Assessing The Safety Benefit of Automatic Collision Avoidance Systems (During Emergency Braking Situations)

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Abstract

Throughout the last decade a number of advanced system concepts for improving safety, efficiency, environmental compatibility and comfort of driving have emerged. One of these, Automatic Collision Avoidance Systems (ACAS) aims to help drivers to avoid accidents by alerting them to a potential collision and initiating braking. This paper assesses the safety effects of ACAS by examining driver response during emergency braking situations.

A series of emergency braking tests were undertaken on a test track. Six subjects (each with at least five years driving experience) were asked to follow a special 'dummy' vehicle and drive the TRG instrumented vehicle. The dummy vehicle, a lightweight trailer unit designed to withstand impacts safely, was then subjected to brake to a stop from three speed levels (60, 45 and 30 mph) with decelerations which varied between 0.65g and 0.95g. The TRG instrumented vehicle enabled detailed information to be collected on driver responses such as relative speed, spacing distance, pedal movement, speed and deceleration levels.

The data analysis has showed that drivers are likely to initiate their braking before the time to collision (TTC) reaches 4 seconds. Consequently, an autonomous ACAS with a 4 seconds TTC threshold would not give warning that could help drivers reducing their response time. Moreover, headway was found to be the main safety factor that ensures drivers would avoid collision.

Introduction

Rear-end collisions between vehicles are a major road safety concern in many countries. Many drivers, follow other vehicles with short headways which leave little safe margin to avoid collision if the lead vehicle brakes unexpectedly and/or sharply. During the last decade the concept of the Advance Collision Avoidance System (ACAS) has been introduced to improve road safety. Such systems aim to help drivers to avoid accidents by alerting them to a potential collision, and sometimes initiating a braking response. Defining thresholds to distinguish between safe and unsafe driving situations is a key factor in the design of any ACAS system. The Time-To-Collision (TTC), i.e. *the time that would take a following vehicle to collide with a leading one, if the current relative speed was maintained from the given headway*, has been widely regarded to be a potential parameter to be used as a threshold measure (Minderhoud & Bovey, 2001)[6]. Van der Horst (1991)[11] suggested a TTC value of 4 seconds to distinguish between safe and uncomfortable situations on the roads. This was supported by Farber (1991)[2]. However, Nilsson et all (1991)[7] produced subjective ratings indicating that a 4 sec. threshold may be "too short", form an experiment to compare three collision-avoiding systems based on a TTC criteria in a car-following task. Hirst and Graham (1997)[3] found that a TTC value of 3 seconds sometimes 'missed' critical situations, although the number of false alarms was reduced. Hogema and Janssen (1996)[4] studied driver behaviour during approaches to a back of queue situation for non-supported and automatic cruise control ACC supported drivers in a driving simulator experiment. They found a minimum TTC value of 3.5 seconds for non-supported drivers and 2.6 seconds for supported drivers. However, the 2.6 seconds value was regarded as a safety concern. Recently, Sultan et all (2002)[10] analysed driver behaviour during normal car-following situations, i.e. *The process when a driver follows a leading vehicle by sustaining comfortable relative speed and headways*). A decrease in observed absolute minimum TTC values was found with the decrease in the speed .

The TTC incorporates two main factors in driver behaviour, the relative speed (DV) and the relative distance (DX) to a preceding vehicle. However, it does not take into account that it takes longer to decelerate from a higher speed for the same level of deceleration, and thus, the use of a constant TTC threshold to distinguish between safe and unsafe situations may be inappropriate. Also, in emergency situations drivers may behave in different ways to normal driving situations.

