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The Impact of Trust on Driver Response to Forward Collision Warning Systems

by

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A Doctoral Thesis

Submitted in partial fulfilment of the requirements

for the award of

Doctor of Philosophy

of Loughborough University

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My greatest thanks go to my family for limitless support and understanding.

Abstract

This thesis reports five studies that investigate the impact of trust on driver response to forward collision warning systems (FCWS). The experiments, while self-contained were conceived to relate together in a cohesive way.

The first three studies investigated the relationship between alarm timing and driver performance in collision situations in a broad range of driving conditions. These studies also established trust models describing changes in driver subjective ratings of trust in response to alarm timing. It was found that an early alarm timing led to quick braking reaction times, resulting from prompt accelerator release. A middle alarm timing induced more consistent braking response than a control condition in which no alarms were presented. A late alarm timing had the potential to delay braking response when driving with long time headways. With respect to trust, early alarm timings induced higher levels of trust than late or middle alarm timings. Moreover the results suggest that the conflict between driver expectation of alarm performance and actual alarm timing results in decreased trust.

Experiment four explored the nature of trust in FCWS. A trust model was proposed that described driver response to false and missing alarms in terms of changes in trust ratings (the 'dynamics of trust'). The proposed model was tested in a driving simulator study in order to confirm its validity. It was found that trust had two different aspects; trust in individual alarms (TIA) and trust in system integrity (TSI) and false and missing alarms affect TIA and TSI respectively. Furthermore, driver response to alarm failure could be interpreted by using TIA and TSI.

The final study considered the effect of alarm timing on driver response to alarm failures; false and missing alarms. It was found that drivers who experienced early alarm timing exhibited negative effects of alarm failures. On the other hand, drivers who experienced late alarm timing were not affected by alarm failure. These phenomena were interpreted from the viewpoint of the relationship between alarm timing, trust, and event awareness.

The contribution of the experimental work to the integration of trust into the design of alarm timing is discussed and the relationship between the experiments explored.

Definitions of particular terms in this thesis

Here terms that were used with a particular meaning in this thesis are defined.

Term: Definition

The dynamics of trust: Changes in driver subjective rating of trust in response to experimental conditions.

Time headway: The time interval between two vehicles in a car following situation based on the driving speed of a following vehicle.

Discouragement: Driver's perception of alarms which are presented after they have started to brake in response to a potential collision event.

Confirmation alarms: Alarms which confirm driver's decision to brake.

Tolerance: Perception of trust that are not impaired by the experience of late alarms.

Triggered alarms: Alarms which are presented based on pre-determined alarm trigger logic.

Untriggered alarm: Alarms which are not presented in imminent collision situations because the warning distance is not achieved.

Behaviour robustness: The degree to which drivers' braking response is affected by false and missing alarms.

Automated response: A tendency for drivers to respond to all alarms without regard to their validity.

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Chapter 1: Introduction

1.1 The background to the study

When driving, drivers must successfully manage the following major tasks; (i) maintenance of lateral control in response to road geometry, (ii) management of longitudinal speed in response to road geometry, forward vision and other vehicles and (iii) achieve adequate awareness of static and dynamic hazards. Failure of driver decision making related to any one the above tasks has the potential to result in traffic accidents.

At a superficial level these do not seem to be hard tasks for drivers to achieve, however, Institute for Traffic Accidents Research and Data Analysis reported that in 2002 there were an estimated 940,000 motor vehicle-related accidents involving 8800 deaths in Japan. In particular, according to the National Police Agency in Japan, rear-end crashes comprised approximately 30.2% of all crashes in 2002. With respect to rear-end crashes, maintaining awareness for forward vision is one of the crucial factors in determining the number of accidents and driver inattention, distraction, and improper lookout (i.e., the driver looked but did not see) have been identified as major causal factors in rear-end crashes (Dingus et al., 1998). Given the number of motor vehicles travelling the roads and freeways throughout the world, not surprisingly, traffic accidents have been recognized as a major social problem to be solved with a high priority.

1.2 The role of technology

Advances in information processing, communications, sensing, and computer control technologies have been achieved to improve the safety of driving or to increase driver comfort. The Intelligent Transportation System (ITS) has been adopted as a general term to describe innovative systems which use the above technologies. However, the road transportation system is extensive and complex and is typically regarded as a set of inter-related sub-systems. Accordingly many terms have been used to describe the introduction of new technology; Advanced Traveller Information System (ATIS), Intelligent Vehicle-Highway Systems (IVHS), and Advanced Driver Assistance Systems (ADAS).

These systems have been classified (Galer, 1993) into broad categories according to whether they:

- i) directly impinge on the driving task (e.g. collision avoidance, intelligent cruise control).
- ii) provide general information relevant to the driving task, environment, and driver. For example, traffic status, accidents, etc.
- iii) enhance the efficiency of driving by providing task specific information (e.g. route navigation systems, surface function condition).
- iv) are unrelated to driving (e.g. telephone, e-mail, fax etc.).

The central focus of this thesis is forward collision warning systems (FCWS). Individual FCWS have slightly different features and functionalities however the design approach typically follows a basic architecture, which is presented in Figure 1-1. Multiple system functions, including sensing, intelligent processing, and communications are required to deliver FCWS and these must be successfully integrated in order to provide drivers with an effective warning system capable of helping to reduce collision accidents.

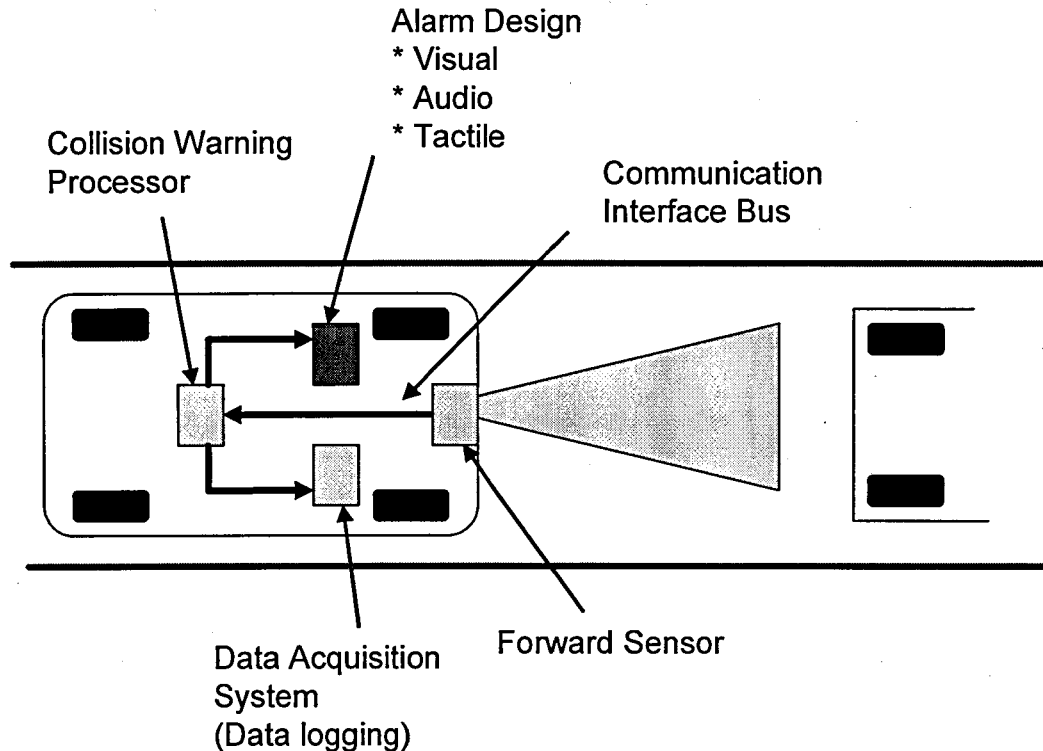


Figure 1-1 Forward collision warning architecture

1.3 Human factors concerns

Once FCWS are a common feature in vehicles it is hoped that they will achieve their promise of increased driving safety. However it has been recognised that human factors considerations are critical to system efficiency (Mast, 1998) and are a central feature of the currently prevailing design philosophy; human-centred system design. Hancock and Verwey (1997) note that current and further technology will allow the system designer to create increasingly intelligent systems, however this does not necessarily mean that the systems are designed intelligently. Inadequate system design without consideration of the human factors perspective will not fully accommodate driver requirements, resulting in poor total system performance under some circumstances.

One of the most frequently proposed arguments is that the introduction of new driver oriented technology may substantially change the driving task (for example Mast, 1998; Dingus and Hulse, 1993). FCWS help drivers to perceive critical situations rather than intervene in the driving task, however, this does not mean that alarms do

not affect driver tasks. Janssen and Nilsson (1993) and Reichart (1993) insist that the way in which the responsibility for action is divided between the system and the driver is a crucial aspect of system design. In an extreme case this may mean that drivers regard alarms as direct triggers for braking actions, as a result drivers mistake the means for the end. The inherent risk of this situation is realised become when alarms are missed due to a system fault and drivers fail to respond to the threat. Conversely past research indicates that there is a possibility that frequent alarms, non-critical event related alarms and false alarms may all reduce driver response to alarms (for example, Horowitz and Dingus, 1992; Dingus et al, 1998). As a result of this the system safety benefit is impaired.

In general, forward collision situations are very time critical and drivers are normally required to take appropriate action within a relatively short time period. Accordingly, alarm timing is a crucial factor for determining alarm effectiveness (Janssen and Nilsson, 1993). Obviously an alarm must provide adequate time for a driver to react to imminent collision situations and alarm timing must be determined with the aim of preventing as many collisions as possible. On the other hand, the determination of effective timing is highly linked to the occurrence of alarm failure (i.e. false or missed alarms) (Hancock et al, 1996, Lee and Kantowitz, 1998). Thus, a comprehensive understanding of alarm timing and its influence on driver behaviour and driver response to alarm failure play a crucial role in the design of FCWS that are effective in all circumstances.

The cognitive characteristics of drivers help to define their information requirements and the optimum formats for ITS interfaces (Lee and Kantowitz, 1998). Furthermore the driver's subjective feelings of trust towards an FCWS plays an important role in its effective use. These considerations indicate that driver trust toward a FCWS should be considered in the design of the system and it is necessary to investigate the above issues from the viewpoint of driver trust in order to accommodate driver requirements in the system design.

1.4 Overall aims of this thesis

This thesis considers three human factors issues which are critical to effective alarm design: driver trust, alarm timing and alarm failure (false and missed alarms). Their interactions are considered in order to establish guidance on the design of FCWS. In particular, it aims to explore:

- alarm timing and its relation to driver behaviour and trust
- the nature of driver trust toward FCWS
- driver response to alarm failure and its relation to alarm timing and trust
- the determination of optimal alarm timings

1.5 The structure of the thesis

The thesis comprises five empirical studies and one literature review, each of which addresses particular issues relevant to the design of FCWS. An overview chapter then synthesises the results and knowledge obtained by these studies, enabling recommendations regarding alarm design.

Figure 1-2 attempts to show the relationship between the chapters in this thesis. The specific literature relevant to driver characteristics and driver performance with and without FCWS and methodologies for assessing driver behaviour comprise the existing knowledge (left hand column). The human factors issues considered in this thesis are represented in the centre column and how they relate to the new research is summarised in the right hand column.

1.6 Chapter-by-chapter brief summary

The first step of this study is a general review of human factors knowledge for FCWS. It considers driver characteristics and performance in collision situations and driver interaction with FCWS. It is clear from the review that FCWS have the potential to reduce accidents caused by driver error. However system effectiveness is highly

dependent on alarm modality and its relation to driver behaviour and the type and timing of alarms may affect the efficiency of driver behaviour. Furthermore, driver interactions with the collision warning system are influenced by multiple factors; situation awareness, complacency, trust, etc. However research has not identified the relationship between these factors and driver behaviour.

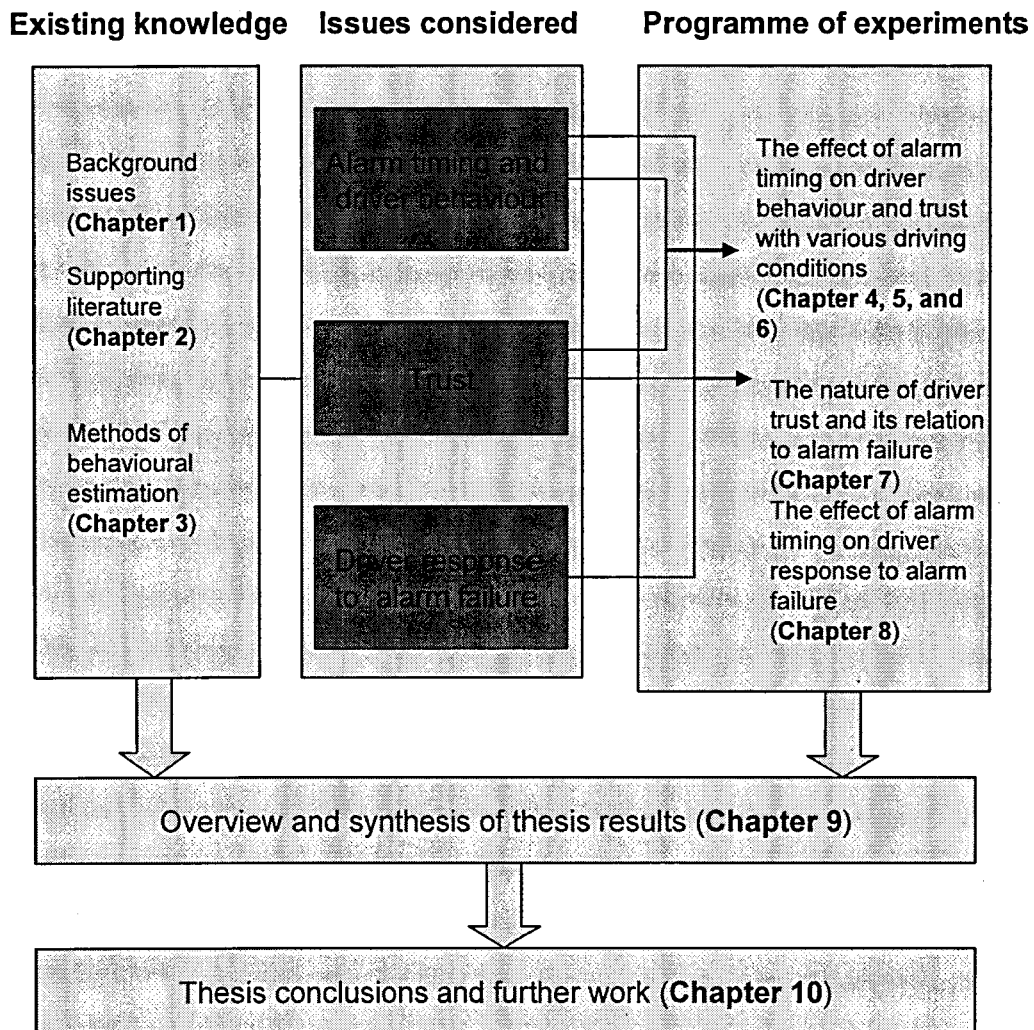


Figure 1-2 Structure of the thesis

In chapter 3, several methodologies for assessing the effect of the introduction of FCWS on driver behaviour are reviewed in order to identify the most appropriate strategy for the current research. Driving simulator studies were subsequently chosen for the behavioural experiments reported in this thesis.

The first three empirical studies reported in chapters 4, 5, and 6 provide a broader understanding of the relationships between alarm timing, driver behaviour and trust. In chapter 4 the effects of three different alarm timings on driver behaviour and trust are investigated with respect to a single scenario. Chapter 5 considers how the presentation of alarms may influence driver behaviour and attitudes toward alarms in more depth by incorporating a wider range of driving conditions; three different driving speeds and two different time headways. Furthermore, chapter 6 reports a study that involves a low speed driving condition (30 mph) with two different decelerations of a leading vehicle.

Accordingly, driver behaviour towards alarm timing with various driving conditions is investigated and the contribution of alarm timing to safe driving is assessed. Furthermore, the relationship between alarm timing and driver trust is established and several important contributing factors which affect driving trust are identified.

Chapter 7 explores the nature of driver trust with respect to FCWS. A trust model is proposed that describes driver response to false and missed alarms in terms of changes in trust ratings (the 'dynamics of trust'). The proposed model is tested in a driving simulator study in order to confirm its validity. It is proposed that trust has two different aspects; trust in individual alarms (TIA) and trust in system integrity (TSI) and false and missing alarms affect TIA and TSI respectively. Furthermore, driver response to alarm failure is explained by using TIA and TSI.

In chapter 8, the effect of alarm timing on driver response to alarm failure is reported. It is proposed that impaired system effectiveness caused by alarm failure may be mitigated by manipulating alarm timing. This phenomenon can be explained by way of the trust model that accounts for the relationship between alarm timing, subjective ratings of trust and event awareness. The empirical results suggest that alarm timings have the particular potential to induce inappropriate driver mental models relevant to

the relationship between trust and event awareness gained through a potential collision event.

Chapter 9 discusses the combined results of the various studies and in doing so forms the basis for provisional design guidelines for alarm timings which are applicable to most circumstances. This is mainly argued from the viewpoint of driver trust.

The conclusions of the thesis are summarised in chapter 10. This includes a statement of the overall and most important contributions of the thesis to new research knowledge and specific requirements for further work.

Chapter 2: Driver response to forward collision warning systems: A review of the literature

2.1 Introduction

There are numerous human factors issues relevant to warning systems that must be taken into account in order to successfully determine system design characteristics. The primary aim of this chapter is to understand which human factors issues related to driver-alarm system interactions should be investigated and to determine which issues must be resolved. As a result, this chapter provides a critique of the literature related to the current thesis.

Figure 2-1 comprises a model for considering driver interaction with forward collision warning systems (FCWS). The original diagram draws on the framework described by Lee and Kantowitz (1998), it is modified for this study. It integrates three important themes that must be accommodated in determining the requirements of design characteristics of FCWS. More specifically, system capabilities, environmental factors, and driver characteristics provide the context for driver interaction with FCWS and play an important role in determining how alarms should be presented to drivers.

