subject vehicle and the intruder vehicle do not stay in the second quadrant at the same time.

Let the distance between the intruding vehicle and the boundary of the second quadrant to be D_I, its velocity to be V_I, then the time t_I need for it to enter the second quadrant is simply:

$$t_I = \frac{D_I}{V_I} \tag{3.30}$$

We assume that when the subject vehicle makes a left turn, it goes along a circular path with constant velocity. This is shown in Fig. 3.29. Also assumed is that the subject vehicle is at the center of its lane before it starts the left turn. A cylindrical coordinate system is used in Fig. 3.29, with the lower left corner of the intersection being designated as the origin. A two-lane road is assumed in Fig. 3.19. w is the width of the road, as the vehicle stays at the center of its lane before the left turn, the r value when it goes through the circular arc is $\frac{3}{2}w$.

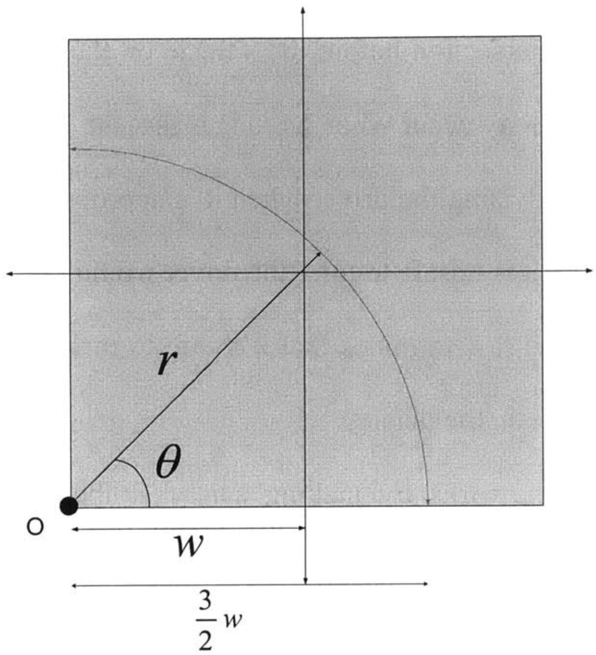


Fig. 3.29 coordinate system for LTA

Let the linear constant velocity of the subject vehicle be V_S, then its corresponding angular velocity through the circular arc is:

$$\dot{\theta} = \frac{V_S}{r} = \frac{2V_S}{3w} \tag{3.31}$$

Let t_S to be time for the subject vehicle between enter and leave the intersection, then t_S is computed as:

$$t_S = \frac{3w\pi}{4V_S} \tag{3.32}$$

Then if $t_S < t_I$, that is the subject vehicle passes the intersection before the intruder vehicle enters the second quadrant of the intersection, and the LTA determines that it is safe to make the left turn and displays a green box.

3.6.2. LTA as Implemented on a Driving Simulator

As will be mentioned in chapter 5, the ICAS and LTA algorithms were implemented on a driving simulator. During the initial testing phase of the algorithms, some subjects claimed that it was very hard to make a left turn in the driving simulation, because the driving simulation cannot accurately reflect real driving during the left turn maneuvers. In particular it was very hard to travel through a circular arc when they make the left turn. Therefore when implemented on the driving simulator, instead of computing t_S with (3.32), t_S was approximated by (3.33), where b is a safety buffer for the approximation:

$$t_S = \frac{3w}{2V_S} + b \tag{3.33}$$

Chapter 4 Numerical Analysis of ICAS

4.1Numerical Simulations

The algorithm of ICAS was introduced in chapter 3. Unlike rear-end collisions, the point at which an alert is issued is largely dependent on the relative positions and velocities of the engaging vehicles, that is their interactions. Therefore it is not appropriate to define what the prescribed braking distance or braking time of an ICAS is. Even for the same velocity and position, braking distance may be different from time to time as the braking distance is dependent on the intruder vehicle as well. As explained in Chapter 3, sometimes an alert can potentially worsen the safety and it may not be appropriate to issue an alert. In this chapter, simulations were performed for an example scenario, so as to give the readers a feeling of whether an alert should be issued, and what braking distances are appropriate.

In the simulation, we use d_o equals 5 feet. We assume that both the subject vehicle and the intruder vehicle travel toward the intersection with constant velocity. The parameters of the intruder vehicle are fixed, that is the intruder vehicle possesses the same initial position $R_I(0)$ and same velocity $\dot{R}_I$ is each simulation. The initial position $R_S(0)$ and velocity $\dot{R}_S$ of the subject vehicle is varied, so we can obtain the information of how the ICAS perform with respect to changes in the subject vehicle's position and velocity, while the position and velocity of the intruder vehicle is unchanged. The subject vehicle started to brake with deceleration rate $-\ddot{R}_S$ of 6.897 $ft/\sec^2$ after a reaction time τ of 1.5 sec. $\dot{R}_I$ was set to be 22 feet/sec, R_I was set to be 100 feet. $R_S(0)$ was varied from 90 to 110 feet, and $\dot{R}_S$ was varied from 17 to 27 feet/sec. Based on the ICAS algorithm in Chapter 3, four regions can be identified on the $R_S(0)$ - $\dot{R}_S$ plane, as shown in Fig. 4.1.

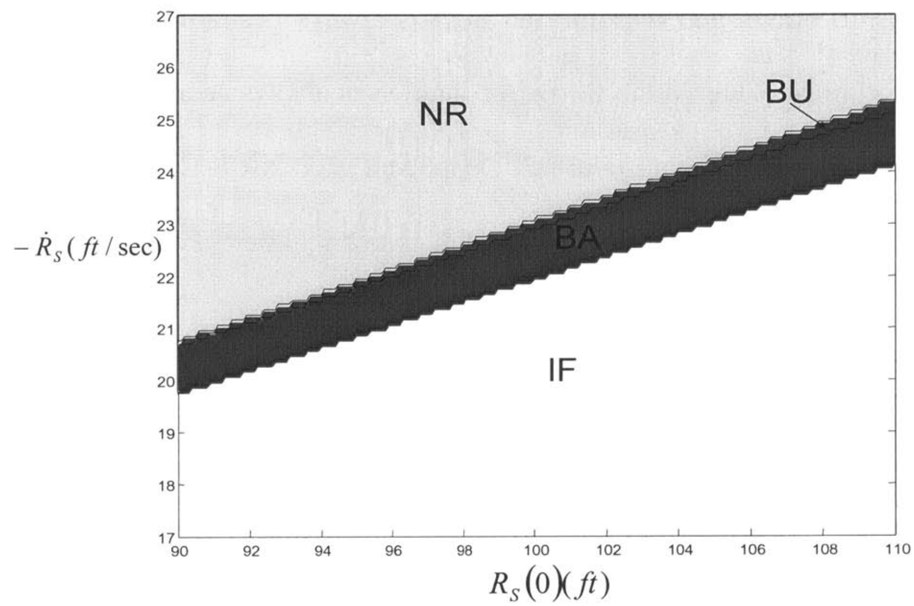


Fig. 4.1 Four regions on the $R_S(0)$ - $\dot{R}_S$ plane

We can see that the $R_S(0)$ - $\dot{R}_S$ plane is divided roughly into four regions. The boundaries between different regions are in a zigzag shape. This is because the simulations were carried out on finite discrete points of the $R_S(0)$ - $\dot{R}_S$ plane. Nonetheless, Fig. 4.1 should provide a picture of how the $R_S(0)$ - $\dot{R}_S$ plane is divided into four regions. The four regions are labeled as IF, NR, BA, and BU. NR stands for "Not Required", BU stands for "Braking Unacceptable", BA stands for "Braking acceptable", and IF "stands for "Intruder enters First". In chapter 3 we explained the effect on ICAS of the order of which vehicle enters the intersection first, Fig. 4.1 strives to illustrate this effect. In Fig.

4.1, the intruder vehicle entered first in the IF region, and the intruder vehicle entered later than the subject vehicle in the NR, BA, and BU regions. This makes sense as for certain $R_S(0)$, a higher $\dot{R}_S$ made the subject vehicle entered first, that is the intruder vehicle entered later. In chapter 3, we said that when the intruder vehicle enters first, it is always beneficial to brake, and therefore an alert is always desirable when there is a potential collision threat. Thus in the IF region, an alert is always acceptable. Out of the IF region is the region where the intruder vehicle entered later. NR is the region that there was no projected collision and therefore and alert is not required. For certain $R_S(0)$, a very high $\dot{R}_S$ means that the subject vehicle passed the intersection much earlier than the intruder vehicle, therefore the NR region is on the upper part of the $R_S(0)$-$\dot{R}_S$ plane. Between the IF region and the NR region is the region where the intruder vehicle entered later, and there was a projected collision threat. Based on the ICAS algorithm in Chapter 3, this region can be further broken down into the BA region, where braking and alert are acceptable, and the BU region, where braking and alert are unacceptable. For certain $R_S(0)$, a lower velocity means that the subject vehicle is more likely to enter the intersection later through braking (therefore a possible lower risk metric). Therefore a lower velocity of certain $R_S(0)$ made it more likely to be in the BA region.

Within the IF region, it is always acceptable to brake. We will proceed to look at the IF region to see within the IF region, where in the $R_S(0)$-$\dot{R}_S$ plane would an alert be issued. And if an alert is to be issued, what is the braking distance. Braking distance is defined to be the distance between the subject vehicle and the intersecting point when the alert was issued. Fig 4.2 shows a plot of braking distances against the $R_S(0)$-$\dot{R}_S$ plane place. The vertical axis corresponds to the braking distances. A value of -10 was assigned to the region outside IF. The negative value means that this is not the region we are interested at.

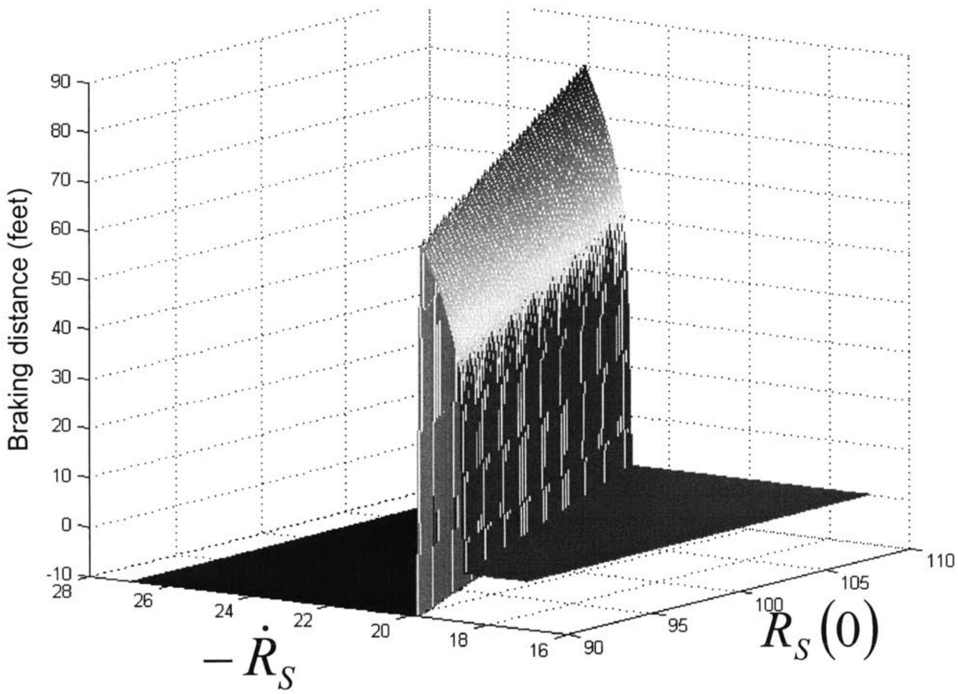


Fig. 4.2 Braking distances against the $R_S(0)$-$\dot{R}_S$ plane

The value zero is assigned to the region within the IF region that no alert was issued as there were no projected collisions, and therefore braking distance is not well defined. For certain $R_S(0)$, higher velocity resulted projected collisions, and therefore the value of braking distance become positive. The braking distance increases as $\dot{R}_S$ increases, because the driver can afford to brake later with a smaller velocity. Now look at Fig 4.3, in which the braking distances were computed with the reaction time τ set to zero. It can be seen that the magnitude of the braking distances in Fig. 4.3 are smaller than that in Fig 4.2. In Fig. 4.2 the maximum braking distance attained was around 80 feet, while the maximum braking distance attained in Fig. 4.3 is smaller than 50 feet. We conclude that when there is a projected collision, the braking distance is higher with higher velocity, and also the braking distance is higher with a larger reaction time.