Following the above argument, Perron et all (2001)[8] studied driver behaviour in emergency situations and suggested the use of brake pedal speed combined with other parameters, to trigger potential ACAS systems. They also reported that 50% of drivers did not step on the brake pedal strongly enough to avoid collision with a decelerating vehicle. Another warning algorithm for ACAS was developed by Burgett et all (1998)[1], in which the lead vehicle deceleration, the relative speed, the spacing distance and the speed level were used to instigate a warning based on two preset calibration parameters: reaction time (RT) and maximum braking level (DC_{max}). This algorithm was tested by Richard and Daniel (2001)[9] , who reported that a reaction time of 1.5sec and a 0.75g braking level would probably trigger a warning for between 4% and 0.5% of deceleration events in urban driving conditions.

This paper examines driver behaviour in emergency braking situations in order to assess the safety benefit of an autonomous ACAS warning system that could uses either a TTC threshold or the RT and DC_{max} threshold. Further discussion indicates areas for future consideration in the design of ACAS.

Experimental Design and Data Collection

Acquiring data on driving behaviour during emergency braking can be a very hazardous task. Subject safety is a major concern and equipment damage is very costly in terms of time and money. In this study, these considerations were largely overcome by using a towed trailer representing a dummy vehicle (Surrogate Vehicle). It is a half body vehicle made of Fibreglass supported by an aluminium truss structure that is able to collapse in a collision. The surrogate vehicle is pulled by a lead vehicle using a 10m long collapsible telescopic tube supported by a stabilising wheel, see Figure 1. The data was collected using the TRG instrumented vehicle (IV) which is equipped with several devices to measure the motion of the vehicle itself and the motion relevant to adjacent vehicles, in this case the surrogate vehicle. Other equipment monitors the behaviour of the subject in the driving seat. The relative speed, spacing distance, speed level, deceleration or acceleration and pedal movements were recorded on the IV hard disk with a 10 Hz frequency. Also, video footage was recorded from four different cameras: front, rear, steering wheel and driver's head. Figure 2: shows the TRG instrumented vehicle and the position of its sensors and instruments.