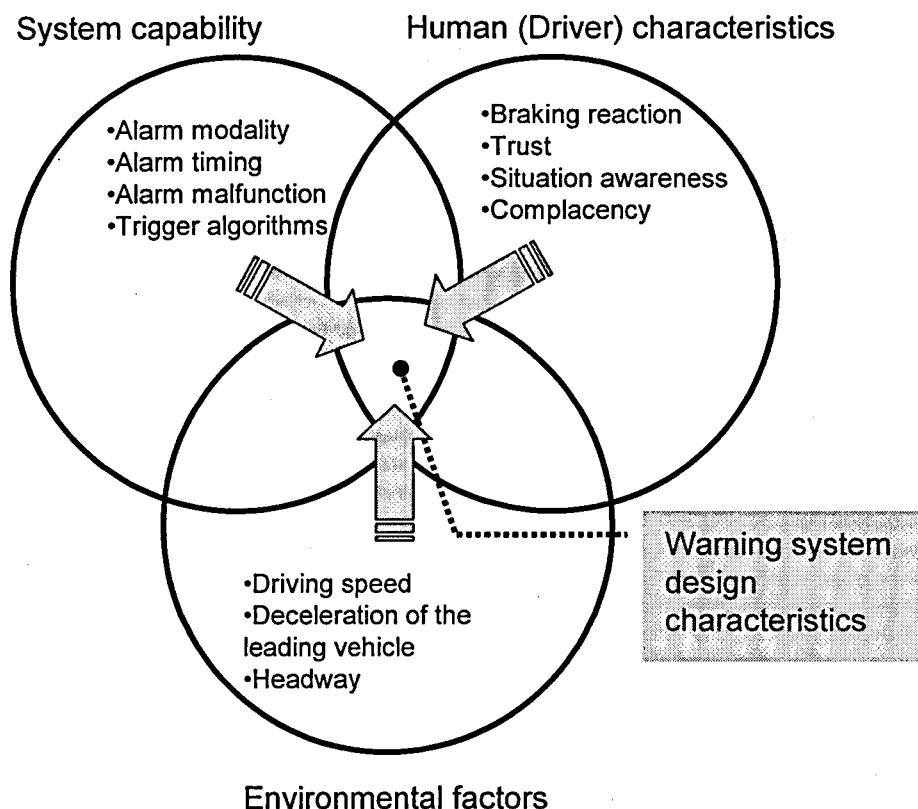


Figure 2-1 The joint influence of system capability, human characteristics and environmental factors on warning system design characteristics

The role of driver characteristics in driving is considered first (section 2.3), this is followed by driver errors (section 2.4). This section includes general human error models and, more specifically, driving-related errors such as late detection which have the potential to induce collision accidents. The driver-based aspects of car following behaviour, including driver choice of speed, perception of imminent collision situations, and basic driver ability to respond to imminent collisions are discussed (section 2.5). Finally driver trust (section 2.8), complacency, and situation awareness (section 2.9) are considered from the view point of driver perception of FCWS.

The section concerned with system capability (section 2.6) describes the primary role of alarms in order to understand the changes in the driver's role following the introduction of FCWS. This is followed by a consideration of alarm modality and alarm timing, which may have the potential to determine system effectiveness. Furthermore the notion of alarm malfunction (section 2.7) is considered as an

importation mechanism for gaining knowledge about driver response to alarm malfunction and its relation to impaired system effectiveness.

It should be stressed here that environmental factors (driving conditions including driving speed and driving severity) are treated as the need arises as issues which may affect alarm capability and driver performance but are not considered independently.

2.2 Overview of drivers' roles in driving

Rasmussen (1983) classified human behaviour into three basic hierarchical categories: namely skill-based, rule-based, and knowledge-based behaviours. This classification is referenced most frequently when general human behaviour in response to differences in human tasks are described. Skill-based behaviour is the lowest level and requires minimum conscious control. It involves automated schemata, or action plans, which enable routine behaviour. For example, walking in familiar places or starting a car by an experienced driver is classified as Skill-based behaviour. Rule-based behaviour involves automated activation of rules or productions. Specifically, pre-learnt rules or know-how are applied to cope with problems when current situations depart from routine ones. Knowledge-based behaviour applies to situations where it is not possible to use typical action patterns in response to past experiences. In such situations people require new decisions or diagnoses to resolve the problems with which they are faced. It can be said that knowledge-based behaviour is one of the most characteristic traits of human beings.

When describing the driver's typical tasks, it is commonly stated that they can be divided into three hierarchical levels (Michon 1985). The three levels underlie the cognitive control of driving and they provide a useful general understanding of the driver's roles in driving. Figure 2-2 shows the hierarchical structure of the road-use tasks, proposed by Michon (1985). In this diagram the strategic level involves the general planning stage of a trip, including the determination of trip goal, route, and modal choice. Plans are derived from consideration of mode, route and timing that can lead to an efficient trip and also accompanying factors such as aesthetic satisfaction that can lead to a comfortable trip. The manoeuvring level defines

negotiation of common driving situations such as curves and intersections, gap acceptance in overtaking or entering the traffic stream. Obstacle or collision avoidance including static obstacles or a leading vehicle are also driver tasks involved in the manoeuvring level. The control level represents driver automated action patterns (i.e. steering, braking, and shifting). At the tactical level it is assumed that each hierarchy dynamically interacts with each other. That is the control level reflects the general goals set at the strategic level. Conversely general trip plans may be occasionally rearranged in response to the outcome of specific manoeuvres.

The different level of decision making reflects the different amount of time available to implement tasks. Decisions at the strategic level generally do not need real time. Trip plans can be implemented before starting to drive and changes in trip plans can be decided many minutes before execution. Decisions at the manoeuvring level are constrained by real time. It is necessary for drivers to implement the appropriate actions in seconds. The control level is mostly time critical and demanding. It requires only milliseconds to implement the critical decision making that may contribute to safe driving. In other words, failure of appropriate decisions at the control level may directly cause accidents.

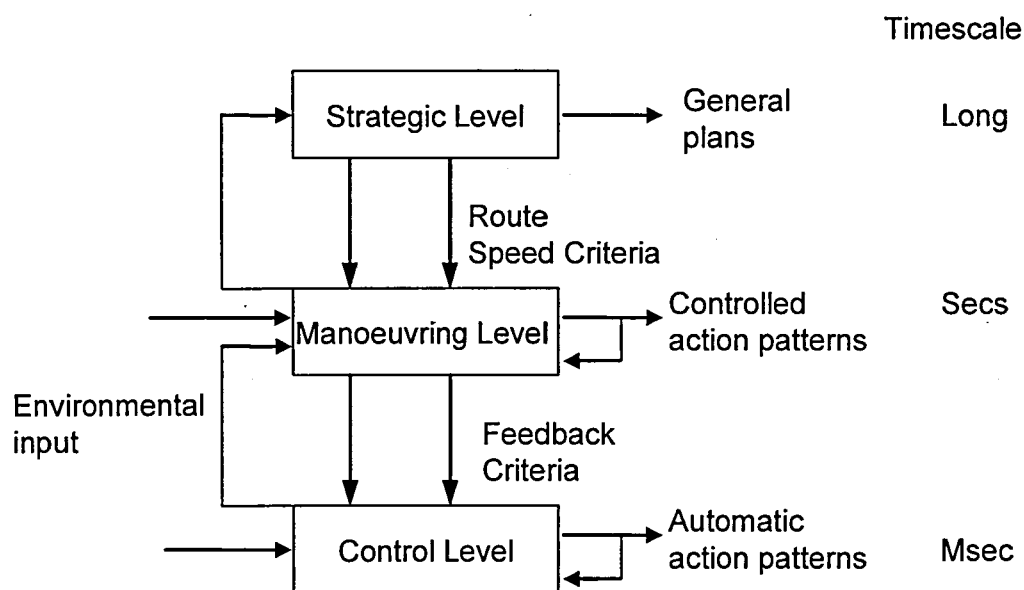


Figure 2-2 Hierarchic structure of the driving task (Michon, 1985)

Table 2-1 Classification of selected driving tasks by Michon's control hierarchy and Rasmussen's skill-rule-knowledge framework (Ranney, 1994)

	Strategic	Manoeuvring	Control
Knowledge	Navigating in an unfamiliar area	Controlling a skid	Novice on first lesson
Rule	Choice between familiar routes	Passing other vehicles	Driving unfamiliar vehicle
Skill	Route used for daily commute	Negotiating familiar intersection	Vehicle handling on curves

The control hierarchy of driving has been related to Rasmussen's taxonomy, as shown in Table 2-1 (for example, Hale et al., 1990; Ranney, 1994). For experienced drivers, most driving tasks cluster in the three cells on the diagonal that runs from the upper left to the lower right box in the figure. The control, manoeuvring, and strategic level tasks are implemented as skill, ruled and knowledge based behaviour respectively. As shown by the examples in other table cells, however, exceptions may occur in response to skilled or novice performance and familiar or unfamiliar situations. For example, novice drivers initially use knowledge based behaviour to shift gears, while experienced drivers use skill based behaviour. Experienced drivers can generally use skill based behaviour for navigating along highly familiar routes or for negotiating familiar intersections. Rule-based behaviour will dominate in unfamiliar situations where previous experience helps select rules in order to manage the situations. However novel or unexpected situations, for which no applicable rules can be adopted will disrupt skill based behaviour and necessitate knowledge based behaviour.

To sum up, driving tasks can be understood in terms of their basic content of skilled human behaviour. In potential collision situations, where drivers must act to prevent collision events occurring, drivers need to expertly execute tasks at the control and manoeuvring levels. These tasks are implemented as automated action patterns (skill based behaviour) or rule based behaviour in response to driving experience or driving situations. Accordingly there is a possibility that a driver's response for surviving an imminent collision situation will be implemented as different types of behaviour in the three-level hierarchy according to their experience or the driving conditions.

2.3 Driver's error in driving

For the last two decades, considerable research has been conducted from various perspectives in order to understand the nature of human error (Lourens, 1990; Michon et al., 1990; Norman, 1981; Reason, 1987; Rumar, 1990;). Rasmussen (1990) has proposed that errors should be considered as a part of normal behaviour. Drivers must cope with a considerable amount of information of an increasingly complicated nature, covering all three levels of the driving tasks discussed above (Michon et al., 1990), and this provides new opportunities for human error to precipitate hazardous situations.

This section will review models of human error in order to provide a background against the behaviour of drivers who have the support of FCWS can be assessed.

2.3.1 Norman's error theory

One of the most influential descriptions of human error has been provided by Norman (1981). He proposed the following three types of errors.

Slips: This is a type of error which is related to events in which the planned action would have achieved the desired goal. In other words, slips may refer to execution failure.

Lapses: This is a type of error which occurs in a memory process. It involves simple forgetfulness, inaccurate memory and so on.

Mistakes: Mistakes reflect execution of plans that would not have achieved the desired goals. They could be called a planning failure.

Generally, slips derive from intrinsic factors which are relevant to personal resources. On the other hand, mistakes derive from external factors such as human interface design for human-machine systems, task environments etc.

2.3.2 Generic error-modelling system (GEMS)

Table 2-2 The major error-shaping factors at each level of performance (Reason, 1987)

PERFORMANCE LEVEL	ERROR-SHAPING FACTORS
<i>SKILL-BASED</i>	1. Recency and frequency of previous use 2. Environmental control signals 3. Shared schema properties 4. Concurrent plans
<i>RULE-BASED</i>	1. Mind set ('It's always worked before') 2. Availability ('First come best preferred') 3. Matching bias ('like relates to like') 4. Over-simplification (e.g., 'halo effect') 5. Over-confidence ('I'm sure I'm right')
<i>KNOWLEDGE-BASED</i>	1. Selectivity (bounded rationality) 2. Working memory overload (bounded rationality) 3. Out of sight out of mind (bounded rationality) 4. Memory cueing/reasoning by analogy 5. Matching bias revisited 6. Incomplete/incorrect mental model

Reason's (1987) generic error-modelling system (GEMS) is a well-established error theory, describing a cognitive framework for identifying common error types. GEMS has integrated theory from information-processing models and Rasmussen's taxonomy of human behaviour. In GEMS, Reason classifies errors as skill-based slips, rule-based mistakes and knowledge-based mistakes. In the domain of human-machine systems, the principal role of the human which is relevant to skill-based behaviour is that of monitor, and thus the preventative form of error is a monitoring failure. Rule-based mistakes and knowledge-based mistakes result from actions that were insufficient to meet the intended goal.

GEMS has not only provided a description of the character of errors, it also includes useful elements called error-shaping factors. Reason describes error-shaping factors at each of the three human behaviour levels and they may be useful in predicting the form of driver errors in driving (Michon et al., 1990). The details are shown in Table 2-2.

Taking the three levels of driver tasks mentioned earlier into account, drivers are likely to make slips or monitoring failures (e.g., passing the intended junction from the motorway, colliding with the vehicle in front) at all task levels. Furthermore at all task levels, drivers are also likely to make mistakes or fail to solve problems (Michon

et al., 1990). In the manoeuvring level, for example, drivers may misjudge the speed of oncoming vehicles, or changes in relative speed with a leading vehicle or attempt a pass that might result in a collision.

The analysis above clearly indicates that the execution of driving tasks is not simple, and in order to prevent drivers from making errors, a very comprehensive and technically sophisticated support system might be needed to cover all situations.

2.3.3 Late detection

With regard to collision accidents between road users, 'Recognition errors', 'Decision errors', and 'Performance errors' might be used to describe the main types of human error (Dingus et al., 1998; Rumar, 1990). Recognition error refers to failure to detect another road user in time to avoid a collision and is the most frequent error type (Dingus et al., 1998). Two main categories of the causes of failure to detect another road user can be given as follows (Rumar, 1990):

- A cognitive error; *"illustrated by a failure to look in the direction of the road user in question, or failure to look for the specific type of road user type in question"*.
- A perceptual error; *"illustrated by the failure to detect another road user in peripheral vision or in situations of reduced ambient illumination"*.

Rumar (1990) insists that the task of detecting oncoming vehicles is not automated and skill-based, but controlled and rule-based. Moreover given the speeds and the masses involved, it is difficult to recover from a detection error once it has occurred, so the driver is particularly vulnerable to this type of error.

In order to decrease collision accidents, the provision of improved support for driver recognition tasks is likely to be a crucial factor. FCWS have an important potential to provide early detection of collision situations. An advance warning of only a second or two is important given the dynamic nature of driving, driver reaction time and the complex nature of the cognitive and perceptual tasks involved.

2.4 Driver response to imminent collisions in car following situations

The review of the literature related to the driver's task and human error suggests that collision accidents may be caused by complex and coincident factors. Accidents may not only derive from late detection of imminent collision situations with a leading vehicle, resulting in a delayed response to the brakes, but also the driving speed or the headway distance with the leading vehicle immediately before the accident. This would be an example of inappropriate driver behaviour at the manoeuvring level. This section summarizes research on the factors which may determine the occurrence of collision accidents. Specifically the nature of 'headway maintenance', 'estimation of time to collision', and 'driver performance in braking response' are discussed.

2.4.1 The notion of headway distance in the vehicle-following situation

A driver's speed choice is one of the most important contributing factors which determine accident involvement and excessive speed can be regarded as a driver error related to collisions (Rumar 1990). If drivers adopt a preferred speed that is higher than the mean speed of other vehicles then they will inevitably be involved in more following situations even if their accident involvement may be more dependent on their risk taking behaviour. However, a number of further driver choices regarding their driving behaviour may influence car following i.e. their propensity to overtake a lead vehicle; their adaptation of short or long headways, their willingness to accept risk of collisions etc. In this section an overview is given of car following strategies including speed choice.

Noguchi (1990) investigated drivers' speed choice by way of in-depth interviews with 26 Japanese drivers. The subjects were asked to imagine themselves driving on a highway or on a motorway with speed limits of 50km/h and 100km/h, respectively. They rated what actual speed they would drive, and also what they would consider to be economic, safe, and pleasant speeds. As can be seen in Figure 2-3, the results suggest that the subjects placed the safe speed above the speed limit. The chosen speed appears to represent a compromise between competing desires for pleasure and

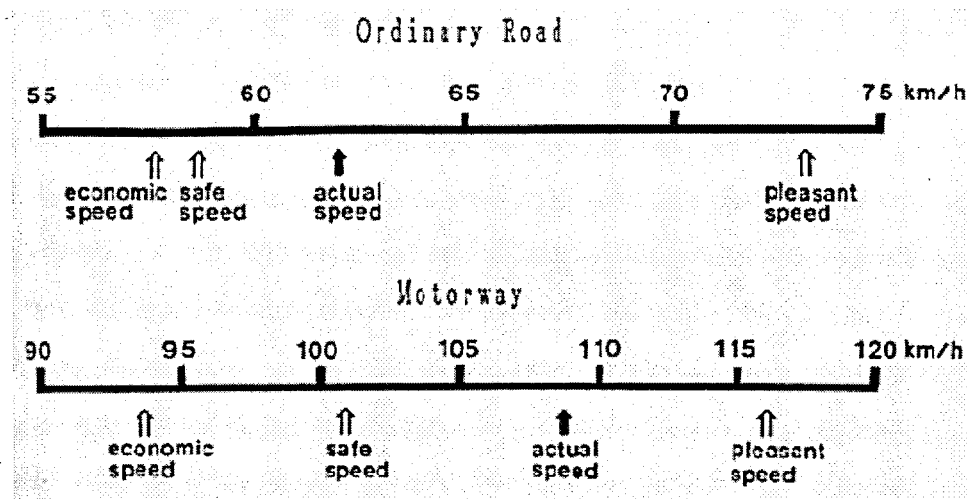


Figure 2-3 Driver's speed choice according to driving speed (Noguchi, 1990)

safety. Interestingly safe and actual speeds are both above the speed limit on both road types. Previous research suggests that increased driving experience leads to increased confidence in one's own driving skills but also reduced concern for risk and driving safety (Duncan et al., 1991; Lajunen and Summala, 1995; Näätänen and Summala, 1974). It has been suggested that a driver's behaviour in traffic may reflect their attitudes, and beliefs and personality characteristics, however, comprehensive understanding of individual driver characteristics and their relation to driver behaviour and accident involvement is still not clear (Lajunen and Summala, 1997).

Evans (1991) argued that speed variance is a more important factor when considering safety than speed itself. This was based on data produced by Solomon (1964) and Cirillo (1968) that showed that a driver driving at close to the average speed has a lower crash risk than drivers driving at higher or lower than average speed. Evans (1991) referenced another study by Hauer (1971) in order to emphasize the importance of driving at a consistent average speed. This research found that crash rates are proportional to the number of times a vehicle is overtaken or overtakes. These are at a minimum when the vehicle is driving at the average speed.

This review will now consider driver behaviour in car following situations using a test vehicle. Colbourn et al., (1987) conducted an experiment using a controlled-track in order to estimate the effect of driving experience on driver behaviour in a vehicle-following situation. 18 male drivers took part in the experiment and were assigned to three distinct groups according to driving experience: inexperienced drivers, drivers

with low experience and experienced drivers. Each group had 6 drivers. Two independent variables were manipulated; driving speed and an instruction to the participants about the possibility of the lead vehicle braking. The different driving speed levels were 48.3, 66.0 and 80.5 km/h and the two different instructed probability levels of the leading vehicle's braking likelihood were 'low' and 'high'. The headway distance to the leading vehicle was recorded and a margin of safety computed by calculating the amount of initial headway lost when the leading car braked rapidly.

The results showed that headway distance increased with driving speed but the difference in probability levels did not affect headway distance. Although there was no statistically significant difference a noticeable trend was found. The increase in headway with speed appeared to vary as a function of driving experience. Furthermore, the study found that safety margins did not change over the speed range tested. That is, drivers adopted headways which were long enough to allow them to stop safely following critical deceleration of the lead vehicle.