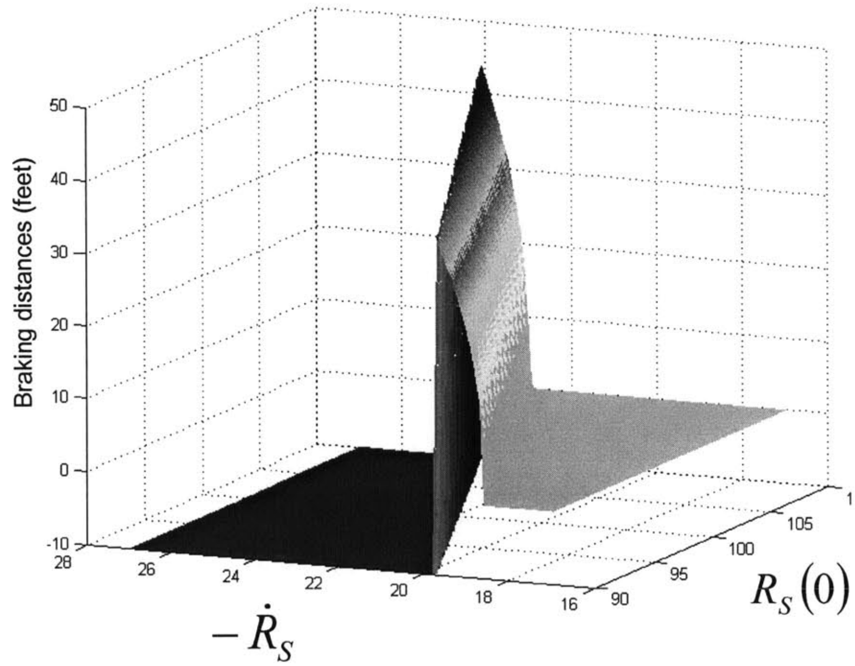


Fig. 4.3 Braking distances against the $R_S(0)$ - $\dot{R}_S$ plane with zero τ

Consider Fig 4.1 again. NR is the region where an alert is not required as there is no projected collision ($d_m^N \geq d_o$). We would like to know what happens if the driver decides to brake based on his own judgment even when there is no alert. Though there is also a sub-region inside IF where an alert is not required, but we won't study this region further as braking is always acceptable within the IF region. However in the NR region, braking may worsen the safety as by definition the subject vehicle enters the intersection first within the NR region. In the study that follows, we assume that when the driver decides to brake based on his judgment, he brakes at the same braking rate as when he responds to an alert. In the NR region, if the driver trusts the CAS and does nothing, then the time before the subject vehicle enters the intersection is:

$$t_S^N = \frac{R_S(0)}{-\dot{R}_S} \tag{4.1}$$

But if the driver decides to brake albeit the fact that there is no alert, then the time before the subject vehicle enters the intersection is:

$$t_S^A = \frac{-\dot{R}_S - \sqrt{\dot{R}_S^2 - 2\ddot{R}_S R_S(0)}}{\ddot{R}_S} \tag{4.2}$$

Note that in the definition of (4.2), the reaction time τ is set to be zero. This makes sense because in this case the driver decides to brake on his own decision, which is not a reaction to an external source.

From (4.2), if $t_S^A \prec t_I$, then it means that the subject vehicle still enters the intersection first, and the risk metric can be computed by (4.3):

$$d_m^A = R_I(0) + \dot{R}_I t_S^A \tag{4.3}$$

Otherwise if $t_S^A \geq t_I$, then it means that the subject vehicle enters later through braking, and the risk metric is then computed by (4.4):

$$d_m^A = R_S(0) + \dot{R}_S t_I + \frac{1}{2}\ddot{R}_S t_I^2 \tag{4.4}$$

By definition $d_m^N \geq d_o$ in the NR region, therefore the braking would make the safety worse if the d_m^A computed is smaller than d_o. We can then proceed by dividing the NR region in Fig. 4.1 into 4 smaller regions.

The BU and BA regions are grouped into one region in Fig. 4.4, labeled as PC. PC stands for "Projected Collision", in which there are projected collisions.

The 4 smaller sub-regions in the NR region are labeled as 1, 2, 3, and 4 in Fig. 4.4

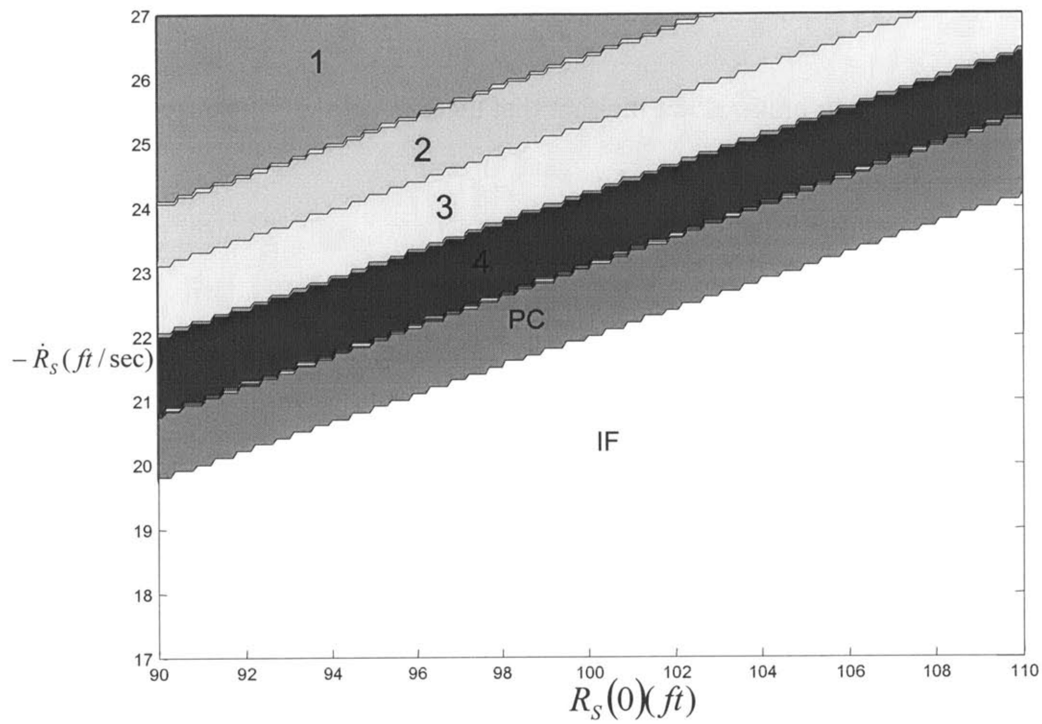


Fig. 4.4 The NR region is divided into four sub-regions

The four sub-regions are:

1. Region 1 is the region where the subject vehicle still enters the intersection first through braking, because of its high velocity. Due to its high velocity, the risk metric resulted is still larger than d_o even though the driver brakes. Therefore it is safe to brake within this region.

2. Region 2 is the region immediately lower than region 1. The subject vehicle is fast enough to enter the intersection first after the driver brakes, but not fast enough to ensure a risk metric larger than d_o. Therefore it is unsafe to brake within this region.

3. Region 3 is the region next to region 2. As its velocity is lower than that of region 2, the subject vehicle enters the intersection later than the intruder vehicle through braking. But as it just barely enters the intersection later than the intruder vehicle, the risk metric would be smaller than d_o. Therefore it is unsafe to brake within this region.
4. Region 4 corresponds to the region with even smaller velocity than that of region 3. So not only does the subject vehicle enter the intersection later than the intruder vehicle in this region, the subject vehicle was slow enough to enter with a risk metric larger than d_o.

Within the NR region, we can identify region 2 and 3 (the central strip within NR) as the regions that are unsafe to brake. If there is no projected collision and thus an alert is not issued, the driver can cause a collision if he is inside region 2 or region 3 and he decides to brake.

Considering Fig. 4.1 again, we would like to know if there is a projected collision, what determines whether it is acceptable to brake (BA) or whether it is unacceptable to brake (BU). In Fig.4.1, the BU region is far smaller than the BA region. We kept everything fixed, except that brake rate is changed from 6.897 $ft/\sec^2$ to 3 $ft/\sec^2$. The resulting $R_S(0)$-$\dot{R}_S$ plane is shown in Fig.4.5. In Fig. 4.5, the BU region is much bigger than that in Fig. 4.1 This is reasonable because with high a braking rate, and therefore higher maneuverability, the vehicle should be more likely to avoid a collision through braking. It is reasonable to predict that the reaction time τ also plays a role in determining whether braking is acceptable or unacceptable when there is a projected collision.

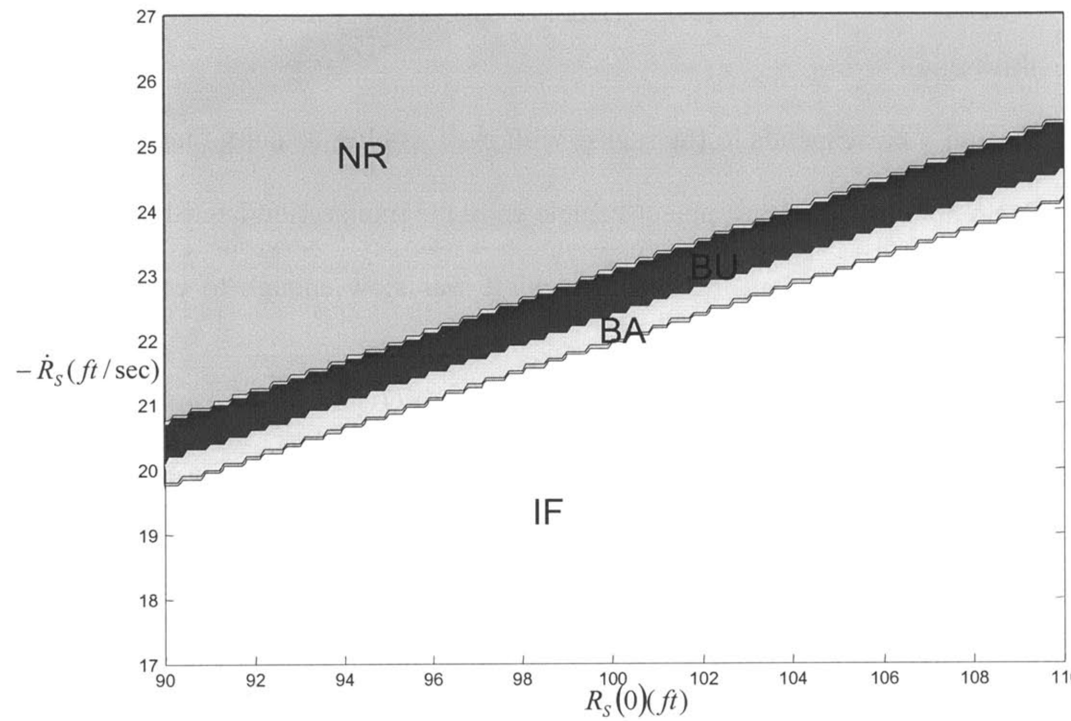


Fig. 4.5 $R_S(0)$ - $\dot{R}_S$ plane with $\ddot{R}_S$ equals 3 $ft/\sec^2$

We performed a series of simulations with projected collisions, by setting d_o equal to 5 feet, $R_I(0)$ equal to 100 feet, $-\dot{R}_I$ equal to 22 $ft/\sec$, $R_S(0)$ equal to 100 feet, and $-\dot{R}_S$ equal to 23 $ft/\sec$. Note that as the subject vehicle possesses a higher velocity, it enters the intersection first and therefore it is out of the IF region. Then we varied the reaction time τ from 0 to 2 seconds, and varied the braking rate $-\ddot{R}_S$ from 0 to 7 $ft/\sec^2$. The resulting $-\ddot{R}_S$ - τ is shown in Fig. 4.6, which the plane divided into two regions. One is the BA region, in which braking is acceptable, and the other is the BU region, in which braking is unacceptable. Fig. 4.6 shows that for certain braking rate, a smaller reaction time makes it more acceptable to brake. For certain reaction times, a higher braking rate makes it more acceptable to brake. This is reasonable because a higher braking rate and smaller reaction time is equivalent to higher maneuverability.