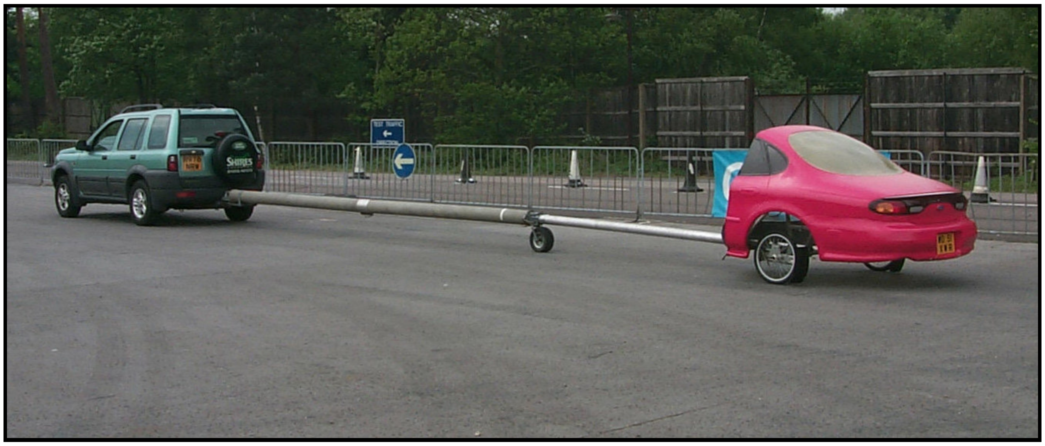

Figure 1: The Surrogate vahicle

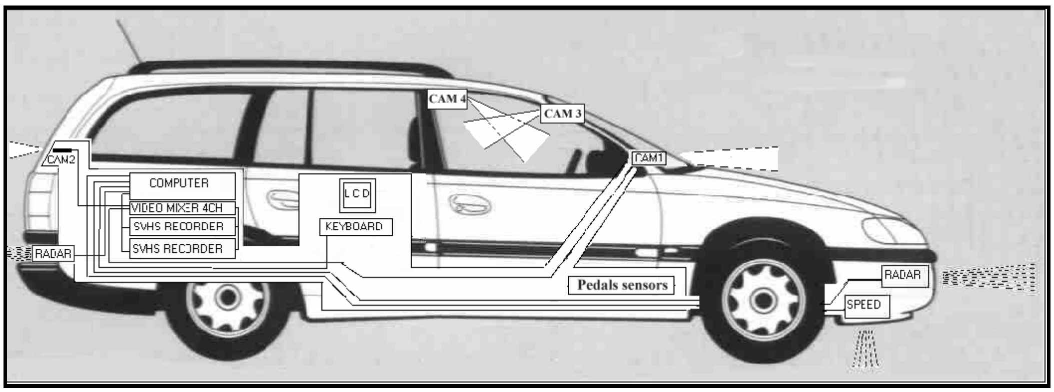

Figure 2: The TRG instrumented vehicle

Several subjects were asked to drive the TRG instrumented vehicle on a test track and follow the surrogate vehicle at a what they individually considered to be comfortable following distance. The test track was two miles long with two straight sections which were long enough to perform emergency braking and wide enough to allow steering to avoid collision in the case the subject felt the need to do so. In order to familiarize subjects with the IV, each was asked to drive the IV from the University campus to the test track (approximately 60 miles). However, no information was giving to the subjects regarding the dummy vehicle and the experiment objectives and purpose. Each experiment was started with four laps where the subject was asked to drive alone and perform several emergency stops from different speed levels (60, 45, 30 mph) to give an understanding of the instrumented vehicle braking capability. At the end of these laps the surrogate vehicle joined the track and the subject was asked to follow it at what he or she considers a safe spacing distance. Some off 20 laps of the experimental course were made, which included three emergency braking events from three different speed levels, i.e. 60, 45 and 30 mph. The lead vehicle was asked to brake very hard to stop, and deceleration rates of between 0.65g and braking level 0.95g were achieved. Efforts were made to distribute the emergency braking events over the experiment course to avoid driver anticipation of when they would be undertaken. Subjects were asked several questions regarding there anticipation, speed level and braking level after each event. In total six subjects, each with at least five years of driving experience, were asked to perform the experiment and all tests where carried out in the daylight and in dry weather. In most cases, drivers were able to brake and stop behind the surrogate vehicle, however, in some cases the driver had to avoid collision by steering away and once a collision took place. Following each experiment, the instrumented vehicle data was filtered, smoothed and prepared for the analysis. Table 1 presents the collected kinematic parameters used for each emergency braking event.

Parameter	Description	Unit
Elapse Time	the accuracy in one thousand of a second	sec
Leading vehicle speed	the dummy vehicle speed	m/s
Leading vehicle Acceleration	(+) ↔ acceleration while (-) ↔ deceleration	m^2/s
Relative distance	The spacing between the leading and following vehicle	m
Relative speed	(+) ↔ Opening & (-) ↔ Closing	m/s
Following vehicle speed	The instrumented vehicle speed	m/s
Following vehicle acceleration	(+) ↔ acceleration while (-) ↔ deceleration	m^2/s
Throttle pedal movement	in percentage to the maximum allowed movement	%
Brake pedal movement	in percentage to the maximum allowed movement	%

Table (1): The kinematic parameters presented in the final data file.

Although the number of emergency tests is not sufficiently large to give conclusive evidence about how drivers behave in emergencies, the detail on each event is substantial and may be taken as an indication. To enable comparisons of driver behaviour to be readily made during emergency braking, several action points were defined, they are:

1- The leader starts braking.
2- The follower responds by lifting his or her foot of the throttle pedal.
3- The follower starts braking by putting his or her foot on the brake pedal.
4- The leader reaches maximum deceleration.
5- The follower reaches maximum deceleration.
6- The TTC reaches its minimum value.

A set of plots for different parameters from the same emergency braking event and the above described action points are shown in Figure 3.