Ohta (1993) demonstrated individual differences in headway distance. This study investigated the correspondence between changes in traffic environment and individual driver's car following behaviour with a field experiment. Headway distances were measured in response to three different driving speeds; 50, 60, and 80km/h and the drivers' attitudes regarding safety were investigated by way of questionnaires. The results showed that car following strategies may vary in response to both driving situation and individual differences. For example, some drivers increased headway distance with driving speed, while others tried to maintain the same headway distance despite changes in driving speed, depending on their attitudes to safe driving.

Taieb-Maimon and Shinar (2001) conducted a field study to estimate drivers' minimum and comfortable driving headway. Thirty participants took part in this study and the participants were instructed to follow a leading vehicle driving at six different speeds (50, 60, 70, 80, 90, 100 km/h) at a comfortable headway and a minimum safe headway as estimated by them. The results showed that each driver managed to successfully keep a constant headway time in response to the different

driving speeds. Although the adopted headways were consistent within drivers, they differed widely between drivers. This result is consistent with Ohta's (1993) results. With respect to minimum headways, the average minimum time headway was 0.66s, and over 90% of the drivers maintained a minimum headway of less than 1.0 s. Furthermore, 25% of the drivers adopted minimum headways of 0.5 s or less. In addition, they insisted that these minimum safe headway times were as short as, or shorter than, their average braking reaction time in conditions where they were fully prepared to react to imminent collision situations. The average comfortable time headway was nearly constant at all speeds, varying only from 0.94s to 1.00s.

In summary, the results discussed in this section suggest that drivers vary in their ability to implement car following strategies. That is, drivers do not always manage car following situations safely. Some drivers tend to keep short time headways which have a greater likelihood of resulting collision accidents. Although the results show the difficulty of generalising human behaviour it can be said that the possibility of occurrence of rear-end collision events is not low given the task complexity and opportunity for error in car following.

2.4.2 Driver's estimates of time to collisions

To prevent potential collision events, a driver may implement steering or braking actions, or some combination of both, based on their judgement regarding the time to an impending collision. Time to collision (T_c) is the conventional term describing the remaining time before the collision. When considering alarm characteristics, it is necessary to know driver ability to estimate the value of T_c in response to various driving conditions. The next section briefly summarises studies which are concerned with the estimation of T_c .

Cavallo et al. (1997) summarised several previous experiments where drivers approached a stationary obstacle and found that they tended to underestimate values of time-to-collision. More specifically, the combined data yielded an approximate underestimation of 20-30% (Figure 2-4).

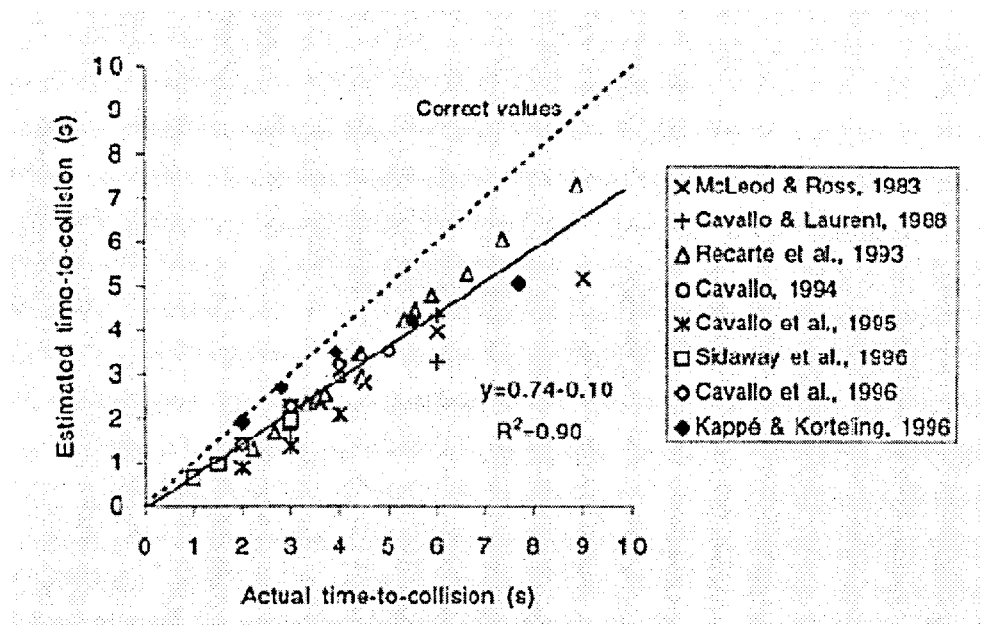


Figure 2-4 Estimated time-to-collision in prior egomotion experiments (Cavallo et al., 1997)

Sidaway et al. (1996) undertook experiments to examine the role of visual information in the estimation of T_c . In experiment I, they manipulated approaching speeds and viewing times to estimate how these factors may affect the estimation of T_c . Three different approach speeds (40, 80, and 120km/h) and six different viewing times (1, 2, 3, 4, 6, and 8 seconds) were involved. Pre-recorded video images that represented a target being approached at 40, 80, or 120km/h were used to create artificial collision scenarios. All the pictures were taken by a video camera positioned on the driver's side of the car. 24 subjects were instructed to observe the recorded view on a television and to estimate values of T_c with the target by pressing a foot switch. After a viewing time dependent on the experimental condition, the videotaped view was replaced by gray screen at 33m from the target. Thus actual time to collision was 3.0, 1.5, and 1.0 seconds for the 40, 80, and 120 km/h velocities respectively. The actual values were compared with driver estimations. The results show that T_c estimation is more accurate with higher approaching speeds and there is no significant difference in T_c estimation with respect to viewing time. That is with even small viewing times, drivers can estimate relatively accurate values of T_c with very limited presentation of optic flow.

Experiment II is essentially a replication of experiment I. The main difference was that each videotape was occluded when the car was exactly 3.5 s from the target sheet. Six different approaching speeds (20, 40, 60, 80, 100, and 120 km/h) and 4 different viewing times (3, 4, 6, and 8 s) were used in this study. As a result, the distances from the target at occlusion were 19, 39, 58, 78, 97, and 117 m for the 20, 40, 60, 80, 100, and 120 km/h velocities, respectively. The results revealed that there was a significant difference in accuracy of T_c with different approaching speeds but the effect of viewing time on accuracy of T_c was not significant.

To sum up, with both of the two experimental scenarios, i.e. a fixed distance and a fixed actual T_c value, the effect of approach speeds was significant. Given that, it can be reasonably concluded that velocity of approach in judging T_c is a crucial factor in accurate estimation.

Cavallo et al. (1997) investigated the effect of road environmental factors on driver estimation of T_c using image sequences showing simulated collision situations. The image sequences showed an approach on a straight road at a constant speed towards a stationary obstacle using a Silicon Graphics workstation. The 'disappearance paradigm' was used in which the film stopped a few seconds before the fictional impact, and twenty-two subjects were instructed to press a button when they expected the collision to take place. Five different road environments were prepared according to the complexity of the visual information (one with only the vehicle obstacle present, and four involving gradual enrichment of the visual scene by adding the roadside, safety posts and texture on the carriageway, see Figure 2-5). Estimated T_c was compared in response to the different road environments.

The results show that the differences in road environments significantly impacts on estimated time-to collision with greater accuracy in more realistic environments. In other words when considering driver performance in simulated imminent collision situations, it is crucial to create realistic road environments in order to increase the reliability of the data recorded.

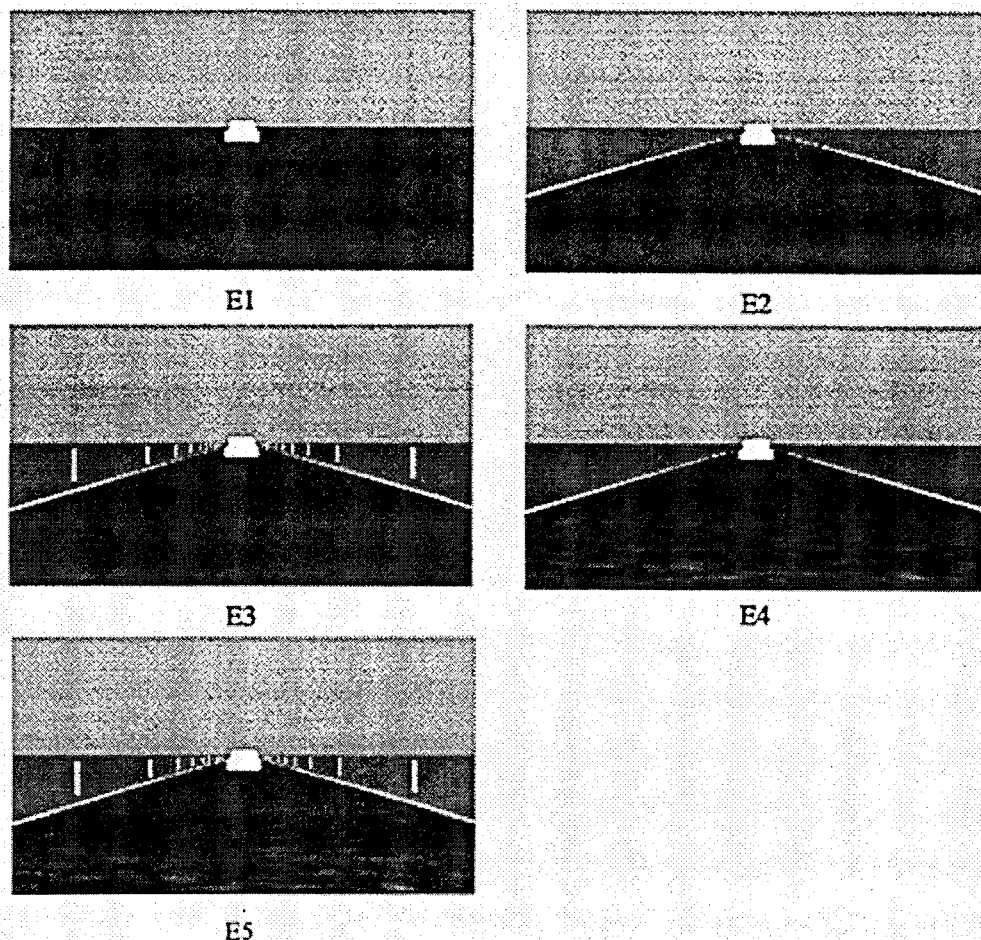


Figure 2-5 The five categories of the road environment factor (Cavallo et al., 1997)

2.4.3 Driver's response to the brakes

When considering human factors issues in FCWS, it is also necessary to gain knowledge about the nature of the driver braking response in critical situations. Here inherent driver performance in braking response without the aid of alarm systems is briefly summarised.

Liebermann et al. (1995) explored the response of drivers to the emergency braking of a lead vehicle with respect to two driving speeds (60 and 80 km/h), two following distances (6m and 12m) and two braking conditions (real and dummy braking). Dummy braking meant that the lead vehicle turned on brake lights but without any braking effort. The dependent variables were the total braking time (TBT) and its subcomponents: braking reaction time (BRT; the time period between onset of the brake lights and release of the accelerator), and accelerator to brake movement time (MT; the time period between release of the accelerator and the application of the

brakes). Fifty-one drivers drove for 45-60 minutes on an open inter-urban road. The results showed that the difference in following distances influenced all three variables. For example, the 6m following distance elicited faster TBTs than the 12m. This tendency was also valid for the other two variables (BRTs and MTs). However the speed factors did not affect braking strategies. As for the comparison between real and dummy braking of the lead vehicle, TBTs for the real braking were faster than those for the dummy braking, resulting in a prompt movement from the accelerator to the brakes.

Schweitzer et al. (1995) estimated drivers' maximum performance in braking reaction (i.e. the time period between onset of the brake lights of a leading vehicle and application of the driver's brakes) with relatively young drivers (aged 21-30 years). They implemented a field trial manipulating driving speeds (60 and 80 km/h), headway distance (6 and 12m), and driver expectancy of braking events (no-expectancy, partial knowledge, and full knowledge of the forthcoming manoeuvre) and estimated how these factors may influence driver braking reactions. The results show that driver braking reaction is not affected by differences in driving speed but varies according to headway distances and driver expectancy. More specifically, the study found a mean braking reaction time of 0.678s for the non-expectancy condition. This mean value was lowered with expectancy and the reaction time reached 0.515s for the 6m headway distance in the full awareness condition.

Green (2000) contributes to a broader understanding of driver braking reaction time by summarising a wide variety of past results and suggests important contributing factors which may affect braking reaction time. Specifically, expectancy has the greatest effect. With high expectancy and little uncertainty, he concludes that the best driver response time is about 0.70 to 0.75 sec, of which 0.2 sec is movement time i.e. the period from release of the accelerator until brake application by referencing a variety of past studies (e.g. Johansson and Rumar, 1971; Norman, 1952; Olson and Sivak, 1986).

Green concludes that with normal, but common, signals such as brake lights, expected times are about 1.25 sec by referencing several studies (e.g. Alm and Nilsson, 1994; Chang et al., 1985; van Winsum and Brouwer, 1997). However driver response time

for surprise events, for example an object suddenly moves into the driver's path from off the road, is about 1.5 sec, including 0.3 sec movement time. For these findings he cites the work of Hankey (1996) and McGehee et al. (2000).

Green also indicates the effect of age, gender, driving urgency, and cognitive loading on braking response by citing past work. Age factors may also affect driver response time with older people responding about 0.3 sec more slowly in many cases (e.g., Summala and Koivisto 1990). With respect to gender, some studies showed that there is no significant difference in braking reaction time between male and female drivers (e.g. Hankey, 1996) but other studies found a faster response by men (e.g. Lings, 1991). Furthermore, cognitive loading significantly influences driver response time. Drivers respond more slowly when there is a high cognitive load, for example, when driving a complex roadway or when using cellular phones (e.g. Nilsson and Alm, 1991). Finally, urgency may affect driver response to the brakes, specifically drivers respond faster when aroused by a shorter time-to-collision (e.g. Hankey 1996).

2.5 Driver behaviour towards forward collision warning systems

Up to this point driver performance without the aid of driver support systems has been considered. However the introduction of FCWS intended to decrease traffic accidents may change the driver's role and behaviour substantially. First this section will briefly summarise the role of alarms by considering past research, including general alarm systems, which have been introduced in industrial domains such as process control systems, aviation and power generation and distribution.

FCWS are subject to a variety of human factors issues which have the potential to influence system effectiveness. When considering the design of in-vehicle collision warning systems, sufficient consideration has to be given to the following questions (Janssen and Nilsson, 1993, Hancock and Parasuraman, 1992):

- 1. What should be the criterion for alarm activation?*
- 2. What action will subsequently have to be performed by the drivers?*

3. How does use of the warning system influence driver behaviour?

The first two issues seem very simple but include fundamental concepts which may determine alarm effectiveness. The first and second questions are relevant to alarm timing and alarm modality respectively. Possibly the most important requirement for designing in-vehicle warnings which support drivers in avoiding accidents is to induce appropriate driver actions in a timely manner and without major disturbance to vehicle control. This section will review these factors from a variety of relevant studies in order to understand the requirements for alarm design that can improve driver behaviour in critical situations. This knowledge will help provide answers for the third question, which is the focus of this thesis.

2.5.1 Role of alarms and their impact on human behaviour

The aim of any warning system is to direct human attention away from other ongoing activities and towards the condition alarmed to reduce accidents and incidents (Wood, 1995). Moreover, warnings have the potential to modify human behaviour in other ways that improve safety. A number of studies have provided specific evidence that human behaviour may be improved by warnings (Byblow and Corlett, 1989; Hakkinen and Williges, 1984; Singer and Dekker, 2000; Sorkin et al., 1988; Stanton and Baber, 1997).

Warnings can properly be viewed as communications between warning systems and the people that use them. A basic model is shown in Figure 2-6 (Laughery and Wogalter, 1997). The model includes a sender, a receiver, a channel or medium through which a message is transmitted, and the message. A receiver is the user of the system to whom the safety information must be communicated. The message is the safety information to be communicated. The medium refers to the channels or routes through which information is sent to a receiver.

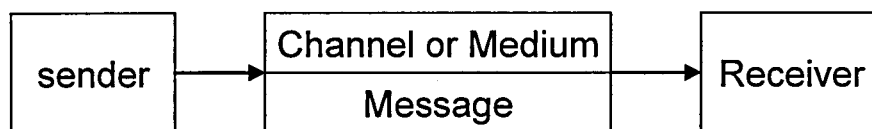


Figure 2-6 Simple communication model as a role of alarms (Laughery and Wogalter, 1997)

Stanton (1994) proposed a conceptual model showing the flow of information between system and users (Figure 2-7) where the transition of alarm information is shown by the arrows. If a safety relevant change has occurred, operators need to be informed about it. Whether alarms are provided or not is determined by measuring a value or, more probably, set of values. If this value is beyond the set threshold alarms are provided using several possible communication media, such as bells, flashing lights, etc. The presentation of alarms helps draw operator attention to the critical event, inducing appropriate operator decision and action. It should be stressed here that Stanton insists that only when the cycle of activities is successful will the appropriate action be taken.

Lehto and Papastavrou (1993) proposed an information processing model in order to discuss issues associated with the effectiveness of warnings. A diagram of the model is shown in Figure 2-8. The model includes six stages, starting with the presentation of the warning information and ending with the required response. Four other intermediate stages are included; they relate to attention, comprehension, beliefs and attitudes and motivation. Given that the warning information is presented, the receiver must notice and attend to it and it is possible to estimate the attention-demanding properties of warnings by measuring reaction time or eye movement. Next, having been attended to, the message must be understood. Having been understood, the warning needs to agree with the receiver's existing attitude and beliefs about a system's likely performance and operational capability. Whether information in a warning is accepted as true or not is critical at this stage. Next, it must motivate people to comply and perform the appropriate behaviour. Finally, the individual must be capable of carrying out the behaviour. It should be stressed here that for the warning to be effective, it must be successful at each of these stages.