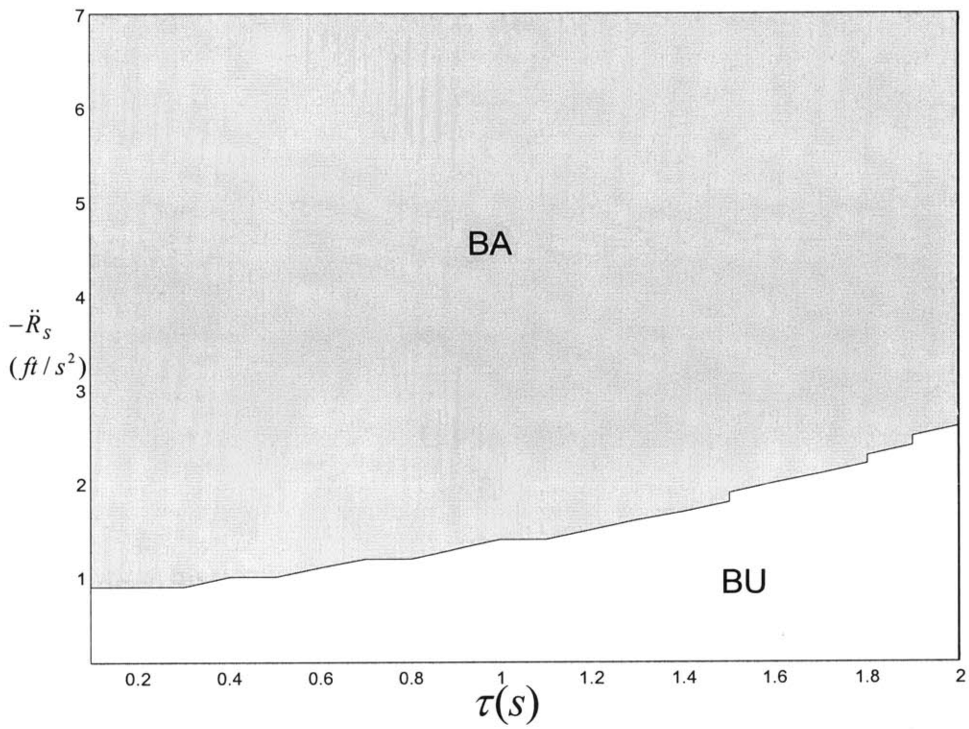


Fig. 4.6 The BU and BA region on the $-\ddot{R}_S$- τ plane.

The BU region can be further divided into two regions as there are possible factors that make braking unacceptable. One is that the subject vehicle still enters the intersection through the braking. The other one is that though the subject vehicle enters the intersection later through braking, it just barely enters later than the intruder vehicle, and therefore no benefit is obtained ($d_m^A < d_m^N$). Indeed factor one also makes $d_m^A < d_m^N$. Fig. 4.7 shows a plot where the BU region is further divided into BU-ef, in which factor one makes it unacceptable to brake, and BU-nb, in which factor two makes it unacceptable to brake.

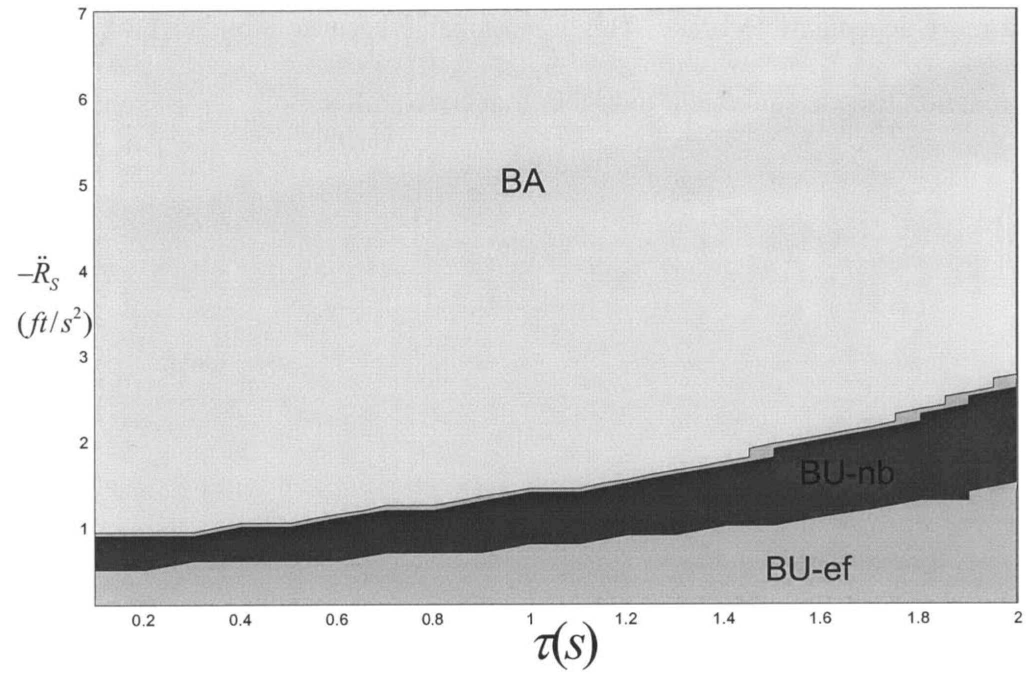


Fig. 4.7 The BU region is further divided into BU-ef and BU-nb

4.2 Performance Based Simulations

According to the discussion of the performance based approach to rear-end CAS in chapter 2, it seems to be natural to perform Monte Carlo simulations to determine the system parameters in the ICAS, such as the size of d_o. Or at least we should obtain the SOC curve of the ICAS to evaluate the system performance. However we determined not to do this as we don't have an accurate trajectory model. The intersection collisions involve much more complicated encounter scenarios and interplays between the engaging vehicles, and it is therefore harder to obtain a trajectory model for intersection collisions. Also based on our human-in-the-loop experiments as will be given in chapter 5, we didn't observe any recognizable probability distributions in the drivers' performance due to the small number of subjects. We will leave this to future experiments in which a large number of subjects are used to determine the drivers' performance distribution and hence the trajectory model. With that piece of information, we can combine the performance-based approach with the ICAS algorithm proposed in chapter 3.

4.3 Necessity of GPS Sensing

In the derivation of ICAS, we have assumed that we have the state information of both of the engaging vehicles, such as their positions and their velocities, and also the position and configuration of the intersection. Fig 4.8 shows the state information required in the ICAS. D_I is the distance between the intruder vehicle and the intersecting point, V_I is the intruder vehicle's speed. D_S is the distance between the subject vehicle and the intersecting point, and V_S is the subject vehicle's speed. These quantities are all positive scalar. The information required can be easily obtained with GPS sensing and an internal map database. We argue in this chapter that this information is necessary as a radar-based system is inadequate.

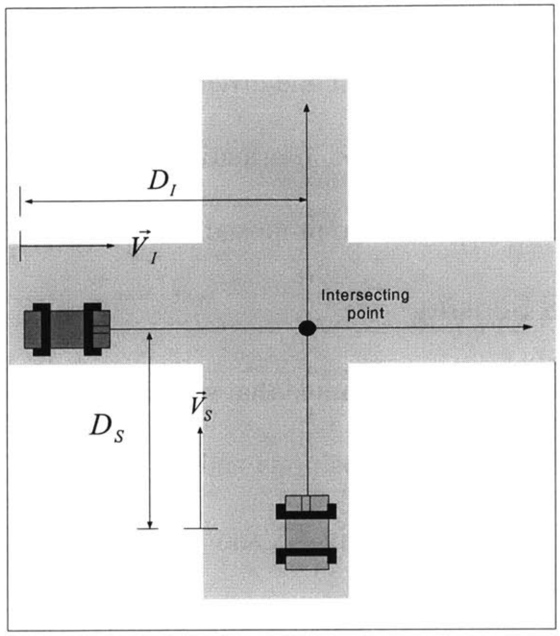


Fig. 4.8 Information required by the ICAS algorithm

Now suppose we have just a radar-based system, then the only information we can obtain by the radar is the range and range rate between the two vehicles.

The range r is defined by:

$$r = \sqrt{D_S^2 + D_I^2} \tag{4.5}$$

The range rate is obtained by taking partial derivative of r:

$$\dot{r} = \frac{\partial r}{\partial D_S}\frac{\partial D_S}{\partial t} + \frac{\partial r}{\partial D_I}\frac{\partial D_I}{\partial t}$$

$$= \frac{D_S V_S + D_I V_I}{r} \tag{4.6}$$

By assuming a Cartesian coordinate, the vector forms of the velocities of the subject vehicle and the intruder vehicle are written as:

$$\vec{V}_S = V_S \vec{j} \tag{4.7}$$

$$\vec{V}_I = V_I \vec{i} \tag{4.8}$$

Then we use a relative coordinate frame with the origin fixed on the subject vehicle, the relative position and the relative velocity of the intruder vehicle with respect to the subject vehicle are written as:

$$\vec{V}_r = \vec{V}_I - \vec{V}_S = V_I\vec{i} - V_S\vec{j} \tag{4.9}$$

$$\vec{D}_r = \vec{D}_I - \vec{D}_S = -D_I\vec{i} + D_S\vec{j} \tag{4.10}$$

The dot product of the relative velocity $\vec{V}_r$ and relative position $\vec{D}_r$ is:

$$\vec{V}_r \cdot \vec{D}_r = -(D_I V_I + D_S V_S) \tag{4.11}$$

With only the information of range and range rate provided by the radar, a natural choice of alerting criteria metric is the time-to-collision τ :

$$\tau = \frac{r}{\dot{r}} \tag{4.12}$$

By using (4.6) and (4.11), the time-to-collision τ is written as:

$$\tau = -\frac{r^2}{V_r \cdot D_r} \tag{4.12}$$

When there is no projected collision, the relative position vector and the relative velocity vector are perpendicular to each other at the point of closest miss (PCM), as shown in Fig. 4.9.

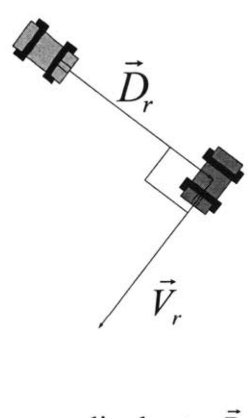


Fig. 4.9 $\vec{V}_r$ perpendicular to $\vec{D}_r$ at PCM

Therefore when there is no projected collision, the dot product $\vec{V}_r \cdot \vec{D}_r$ becomes zero at PCM and hence the time-to-collision τ approaches infinity at PCM. When there is projected collision, r is simply zero at PCM. As there is an r^2 term in the numerator of τ to balance the effect of $\vec{V}_r \cdot \vec{D}_r$ in the denominator, τ goes to zero instead of infinity at the PCM.

Four simulation scenarios were performed to see how τ varies.

Scenario 1: Subject vehicle travels towards the intersecting point, while the intruder vehicle stay stopped behind the stop line. (5 feet from the intersecting point) See Fig. 4.10.

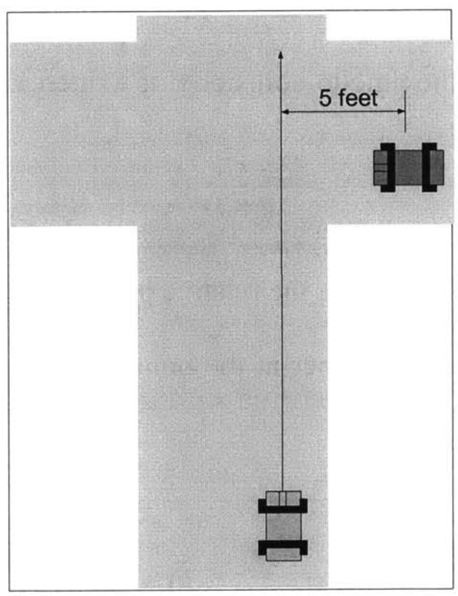


Fig. 4.10 Scenario 1

The subject vehicle was initially 200 feet away from the intersecting point. A plot of τ against how far the subject vehicle has traveled, d, is shown in Fig. 4.11.

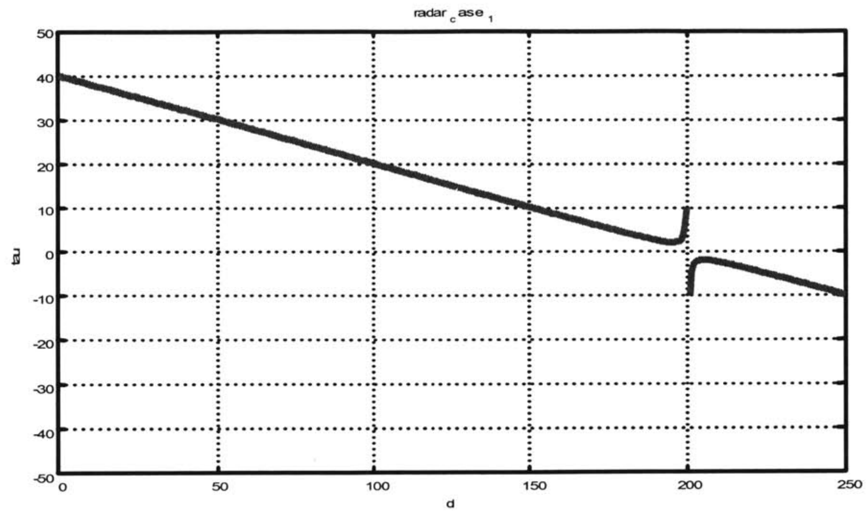


Fig. 4.11 τ against distance traveled by subject vehicle for scenario 1

As there is no projected collision, the PCM is at the point where the subject vehicle traveled 200 feet, and τ approaches infinity at d equals 200 feet. Note that the portion of the curve just right before d attains 200 feet has positive second derivative.