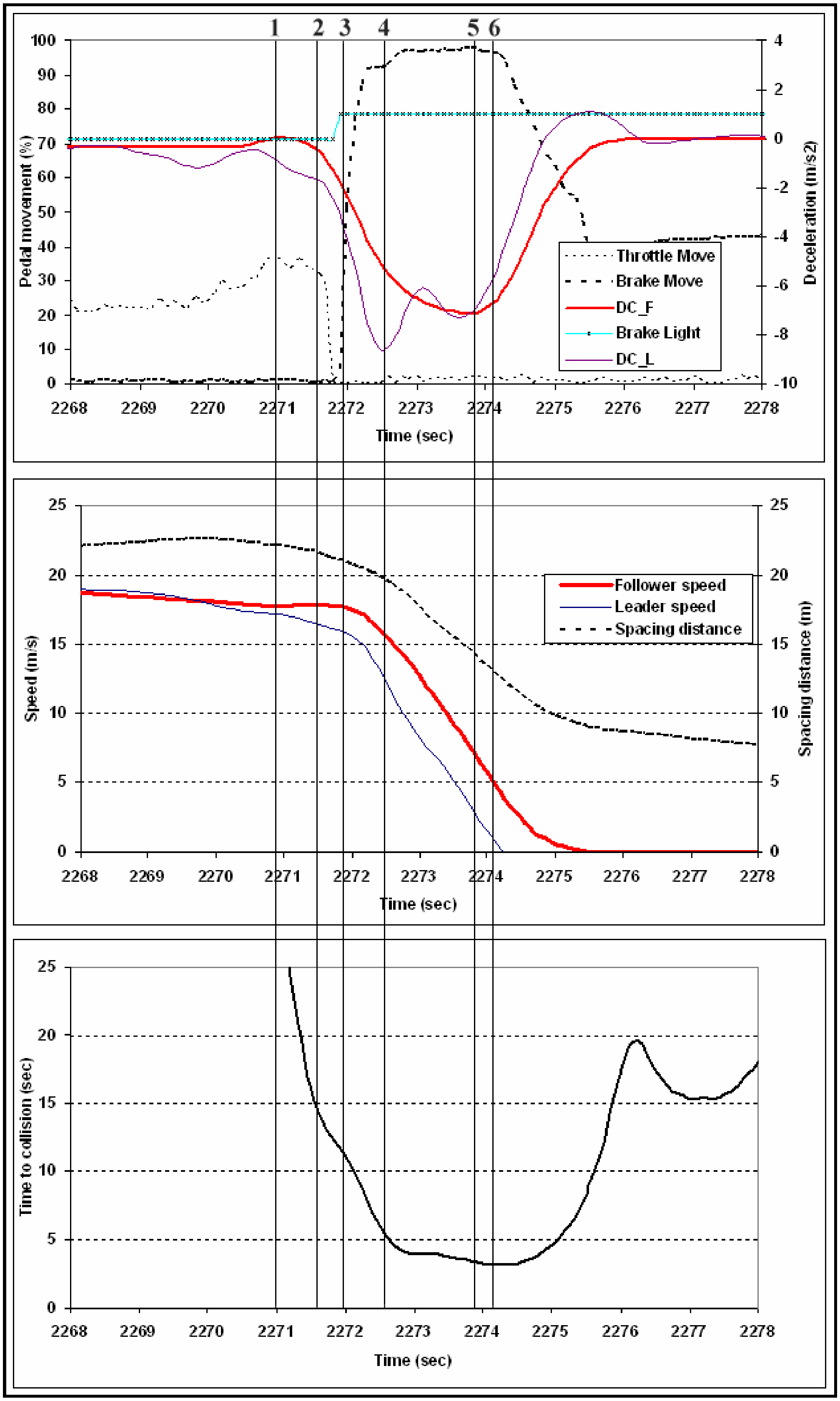

Figure 3: Three graphs showing kinematics parameters during an emergency braking incident

Assessing ACAS

The two stages that summarise the action of an ACAS, are:

- To initiate a warning to the driver about potentially dangerous situations.
- To undertake initial braking to minimise the risk of a collision before the driver starts to respond.