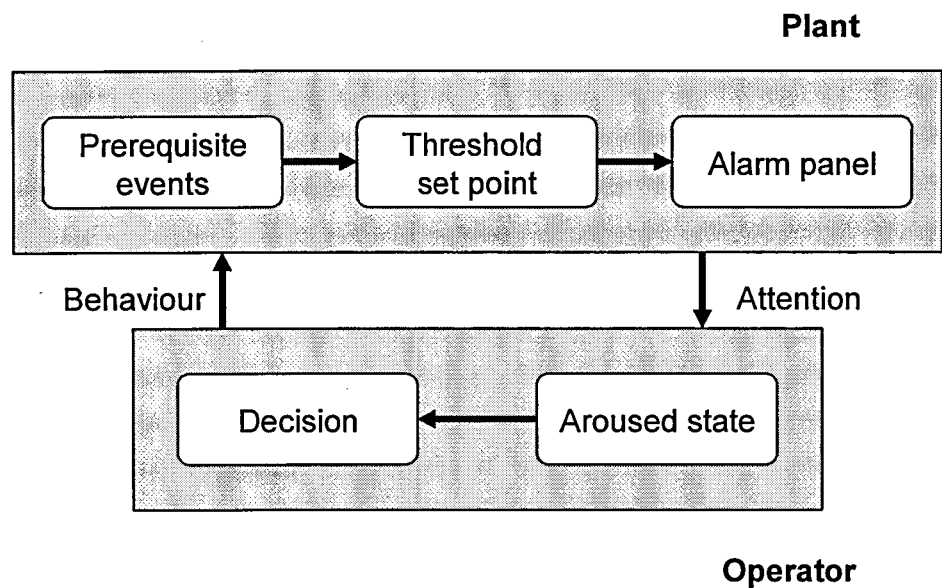


Figure 2-7 A systems model of alarms (Stanton, 1994)

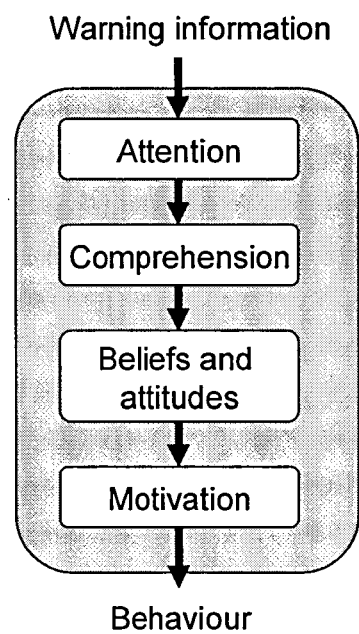


Figure 2-8 A human information-processing model of stages leading to compliance behaviour (Lehto and Papastavrou, 1993)

Ward and Hirst (1997) related Rasmussen's levels of cognitive functioning and information representation to Michon's (1985) levels of driving tasks. Specifically, skill, rule, and knowledge-based driving task levels of functioning mapped on to control, manoeuvring, and strategic levels respectively. Furthermore this study proposed levels of driving tasks which in-vehicle information systems, including FCWS, can support. They concluded that FCWS may help at the manoeuvring level. Janssen et al. (1993) also reached the same conclusion about FCWS and their relation to driving tasks.

To sum up, when designing FCWS it is necessary to consider the entire flow of driver behaviour from the presentation of alarms to driver action to achieve the desired alarm effect.

2.5.2 Alarm modality and its contribution to safe driving

Although there are no particular recommendations for the selection and design of appropriate alarm modalities for in-vehicle warning systems, at least three types of modality (visual, audio and tactile) and their combination are available for collision warning systems (Gupta et al., 2002). With respect to driver preferences for alarm modality, research in the aviation domain, where alarm systems have been commonly used, indicates that pilots prefer visual over auditory warnings when there is enough time to react Stokes et al. (1990). However, human preference for alarm types is likely to be different when a time critical response is required. The next section will review past research regarding alarm modality for FCWS.

Hirst and Graham (1997) considered the differences in the kinds of images which have been provided as visual alerts in FCWS and found the following results. Compared to abstract visual displays, pictorial visual displays may induce more prompt response to the brakes. Their study indicated that the design of visual warning images is a critical factor in determining driver response. They found that more intuitive images, which represented critical situations directly, led to a quicker response to the brakes. Dingus et al. (1998) conducted several on-road experiments to determine how collision warning displays can influence driver behaviour regarding headway maintenance. First, they found that alarm displays, which gave graded

warnings as well as headway maintenance information, encouraged drivers to maintain larger, safer headway distances than when they drove without any display. Second, combined visual/auditory displays induced increased headway distance compared to solely visual or auditory displays. It was concluded that warning displays regarding headway distances have the potential to help drivers maintain safer headways.

Alm and Nilsson (2000) investigated visual warning messages in incident warning systems and estimated the effect on traffic safety of the difference in level of detail. Simple white poles on the left and right sides of the road with a flashing red light and three levels of detail of warning messages were prepared; level 1 consisted of a warning pole plus information on the types of incident warned about (i.e., warning, congestion, accident, and roadwork), level 2 included warning poles, information on type of incident plus distance to the incident (i.e., warning, congestion, accident and roadwork in 1 km), and level 3 was a warning pole, type of incident, distance to incident and a recommendation of action to avoid the negative effects of the incident (i.e., warning, congestion, accident, and roadwork in 1 km, reduce speed). The distance between the location of the warning messages and the incident was 1 km. A driving simulator was employed in this study with fifty participants. Driving performance data including driver speed and speed variation were compared in response to the differences in warning messages.

The results showed that all warning messages influenced driver behaviour positively, resulting in earlier reduction of driver speed compared with a 'no alarms' condition. An assumption that a low level of detail in a message would cause greater variation in driver behaviour was not confirmed and relatively long warning messages were not found to affect driver workload. It can be said that for such incident warning systems in which alarms are provided that are not time critical, the difference in warning message does not impair alarm effectiveness and a range of message types may contribute to safe driving.

However, it should be noted that alarm modality may affect driver workload in some situations, resulting in impaired driver performance with a warning system. Lee et al. (2001) reported an investigation concerning a speech-based interface and its

influence on driver behaviour. In this paper a driving simulator study was conducted in order to estimate the effect of speech-based in-vehicle information on driver braking reaction. The results show a 30% (310ms) increase in reaction time when the speech-based system was used, compare with a baseline condition with no system. Subjective workload ratings also indicated that speech-based interaction introduces a significant cognitive load which has important implications for the design of warning systems.

Alarms should be provided in a manner such that the presentation of alarms does not cause drivers distraction since drivers need continuous attention to the road in order to respond to changing traffic situations. However, in relatively time critical situations, such as rear-end collision situations, prompt response to alarms might be crucial to avoid collisions. Given these assumptions, auditory signals might be the most appropriate strategy for alarm presentation (Doll et al., 1984, Zwahlen, 1985). Graham (1999) assessed the effect of differences in the characteristics of auditory alarms on driver response in a collision avoidance system. In this study auditory icons which convey system information by analogy with everyday events were used. Auditory icons are based on the way people hear the world in their everyday lives and their meanings should be easily learned and remembered (Gaver, 1986). Two icons, the sounds of a car horn and of skidding tyres, were compared with respect to conventional warnings, a simple tone and a voice saying 'ahead' in the imminent collision situation. Participants sat in an experimental vehicle with a road scene projected ahead, and they were instructed to brake in response to on-screen collision situations and their accompanying warning sounds. Driver responses to alarm sounds were measured. The results revealed that the auditory icon warnings in the experiment had a significant ability to induce drivers to respond to the brakes quicker than the conventional warnings. However, the auditory icons led to an increased number of false-positive reactions where drivers responded to the auditory icons and hit the brakes in response to a non-collision situation more frequently, compared to the conventional warnings. It can be concluded that the auditory icons may have the potential to induce a relatively high level of perceived urgency. However, with respect to the acceptance of auditory alarms, Dingus et al. (1998) suggest that drivers may be startled, annoyed, or both, by auditory alarms in some situations, resulting in disuse of warning systems.

2.5.3 Alarm timing

In addition to alarm modality the timing of the alarm is a crucial factor in determining alarm effectiveness in time critical situations. A poorly timed warning may actually undermine driver safety (McGehee and Brown, 1998). This section reviews alarm timing in FCWS.

A time-budget analysis method has been proposed in order to determine the onset of alarms (Geiser and Nirschl, 1993). According to this analysis (Figure 2-9), a warning reserve time $\Delta\tau$, i.e. the time span in which alarms are available, is derived based on time intervals i.e. driver reaction time to alarms ΔT_{rea} , minimum duration of driver action needed to respond to a collision ΔT_{min} , position of normal action onset without the aid of alarms T_{norm} and so on. Alarms which are provided before $\Delta\tau$ can be regarded as early alarms, conversely alarms which are provided after $\Delta\tau$ can be regarded as late alarms. The timing of alarms might be chosen early enough to enable drivers to react appropriately, however alarms which are presented too early might be viewed as annoying ones.

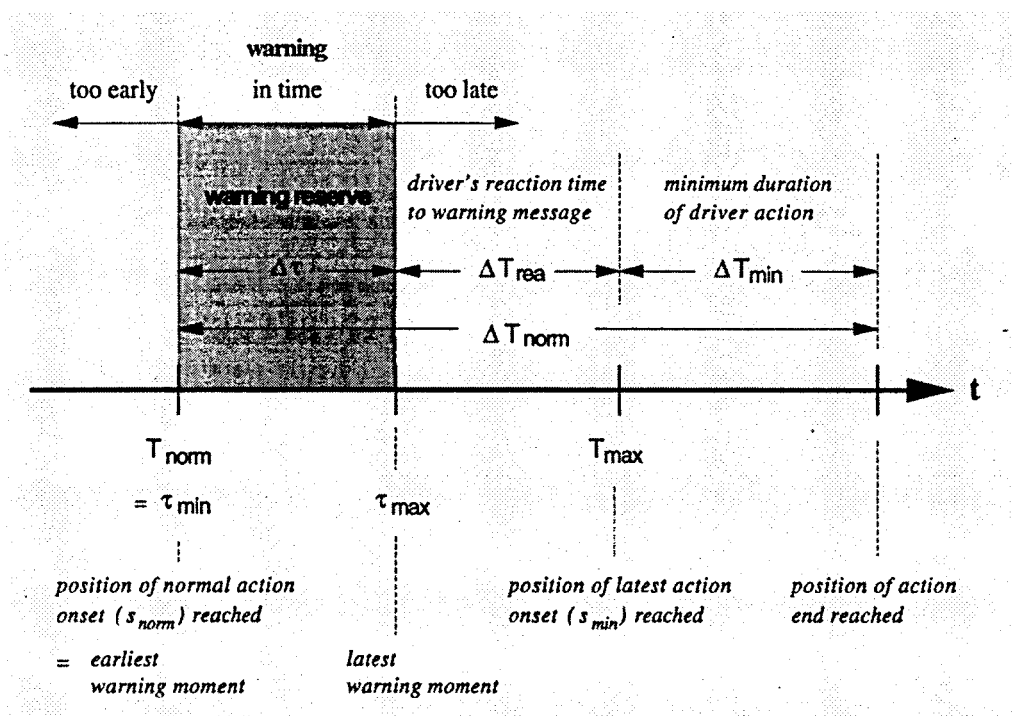


Figure 2-9 Time schedule of driver-driver warning assistance interaction (Geiser and Nirschl, 1993)

Lee et al. (2001) note that if the collision warning system acts trigger an appropriate response from drivers, then a relatively late warning, that minimises false warnings, might be the best design alternative. However if the collision warning system acts to redirect driver attention towards a critical event, then early alerts would provide a greater safety benefit. This contradiction suggests that the best strategy depends on the driver's expected role in collision warning system design.

Gupta et al. (2001) considered alarm sensitivity and type of alarm signal and investigated how these factors may affect driver behaviour using adverse condition warning systems for slippery road conditions. This type of system attempts to provide drivers with an alerting warning whenever there is a possibility of a skid or a rollover due to snow or icy road conditions. A driving simulator providing virtual driving conditions was employed. The Microsoft Sidewinder Force Feedback steering wheel package was used to control the simulated vehicle, and to provide force feedback through the steering wheel. Two different values of alarm sensitivity (low and high sensitivity) were used which gave two conditions within the alerting level. Theoretically the high sensitivity alerting level should have inevitably produced more alerts, and thus might be expected to result in a perception of greater false alarms than the low sensitivity alerting level. Driver performance data regarding response time to icy road conditions with and without the aid of alarms were assessed. The results showed that velocity at the instance of a skid was higher for the low compared to the high sensitivity alarm. These results may be caused by more time being available to drivers in the high sensitivity alarm condition to reduce their vehicle speed before the onset of a skid. However an analysis of driver steering wheel response found that input was significantly greater for the high sensitivity, compared to low sensitivity alarms, indicating a greater deviation; drivers turned the steering wheel more for the high sensitivity alarms. Furthermore, high sensitivity alarms led to greater negative subjective evaluations by the drivers than low sensitivity alarms. These results indicate that high sensitivity alarms i.e. early alarms are not always necessarily preferable.

A high fidelity driving simulator study was completed in order to investigate the relationship between alarm timing and driver response to alarms in the context of

FCWS (Lee et al., 2000, Lee et al., 2001). Relatively early and late alarms were considered in order to identify how differences in alarm timing might affect driver performance in imminent collision situations. This experiment involved 120 drivers and the results showed that the presentation of alarms reduced collision rates, compared to driving without alarms. Furthermore early alarms reduced collision rates more effectively than late alarms. The early alarms led to more prompt accelerator release than late alarms, resulting in a faster response time to the brakes. These results indicate that an early alarm timing has the potential to provide more effective warning of imminent collisions than a late alarm timing in some situations.

To sum up, optimising alarm timing comprises a trade-off between alarm effectiveness and driver acceptance. An early alarm timing, certainly, has the potential to lead to a prompt response to critical situations, however it may cause a negative driver perception of the warning systems. When considering the design of alarm timing, it is necessary to choose alarm timings which can maintain alarm effectiveness and appropriate levels of acceptance.

2.6 Driver response to alarm malfunction

Reliability and its influence on driver behaviour is an important consideration for alarm design. Usually false alarms are the result of a fault indicated by monitoring circuitry where no fault exists (Bliss and Dunn 2000). Missing alarms can be seen as a fault of omission where alarms are missed even though critical conditions have occurred. Signal detection theory (SDT) provides a theoretical means of determining thresholds for alarm activation on the basis of achieving a balance between the need for secure detection of critical situations and the avoidance of false alarms (Swets and Pickett 1982). The fundamental issue in setting the decision threshold is a trade-off between the cost of a missed and a false alarm. However, Parasuraman et al. (1997) argue that if a system is designed to minimise missed alarms, then the problems of an increase in false alarms become inevitable. In reality the occurrence of false and missed alarms does not simply result from theoretical considerations but from system failure, e.g. sensor failure or inadequate performance, data processing limitations or output failure caused by electrical problems or component malfunction etc.

There now follows an overview of alarm malfunctions and their influence on human behaviour followed by a review of previous studies concerned with driver response to alarm failure in order to identify human factors design requirements for FCWS.

2.6.1 The effect of false alarms on human behaviour

Breznitz (1983) successfully demonstrated the effect of false alarms on human behaviour. Specifically, this study introduced a 'cry-wolf' effect in order to investigate human behaviour towards false alarms. The research successfully showed that false alarms may affect human behaviour by inducing increased physiological stress and predicted response behaviour using heart rate and skin conductance levels. This study suggests that people who experience false alarms may demonstrate a subsequent change in response to an alarm system.

Bliss et al. (1995) also considered the effect of false alarms on people, using objective measures to describe their response to alarm systems. A total of 138 undergraduate students performed a cognitively demanding psychomotor primary task; at the same time, they were presented with alarms of varying reliabilities (25, 50, and 75 % of true alarms) and urgencies (green, yellow and red visual alarms presented with low-, medium-, and high-urgency auditory alarms). All the auditory alarms representing different levels of urgency were recorded from commercial aircraft simulators. Frequency, speed, and accuracy of the subjects' alarm response were measured with respect to differences in alarm reliability and urgency. The results showed that the percentage of alarm responses observed decreased as alarm reliability decreased. Subjects made more responses to high-urgency alarms than to low urgency-alarms, regardless of the false alarm rate. However alarm urgency did not affect alarm response speed and accuracy.

Bliss and Dunn (2000) investigated the effect of increased workload levels of primary and secondary alarm tasks on alarm response time, accuracy and frequency. All participants performed the tracking, monitoring and resource management tasks which were designed to simulate activities performed by pilots during flight. At the

same time, they were presented with intermittent alarms as the secondary tasks. The number and types of tasks to be performed were manipulated in an attempt to vary primary task workload. The difficulty of the secondary task, i.e. responding to alarms, was manipulated by changing the temporal spacing (activation rate) of the alarms. Specifically in the low workload condition, alarms were evenly distributed across the entire session. In the high workload condition alarms were presented frequently compared with the low workload condition. Each alarm had a visual and auditory structure. The auditory portion of the alarm signal was recorded from a commercial aircraft simulator. Alarm reliability was 60%. Accordingly 40% of false alarms were presented. Operator response time, frequency and accuracy were measured as dependent variables. The results revealed that response time was reduced with increased primary task workload. Response frequency also decreased as a function of increasing primary task workload. With respect to the effect of secondary task workload on alarm response performance, although there was no effect for response time or accuracy, alarm response frequency decreased as secondary task workload increased. This study indicates that alarm response performance may depend on the demand level of other tasks. Furthermore, if alarms are provided frequently, for example in situations where multiple alarms are introduced, operator response frequency may decrease.

Getty et al, (1995) considered positive predictive values (PPV) which theoretically determine thresholds for issuing a warning in the design of alarm systems. A low PPV value refers to high detection sensitivity, indicating a small proportion of missed events to which an alarm should be provided. By implication, a low PPV has the potential to provide an increased frequency of false alarms. PPV was manipulated with 5 different values; 0.25, 0.39, 0.50, 0.61, and 0.75 and the effect of PPV values on the latency of operators' responses to a warning in a laboratory experiment was investigated. The results show that participants respond slowly to low PPVs and quickly to high PPVs. It would appear that in certain situations the cry-wolf effect may be manifested by degraded alarm response speed rather than by ignoring alarms. That is, participants tended to respond to non-valid alarms very slowly.

Other research has also considered the effect of alarm validity on human response to alarms and has generally indicated that people tend to ignore or respond to non-valid alarms slowly (for example; Kerstholt and Passenier 2000; Maltz and Meyer 2001).

Historically, the aviation domain had problems with excessive false alarm rates, resulting in pilots ignoring or disabling warning systems with major implications for safety (Sorkin 1988). Alarm designers have developed improved ways of controlling cockpit alarm systems but the problem has not been solved completely (Bliss 2003). Given that, unlike commercial and military pilots, car drivers are not selected, trained or regulated, issues relevant to false alarms in the vehicle domain have an elevated importance (Hancock and Verwey 1997).

The results of previous studies regarding driver behaviour towards FCWS suggest that a high frequency of non-valid alarms has the potential to induce the crying wolf effect, resulting in a reduced response to valid alarms (Horowitz and Dingus, 1992; Tijerina and Garrott, 1997). Bliss and Action (2003) manipulated alarm reliability (50, 75, 100 %) in order to investigate its effect on driver behaviour towards a collision warning system. A driving simulator based collision warning system that warns drivers of the approach of a car from the rear of their vehicle was used. 70 undergraduate volunteers took part in this study and they were instructed to maintain a maximum speed of 70 mph (112.65 kph) and also to check their rear view mirror frequently to avoid collisions with an approaching vehicle from behind their vehicle even though alarms were provided. False alarms were presented on occasion according to alarm conditions. Alarm response frequency and collision rate, according to alarm reliability, were measured. The results showed that alarm response frequency decreased as alarm reliability was impaired. This suggests that the cry-wolf effect may occur with automotive alarm systems, resulting in reduced response to unreliable alarms. An important finding of this study was that drivers who experienced the least reliable alarms avoided collisions most successfully. This indicates that low reliability alarms may induce more careful driving while drivers who have the support of high reliable alarms, may be subject to behavioural adaptation.