Scenario 2: The intruder vehicle stays stopped at the intersection point and the subject vehicle travels toward the interesting point. Again the subject vehicle was initially 200 feet away from the intersection point. See Fig. 4.12

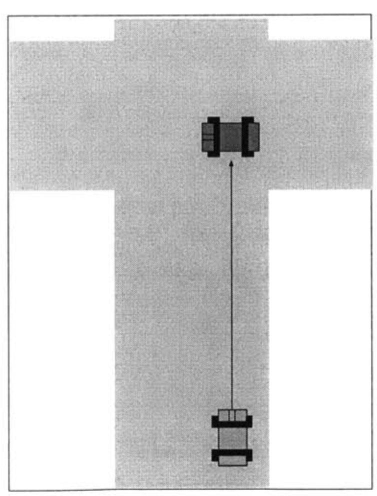


Fig. 4.12 Scenario 2

The τ -d plot of scenario 2 is shown in Fig. 4.13. As there is a collision at the intersecting point, the PCM is at the intersection point, τ doesn't approach infinity at the PCM. The plot is a straight line and passes through the *d*-intercept at *d* equals 200 feet. The second derivative is zero along the whole plot.

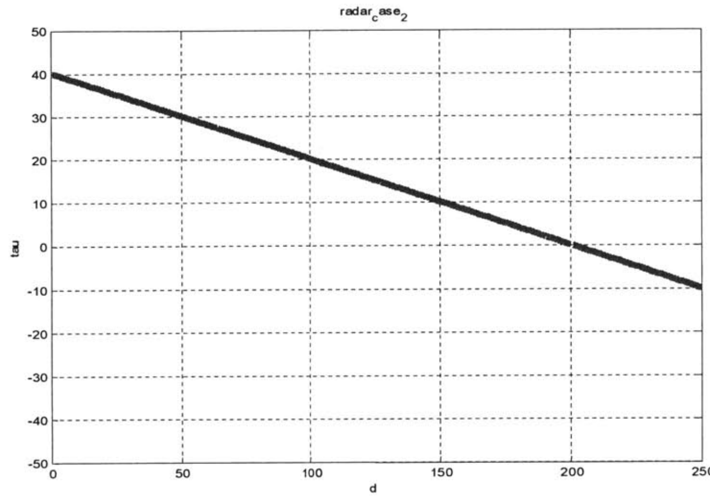


Fig. 4.13 τ against distance traveled by subject vehicle for scenario 2

Scenario 3: Both of the vehicles travel toward the intersecting point, but the intruder vehicle travels faster than the subject vehicle and there is no projected collision. See Fig. 4.14.

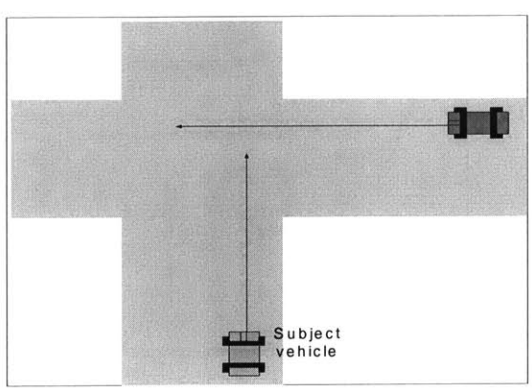


Fig. 4.14 Scenario 3

The τ -d plot for scenario 3 is shown in Fig. 4.15. The PCM is at a point before the subject vehicle arrives at the intersecting point, and τ approaches infinity at the PCM. Right before the PCM, there is a portion of the plot that has positive second derivative.

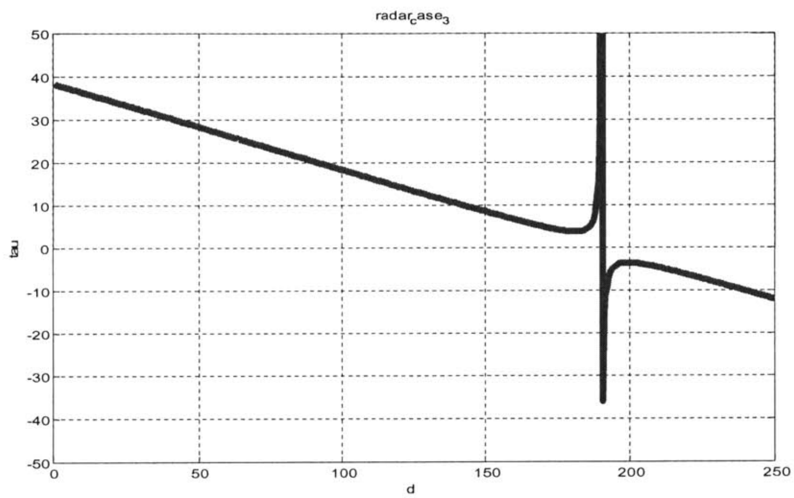


Fig. 4.15 τ against distance traveled by subject vehicle for scenario 3

Scenario 4: Both vehicles travel toward the intersection point with the same velocity, and there is a projected collision, as shown in Fig. 4.16.

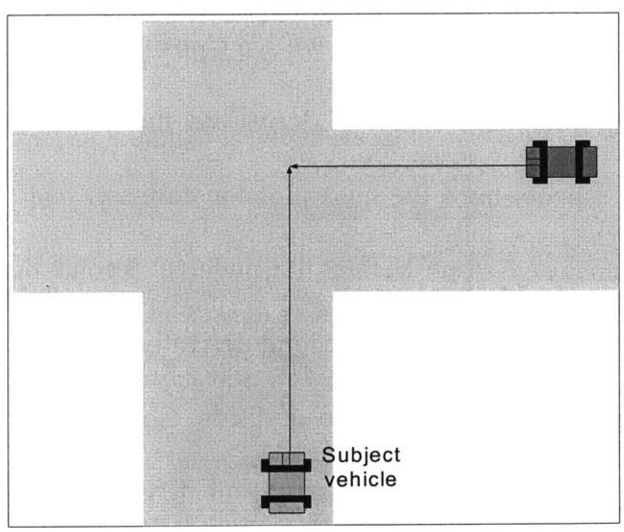


Fig. 4.16 Scenario 4

The τ -d plot for scenario 4 is shown in Fig. 4.16. As there is a projected collision at the intersection point, the PCM is at the intersection point. τ doesn't approach infinity in the plot. It is a straight line throughout the whole plot, and this τ -d plot is the same as that of scenario 2.

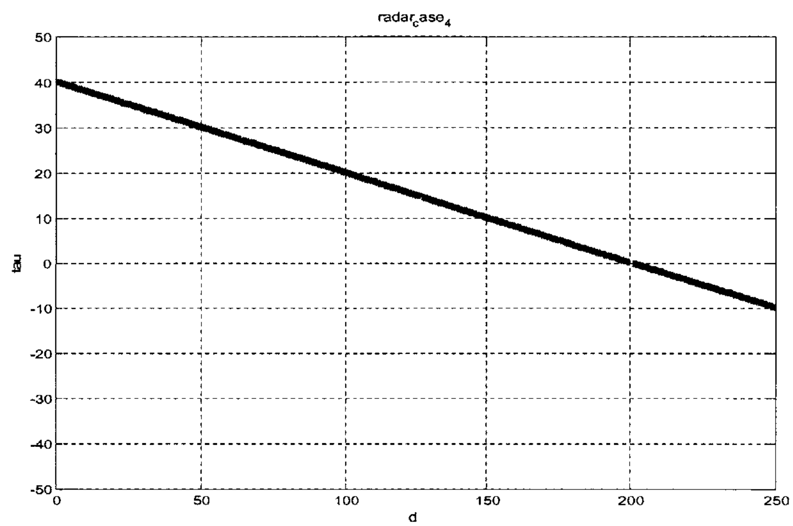


Fig. 4.17 τ against distance traveled by subject vehicle for scenario 4

There are two conclusions we can draw. By having τ as a function of d (or time), we can only detect that there is no collision when we see a positive second derivative in the τ -d plot. Before detecting this positive second derivative, there is always a chance that there is a collision. For instance, both the τ -d plot for collision and no collision cases are straight lines with negative slope before the positive second derivative part appears. Similarly, before detecting this positive second derivative part, there is always a chance of detecting this part later and there is no collision. So if it is a no collision case, the system can only make the decision of not issuing an alert when it sees the positive second derivative. For a collision case, there is no way for the system to know whether there is a collision threat or there is no collision threat before it crashes. The second conclusion is that the system cannot differentiate scenario 2 and scenario 4, as the τ -d plot of them are the same. This is hazardous because in designing the alerting algorithm, the fact that whether the intruder vehicle is moving plays a vital role as it determines when the subject vehicle has to brake. In conclusion, a CAS that based its sensing only on radar is incapable of handling intersection collisions effectively.

Chapter 5 Human-in-the-loop experiments

5.1 Experimental Verifications

This chapter presents the design of the human-in-the-loop experiments and its results, which provides us insights in the effectiveness of the proposed alerting system and its effects on human driving behavior.

Although it is claimed in chapter 3 that the design of the alerting system has already taken into account the uncertainties of human driving behavior and efforts have been spent to make sure that the alerting system accommodates as many drivers as possible, it is obvious that the CAS cannot claim to be effective before being tested with human subjects. In the last chapter, assumptions on human driving behaviors were made and numerical simulations were performed accordingly. However since these assumptions may be unable to capture all the uncertainties involved in human driving, human-in-the-loop experiments are needed.

Instead of using a real car to test the alerting system, we used a driving simulator. It is understood that the results obtained would be different if a real car was used, but nonetheless experimental data obtained through the driving simulator can provide us with insights about the effect of the CAS.

The driving simulator is converted from a Volkswagen Beetle, with the engine, transmission, and brake hydraulics stripped off. A PC-based driving simulation program is installed in the driving simulator, and an overhead projector displays the driving scene onto a screen in front of the car. Its pedals and steering wheel are wired to control the car's apparent motion. An electric motor attached to the steering column provides realistic feedback as the driver turns the wheel. Data on car speed, position, acceleration, driver inputs, and CAS outputs are recorded by the simulator system. A picture of the driving simulator is shown in Fig. 5.1.