Initiating a warning is the crucial stage, as an ACAS cannot start to respond until a danger threshold is passed, and drivers also need such warnings to shorten their reaction time. In order to assess the benefit of ACAS, two theories of collision warning were tested and assessed for the extent to which they could successfully give advance warning to a driver.

1- The Time To Collision Theory:

In the literature several researchers had considered time to collision (TTC) as a potential parameter to distinguish between dangerous and safe situations. Therefore, the TTC values were gathered for all subjects at the action points 2, 3 and 6 and compared to proposed TTC thresholds from the literature. The TTC values at action points 2, 3 and 6 with respect to speed are shown in Figure 4. The data has shown the TTC_{min} (action point 6) had an average value of 2.4 sec and the effect of speed was not clear ($r^2 = 0.34$). It is interesting to note that all subjects had started their response with a TTC over 4 sec (a threshold which was proposed by Van der Horst (1991)[11] and supported by Farber (1991)[2]). However, the results agree better with Nilsson et all (1991)[7] who suggested that a 4 sec TTC is too short for a warning threshold. Only twice did a driver respond with a TTC of less than 4 second.

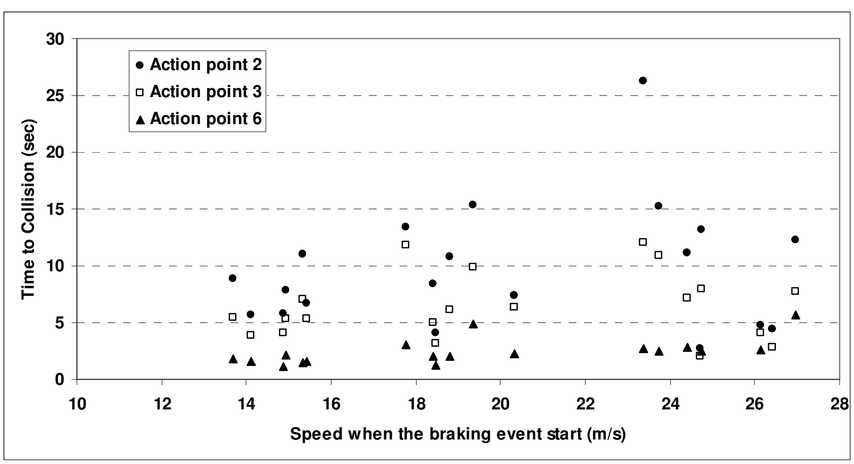

Figure 4: TTC values at action points 2,3 and 6 with respect to speed.

The data also implies that an ACAS system with a four second TTC threshold will be at least 0.5 second late in giving a warning to drivers. The lag time between the moment when drivers started their response and TTC reaching 4 sec is shown in Figure 5. Ideally, an ACAS system should give an early warning to a driver, but the problem is that a higher TTC threshold of say 7 or 8 sec will result in a high percentage of false alarms. This could irritate drivers and result in the ACAS being switched off. In conclusion, the time to collision could be used to describe critical and dangerous car following situations, but an ACAS using TTC as a main parameter in its warning algorithm may not have a noticeable safety benefit as drivers should start their responses earlier.