Finally it should be stressed here that driver perception of the validity of alarms may influence the occurrence of alarm malfunction. Wheeler et al. (1998) suggested that a perceived false alarm can occur in some situations and this type of false alarm may impair system effectiveness in a similar way to real false alarms (i.e. those that occur when alarms are presented to drivers in the absence of potential collision events). They argued that perceived false alarms are associated with situations in which a driver has already recognised critical events before the presentation of an alarm. It is arguable that alarms which are provided after drivers have already recognised imminent collision situations and begun to implement some action to avoid a collision, can be viewed as incorrect or inappropriate alarms. The issue of perceived false alarms can be linked to the design of alarm timing and it is necessary to explore the perception of alarms from the driver's position in order to understand alarm timing and its relation to perceived false alarms

2.6.2 The effect of missing alarms on human behaviour

The primary aim of alarm systems is to provide alarms when necessary, and considerable effort is usually made to avoid missed alarms. However Bliss (2003) found that the occurrence of missed alarms accounted for 13 % of all alarm-related events in the database of the Aviation Safety Reporting System. It is likely that FCWS in the vehicle domain will provide missed alarms at relatively higher rates due to the complexity of the driving situations involved and limited development of the technical systems.

Missing alarms may reasonably be expected to result in more serious consequences than false alarms. Although final responsibility for avoiding collisions must be held by drivers if drivers are too reliant on an alarm system it is possible that a missed alarm may lead to a delayed response to an imminent collision situation. This phenomenon is predictable given the changes in driver tasks or work load caused by the introduction of in-vehicle information systems (Mast, 1998). However despite the considerable accumulated knowledge about false alarms there has been relatively little research on the human factors of missing alarms. An exception is the indication that

the failure to supply warnings could result in greatest risk (Hancock and Parasuraman, 1992; Sorkin et al, 1988).

2.7 Driver trust in warning systems

The concept of trust has been recognised as an important factor when describing interactions between human and machines. It is well established that trust between humans and automated systems can affect the degree to which people accept and rely on automated systems. It therefore follows that the level of trust between a driver and a driver support system may limit the situations in which a promised positive effect is possible.

In this section the history of research on trust from both sociological and human machine interaction perspectives is reviewed in order to understand how trust can be applied to the domain of FCWS.

2.7.1 trust between humans

The contemporary study of trust started in the social sciences. Relationships between humans have been investigated and several definitions of the nature of trust have been proposed in the psychological literature. Barber (1985) insisted that trust between humans is based on expectations that involve some of the fundamental meanings of trust and has a multidimensional character. Moreover, each dimension is subject to a different **expectation** about the nature of an interaction. Three specific expectations have been proposed namely **persistence**, **technical competence** and **fiduciary responsibility**. Persistence is the most general expectation and represents fulfilment of the natural and moral social order. Our expectation that nature works in a lawful, predictable way reduces the complexity in our world by limiting possible outcomes. Our expectation of constancy in natural physical laws is expressed in statements like 'as night follows day'. Expectation of technical competence refers to the ability of the other partner to produce consistent and desirable performance and can be subdivided to define three types of expertise: everyday routine performance, technical facility,

and expert knowledge. The third dimension of trust, fiduciary responsibility, refers to the expectations regarding moral and social obligations that people should hold the interests of others above their own. This dimension plays an important role when agents cannot be evaluated because their expertise is not understood, or in unforeseen situations where performance cannot be predicted.

Rampel et al. (1985) have proposed a model for **the development of trust** in another person as a relationship progresses and identified three components according to increasing levels of attributional abstraction, namely **predictability**, **reliability** and **faith**. At each stage, trust is based upon the outcome of the earlier stages. Early in a relationship, a person's trust in another person is dominated by predictability that is informed by the consistency of successive actions or decisions. As relationships progress there is an inevitable shift in focus away from assessments related to specific behaviours to an evaluation of the qualities and characteristics attributed to the partner, that is, perceived reliability dominates trust. The final stage in the growth of interpersonal trust is termed faith. Faith reflects an emotional security on the part of individuals, which enables them to go beyond the available evidence and feel, with assurance, that their safety is assured despite of an uncertain future. In summary, past predictability and dependability are critical to the development of faith. This perspective suggests that interpersonal trust has three aspects related to different types of expectation of other people and has a dynamic nature associated with past experience.

2.7.2 Trust between human and machines

As technology has developed, human support systems with increasing degrees of automation have been introduced in large complex systems such as aviation or nuclear power plants. Satchell (1998) states that "*Automation is the replacement of human activities by machine activities*", and one aim of introducing automated systems is to reduce human operators' tasks and mitigate the incidents caused by operator errors. However, not all of the human tasks relevant to control systems can be replaced by machines and human supervisory control remains. This means that operators and machines must share tasks in order to control a system and maintain system efficiency.

The importance of the concept of trust between humans and machines arises and a semi-intelligent machine can be proposed as an operator's partner in a control system (Muir 1987; Zuboff 1988).

Zuboff (1988) has investigated operators' trust in, and use of, automation following its introduction into the workplace. Her studies suggested that the operators' lack of trust in the new technology may impair potential system efficiency. Conversely operators sometimes place too much trust in the new technology, resulting in a failure to intervene when the technology fails. According to Zuboff's account of operator trust in mechanical systems, trial-and-error experience may contribute to both the development and underdevelopment of trust. That is operator's trust may vary according to knowledge about the systems based on experience with these systems. In other words, operator trust never develops without experience of system usage.

Muir (1994) proposes a theoretical model of trust between humans and machines (table 2-3) showing a comprehensive understanding of how human trust in machines is constructed. This model is based on trust between people as a starting point and extends it to the human-machine relationship. It is an integrated model created by crossing Barber's model and Rempel et al.'s model described above. Muir insists that "Barber's model provides the broader context and richness of meaning needed to characterize the myriad interactions in a complex and hierarchical supervisory control environment and Rempel et al.'s model provides the dynamic factor needed to predict how trust may change as a result of experience with a system". That is, trust in machines also has three different dimensions: persistence, technical competence, and fiduciary responsibility. Also each dimension changes its aspects according to an operator's experience of a system. In the first stage an operator's trust will be dominated by predictability, being judged by an evaluation of the consistency and desirability of the system's current behaviour. As the relationship between human and machine matures, trust will be dominated by a different aspect, dependability.

Table 2-3 An integrated model of trust in human-machine relationship, created by crossing Barber's (1983) model of the meaning of trust (row) and Rempel et al.'s (1985) model of the dynamics of trust (columns). Statement in the cells exemplify the nature of a person's expectations of a referent (j) at different levels of experience in a relationship (Muir, 1994)

expectation	Predictability (of acts)	Dependability (of disposition)	Faith (in motives)
Persistence of	Event conform to natural laws	Nature is lawful	Nature laws are constant
- Natural physical	Human life has survived	Human survival is lawful	Human life will survive
- Natural biological	Human and computers act 'decent'	Humans and computers are 'good' and 'decent' by nature	Human and computers will continue to be 'good' and 'decent' in the future
- Moral social	j's behaviour is predictable	j has a dependable nature	j will continue to be dependable in the future
- Technical competence	j's behaviour is consistently responsible	j has a responsible nature	j will continue to be responsible in the future
- Fiduciary responsibility			

The process of attributing dependability is based on the accumulation of behavioural evidence that supports perceived predictability. The final stage in the growth of trust in machines is faith where human operators will believe past predictability and dependability in the face of an uncertain future beyond the behavioural evidence generated by the system.

Muir and Moray (1996) estimated the nature and dynamics of human trust in machines using a medium-fidelity process control simulation of a milk pasteurization plant. The operator's task was to control the pasteurization process, maximizing system output within safety constraints. The plant was mostly controlled by an automated system but a pump sub-system was semi automated. Thus the normal operating mode was automatic, but operators could switch between manual and automatic control whenever they wished. Only the properties of the pump were manipulated in response to experimental conditions and all other subsystems were consistently exact. Three different kinds of pump, each with a different error mode (exact, constant proportional error and a variable error) were prepared for this study. Operators' subjective ratings of trust, measured by way of rating scales, were used to

evaluate the nature of trust in machines. In the analysis, simple linear regression analyses were conducted to identify important contributing factors to describe trust in machines. One regression model showing the relationship between technical competence and fiduciary responsibility for describing development of trust in automated systems found that technical competence of the automated system was more important than fiduciary responsibility to describe trust in the automated system. This result indicates that technical competence depending on system performance and system reliability may represent operators' subjective ratings of trust in the automation.

Lee and Moray (1992) also investigated the dynamics of operators' trust in an automated system using a semi-automatic pasteurisation plant. A medium-fidelity, simulated, orange juice, pasteurisation plant was created. The simulated plant included provisions for both automatic and manual control. The operators could control feedstock pump rate, steam pump rate, and heater setting either manually or by engaging the automatic control. The operator's task was to control this plant and create orange juice as much as possible by using automatic control, manual control, or any combination of the two. With respect to system fault conditions, the feedback pump was programmed to perform with a variable level of performance. Four different magnitudes of fault (15%, 20%, 30%, and 35%) were prepared. The magnitudes of the fault corresponded to the difference between the actual and the target pump rate. In order to measure operators' subjective ratings of trust in the automated system, a 10 point rating was used in this study. In a time series analysis of the dynamics of trust, it was shown that the system fault led to decreased trust and as the magnitude of the fault increased, trust decreased. Furthermore Lee and Moray (1994) focused on the operators' allocation strategy between automatic and manual control and found that both trust in automated controllers and self-confidence in manual control abilities may dramatically influence the operators' allocation strategy. Specifically they found that automation was used when trust exceeded self-confidence, and manual control when the opposite was true.

Parasuraman and Riley (1997) focused on human use, misuse, disuse and abuse of automation in order to explore how humans behave with automated systems and how abuse of automation impairs system efficiency. In this study they found that trust

determines automation usage, that is, operators may not use an automated system which they believe to be untrustworthy. Conversely they may continue to use an automated system even when it malfunctions. Riley (1996) indicated that system accuracy impacts on trust in automation and trust in automation influences reliance on automation.

Though it can be reasonably concluded that trust in automated systems has a dynamic nature, varying according to system faults or system reliability, the following research evidence provides interesting suggestions. Abe et al. (2000) and Itoh et al. (1999) conducted an experiment using a mixed-juice, pasteurisation plant simulation and found that the dynamics of trust in automated systems depends on not only system reliability but also malfunction occurrence patterns. Specifically, discrete malfunctions do not influence decreasing trust but continuous malfunctions significantly decrease operators' trust even if the malfunction rate is the same. Itoh et al. (1999) and Moray et al. (2000) suggest that trust declines when a human disagrees with a control strategy that an automated system performs even if this strategy is required to maintain system efficiency. This result suggests that a conflict of "opinion" between human and machine may cause decreased trust in automated systems even if automated systems are reliable.

Dzindolet et al. (2003) interestingly concluded that when an automated support system made errors and operators' trust was impaired, knowing why the system might fail increased trust in the automated system and increased operator reliance. These results indicate that enhancing the operators' mental model of the automated system (i.e. how does the automated system work?) allowed the operators to accommodate poor performance and increased their trust in the system.

Meyer (2001) provided an interesting perspective on alarm type and its influence on operator trust, indicating that a simple notion of trust in warning systems may need to be refined. This study distinguished between two types of operator trust in relation to warning systems that are subtly but significantly different; one he termed compliance and the other reliance. In compliance the operator responds to alarms promptly, assuming that they reliably indicate a hazard or fault condition. However, in the absence of an alarm ('green light' condition) the operator will assume that there is

probably no hazard and proceeds with caution. In reliance the operator assumes that there will be no hazard unless the alarm is given; the green light condition reliably indicating a lack of hazard.

2.7.3 Driver trust in FCWS

In-vehicle driver support systems are intended to help drivers implement tasks more efficiently or safely. In other words the appropriate co-operation between drivers and driver support systems enables increased system effectiveness. This implies that driver trust may play an important role in optimising collision warning system performance. Hancock and Parasuraman (1992) stated that neglecting the human component in driver support systems can lead to the failure of system efficiency and emphasized the importance of driver trust in predicting subsequent driver behaviour towards such systems. Lee and Kantowitz (1998) insisted that trust plays an important role when developing a functional description of the driver's interaction with ITS technology and Stanton and Young (1998) argue that trust should be considered an important psychological factor in the development of successful vehicle automation. Driver acceptance of FCWS is also an important factor to consider in the design of FCWS according to Groeger et al. (1993). Driver acceptance may be strongly influenced by driver trust since if drivers distrust a collision warning system then it is impossible for drivers to accept that system.

Although the importance of driver trust has been widely recognized, specific research evidence regarding how driver trust may influence driver behaviour towards FCWS, or what factors may affect driver trust, has been inadequate. Furthermore the importance of driver trust in FCWS is unclear.

2.8 Automation-induced complacency and situation awareness

In order to understand driver interactions with FCWS which may impact on system efficiency in more detail it is necessary to identify the contributory factors. Wickens et al. (1998) provide a suggestive general framework for examining the human performance issues discussed in this section (figure 2-10). Two elements of human interaction with automated systems; situation awareness and complacency, which may apply to FCWS will now be discussed.

2.8.1 Situation awareness

Researchers have yet to fully agree on a definition for situation awareness. The concept of situation awareness has been regarded as both a product, involving knowledge, and as a process, involving perception (Satchell, 1998). The most complete definition of situation awareness is "the perception of the elements in the environment with a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" (Endsley 1988).

The requirement for situation awareness has become obvious in the process of task allocation between humans and machines during automation. In aviation, for example, state of the art technology, such as avionics has changed the pilot's task dramatically. The pilot does not directly control the aeroplane but supervises the automated flight control systems. When the automated systems fail or in the presence of conditions that the automated system is not designed to handle, the pilot must intervene and control the system manually and good situation awareness is critical.

It is very important for the pilot to understand what the system is doing in order to take an appropriate action when required. Endsley (1995) presented a theoretical model of situation awareness based on its role in dynamic human decision making in

a variety of domains. In this model she insists that situation awareness (SA) has three hierarchical phases.

Level 1 SA refers to perception of the elements in the environment. The first step in gaining SA is to perceive the status, attributes, and dynamics of relevant elements in the environment. An automobile driver needs knowledge of where other vehicles and obstacles are, their dynamics, and the status and dynamics of their own vehicle. Level 2 SA refers to comprehension of the current situation. In the second step human operators must comprehend situations where what is going on is based on a synthesis of disjointed level 1 elements in order to determine how well different system components are functioning. Level 3 SA is concerned with projection of future status. In this final stage of development of SA operators may gain the ability to project the future action of the elements in the environment. This ability is based on SA of level 1 and level 2, being achieved through knowledge of the status and dynamics of the elements and comprehension of the situation. With respect to the driving domain, a driver needs to detect possible future collision threats in order to act effectively.

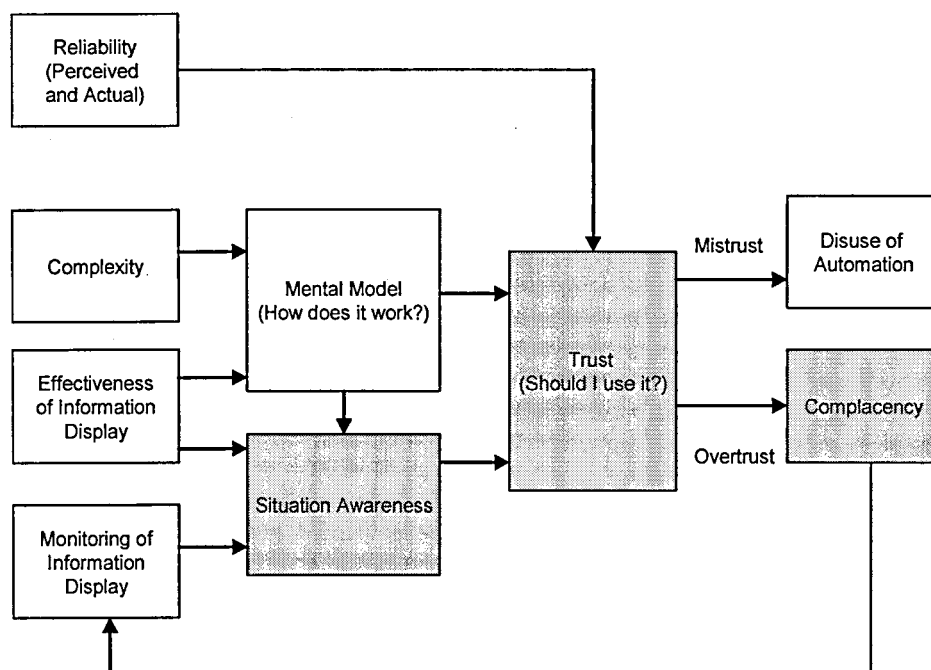


Figure 2-10 Framework for examining human performance issues (Wickens et al., 1998)

A number of studies, which are associated with situation awareness, have been conducted in addition to the definitive research mentioned above (Endsley et al., 1995; Sarter and Woods, 1995; Smith and Hancock, 1995). For example, Endsley et al. (1995) indicates that low SA corresponds with out-of-the-loop performance decrements. This means that as an operator's task shifts from active to passive processing, the operator's SA may decrease under automated conditions. This result suggests that in order to maintain operator's SA in control systems it is necessary to keep the operator involved in the decision loop even when the operator does not directly control the system. Sarter and Woods (1995) suggest that in situations where a large number of functions and options are available for carrying out a given task under different circumstance, new types of mode-related problems may happen. This means that as the strategy for control systems become more flexible, operators may fail to choose the appropriate mode for the situation.

In contrast to the aviation sector the introduction of FCWS does not provide a dramatic change in driver task or a mode change in driving, however the introduction of FCWS may influence the driver's need to attend to forward vision, resulting in changes in situation awareness. For example, in level 3 SA; how drivers detect possible collision situations may be affected by the introduction of FCWS. Furthermore, according to the framework, situation awareness may also be affected by the driver's mental model of how the collision warning system works. That is, drivers understanding of how collision warnings are provided may play an important role in developing situation awareness which subsequently determines driver behaviour towards the collision warning system.

2.8.2 Complacency

Wiener (1981) defined complacency as "a psychological state characterised by a low index of suspicion". Pilot "complacency" has long been implicated as a possible contributor to aviation accidents. The issue has been investigated by a number of authors (Farrell and Lewandowsky, 2000; Molloy and Parasuraman, 1996; Moray, 1990; Moray, 2000; Ockerman and Pritchett, 2000; Parasuraman et al., 1996; Sarter et

al., 1997; Singh et al., 1993; Skitka et al., 1999). For example, Singh et al. (1993) state that automation-induced complacency is a function of operator trust in, and reliance on, automation. Molloy and Parasuraman (1996) found that compared with manual control, monitoring for a single failure of system control is poorer under automated control. Skitka et al. (1999) compared error rates in a simulated flight task with and without a computer that monitored system states and made decision recommendations. The results showed that when the computer worked correctly, operators in the automated system condition made fewer errors than those in the non-automated conditions. However when the computer did not work correctly much higher error rates were observed in the automated condition than the non-automated condition. Parasuraman et al. (1996) showed that temporary return of the automated task to the operator was a possible countermeasure to monitoring inefficiency. This result suggests that dynamic task allocation between human and machine may help to enhance the monitoring of automated systems.