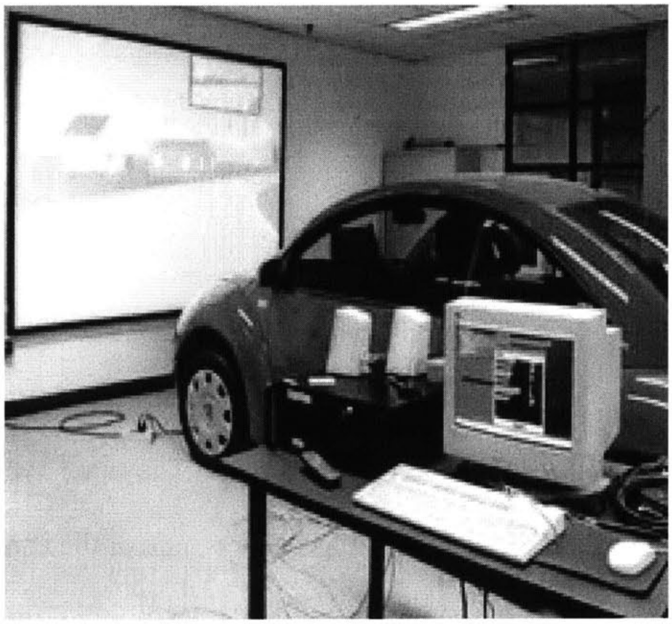


Fig. 5.1 Driving Simulator

5.2 Experimental Protocol

Six human subjects were volunteered to drive through four sets of driving scenarios respectively. The CAS was loaded into the PC that contains the driving scenarios and attached to the driving simulator. The CAS could be turned off, so that we could compare the results between the experiments with CAS and those without CAS. Each of the subjects was asked to drive two scenarios with the presence of CAS, and two identical scenarios without the presence of CAS. The order of these scenarios was counterbalanced and therefore different among each human subject, so the probable effects of ordering of scenarios on human performance are minimized. The reason to break down the driving scenarios into four instead of two is to avoid making the scenarios too long, which may induce fatigue and motion sickness to some subjects. One thing to note is that motion sickness is one of the sources that make simulation driving different from real driving. We call the two scenarios scene 1 and scene 2 respectively. The subjects had to drive through a series of intersections in scene 1 and 2. There are two aspects of the CAS that we wanted to test. One is the ICAS proposed in chapter 3; the other is a Left Turn advisory system (LTA). The drivers had to drive through a series of intersections at approximately 30 to 40 miles per hour in the two scenarios. At each of the intersections, cars were programmed to move toward the intersection from both the left side and the right side. Some of the intersections were programmed to be No Threat scenarios, and cars from both the left and right sides would stop in front of the stop line. There were no collision threats at these intersections. The other types of intersections were Threat intersections. At these Threat intersections, one of the cars (it could be either the left one or right one) was programmed to cross the intersection instead of stopping in front of the stop line. By doing so, there were potential collision threats at these intersections. Three types of intruding vehicles were present at these Threat intersections. They were Hitting (**H**), Miss In Front (**F**), and Miss In Back (**B**) respectively. The **H** vehicles traveled with a velocity based on the velocity of the subject vehicle. Before a certain point was reached (a Freedom Point), the **H** vehicles traveled with the aim to crash into the subject vehicle directly. After the Freedom point, the **H** vehicles were released from their coupling with the subject vehicle, and were allowed to travel with whatever velocity they had at the Freedom Point. Therefore the subject vehicle would crash into the **H** vehicles if it traveled with constant velocity, it had to either accelerate or decelerate to avoid the collisions. The **F** vehicles were programmed to miss in front of the subject vehicle. As the speed of **F** depends on the speed of the subject vehicle, the miss distances between the **F** vehicles and the subject vehicles are different for each case. As an example, for a subject who maintains a constant velocity of 60 ft/sec, the miss distance between the **F** vehicle and the subject vehicle is 70 feet. Similarly it was released its coupling with the subject vehicle after the Freedom Point. This behavior also applied to the **B** vehicles. The subject vehicle can avoid collisions with the **F** vehicles by maintaining constant velocity or decelerating, but it would crash into the **F** vehicles by acceleration. The **B** vehicles are programmed to miss the subject vehicle at its back. The subject vehicle can avoid collisions with **B** vehicles by maintaining constant velocity or acceleration, but would crash into the **B** vehicles by deceleration.

There were eight Threat intersections in scene 1, among them four were **H**, three were **F**, and one was **B**. This is shown in Fig 5.2. There were twelve Threat intersections in scene 2, among them four were **H**, three were **F** and five are **B**. This is shown in Fig 5.3. This gave eight **H**, six **F**, and six **B** in twenty Threat cases.

Threat number	1	2	3	4	5	6	7	8
Threat types	**F**	**H**	**F**	**H**	**H**	**H**	**F**	**B**

Fig. 5.2 Threat types for scene 1

Threat number	1	2	3	4	5	6	7	8	9	10	11	12
Threat Types	**H**	**B**	**F**	**B**	**H**	**F**	**B**	**B**	**H**	**B**	**H**	**F**

Fig. 5.3 Threat Types for scene 2

Before starting the actual data taking scenarios, the subjects were given some practice scenarios to familiarize themselves with the driving simulator. This is because driving a simulation is different from real driving, and practice scenarios can improve the data collected in the sense of reflecting reality by removing unfamiliarity. For instances, crashes due to unfamiliarity of the driving simulator can be reduced.

The CAS issued an audio alert when the CAS algorithm predicted a potential collision threat. Similarly, the subjects were familiarized with this audio alert before the scenarios began. The subjects were given as many practice and familiarization sessions needed until he or she felt confident enough to move on to the actual data taking scenarios.

At some intersections in the scenarios, the subjects were prompted with an audio signal to make either a left turn or a right turn. Among these intersections, there was oncoming traffic in three of them (one in scene 1 and two in scene 2). At these three intersections, the subjects were asked to make a left turn. However since there was oncoming traffic on the other lane, the subjects had to wait until there was a gap between two oncoming vehicles that was large enough for the subject to drive through. The gaps between successive oncoming vehicles were increased progressively. The LTA was designed to help the driver to decide when the gap was big enough for the driver to drive through. In the cases when the LTA was turned on (LTA was turned on when the CAS was turned on), a color box showed up at the lower left corner of the projection screen as when the subject was notified to make a left turn. The box was in a red color when the LTA algorithm determined that the gap was not big enough, while the box was in a green color when the LTA algorithm determined that the gap was big enough. When the LTA was turned off, the subjects had to count on themselves to judge whether the gaps were big enough.

As pointed out earlier CAS could have potential benefits in safety to those people with degraded cognitive, sensory, and motor ability, it is therefore interesting to see if there is any difference in performance of the CAS between young and old people. Therefore of the six subjects, three of them were young and three of them were old. We used 50-year-old to be a dividing line between old and young. The ages of the young subjects were 22, 42, and 29 respectively. The ages of the old subjects were 61, 65 and 69 respectively. In order to obstruct the visibility and increase the subjects' reliability on the CAS, the driving scenarios were programmed to be foggy. The depth of opacity (the distance that the subjects were able to see into the fog) was set to be 2000 feet. According to the subjects, the fog did increase the difficulty of the driving tasks.

5.3 Results

5.3.1 Average Miss Distances and Velocities

To analyze the driver performance with and without the CAS, dynamics data (such as position, velocity, acceleration etc.) and those associated with the CAS were collected. Data was collected at a time step of 0.05 sec. We used the average miss distance as one of the metrics to measure the effectiveness of the CAS. Miss distance is defined to be the minimum separation between the subject vehicle and a particular Threat vehicle (**H**, **F**, or **B**). The average miss distance in scene 1 is then the mean of miss distances among the eight threatening intersection cases for a given subject and that of scene 2 is the mean of miss distances among the twelve threatening intersection cases. We use A1 to designate scene1 with presence of CAS, A2 to designate scene 2 with presence of CAS, NA1 to designate scene1 without presence of CAS, and NA2 to designate scene 2 without presence of CAS. We used Y1, Y2, and Y3 to designate the three young subjects respectively. Also we used O1, O2, and O3 to designate the three old subjects respectively. The order of scenarios given to the subject is listed in Fig 5.4. Fig 5.5 summarizes the average miss distances of each subject in each scenario.

	1	2	3	4
Y1	A1	A2	NA1	NA2
Y2	A1	NA1	A2	NA2
Y3	NA1	A1	NA2	A2
O1	A1	A2	NA1	NA2
O2	A1	NA1	A2	NA2
O3	NA1	A1	NA2	A2

Fig. 5.4 Orders of the scenarios given to the subjects

	A1	**NA1**	**A2**	**NA2**
Y1	50.2652	43.8778	44.5563	44.1995
Y2	40.5811	39.4258	37.2994	38.6443
Y2	33.1686	48.5865	35.3527	35.2731
O1	26.6101	45.2310	43.3726	43.3764
O2	63.1912	76.6770	58.5880	56.4603
O3	52.4676	52.2991	43.0484	56.7755

Fig. 5.5 Average miss distance of each subject (feet)

It is also interesting to know whether the presence of CAS would change the driving behavior of the subjects. For example, the subjects may feel complacent and have a sense of safety with the presence of CAS, and therefore drive more aggressively than they would when there was no CAS present. The average velocity of the subjects in each scenario can in some degree reflect whether this happened. The average velocities of each subject over each entire scenario are summarized in Fig. 5.6.

	A1	NA1	A2	NA2
Y1	26.4961	31.8773	29.6845	32.9380
Y2	42.7683	43.2013	42.8327	42.7021
Y3	38.4261	40.7306	40.2506	40.2590
O1	44.1365	37.0488	36.2879	35.1580
O2	37.2893	39.2134	39.6389	37.8663
O3	53.1299	38.3266	49.8285	45.5108

Fig 5.6 Average velocity of each subject (feet/sec)

In order to determine whether the CAS made any differences in the average miss distances and average velocities, a T-test was performed on the data In Fig. 5.5 and Fig. 5.6. However the t values found were too small to indicate any statistical significance. This can be attributed to the fact that the sample size is so small (with just six subjects), which in turn makes the t values small. But if we regroup the data in Fig 5.5 and Fig 5.6 in a different way, we can see some interesting patterns emerge.

Instead of listing each individual subject's average miss distance and average velocity, we average these values among all the subjects, among just the young subjects, and among just the old subjects. The results are shown in Fig 5.7 and Fig. 5.9 respectively. Fig. 5.7 shows the average miss distances of all people, the young subjects and the old subjects in each scenario. Fig. 5.9 shows the average velocities of all people, the young subjects and the old subjects in each scenario. Fig 5.8 presents a graphical representation of the data shown in Fig 5.7. The error bars are also shown based on the standard error of the data. In the **A** cases, we see that there is significant overlap of the error bars, which should be is indicative of the few number of subjects.

Looking at Fig 5.7, the average miss distances decreased with the presence of CAS in both scene 1 and scene 2 across all groups. This trend emerged for

	A1	**NA1**	**A2**	**NA2**
All	44.3807	51.0162	43.7029	45.8049
Young	41.3383	43.9634	39.0695	39.3723
Old	47.4230	58.0690	48.3363	52.2374

Fig. 5.7 Average Miss distances for each age groups (feet)

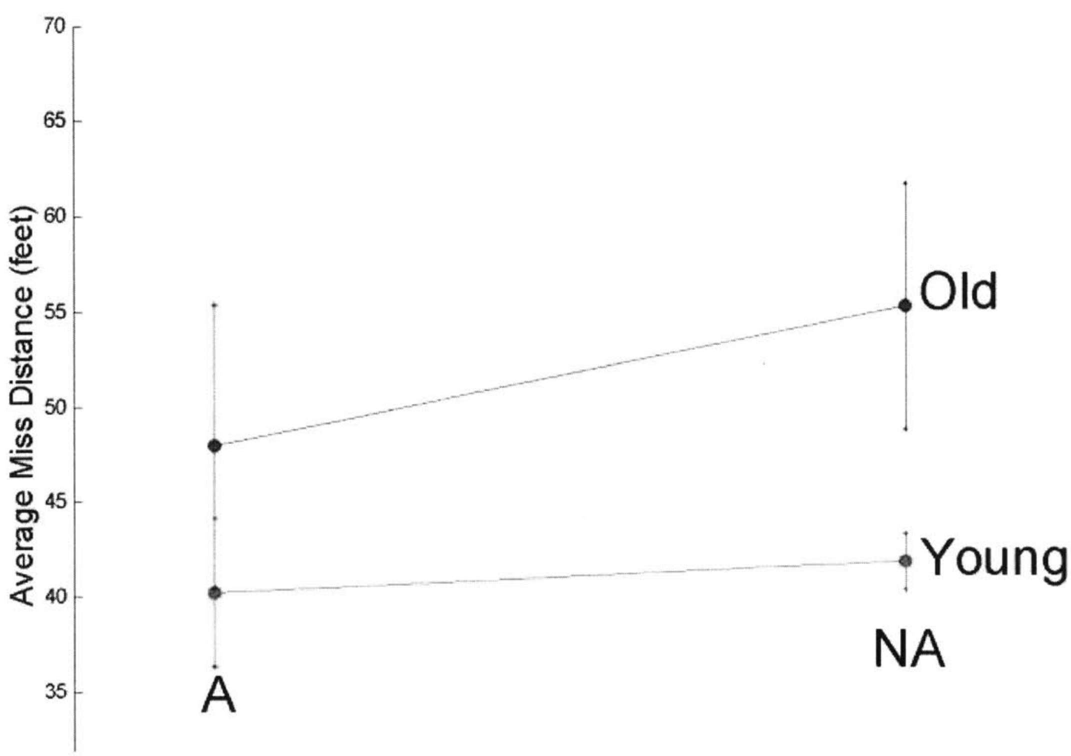


Fig. 5.8 Graphical representation of the data in Fig. 5.7

the group of all subjects, the group of young subjects, and also the group of old subjects. The goal of the CAS was to avoid collisions with other vehicles, and which would mean increasing the miss distances between the subject vehicles and the intruder vehicles. However the data shown in Fig. 5.7 shows just the opposite, the presence of the CAS had indeed decreased the average miss distances between the subject vehicle and other vehicles. There are two explanations to this dilemma. One is that the CAS is simply ineffective and the presence of it ruins safety. The other one is that the subjects drive more aggressively when the CAS is present, possibly due to over trust. We believe that the latter is true, as more data which is to be given later all point to this fact. When the CAS was present, the subjects probably would just the beat the traffic when there was a close miss with another vehicle, because they thought that the CAS could provide them some protection even when they tried to beat the traffic. Indeed we can see that the younger subjects have a smaller average miss distance than that of older subjects (in both scene 1 and scene 2, be it with or without the CAS), which confirms the common impression that younger people are more aggressive in driving and are more willing to take risks.