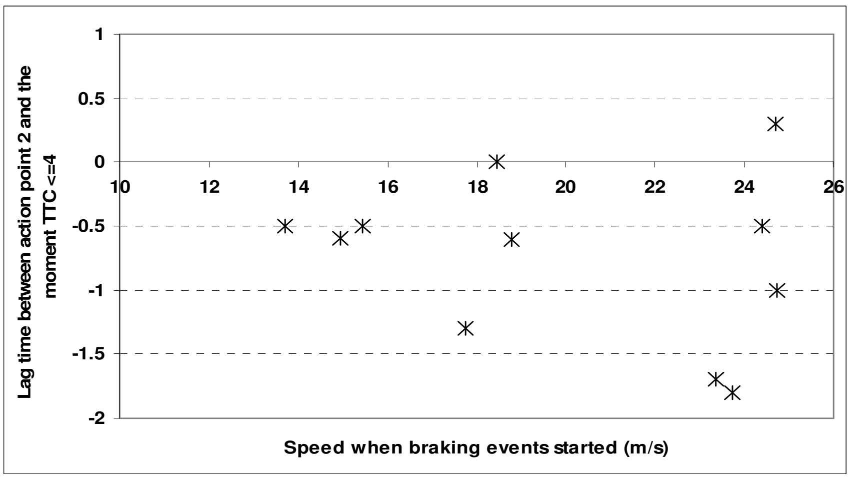

Figure 5: The lag time between action point 2 and the moment when TTC is equal to 4 second with relation to speed.

2- The Reaction Time and Maximum Braking Theory:

This theory has been suggested by Burgett et all (1998)[1]. It uses all available kinematic parameters such as spacing, speeds and deceleration or acceleration from both the leading and following vehicles to initiate a warning. The warning criteria can be summarised as:

- The leader continues to decelerate at the current rate to a stop.
- The following vehicle maintains the same constant speed until the driver responds to the warning by applying the brake.
- The time required for an inattentive driver to respond to a warning by applying the brake pedal is 1.5 sec.
- The alerted driver needs to brake at a constant deceleration rate of 0.75g.
- The minimum distance between the vehicles during or after braking is two meters.

The above assumptions were incorporated into an equation, which then used to determine the Virtual Warning Instigation Moments (VWIM) in our experiments. Next, the time lags between the time when drivers started to respond (action point 2) and the VWIM were determined, see Figure 6. The data has shown that the above algorithm is much better in comparison to the TTC theory as the average lag time was found to be -0.2 sec and not influenced by the speed level. Non-the-less, drivers reacted more quickly than the proposed algorithm in most of the tests. This could be explained by the drivers being more alert during the experiment. The main question that needs to be answered is whether or not such an ACAS would have an added safety benefit?. During our experiment some critical incidents were observed. More than once, a driver avoided collision by swerving and, in one case, a collision took place between the IV vehicle and surrogate vehicle. Although, the number of these critical incident is small they may give us an insight about the benefits of ACAS. The data showed that the ACAS would give a warning before drivers would normally start their response, although the warning lag was found to be within only 0.5 sec, a time which is insufficient to lead to faster drivers' response. Nevertheless, an ACAS coupled with braking system should give a safety gain.

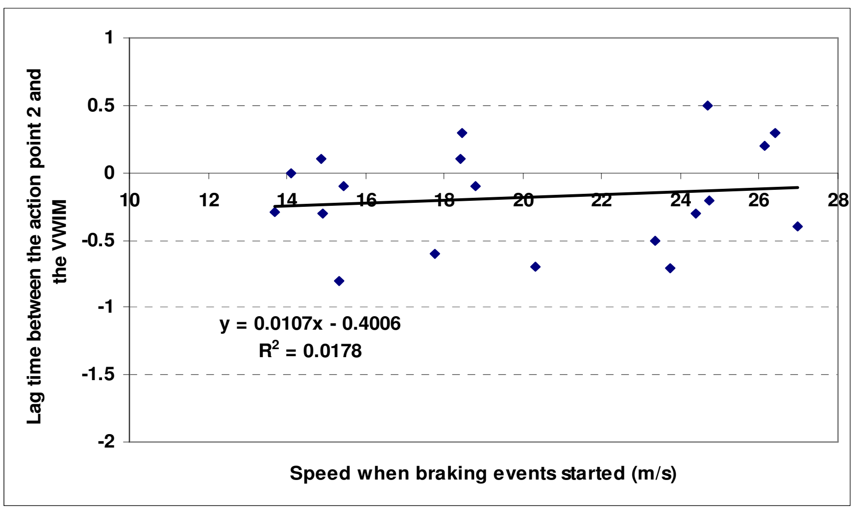

Figure 6: The lag time between the action point 2 and the moment of VWIM for an ACAS.