Briefly summarizing these results indicates the following issues regarding operator complacency in automated systems: (1) poor task monitoring may occur in highly automated control systems, (2) over-confidence and over-reliance on automation may lead to decreased vigilance performance and as a result, operators may fail to recognise automation failures and (3) dynamic task allocation may be a possible countermeasure to vigilance performance inefficiency under highly automated systems.

However, Moray (2000) disagrees with previous research related to complacency and suggests that current research does not provide evidence for complacency in monitoring rare events because a failure to detect a signal is not in itself a sign of complacency. His research suggests that even a 'perfect' observer who is well trained and fully vigilant may fail to detect a warning signal. Moray defined complacency as follows. "The behaviour of an observer is complacent if a source is sampled (monitored) less frequently than is warranted by the statistics of occurrence of the signals to be detected". This statement means that "complacency is about monitoring, not about detection."

Satchell (1998) argues that complacency and situation awareness are linked. Excessive trust generates complacency, which can interfere with sustained attention and hence situation awareness. In order to enhance efficiency of FCWS it is necessary to consider possible factors that may impair driver performance in imminent collision situations due to the introduction of FCWS. The problems associated with in-vehicle collision warning system induced complacency are possibly linked to driver detection or recognition performance. Although it is likely that FCWS can help reduce driver error caused by inattention, if drivers become over reliant and start to believe that critical situations will never happen if a warning is not presented, then driver response to alarm failure may be undermined.

2.9 Chapter conclusion

The literature relevant to the driver characteristics and their interactions with FCWS has been reviewed in this chapter. Evidence has been presented of the need for driver support to increase safe driving. For rear-end collision situations in particular there is a possibility that even slightly reduced driver inattention to forward vision may induce serious accidents due to limited driver performance in car following situations. Thus FCWS have the potential to decrease accidents caused by driver error.

However system effectiveness is highly dependent on alarm modality and its relation to driver behaviour; the type and timing of alarms may induce more efficient driver behaviour. It must also be stressed here that driver interaction with FCWS plays an important role in determining system effectiveness. Furthermore, driver interactions with warning systems are influenced by multiple factors; situation awareness, complacency, trust, etc. Although a large number of researches have been carried out, the question of relationships between these factors and driver behaviour is still open.

In particular, one of the most important issues requiring further investigation in alarm timing and its relation to driver trust for the design of FCWS. Moreover, with respect to driver interactions with FCWS, it is necessary to consider driver response to alarm failures and establish an approach for mitigating the impact on system effectiveness

caused by false and missing alarms from the viewpoint of driver trust. The empirical work considered in the subsequent chapters addresses these issues.

Chapter 3: Methods for assessing driver response to forward collision warning systems

3.1 Introduction

How can we assess driver response to forward collision warning systems (FCWS) and the contribution to safe driving for the systems? The successful assessment of any active driver support system must overcome significant difficulties. Driver behaviour, supported or un-assisted, is the product of a complex set of interacting factors (driver characteristics, physical road environment, regulation, dynamic traffic situation etc.) which are generally not open to control or manipulation in on-road trials. Any methodology must be assessed in terms of its safety, validity, reliability, practicality and resource requirements. Behavioural simulation with driving simulators has been identified as very powerful tools for estimating driver response to new technologies. However this method has benefits and limitations which largely derive from technical characteristic. Comprehensive understanding of driving simulators would be required.

3.2 The aim of this chapter

The primary aim of this chapter was to evaluate driving simulator methodologies that might have the potential to assess the effect of introducing FCWS on driver behaviour in order to justify the current research. Furthermore specific facilities and measurement procedures used in the thesis are described.

3.3 Driving simulation: benefit and limitations

The driving simulator study is an alternative to field studies in real traffic and has been used as a powerful method for assessing driver behaviour with respect to driver support systems (Janssen and Kuiken, 1993). Compared to a field study, a driving simulator can reproduce the same experimental conditions for all subjects and critical driving conditions can be investigated without physical danger for subjects thus overcoming some of the disadvantages of a field study. Simulation not only provides controlled experimental conditions with subjects but also enables secure manipulation of driving conditions including headway time, deceleration of a leading vehicle and so on in order to deliver data which can cover a wide variety of driving situations.

There are different levels of simulator sophistication with different characteristics and capabilities; very simple static mock-ups, video game solutions, somewhat more advanced equipment with some control possibilities and very high fidelity simulators. Nilsson (1993) argues that an advanced simulator is preferable for estimating the complete driving task, particularly when the driver's reactions and manoeuvring play a crucial role. She also proposed several requirements to be fulfilled as design criteria.

- "The simulation must run in real time."
- "The model describing the vehicle must be complete in the sense that all the subsystems such as engine, brakes, transmission, steering system, suspension etc. must be modelled."
- "The model describing the vehicle characteristics must be able to represent front/rear wheel drive, and different levels of understeer and oversteer."
- "The vehicle model must also be able to reproduce the effects of the interface between vehicle and road, for example slippery surfaces and gravel roads."
- "The simulator must have a wide angle visual system, preferably in colour. The picture should contain enough detail to give a realistic driving impression."
- "The simulator must have a moving base system for the simulation of inertia forces."
- "It is crucial that the time delay introduced by the simulator is short compared to the lags of real vehicles (100-250 ms). That is, the driver must not

experience a delay between a certain manoeuvre (for example a steering wheel turn) and the corresponding changes in the visual scene.”

However Nilsson (1993) also identifies two important limitations regarding driving simulator studies. One is that there are situations where physical laws limit the use of a driving simulator, even if it is advanced. It is impossible for a fixed based simulator to provide some types of vehicle motion i.e. roll, pitch and so on. Furthermore, the driver experiences a lack of correspondence between visual and motion sensations, which can induce uncertainty and abnormal behaviour, even with a moving base system. The other major constraint is that it is impossible to fully reproduce the real traffic environment, with all its complexity and huge variability, resulting in a limited simulation of the real world driving context and consequently a driver response that is not exactly equivalent to real world driving.

It is also assumed that the absence of risk of a real accident may affect driver attitude in experiments, and it is necessary to engage driver motivation to the levels found in ‘real’ driving.

These three limitations have a major impact on the validity of data obtained in driving simulator trials. That is, it is impossible to fully generalize from simulator driving to real vehicle driving. Nilsson (1993) says the question of validity is not satisfactorily answered yet. Any interpretation of absolute values themselves must be treated with caution, however it is reasonable to estimate relative differences in driver behaviour in response to experimental conditions. That is we can anticipate how FCWS may influence driver behaviour by comparing driver performance data supported by warning systems with driver performance for normal driving situations in the controlled experimental scenarios.

The behaviour of individual drivers with respect to the human factors of FCWS will be considered in this thesis in order to identify the problems which might impair the potential contribution of such systems to safe driving. Accordingly a driving simulator is entirely appropriate for achieving the aims of this study despite its inherent limitations.

3.4 Performance of Driving Simulators Used in this thesis

Two driving simulators were employed in this research. In this section, the performance capability of each simulator is summarised in order to clarify the validity of the experimental studies completed.

3.4.1. Leeds Advanced Driving Simulator

Data were collected using the Leeds Advanced Driving Simulator (LADS; further details can be seen at <http://www.its.leeds.ac.uk/facilities/lads/> as of September 2004), which uses complex computer graphics to provide a highly realistic automobile operating environment. The total horizontal field of view is 230°. The vertical field of view is 39°. A rear view (60°) is back projected onto a screen behind the car to provide an image seen through the vehicle's rear view and wing mirrors. The car used in the studies reported here was a Rover 216GTi four-door sedan modified for use in the simulator. Although the simulator had a fixed base, physical and functional fidelity were reasonably high and drivers were provided with realistic driving conditions. Drivers received feedback regarding vehicle control from the steering wheel, brakes, accelerator, and gearshift controls in a similar way to a real car. Moreover, visual and auditory stimuli accurately represented environmental changes in response to driver action. The simulated driving environment was created using a Multi-Gen Creator with Road Tools option. The frame rate was fixed to a constant 30Hz.

Several studies have investigated and confirmed the validity of the LADS (for example, Carsten et al, 1997)

3.4.2. Driving simulator owned by Japan Automobile Research Institute

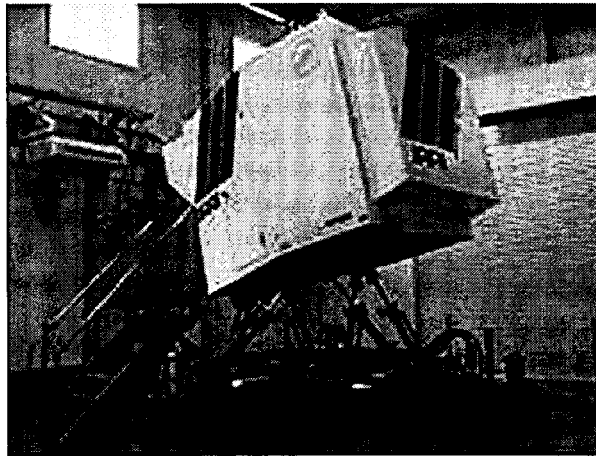


Figure 3-1 JARI driving simulator

The driving simulator owned by the Japan Automobile Research Institute (JARI) also uses complex computer graphics to provide a highly realistic automobile operating environment created by the MultiGen Creator. The frame rate is fixed to a constant 60Hz. The cab and screens are mounted on a six-degree-of-freedom motion base to provide motion cues to the drivers. The cab is 2.3m wide, 3.95m long and 2.3m high and is also equipped with a screen which gives a total horizontal field of view of 50° and a vertical field of view of 35° (Figure 3-1). Drivers receive feedback regarding vehicle control from the steering wheel, brakes, accelerator, and gearshift controls in exactly the same way as in a real car. Moreover, visual and auditory stimuli accurately represent environmental changes in response to driver action. The validity of this simulator has been established in research studies (Soma et al., 1997).

3.5 Algorithm for triggering alarms

Both simulators were used for experiments involving car following situations in which the following vehicle was equipped with a simulated FCWS. Several algorithms have been developed for alarm trigger logic in the design of FCWS. Although this research does not focus on the differences in driver behaviour according to variations in alarm trigger logic, it was necessary to select an algorithm for use in the simulator studies. In this section the differences between three widely used

algorithms are described in order to justify the algorithm used in the research reported here.

3.5.1 Time to collision (TTC)

This is a simple alarm trigger logic where the time until a collision between leading and following vehicle determines the generation of warnings. A specific TTC trigger value is typically selected on the basis of assumptions regarding driver braking reaction time. The equation is as follows (Farber, 1991):

$$TTC = D / (V_f - V_l) \quad (1)$$

Where:

TTC is the time to collision

V_f is following vehicle speed

V_l is leading vehicle speed, and

D is current headway.

Farber also suggests that a threshold of 4 sec may be suitable for triggering alarm timing. As can be seen in this equation, there is no consideration regarding the deceleration of the leading vehicle, thus it is possible that TTC based triggers are less effective when there is a sudden deceleration of a leading vehicle, resulting in an increased possibility of collision accidents.

3.5.2 Closing rate algorithm (CRA)

The closing rate algorithm (CRA) is based on decreased rates of relative speed between leading and following vehicle and the equation is as follows (Farber 1994):

$$D_w = (V_f - V_l)RT + \frac{(V_f - V_l)^2}{2D_f} \quad (2)$$

Where:

D_w is the warning distance

D_f is deceleration of the following vehicle

V_f is following vehicle speed

V_l is leading vehicle speed, and

RT is a response time of following driver.

As can be seen in this equation, CRA has two free parameters RT and D_f determining alarm sensitivity. It should be noted that the CRA establishes no minimum following distance, that is, no warning is provided unless the following vehicle is closing on the lead vehicle, i.e., $V_f - V_l > 0$. Thus it is possible for two vehicles to be driven at high speed with short headways without triggering the alarm.

3.5.3 Stop distance algorithm

The Stop-Distance-Algorithm (SDA) has been recognised by the International Organization for Standardization (ISO/TC204/WG14). The SDA is so termed because a warning distance is defined based on the difference between the stopping distances of the leading and following vehicle and it is expected that the SDA will be introduced as the main alarm trigger logic in the design of future production FCWS (Wilson et al., 1997).

$$D_w = V_f RT + \frac{V_f^2}{2D_f} - \frac{V_l^2}{2D_l} \quad (3)$$

Where:

D_w is the warning distance

D_f is the deceleration of the following vehicle

D_l is the deceleration of the leading vehicle

V_f is following vehicle speed

V_l is leading vehicle speed, and

RT is a response time of following driver.

This algorithm has three free parameters: RT is the assumed reaction time of the driver of the following vehicle and D_l and D_f are the assumed deceleration of the leading and following vehicle respectively. Warning distance (D_w) is dependent on the values of these free parameters.

Faber (1994) indicates that the warning distances produced by the SDA are more sensitive to the difference in speed between the two vehicles than the CRA. This is because with the SDA, the warning distance increases with the difference between the squares of the speed ($V_f^2 - V_l^2$), while with the CRA, the warning distance increases

Table 3-1 Warning distances with CRA and SDA algorithms for the two cases

	$V_f=V_l=55$ mph	$V_f=65$ mph, $V_l=55$ mph
CRT ($D_f=0.31g$, $RT=2.5s$)	no warning	14m
SDA ($D_f=0.6g$, $D_l=0.35g,RT=2.05g$)	14m	44m

with the square of the difference $(V_f-V_l)^2$. Accordingly there is a possibility that the SDA provides alarms more often than the CRA.

A study showed the difference in the warning distance produced by CRA and SDA (Farber 1994). Table 3-1 illustrates the difference in warning distances produced by CRA and SDA algorithms for two cases.

The SDA was used in all of the experiments in this research because it is the alarm logic which probably has the greatest potential to improve safe driving.

3.6 Measures

3.6.1 Measuring of driver trust in FCWS

The contribution of different aspects of FCWS performance is important when measuring driver ratings of trust. As already argued above trust in automated systems is a multidimensional phenomenon defined by three types of expectation (persistence of natural laws, technically competent performance, and fiduciary responsibility). Furthermore each expectation also dynamically varies in three dimensions (predictability, dependability and faith) in response to driver experience. In this research consideration of subjective ratings of trust was related to alarm timings and alarm malfunction. Alarm timing is strongly linked to technical system capability and alarm malfunction depends on technical system reliability. Thus driver trust in FCWS largely reflects one aspect of trust; technical competence. This study focused on relatively short term effects of alarm timings and alarm malfunction on trust. It was assumed that trust ratings would not be influenced by different levels of experience.

In this study Lee’s method (Lee and Moray, 1992), originally modelled on those used by Muir (1989), was used to estimate driver specific subjective ratings of trust in FCWS. This method of measuring ratings of trust is relatively simple and is very appropriate for use in simulator based experimentation. Lee and Moray (1992) used a simple 10-point rating scale (Figure 3-2). The ‘1’ extreme of the scale was marked with ‘NOT AT ALL’. At the other extreme, the ‘10’ was marked with ‘COMPLETELY’. The same technique to estimate driver trust in FCWS was used in this thesis. All subjects gave a verbal judgement of their trust for the following question; *how much do you trust the warning system?*

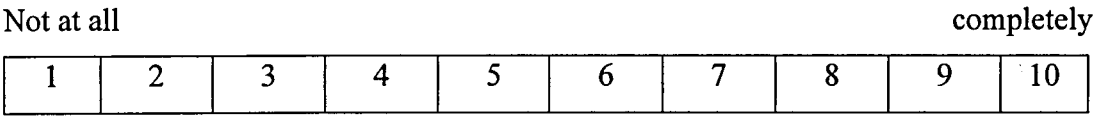


Figure 3-2 10-point rating scale of trust

In addition to being easily understood by the subjects the method can be used quickly after each driver response (using a loudspeaker and microphone in the simulator) without disturbing the subject’s ability to concentrate on the driving task.

In chapter 5 an estimate of driver perception of alarm timing is reported using a simple three level estimation; early, correct, or late. All subjects gave a verbal judgement of their perception of alarm timing for the following question; **how would you rate the alarm timing?**

3.6.2 Driver performance measures

In order to investigate driver performance in imminent collision situations a number of measures were used. Three measures characterising the response process were used to observe how the collision warnings influenced driving performance in imminent collision situations: *Braking event to brake onset time*, *Braking event to accelerator release time* and *Accelerator release to brake onset time*. Two measures were implemented to assess the relationship between the presentation of alarms and driver behaviour more directly: *Alarm to brake onset time* and *Alarm to accelerator release time*. Finally one variable of braking profile describing driver braking

response was measured: *Maximum deceleration*. Figure 3-3 shows typical concepts of each transition time. The definition of each variable was as follows.

i) *Braking event to brake onset time*: This is the time period between the braking event and application of the brakes. This transition time represents the time period between the occurrence of a critical event and the driver's final action i.e. application of the brakes. It is assumed that this variable is influenced by every factor including alarm timing. This variable comprises the following two reaction times.

ii) *Braking event to accelerator release time*: This is the time period between the braking event and driver's release of the accelerator. It provides an indication of the driver's recognition of the imminent collision event.

iii) *Accelerator release to brake onset time*: This describes the time between the driver's release of the accelerator and application of the brakes. It provides an indication of the driver's speed of decision making of the need to brake after recognising the potential threat.

iv) *Alarm to brake onset time*: This is the time period between alarm onset and application of the brakes. It represents the relative relationship between the timing of the alarm and the timing of application of the brakes.

v) *Alarm to accelerator release time*: This is the time period between alarm onset and the driver's release of the accelerator. It represents the relative relationship between the timing of the alarm and the timing of release of the accelerator.

vi) *Maximum deceleration*: This is defined as the peak braking effort for avoiding imminent collisions. It provides an indication of the strength of the drivers' braking response, i.e. their sense of urgency.