	A1	NA1	A2	NA2
All	40.3744	38.3991	39.7539	39.0724
Young	35.8968	38.6031	37.5839	38.6330
Old	44.8519	38.1963	41.9184	39.5117

Fig 5.9 Average velocities for each age group (feet/sec)

Fig. 5.9 shows that when the CAS was not there, the average velocities of both the young and old subjects are about the same, be it in scene 1 or in scene 2. Fig 5.10 presents a graphical representation of the data shown in Fig 5.9. In both the **A** and **NA** cases, we see that there is significant overlap of the error bars, which again should be attributed to the few number of subjects When the CAS was there, the young subjects drive slower in the presence of CAS, while the older subjects drove faster in the presence of CAS. It may seem that this result contradicts the result drawn from Fig. 5.7. The average miss distances indicate the behavior of the subjects in the vicinity of an intersection

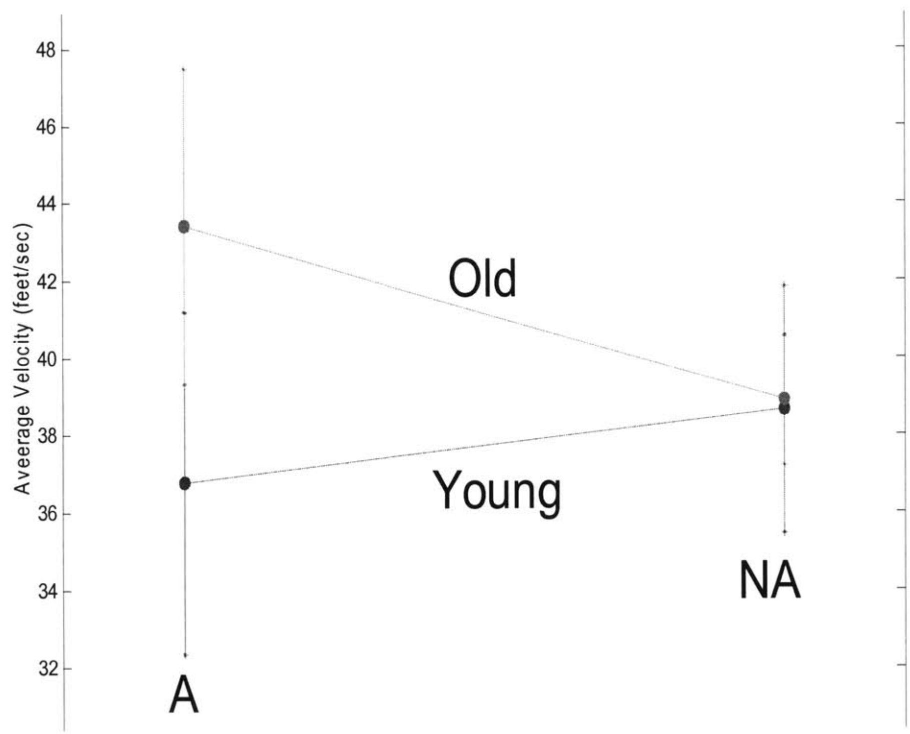


Fig. 5.10 Graphical representation of the data in Fig. 5.9

and in intruder vehicle, while the average velocities describe the subjects' behavior over the whole scenario. We can say that driving faster means driving more aggressively in general, but it does not imply driving aggressively in the vicinity of an intersection. The fact that the old subjects drove faster with CAS means that they are more confident in the presence of CAS in general. While the young subjects may have been less confident with the presence of CAS in general. Though the result here does not have statistical significance due to the small size of samples, it is interesting to investigate whether this trend is observed with more subjects. For instance, it is interesting to know why the young subjects become more confident at the intersections but less confident in general with the presence of CAS.

5.3.2 Alerting Rate and Crashing Rate

		Crashes		Alerts		Average Miss Dis. (feet)	
		A	NA	A	NA	A	NA
All	F	0.0000	0.0000	0.0000	0.0000	53.1551	55.8686
	H	0.0208	0.0000	0.2500	0.0000	45.9170	46.9592
	B	0.0556	0.0000	0.1667	0.1667	36.2643	38.3608
	LT	0.0000	0.1667	N/A	N/A	N/A	N/A
Young	F	0.0000	0.0000	0.0000	0.0000	47.0660	46.1497
	H	0.0000	0.0000	0.1250	0.0417	35.7677	38.9550
	B	0.0000	0.0000	0.1667	0.0000	38.4435	38.4928
	LT	0.0000	0.3333	N/A	N/A	N/A	N/A
Old	F	0.0000	0.0000	0.0000	0.0000	59.2443	65.5426
	H	0.0417	0.0000	0.3750	0.2083	56.0662	54.9635
	B	0.1111	0.0000	0.1667	0.0000	34.0850	38.2288
	LT	0.0000	0.0000	N/A	N/A	N/A	N/A

Fig 5.11 Crashes, Alerts and Miss Distances categorized threat types

Fig 5.11 shows the number of crashes, alerts triggered and the miss distances for each age group in each Threat types respectively. First let us begin with the Alerts Column. The Alerts column is further divided into two sub-columns, one with the header **A** and the other **NA.** **A** stands for the scenarios with the CAS turned on, under which an alarm was issued to the subjects when the algorithm deemed necessary. The **NA** stands for the scenarios where the CAS was turned off. By turning off the CAS we mean that the CAS algorithm was still running in the background, but the alarms were not issued to the subjects when the CAS algorithm figured that an alarm was needed. By recording the alarms generated by the algorithm when the CAS was turned off, we can gain an insight into whether the driving behavior under the NA condition would have generated alarms had the CAS being turned on. For example, on the entry corresponding to the column **A** and row **H** for Young subjects, the number is 0.125 (3/24). 8 is the total number of Threat **H** in scene 1 and scene 2, and we have 3 subjects, therefore the total number of **H** threats for young subjects is simply 8x3=24. 0.125 (3/24) means that among these 24 **H** threats, alarms were triggered 3 times. **A** means that the alarms generated were issued to the subjects and the subjects knew that they would receive alarms. The entry corresponding to the column **NA** and row **H** for young subjects reads 0.04 (1/24). This means that only one alarm was triggered among the 24 **H** threats. As this entry corresponds to the column **NA**, it means that the alarms triggered were not issued to the subjects, and the subjects didn't know that the CAS algorithm was running in the background. The comparison between these two numbers (0.125 (3/24) and 0.0417 (1/24)) tells that the young subjects' driving behavior tended to generate more alerts for the **H** threats when the CAS was active. Now we proceed to look at other types of threats. Neither the old subjects nor young subjects generated any alerts for **F** threats (both **A** and **NA** cases). However, both the young subjects and old subjects generated more alerts in **A** scenarios than in **NA** scenarios, for both the **H** and **B** threats. When the CAS was turned off, they drove in a safer way such that the CAS rarely generated alarms. But when the CAS was turned on, they drove in a less safe way such that the CAS generates more alarms. This result passes the sign test ($p<0.05$) for the statement that people tend to drive more aggressively when the CAS is present than when the CAS is not present, and this confirms our earlier statement.

Now let's compare the number of alerts generated between different age groups. Young subjects generated 3 alerts out of 24 **H** threats (0.125) for **A** scenarios, while the number for old subjects is 0.375 (9/24). When the CAS was turned off in **NA** scenarios, young subjects would have triggered alert at an alert rate of 0.04 (1/24) for **H** threats and old subjects would have had an alert rate of 0.208 (5/24) for **H** threats. For **B** threats, young subjects had 0.1667 (3/18) in **A** scenarios, and the old subjects had the same rate. Though the performances for **B** and **F** threats were the same for young and old subjects, it is evident that the old subjects generated more alerts than young subjects for the **H** threats. By the fact that the old people generate more alerts than the young people, can we also say that old people drive more aggressively than young people, and therefore contradict our earlier claim that young people drive more aggressively than old people? The answer is no. When people generated more alerts in **A** scenarios then in **NA** scenarios, we can reason that they drove more aggressively in **A** scenarios. However, the reason that old people generate more alerts than young people should be attributed to the fact that the old people may have degraded cognitive and motor ability, and thus are less likely to maintain a safe separation from the intruding vehicles. Therefore people with degraded cognitive and motor ability, such as old people, have a higher need of CAS.

Now we move onto the Crashes column. It shows that young people didn't crash at all. The old people crashed 0.0417 (1/24) times for **H** threats and 0.1111 (2/18) times for **B** threats respectively under the **A** scenarios. First, this result suggests that old people are more likely to crash than young people. Again this points to the fact that old people have a higher need for extra safety measures such as CAS than young people. Secondly, people didn't crash at all under the **NA** scenarios, which suggests that people crash easier when CAS was present than when CAS was not present! On the surface it seems that the CAS was ineffective and indeed worsened the safety rather than improved safety. If we look at the alerts generated in **A** scenarios and **NA** scenarios again, we know that the CAS didn't worsen the safety directly, but worsened safety indirectly by making the people drive more aggressively than when the CAS was not present. Based on the analytical and numerical analysis performed previously, the CAS should help to improve safety. As CAS is not an autonomous system, human factors come into play. The complacency of human beings and risk homeostasis are the culprits leading to reduced safety when CAS is present. Therefore before applying CAS on real vehicles, we have to make sure that the drivers are educated to use the CAS properly.

Now we will analyze the results across different threat types. Young people generated more alerts for **H** threats than for **B** threats, and old people also generated more alerts for **H** threats than for **B** threats. Both the young and old people didn't generate any alerts for **F** threats. The reason that no alerts were generated for **F** threats is because the intruding **F** vehicle was always in front of the subject vehicle with a significant gap unless the subjects accelerates when the subject approached the intersection, which is unlikely. However for **B** threats, if the subjects decelerated (which is likely), the subjects would decrease the separation distance from the intruding vehicles. This is the reason that **B** threats generated more alerts than **F** threats. But still, the **H** threats generated more alerts than **B** alerts since in these cases the intruding vehicles were programmed to crash into the subject vehicles. One thing to note is that **B** threats were more dangerous than **H** threats. The Crashes column suggests that old subjects were more likely to crash for **B** threats than **H** threats, as indicated by the numbers 0.1111 (2/18) and 0.125 (3/24) respectively. The reason is that deceleration decreases miss distances which makes **B** threats more dangerous. Indeed if we look at the Average miss distances column for old people, we can see that the miss distances are lower for **B** threats than for **H** threats. This phenomenon doesn't appear for young people. Perhaps this is due to the specific structure of the driving simulator used in the experiments. As a one screen system was used instead of a wide angle screen, the **B** intruding vehicles would be left out of the projection screen after a certain point. We speculate that young people have a higher cognitive ability to judge where the **B** vehicles are even those **B** vehicles were not projected on the screen.

5.3.3 Driving Trajectories and Locations of Alerts

Fig. 5.12 shows a plot of velocities against distance traveled for 6 subjects. The trajectories shown are for the first intersection of scene 2, where there was an **H** threat. In the cases shown CAS was turned on, and hence the trajectories were denoted with **A2** (e.g. **Y2A2**). **Y*n*** specifies the nth young subject, while **O*n***, specifies the nth old subject. The intersection was at 1200 feet, and the trajectories before the subject vehicles enter the intersection are shown. Circles denote the points where an alert was issued to the subject.

Alerts were issued to Y1, Y3, and O2 respectively. This plot provides an example of how the CAS responds when it is applied. We see that every subject except Y1 decelerated before entering the intersection. This is the normal behavior, as the threat was an **H** one, people should decelerate in order to avoid a collision. However, Y1 did the opposite. Y1 tried to avoid the collision by acceleration and beating the intruding vehicle. Again this is another piece of evidence that young people drive more aggressively. We cannot define a region in the velocity-position (distance traveled) plot where the alerts are issued. This is because the alerts are given off based on the relative positions and velocities between the intruder vehicle and subject vehicle, and the velocity profiles of the intruder vehicles in the experiments were based on the velocity profiles of the subject vehicle. What we can say from Fig 5.12 is that alerts were given off at more or less the same region in the plot for Y3A2 and O2A2. Of Course, the trajectories for Y3A2 and O2A2 are different after the alerts were issued, as it can been seen that O2A2 has a more aggressive braking maneuver than that of Y3A2.