Discussion and Conclusion

The above tests have shown that ACAS cannot rely on a simple TTC threshold for collision warning instigation. A successful ACAS has to be more complex, assessing a range of kinematics parameters with the lead vehicle, especially its deceleration. However, that may still not be of benefit as drivers were able to respond early and outperform the ACAS in many cases. Therefore, ACAS should include some type of technology to support drivers during their braking. The way an ACAS could support a driver during emergency braking and after starting his or her response is still unclear. The data has shown that subjects were able to make use of all available brake ability of the IV , activating ABS braking and pressing the brake pedal all the way down. In the accident case the subject responded with a 0.8 sec reaction time and was pressing the brake pedal fully within 0.7sec from the moment he started to lift his foot from the throttle. However, the test driver did not steer away to avoid a collision, but instead stayed frozen as if bracing for the accident. Similar observations with regard to reaction time were noticed during the cases where drivers had to avoid collision by swerving. The problem lays in the time to collision at the moment when a driver starts his response, the lower the TTC the more serious the situation. The TTC can be calculated from the following formula:

$$TTC(\sec) = -1 * \frac{DX(m)}{DV(m/\sec)}$$

DX: The spacing distance. & DV: The relative speed]

If we assume that both vehicles have nearly the same speed when the leader starts to brake, then the relative speed value at the moment the follower starts responding will be influenced by two parameters:

(i)- the deceleration of lead vehicle.

(ii)- the driver reaction time.

Drivers have no control over the lead vehicle deceleration, and reaction times are more to do with driver anticipation and, in the case of alert drivers, a one sec covers 75% of reaction times (Johansson and Rumer, 1971)[5]. Therefore, the main factor which could contribute to increase safety during emergency braking is spacing distance over which drivers have full control. However, consideration of the spacing distance alone is not enough for safety, the higher the speed the longer the stopping distance. Instead, the time headway has to be considered as it incorporates both speed and spacing distance. The data has shown that the shorter the time headway at the start of the incident the higher the ratio between the follower and leader maximum deceleration. The relation between the time headway and the (DC_F_{max}/DC_L_{max}) ratio is shown in Figure 7 .

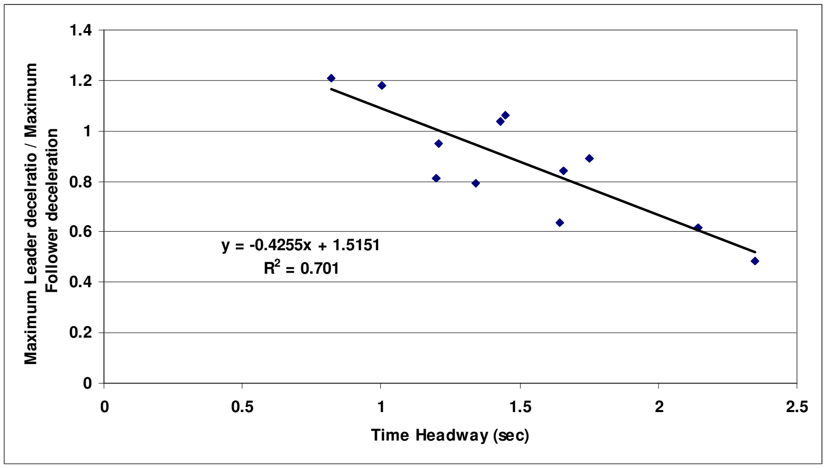

Figure 7: The relation between the time headway and the ration (DC_F_{max} / DC_L_{max}).

In conclusion, an ACAS could always contribute to increase drivers awareness if it has the right collision warning formula, and should never encourage drivers to have shorter time headways when they follow other vehicles. However, further research and testing need to be undertaken to fully understand drivers and how future ACAS could interact with drivers, leading into less rear collision and safer roads.

Acknowledgements

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