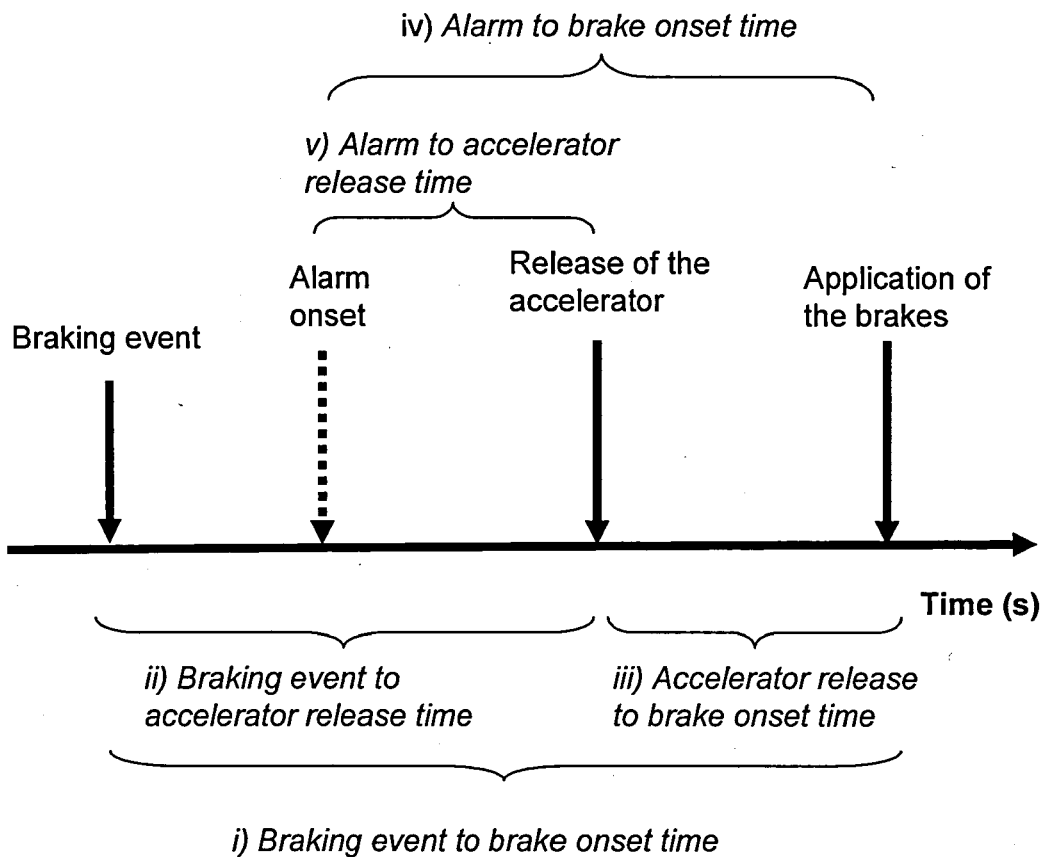


Figure 3-3 Measurements procedure

In the subsequent chapter, the effect of alarm presentation on driver behaviour will be discussed using the measures proposed above. It is argued that these dependent measures adequately describe driver response to imminent collision situations and the relationship between the presentation of alarms and driver braking reaction.

3.7 Chapter conclusion

In this chapter several methods for exploring driver behaviour have been described and their particular benefit and inherent limitations have been identified. Accordingly, driving simulators were selected to undertake the research. Furthermore it was argued that the two driving simulators which were used in this study had sufficiently high fidelity to be able to reproduce driving conditions in a realistic manner. Consequently

it is reasonable to expect that data obtained from the simulator studies have the potential to estimate driver behaviour towards FCWS. Finally the objective driver performance measures and subjective measures of driver response used in the simulator studies were described and justified.

Chapter 4: The timing of alarms and their influence on driver trust and car following behaviour

4.1 Introduction

As already mentioned, substantial safety benefits have been associated with the introduction of FCWS, however it is necessary to identify and optimise the human factors issues which determine alarm effectiveness in order for the potential benefits to be achieved.

Hirst and Graham (1997) found that an auditory tone is the most effective output mode to enable drivers to respond quickly to critical situations. Another important factor that needs to be considered is the timing of the alarms. The timing of the alarms may not only influence alarm effectiveness but also affect driver acceptance. Different levels of acceptance are likely to be associated with alarms that are perceived to be early or late because of a mismatch between the driver's understanding of the traffic situation and the system's output. If the discrepancy is large then the alarm may be perceived as inappropriate. Furthermore, driver trust in alarms reflects driver perception of alarm timing and subsequently influences driver response to alarms.

Knowledge of the influence of alarm timing on driver trust is therefore crucial when considering the design of FCWS. However, little is known about the actual relationship between alarm timing and driver trust. Accordingly, this chapter focuses on how different alarm timings may affect driver trust and also how driver response to different alarm timings influences system effectiveness in order to determine the alarm timings that can maximise the alarm effect.

4.2 The aim of this study

The fundamental purpose of this study was to determine the effect of different alarm timings on driver trust and to create a model of the dynamics of trust for anticipating how driver trust may vary according to alarm timing. The study also investigated how driver braking strategies can be affected by different alarm timings in imminent collision situations.

4.3 Method

4.3.1 Apparatus

The research was completed using The Leeds Advanced Driving Simulator (see chapter 3). The visual scene was a computer generated environment which included other vehicles, buildings and pedestrians. The road environment comprised an urban street with a single-carriageway road.

The following vehicle, 'driven' by the subjects, was equipped with a simulated FCWS. Although several algorithms have been used for alarm trigger logics, a Stop-Distance-Algorithm (SDA) was used in this experiment. This algorithm has three free parameters: reaction time (RT), deceleration of the leading vehicle (D_l) and deceleration of the following vehicle (D_f). Warning distance (D_w) is found on the basis of these parameters and velocity of the leading (V_l) and following (V_f) vehicle (see chapter 3).

This study examined driver response to three different values of alarm timing (late/early/middle) and one fixed value of alarm timing (middle) in two conditions: a condition in which alarms were produced with variable timing (non-consistent) and a condition in which the timing of all alarms was consistent. More specifically, three D_f levels, namely 0.75g 0.55g and 0.35g were used for the late middle and early timings of the alarm respectively. The other parameters had the same value in all conditions; $RT=1.25s$ and $D_l=0.5g$. The values of these parameters were chosen to reflect

realistic values for the deceleration level of the following vehicle and driver braking response time. A pilot trial was undertaken in order to confirm that there was sufficient difference in alarm timing between conditions based on absolute values and driver perception.

The warning system provided drivers with a simple auditory buzzer alarm. The auditory tone comprised 7 peaks in the entire wavelength and lasted approximately 2.0 s. The prominent frequency of the auditory tone was 4000 Hz.

4.3.2 Subjects and experimental design

The experiment involved 24 drivers (12 women and 12 men) aged between 20 and 60 years ($M=31.5$, $SD=8.9$). All were licensed to drive and had normal or corrected-to-normal vision. Each driver was paid £10 for the time taken to complete the experiment.

The participants were randomly assigned to the two experimental conditions defined above, with 12 in each condition. In the non-consistent alarm condition alarms were provided with variable timing (early/middle/late). The purpose of this condition was to investigate the effect of alarm timing on driver braking response and driver trust. The order of presentation for different timings of the alarm in this condition was counterbalanced across the drivers. In the consistent alarm condition alarms were always provided with the same timing (middle). The purpose of this condition was to estimate the potential benefit of middle alarm timing for improving driver braking behaviour.

Each condition comprised two sessions; session I and session II. Session I involved five braking events without the FCWS activated. Session II involved six braking events with the support of the warning system. The sequence of events of this study can be seen in Figure 4-1.

As the aim of this study was to investigate the effect of introducing a warning system on driver behaviour the unassisted driver performance data obtained in session I were regarded as normal driver performance before the introduction of the FCWS.

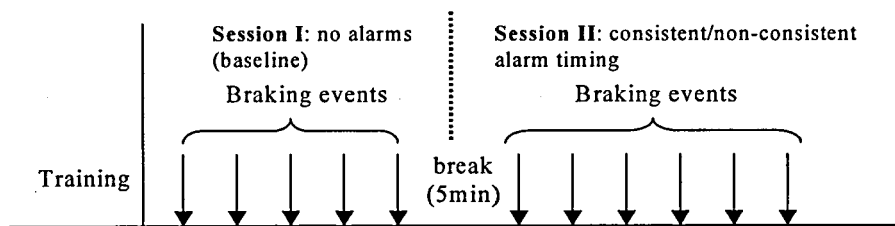


Figure 4-1 The sequence of events

Session I data were therefore collected first for all subjects and there was no counterbalancing of session orders.

In each braking event the leading vehicle suddenly decreased its speed with 0.9g-deceleration with illumination of the stoplights until the vehicle came to a stop. The braking events occurred irregularly depending on whether the driving speed was 45 mph (72.0 kph) with a tolerance of $\pm 5\%$ or not in order to prevent drivers from predicting their occurrence. Furthermore in situations where the collision event occurred, the time headway between the leading and following vehicle was fixed at 2.0s by manipulating the leading vehicle's speed in response to the following vehicle's speed. Accordingly the time headway was nearly the same for all drivers immediately before the occurrence of potential collision events.

The timing of each alarm was dependent on the pre-determined parameters and on a common start point: the onset of deceleration of the leading vehicle. In Table 4-1 the parameters for each of the experimental conditions is summarised. Alarm time in Table 4-1 is defined as the elapsed time from when the leading vehicle begins to brake to when the alarm is presented. As can be seen in the table, early, middle, and late alarms are provided at 0.05sec, 0.64sec, and 0.99sec after the leading vehicle brakes (mean values).

Table 4-1 The summary of experimental conditions

Condition	Initial velocity (km/h)	Lead vehicle deceleration (g)	Initial headway (s)	Algorithm parameter	Mean value of alarm time (s)
Early alarm timing	72.4	0.9	2.0	RT=1.25s D _r =0.50g D _f =0.35g	0.05
Middle alarm timing	72.4	0.9	2.0	RT=1.25s D _r =0.50g D _f =0.55g	0.64
Late alarm timing	72.4	0.9	2.0	RT=1.25s D _r =0.50g D _f =0.75g	0.99

4.3.3 Procedure

Upon arriving at the simulator facility, participants completed an informed consent form and were briefed on the operation of the simulator. All participants were given two tasks. One was to keep their own speed at 45mph. The other was to follow a leading vehicle but avoid rear-end collisions by taking appropriate action when the leading vehicle decelerated. However, the drivers were directed to only use the brakes rather than implement lane changes to avoid a collision. About 8 second after each braking event, the leading vehicle gradually began accelerating again. Subjects were instructed to gradually accelerate until they reached the target speed. In order to familiarize themselves with the simulator and to eliminate learning effects each participant was given a 10 minute practice drive with braking events where prompt braking responses were needed to prevent collisions. This was followed by session I and session II. After session I each participant took a five-minute break.

The subjects experienced repeated alarms in a relatively short driving session which is unlikely to be representative of realistic driving conditions, however the purpose of this study was to investigate relative differences in driver behaviour with respect to alarm timings rather than absolute capability.

4.3.4 Dependent measures

Five dependent measures describing the driver's braking response and one dependent measure describing driver trust in the system were recorded:

- *Braking event to brake onset time*
- *Braking event to accelerator release time*
- *Accelerator release to brake onset time*
- *Alarm to brake onset time*; This variable was only calculated in session II.
- *Alarm to accelerator release time*; This variable was only calculated in session II.
- *Driver subjective rating of trust*

The definition of each variable is given in chapter 3.

4.4 Results and discussion

One driver in each condition did not manage the speed maintenance task adequately and one driver who was allocated to the non-consistent warning condition rated the alarm from the viewpoint of sound quality and sound volume. Consequently these three drivers were omitted from the following data analyses. The statistical analysis including the subsequent chapters was conducted using the *Statsoft STATISTICA* (Windows Version, Ver.6).

In this experiment none of the subjects suffered collisions and so the effect of collision events on driver behaviour could be ignored.

4.4.1 Driver trust according to alarm timing and its consistency

First of all, the influence of alarm timing on driver trust in alarms was considered. Figure 4-2 illustrates the mean values of trust for late, middle and early alarm timings in the non-consistent condition. A one-way ANOVA on driver trust showed a significant effect for alarm timing ($F(2,48)=9.68, p<0.01$). This result indicates that, compared with the early or middle timing of the alarm, driver trust in the late timing of the alarm was lower.

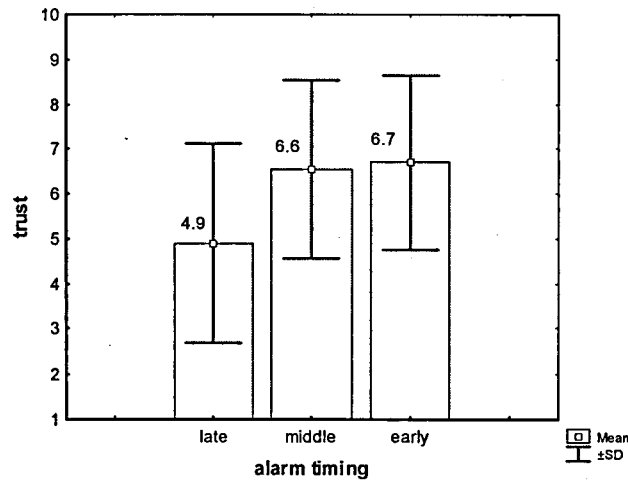


Figure 4-2 The effect of alarm timing on driver trust

Next, the differences in variation of trust ratings between the consistent and the non-consistent alarm were considered. Figure 4-3 illustrates mean trust values with standard deviations for the consistent (M=5.2, SD=1.87) and non-consistent alarm timing (M=6.1, SD=2.18). The consistency of alarm timing might reasonably influence ratings of trust and so the variation in trust scores for the consistent and non-consistent alarm timing were then compared. The Levene-test showed that the difference in the variation in trust ratings between the consistent and the non-consistent conditions was not statistically significant ($F(1,124)=2.50, p>0.10$).

It is not surprising that ratings of trust vary according to alarm timing in the non-consistent condition. However, it is interesting to note that ratings of trust in the

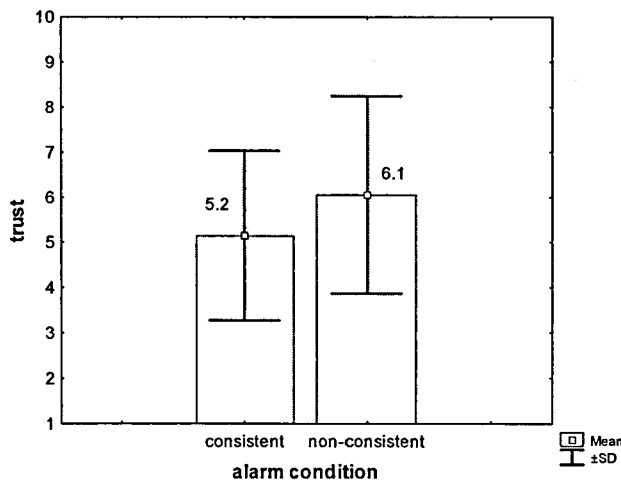


Figure 4-3 The effect of alarm timing consistency on trust

consistent condition also varied at the same level as the non-consistent condition. In this experiment driving speed and headway time in the vehicle-following situation were almost the same in each braking event thus it was expected that variation in the alarm time for the consistent condition ($M=0.681s$, $SD=0.097s$) would be relatively small, compared with the non-consistent condition ($M=0.552s$, $SD=0.399s$). However the variation in ratings of trust for the consistent condition was not small.

A possible explanation of this phenomenon is the sensitivity of trust estimation by drivers. It is possible that driver perception of the 'same' alarm timing varied for two reasons. One possibly derives from driver sensitivity to small variations in alarm timing. Actual alarm timing can vary a little in response to driver braking effort or small variations in driving speed affecting the timing to achieve the warning distance, possibly resulting in relatively wide variation in ratings of trust. This is a characteristic of the SDA. The other may derive from driver attention to the driving task which changes from moment to moment. That is difference in driver attention may affect ratings of trust.

4.4.2 Driver braking process in response to alarm timing

First, in order to understand the net effect of different alarm timings, the time delay to the driver's application of the brakes following an alarm was considered. Figure 4-4 illustrates the braking event to brake onset time for each alarm timing and for the baseline measurements in the non-consistent alarm condition. The results show that,

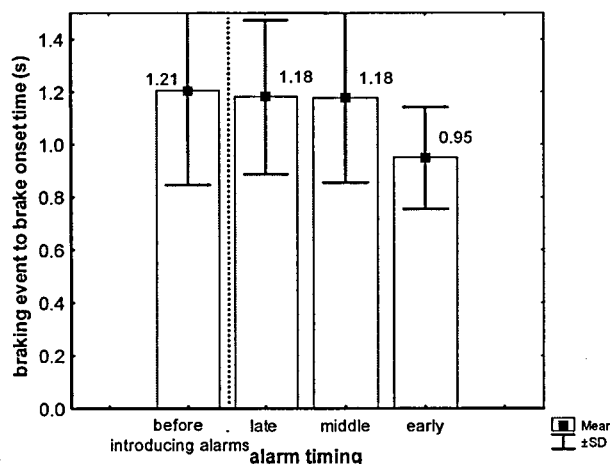


Figure 4-4 The effect of alarm timing on braking event to brake onset time

compared with the other conditions, early timing of the alarm contributed to a reduction in the transition time, ($F(3,70)=3.71, p<0.05$). For the other conditions, the mean transition time was almost the same as that achieved by drivers before the introduction of the warning system.

Two driver performance variables that might have contributed to an improved braking response to collision situations were also considered: the timing of the driver's release of the accelerator and the period of time between accelerator release and application of the brakes. Figure 4-5 illustrates mean values for braking event to accelerator release time for all alarm conditions. The graph shows that drivers released the accelerator quicker with the early alarm timing compared with the other conditions. Furthermore, the timing of the drivers' release of the accelerator for the late and middle alarm timing were similar to their performance before the introduction of the warning system ($F(3,70)=1.93, p=0.13$). Figure 4-6 illustrates the mean values of accelerator release to brake onset time for all alarm conditions. There are no differences between conditions.

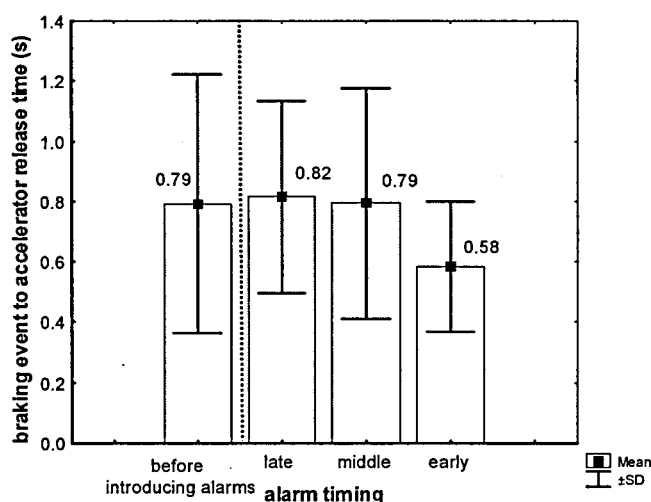


Figure 4-5 The effect of alarm timing on braking event to accelerator release time

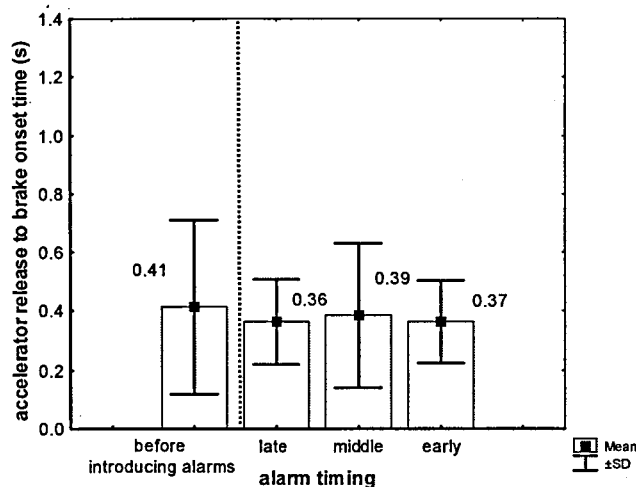


Figure 4-6 The effect of alarm timing on accelerator release to brake onset time

These results indicate that the early alarm timing helped drivers to release the accelerator quickly rather than decrease the period of time between releasing the accelerator and application of the brakes. Thus an early alarm enables drivers to recognise an imminent collision situation more quickly then apply the brakes if appropriate.