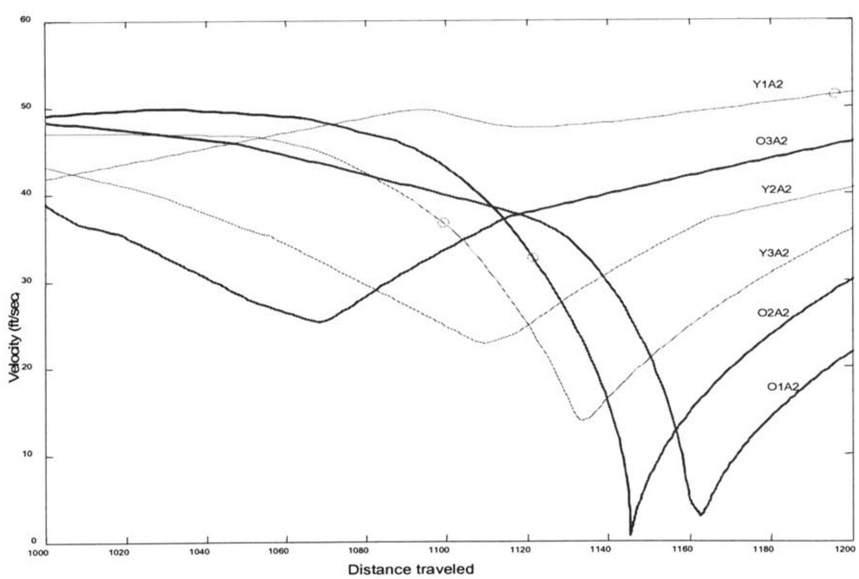


Fig 5.12 Velocity against distance traveled for A2 cases

5.3.4 Responses to Alerts

One important aspect of CAS is the reaction time and braking rate with regard to an alert. Fig 5.13 shows the response of O2A1 (the second subject in scene1, which CAS turned on). The upper graph of Fig 5.13 shows a plot of alerts against time. The value of alerts is set be 1 when the alert was issued. In the figure, alerts were given at 318.13 seconds and 365.47 seconds after the simulation started respectively. The lower graph of Fig 5.13 shows the braking rate of the subject. In responding to the alert issued at 318.13 seconds, the subject started braking at 319.08 seconds, with a reaction time of 319.08-318.13=0.95 seconds. The braking rate for this braking maneuver was 19.15 $ft/\sec^2$. In responding to the alert issued at 365.74 seconds, the subject started braking at 369.07 seconds, with a reaction time of 369.07-365.47=3.6 seconds. The braking rate for this braking maneuver was -21.7 $ft/\sec^2$.

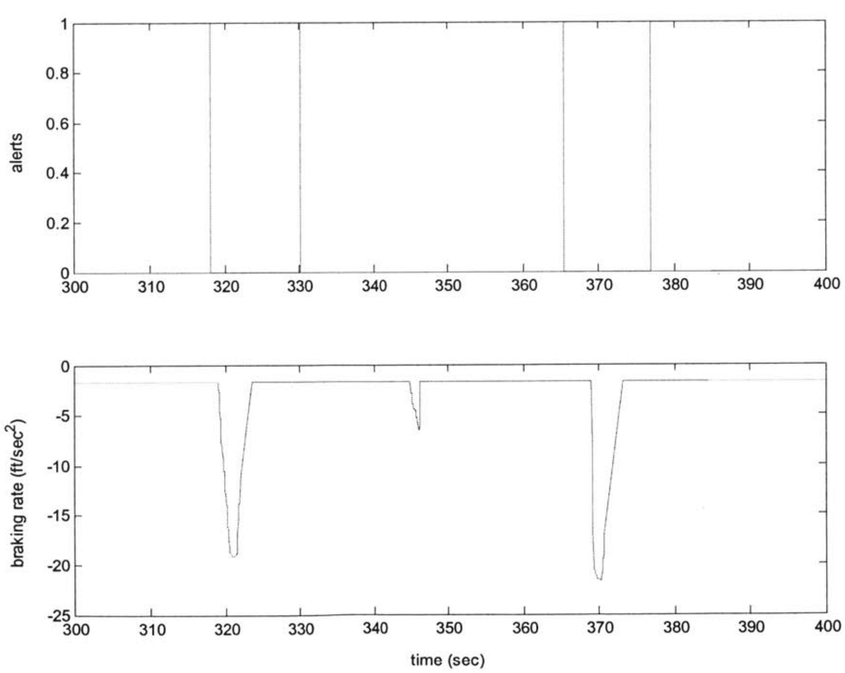


Fig. 5.13 Braking rate in response to an alert for O2A1

Based on the reaction time and braking rate of different braking maneuvers, we can compute the average reaction time and braking rate in correspond to an alert. However, sometimes reaction time is not well defined, such as the example of O3A2, which is shown in Fig 5.14.

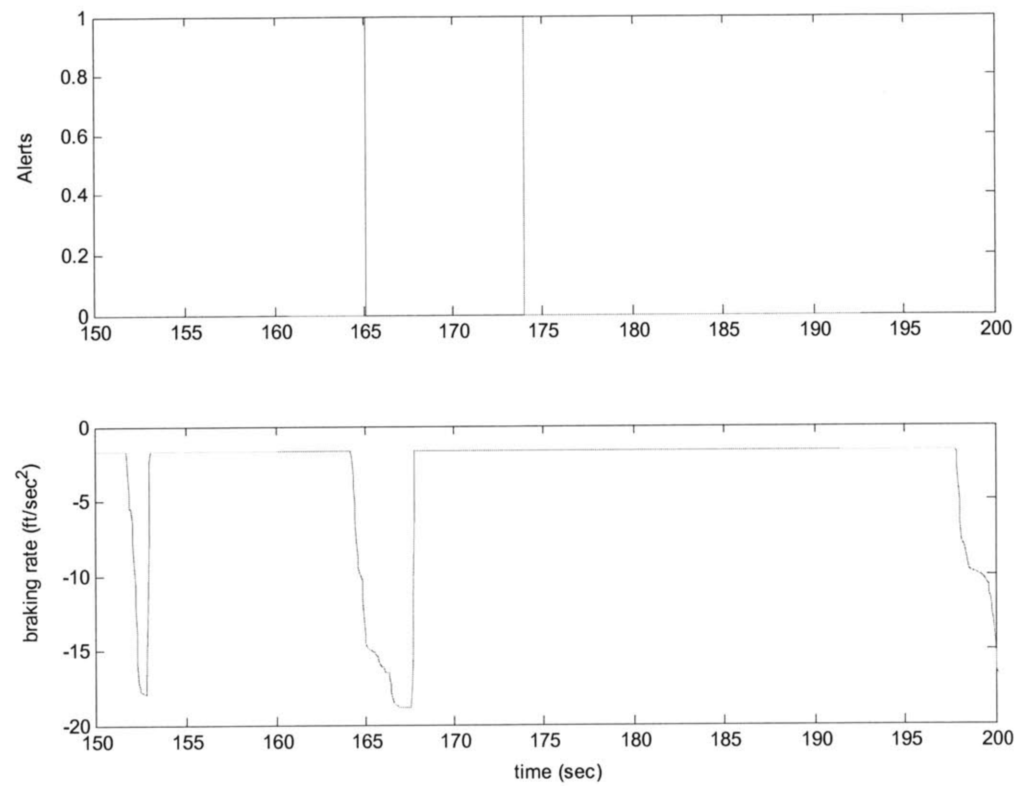


Fig. 5.14 Braking rate in response to an alert for O3A2

In the case shown in Fig 5.14, the alert was issued at 165.11 seconds, while the subject started the braking maneuver at 164.2 seconds. The subject started the braking before the alert was issued. This is because the driver himself sensed the need to brake. Therefore the braking maneuver cannot be considered as a response to the alert. We therefore just consider braking to be a response to an alert when the braking time started later than the time when an alert is issued. There is some controversy about this cutoff method. In some cases we recorded extremely fast response time. In those cases chances are the subjects might had determined to brake even though the alert wasn't there. But it also may be possible that these subjects had extremely fast response time.

There are also cases when alerts were simply ignored by the subjects. Consider the case of Y2A2 as shown in Fig 5.15.

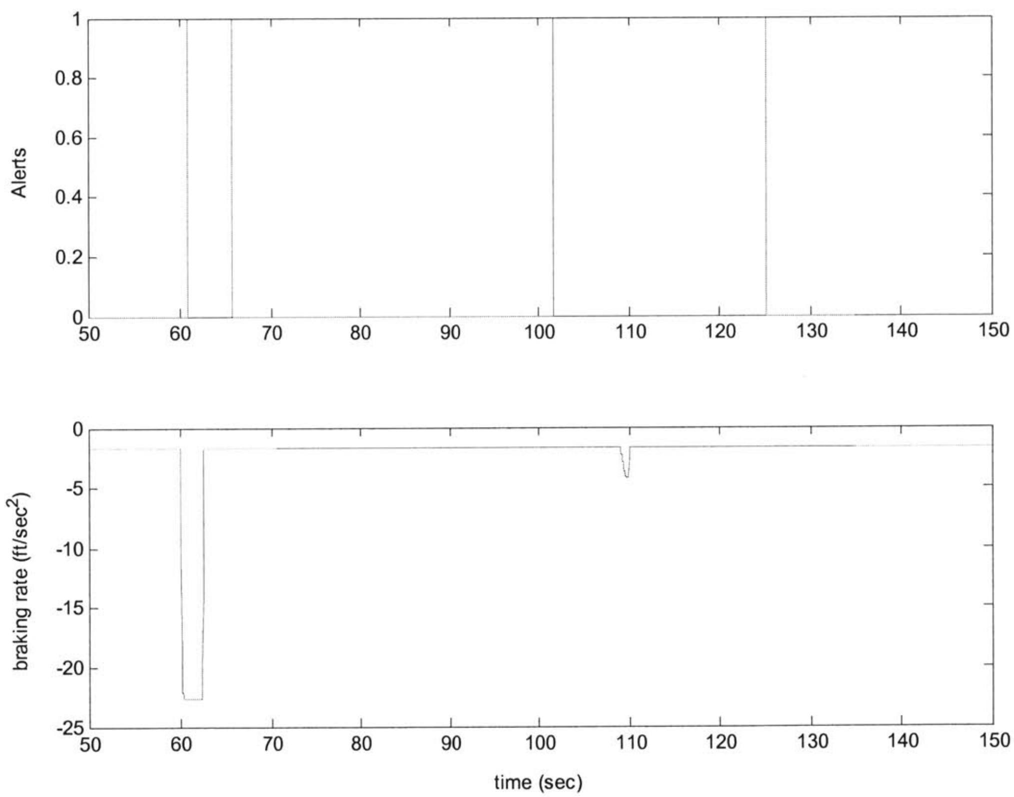


Fig. 5.15 Braking rate in response to an alert for Y2A2

Consider the braking rate corresponding to the second alert. The magnitude of this braking is so small when compared to normal braking maneuvers in response to an alert. Is this really a braking maneuver? Or is this just a velocity adjustment? If we look at Fig. 5.16, in which the plot of distance traveled against time is shown instead of the braking rate, we can see that the braking couldn't be a response to an alert. The second circle on the curve labels the position of the intersection, which is 4350 feet down the road. The graph indicates that the subject passed through the intersection at 104.31 seconds. However the braking started at 109.02 seconds, almost 5 seconds after it passed the intersection. Therefore the braking cannot be related to the alert issued. If this is not the braking correspond to an alert, then where is the braking corresponding to the alert issued? The answer is that the subject simply ignored this alert, based on his own judgment. Indeed in other cases, we also observed that the subjects ignore alerts sometimes.

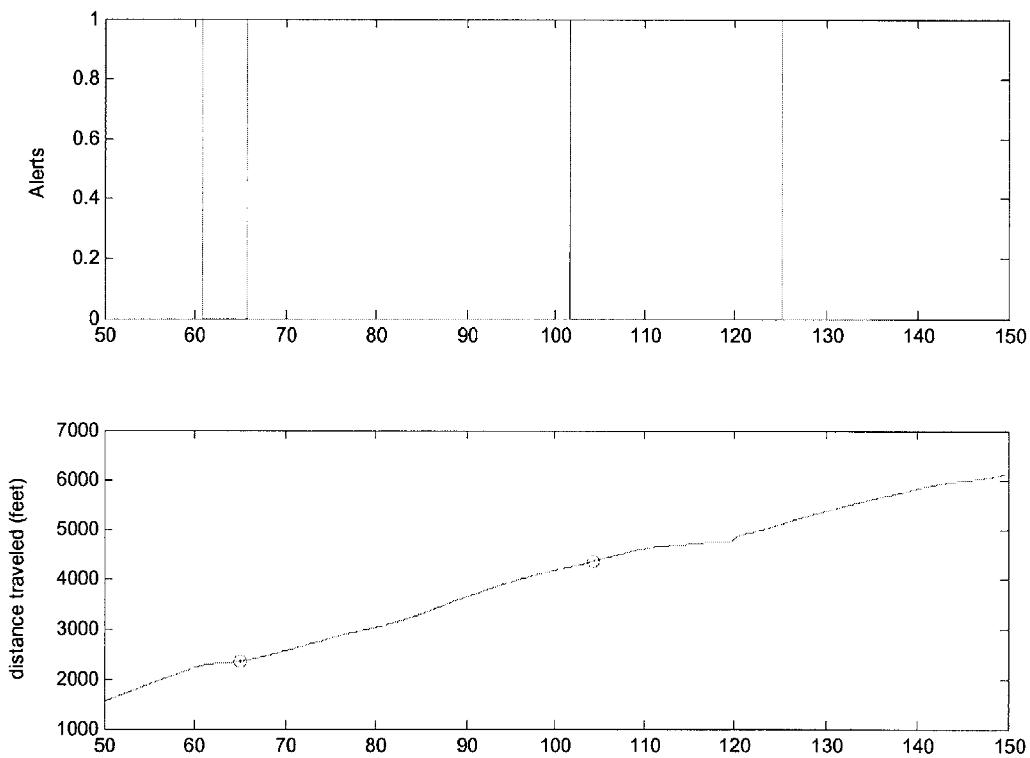


Fig. 5.16 Alerts and distance traveled, Y2A2

Based on the braking maneuvers we recognized as responses to alerts, we summarized the results in Fig 5.17.

	Cases	Reaction time (sec)	Braking rate (feet/sec^2)
Young	Y3A1	0.62	-20
	Y3A2	0.2	-13.28
Old	O1A1	1.15	-20.23
	O1A2	0.45	-21.08
	O2A1	0.95	-19.15
	O2A1	3.6	-21.7
	O2A2	1	-21.98
	O2A2	1.37	-22.61
	O3A1	1.87	-22.5
	O3A2	1.79	-22.61
	O3A2	1.47	-22.04

Fig. 5.17 Reaction time and Braking rate for different subjects

Fig 5.11 indicates that when the CAS was turned on, 6 alerts were issued to young subjects in total, while Fig. 5.17 shows that we can only recognize 2 responses to the alerts. In contrast, 12 alerts were issued to old subjects and we can recognize 9 responses. The moral is that the young subjects are more capable of judging the need to brake on their own, and therefore can often brake before the CAS notified them to do so. The other moral is that the young drivers are more confident with their own judgment, so they ignored the alerts (when they thought the alerts were unnecessary) more often than old subjects. Lastly, sometimes they even tried to accelerate to beat the intruding vehicle, and therefore there was no braking rate being recorded. Based on the data in Fig 5.17, we obtained an average reaction time for old people of 1.5167 seconds, with an average braking rate of -21.5444 $ft/\sec^2$. The average reaction time for young people was 0.41 seconds, with an average braking rate of -16.64 $ft/\sec^2$. The reaction time for young subjects is significantly shorter than that of old subjects, but their braking rate is smaller than the old subjects. We can interpret the result in the sense that because the young subjects respond much faster, they can afford a smaller braking rate. We can also say that because they have a higher degree of control over the situation through the scenarios in general, they didn't have to count on sudden and hard braking to avoid the collisions. A histogram of the reaction time of the old people is shown in Fig. 5.18, in which the distribution of the reaction time of old people is shown.

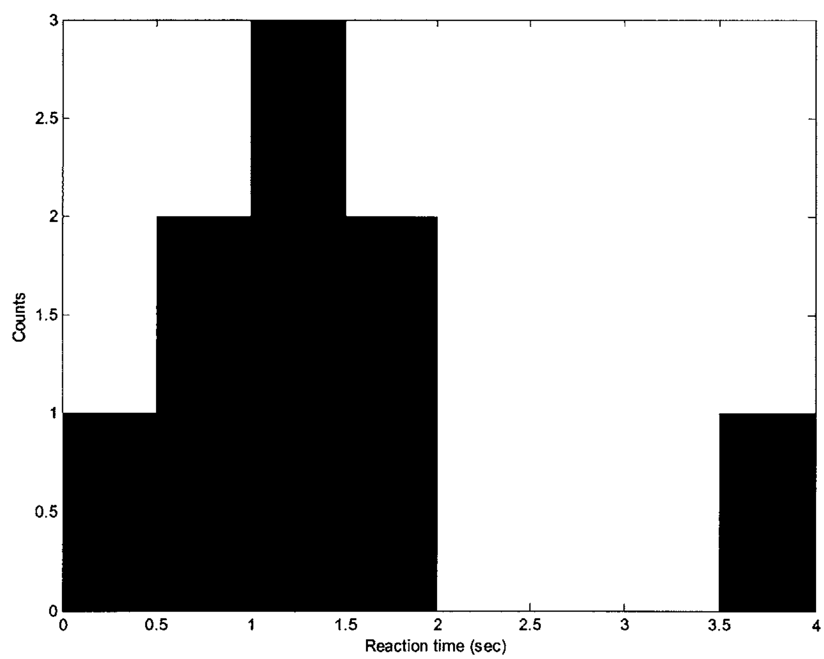


Fig. 5.18 Distribution of old people's reaction time

5.3.5 Effects of the Left Turn Advisory

The Left-turn advisory (LTA) will be discussed in this session. The number entries in Fig 5.20 are the average gap sizes between the two vehicles through which the car turned. A bigger gap means that the driver was more risk averse, because a bigger gap provided a bigger window for the vehicle to make a left turn, see Fig 5.19.

Nominally, the LTA should increase the situation awareness of the subjects. Fig. 5.20 shows the average gap sizes with (A) and without (NA) LTA for all the subjects, young subjects and old subjects.

It can be seen that both the young subjects and the old subjects had smaller gap sizes when the LTA was turned on. This implies that the LTA did increase the situation awareness of the subjects, so the subjects were willing to make the left turn when the safe window is smaller. Also, the young subjects had smaller gap sizes than older subjects with and without the LTA, which once again confirm the common believe that old people are more risk averse. A graphical representation of Fig. 5.20 is shown in Fig. 5.21.

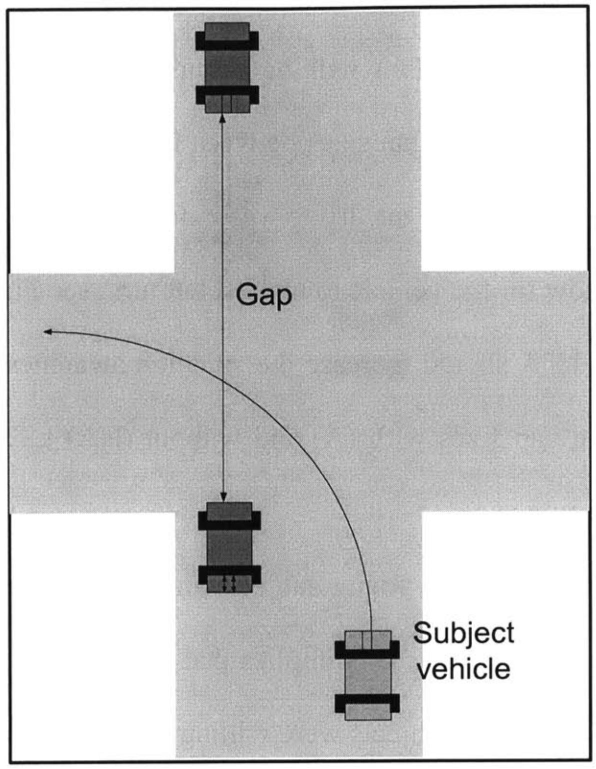


Fig 5.19 Definition of a gap

	A	NA
All	322.2222	347.2222
Young	261.1111	272.2222
Old	383.3333	422.2222

Fig. 5.20 Average gap sizes for different groups

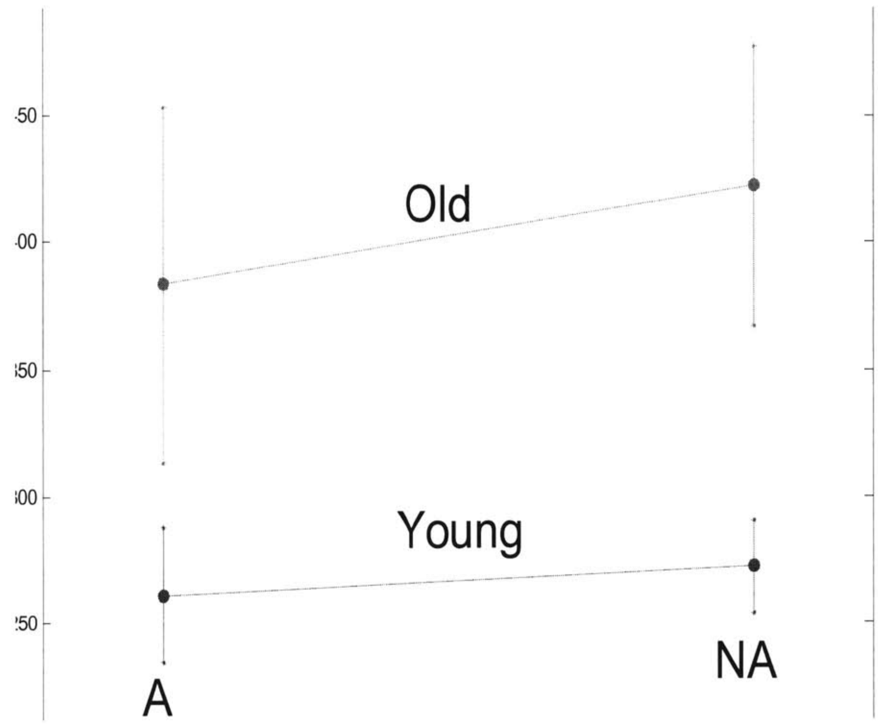


Fig. 5.21 Graphical representation of data in Fig. 5.20

Chapter 6 Summary and Conclusions

6.1 Summary

The generic representation of a CAS was presented, along with an outline of some rear-end CAS algorithms. Algorithms based on kinetics and dynamics, and also algorithms based on performance metrics were introduced.

The problem of intersection collision avoidance was discussed. It has been shown that intersection collisions are much more complicated than rear-end collisions. Driver intent, encounter scenarios and interplays between engaging vehicles all play a larger role than in rear-end collisions.

By utilizing the knowledge of the geometry of an intersection, an approximation was adopted to allow for the development of an analytical graphical tool. This analytical graphical tool allowed us to visualize the complicated interactions between engaging vehicles, and to develop the ICAS algorithm accordingly. It has been shown that the order of which vehicle enters the intersection first has significant effect on the efficiency of the ICAS algorithm, and under some situations the ICAS may worsen safety through alerting. We identified three possible configurations of intersection collisions, and analyzed how the algorithm works in each of these configurations. The effects of the possible difference between reality and the underlying assumptions of the algorithm on the system performance have been analyzed.

A Left Turn (LTA) algorithm has been proposed. The LTA algorithm aims to mitigate left turn collisions through advice on when to start the turning maneuver.

Numerical analysis of the ICAS algorithm was performed. Different regions in the state space were identified according to their characteristic, such as when there is collision threat, and when it is suitable to brake. Braking distances were computed. The effects of varying parameters such as braking rate and reaction time on the braking distances and region identification were discussed.

It was demonstrated that the combination of GPS sensing and an internal map database is necessary for the ICAS to work.

The prototype ICAS was implemented and tested in a driving simulator.

Human-in-the-loop experiments were performed to evaluate the ICAS and LTA algorithms. It was found that young people drive more aggressively than old people, and people drive more aggressively when the CAS was present.

6.2 Contributions

The contributions of this thesis are as follows:

1. Based on the foundation of rear-end collisions, a mathematically rigorous algorithm was developed for intersection collision avoidance.
2. Identified the inherent difficulties in developing an ICAS, and what set this problem apart from rear-end collisions.
3. Devised a graphical tool based on utilizing the configuration of an intersection, which can unveil the complicated interplays between the engaging vehicles.
4. Pointed out the importance of the order of which vehicle enters the intersection first, and its significance on ICAS system performance.
5. Proposed a game theory point of view towards the problem of intersection collisions, which could lead to possible future research.
6. Demonstrated that GPS sensing is much more efficient than radar-based sensing.

7. Performed human-in-the-loop experiments to identify the differences between old and young people.
8. Showed that people were more aggressive when the CAS was present due to over trust or risk homeostasis.

6.3 Recommendations on Future Research Directions

Large scale human-in-the-loop experiments are recommended in order to confirm or deny the conclusions we have drawn in chapter 5. Such experiments can also allow the construction of more accurate human models in intersection collisions. These human models can be used to build trajectory models so the algorithm proposed in chapter 3 can be augmented with a performance-based approach. Game theory can be used to analyze the interactions between engaging vehicles, and thus refine the algorithm proposed in chapter 3.

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