4.4.3 Driver response to alarms according to their timing

Up to this point in the analysis, the results suggest that driver braking strategies with a late alarm timing were not significantly different to those without the warning system. However, this conclusion was based on a consideration of the onset time of braking events i.e. the onset of deceleration of the leading vehicle. In order to understand their response to imminent collision situations in more detail, the relationship between the timing of the alarm’s onset and the drivers’ operation of the accelerator was considered.

Figure 4-7 illustrates mean values of alarm onset to accelerator release time for all alarm conditions. This transition time represents the delay following an alarm before drivers release the accelerator. The results show that, compared with late and middle alarm timing, there was an appreciable time gap before drivers released the accelerator following an early alarm. For the middle alarm timing, drivers released the accelerator immediately after the alarm onset. Interestingly, for the late alarm

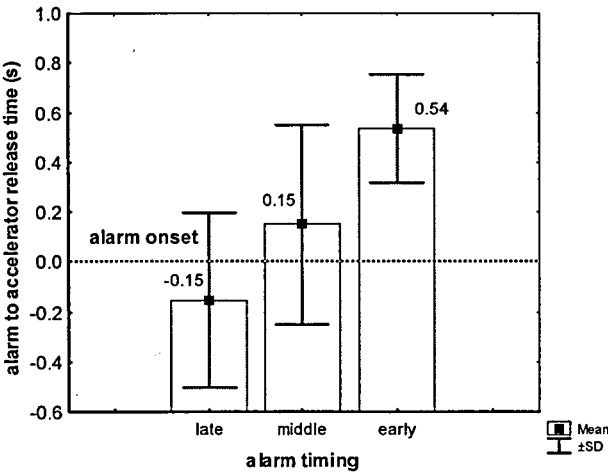
timing, drivers began to release the accelerator before the alarm onset. These results indicate that (i) the early alarm timing may provide drivers with more time before drivers decide to release the accelerator and (ii) that for late alarms, drivers may begin to implement an action for avoiding an imminent collision before the alarm onset.

If these results can be interpreted phenomenologically then the following explanation can be provided. For early or middle alarms, alarms were provided before drivers released the accelerator. In particular, early alarms helped the drivers to recognize imminent collision situations more efficiently, compared with other alarm timings. Accordingly it is possible that early alarms play a role in triggering driver action for collision avoidance. On the other hand, for late alarms the drivers heard the alarm after they had released the accelerator and it is arguable that late alarms no longer function as alerts for avoiding collision accidents.

4.4.4 Relationship between alarm timing and trust

Up to now driver subjective rating of trust and driver objective performance data were considered separately. The analysis now integrates the objective data and the subjective data in order to explore the relationship between driver trust and alarm actual driver performance with alarms in response to their timings.

Figure 4-7 The prelateship between alarm timing and alarm to accelerator release time



4.4.4.1 Static relationship between driver behaviour and trust

In this analysis, the time reference point changed to the onset of braking by the drivers and the time period between alarm onset and the application of the brakes was used as an objective indicator. From this perspective the presentation of alarms will have a negative time value if they occur after driver braking starts and a positive value if they occur before.

Z-scores were used as a measure of subjective driver response. A distribution value x being determined by its mean μ and standard deviation σ is converted into its value z by the formula below.

$$z = \frac{x - \mu}{\sigma}$$

The use of this transformation minimises differences in judgement of trust between individuals and emphasizes variation in judgements of trust. Accordingly, the Z-scores represent how far each subject's trust estimation is different from the centre of distribution of ratings of trust.

Figure 4-8 comprises a scatter plot showing alarm to brake onset time and Z-scores of trust. The results show that alarms that are provided after the driver has initiated braking (negative values of alarm to brake onset time) are associated with low ratings of trust. Trust ratings get higher as the time gap between alarm onset and brake application increases because the earlier the alarm, the more time the driver has before needing to brake and the greater the safety benefit. A positive correlation between objective data and subjective data was found ($r=0.50$, $p<0.05$). This not only supports the previous results i.e. trust in early alarm timings is higher than trust in late alarm timings but also suggests that "unhelpful alarms" that are provided after drivers have started to brake may lead to decreased trust.

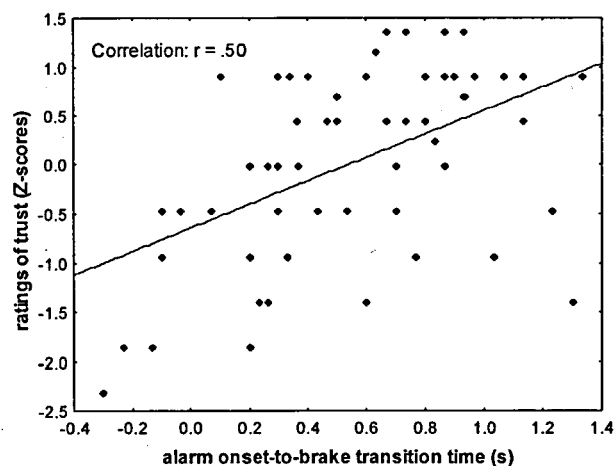


Figure 4-8 The relationship between trust and alarm to brake onset time

4.4.4.2 Dynamics of trust in FCWS

In the last analysis, a static model of driver trust in the warning system was identified using the objective data related to driver response to alarms. A trust model will now be proposed that incorporates possible factors driving the dynamics of trust using multiple regression analysis.

The analyses discussed earlier suggest that alarm timing has the potential to affect ratings of trust. Moreover it was found that the presentation of early alarms may lead to more prompt accelerator release compared with unassisted driver performance. These results indicate that the improved performance in the timing of accelerator release caused by the presentation of alarms may have the potential to influence trust dynamics. Accordingly, the difference between braking event to accelerator release time without the aid of alarms and alarm time (i.e. the elapsed time between the leading vehicle beginning to brake and when the alarm is presented) was used as a causal variable. We termed it (RAT-AT).

Moray et al. (2000) found that when investigating the dynamics of trust in automated systems in a time series, the value of subjective ratings of trust for the previous trial may contribute to increases in the validity of trust models. Following this earlier research, the subjects' trust ratings which were measured on the immediately preceding trial were used as a causal variable. The occurrence of an alarm presentation after drivers had started to brake was proposed as another factor driving driver trust. The previous analysis showed that drivers may brake before the

presentation of alarms depending on alarm timing, but given the aims of FCWS, it is arguable that alarms which are presented after drivers have started to brake may be viewed as unhelpful alarms, depressing ratings of trust. This variable was termed Discouragement. To sum up, three potentially exploratory variables were used in total for the multiple regression analysis. The results were as follows.

$T_n = 0.32(RAT-AT)_n - 0.44(Discouragement)_n + 0.576T_{n-1}$ ($r^2 = 0.62$), where T is the rating of trust, $(RAT-AT)$ is the remainder of the mean value of braking event to accelerator release time before the introduction of the warning system for each subject and alarm time for each braking event, and Discouragement is the occurrence of alarm presentations after drivers have started to brake. Discouragement is treated as a discrete (0,1) variable (Discouragement=1 if there is discouragement, otherwise Discouragement=0). The subscripts (n and $n-1$) indicate the current trial and the previous trial. The resulting regression model was reasonably reliable, $F(4,43)=17.71$, $p<0.01$.

The results suggest that ratings of trust for the previous trial may have an impact on present level of trust, which is consistent with previous research on dynamic models of trust. Furthermore, a causal factor driving the dynamic of trust, "RAT-AT", has a positive coefficient, consequently, as the time period between alarm onset and accelerator release without the warning system increases trust becomes greater. Thus, if the timing of the presentation of alarms is later than the timing of the driver's own performance in accelerator release, trust may be decreased. This indicates a driver expectation that alarms should be provided earlier than a driver's own performance in releasing the accelerator without the aid of alarms. An interesting property of the equation is that the Discouragement factor decreases trust, that is, if drivers hear the alarm signal after they have already implemented the brakes then their rating of trust in the alarms is lowered. The discouragement is analogous to a conflict situation in which the system's decision to trigger alarms and the driver's decisions regarding actions for avoiding critical events are different. It might be necessary for alarm systems to prevent this kind of conflict in order to maintain driver acceptance of the alarm system.

4.4.5 Potential benefit of middle alarm timing

As mentioned above, trust in alarms with a middle alarm timing was relatively high compared with that for late alarms. If this phenomenon is considered from the perspective of driver acceptance of the warning system then there is a possibility that driver braking performance might be improved by middle alarms. In order to estimate the potential benefit of middle alarm timings, driver behaviour in the consistent alarm condition where all alarm timings were middle in now considered.

Figure 4-9 represents braking event to brake onset time across all trials in the consistent alarm condition with the histogram to the left representing the data for the five braking events without the collision avoidance system, ($M=1.16s$ and $SD=0.29$). The histogram on the right side represents the data for the six braking events with the middle timing of the alarm ($M=1.09s$ and $SD=0.22$).

The results indicate a shift in the frequency of transition times towards lower values with the introduction of the warning system. More specifically, the values of transition time for the period time between 1.8s and 2.2s in the baseline condition disappear in the middle timing of the alarm condition. In contrast there are observations in the 0.6s to 0.8s category in the middle timing of the alarm condition. The Levene test was used to investigate differences in variance in transition time values with and without the FCWS. A significant difference in variance was found ($F(1,118)=3.03$, $p=0.084$). With respect to mean values, there were also significant differences between the two conditions ($F(1,108)=3.19$, $p=0.077$).

Although any interpretation of these results must be treated with caution, the data suggest a potentially valuable finding for the design of alarm timing. That is, middle alarms have the potential to encourage prompt braking reaction to imminent collision situations. Furthermore it should be stressed here that the middle alarm timing may decrease variation in braking reaction, resulting in more stable collision avoidance behaviour. It might be expected that the difference in braking reaction time before and after the introduction of warning systems would be small for the middle alarm

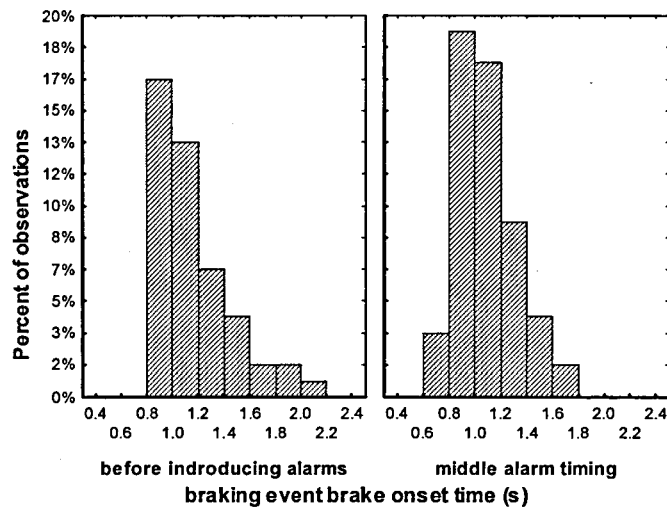


Figure 4-9 The comparison of braking event to brake onset time between middle alarm timing and before introducing the warning system

timing, because middle alarms are not presented early enough to significantly decrease braking reaction time.

Drivers show considerable variation in braking response when driving without the aid of alarms, and a delayed braking response in some situations has the potential to induce collisions. Therefore decreased variation in braking response to imminent collision situations has the potential to reduce accidents.

To sum up, these results suggest that the middle alarm timing may have contributed to decreased variation in driver braking response time compared with the baseline condition. The larger standard deviation indicates that drivers did not always implement a timely response to imminent collisions. Thus a middle alarm timing may be able to improve driver response by encouraging more consistent braking behaviour.

4.5 Concluding remarks

The present study investigated how the timing of an alarm can influence driver trust in FCWS and addressed the effects of three different alarm timings on driver braking strategies. Furthermore, driver response time to imminent collisions was compared

with, and without, a FCWS with a middle alarm timing. The results support important conclusions for this chapter.

First, for the different alarm timings and their influence on trust, it is concluded that late alarms lead to decreased trust compared with early or middle alarms. This result indicates that the timing of the alarm itself may have an influence on subjective ratings of trust in FCWS and drivers may judge whether an alarm is trustworthy or not according to its timing independent of its validity. The variation in ratings of driver trust in consistent alarm timings is similar to that in variable timings with a relatively wide range in judgments of trust. This result indicates that driver trust may be sensitive enough to vary in response to driving conditions.

Second, with regard to driver braking strategies in relation to alarm timing, an early alarm timing may contribute to a faster driver response to the brakes. This improvement in driver performance in imminent collision situations comes from a more timely release of the accelerator, compared with middle or late alarm timing. Interestingly, driver braking strategies with late alarms were similar to those undertaken without warning devices; drivers tended not to wait for late alarms and started to brake before an alarm was provided. Thus a relatively early alarm timing may help drivers to avoid an imminent collision by eliciting rapid braking but if drivers recognize hazardous situations before an alarm is presented then this alarm may be of no value to the driver, resulting in no contribution to improved performance.

Third, from the analyses of driver trust and its relation to driver response to imminent collision situations, it is concluded that trust ratings get higher as the time gap between alarm onset and brake application increases because the earlier alarm provides the driver with more time before needing to brake and the additional 'decision time' induces greater the trust. As for the dynamics of driver trust in alarm timing, it can be said that the relationship between the timing of driver release of the accelerator and the timing of alarm presentation is an important factor which determines decreased or increased trust and it is important that alarms should be presented before drivers release the accelerator. If alarms are presented after drivers

have started to brake then these alarms may be viewed as unhelpful alarms, resulting in decreased trust in alarms.

It follows from the above conclusions that further consideration is required regarding perceived false alarms and their influence on driver trust and braking strategy. In this experiment it was assumed that all alarms given to the drivers were true alarms. However the results obtained from the experiment show that drivers respond to different timings of the alarm in different ways and judge trust in alarms accordingly. Alarms that are provided after drivers initiate actions for avoiding imminent collisions may be viewed as unhelpful even though they are valid alarms. Although the subjects were not asked to say if they thought that late alarms were false alarms, the results indicate that late alarms have a greater potential to be viewed as unhelpful and may be judged as perceived false alarms with an associated reduction in trust.

Finally, it was found that middle alarm timing has the potential to improve driver performance in imminent collision situations by reducing variation in braking response. Interestingly, driver trust in middle alarms was similar to trust found with early alarms. System acceptance is crucial to widespread adoption of warning devices (Groeger et al., 1993) and the results of the current study indicate that drivers may accept warning systems with middle alarm timing more readily. Designers should consider this result when determining alarm timing if the purpose of FCWS alarms is not simply to decrease response time to imminent collisions. Certainly early alarms can help drivers achieve a quick response time to imminent collisions, but there is a possibility that the provision of early alarms will also increase the proportion of nuisance alarms. This study provided evidence that middle alarm timing may contribute to safe driving through consistent driver braking response to imminent collision situations and has the potential to help solve the trade-off problem between early alarms and nuisance alarms.

Chapter 5: The influence of alarm timing on driver trust and car following behaviour under different levels of driving demand

5.1 Introduction

In chapter 4, the effect of three different alarm timings on driver behaviour and trust in common driving conditions was considered. Differences in alarm effectiveness and driver subjective ratings of trust according to alarm timings were also identified. However in order to provide human factors guidance on the design of forward collision warning systems (FCWS) appropriate to more generalised conditions, it is necessary to gain knowledge about the effect of the presentation of alarms on driver behaviour in a wider range of driving conditions.

5.2 The aim of this study

The primary aim of this study was to understand how the presentation of alarms might influence driver behaviour and trust toward alarms in more depth by considering a wider range of driving conditions; three kinds of driving speeds and two kinds of time headways.

5.3 Methods

5.3.1 Apparatus

The research was completed using The Leeds Advanced Driving Simulator (see chapter 3). The visual scene was a computer generated environment which included other vehicles, buildings and pedestrians. In this study a simulated rural road environment was created with a single carriageway, a leading vehicle, and the occasional appearance of oncoming vehicles.

The following vehicle, 'driven' by the subjects, was equipped with a simulated FCWS. Although several algorithms have been used for alarm trigger logics, a Stop-Distance-Algorithm (SDA) was used in this experiment. Details of the SDA are given in chapter 3.

Two different timing characteristics of the alarm timing (late/early) were prepared by manipulating D_f (0.60g for late, 0.45g for early). The other parameters had the same value in all conditions ($RT=1.25\text{sec}$, $D_f=0.5\text{g}$). These parameters were chosen by considering three issues. The first was correspondence with 'real-world' values; The values were representative of those that would be experienced in on-road driving and should therefore appear rationality to the participants. The second was the relative difference in perceived alarm promptness between the alarm timings. It was important that the participants perceived clear differences between the parameter values used. The third was with respect to the experiment designed in chapter 4; different parameters were chosen in order to explore a broader range of values. The parameter values chosen were confirmed in pilot trials using the experimental scenarios. The warning system provided drivers with a simple auditory alarm which lasted approximately 2.0 s and the prominent frequency of the tone was 4000 Hz.

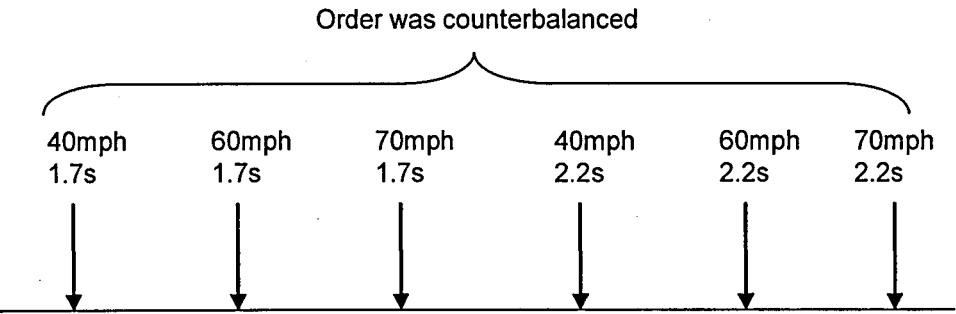
5.3.2 Subjects and experimental design

Twenty two participants (11 women and 11 men) ranging in age from 23 to 61 years ($M=31.9$, $SD=9.3$) took part in the experiment. All were licensed drivers with driving experience of two years or more. Each received a financial compensation of £10 for their participation.

11 subjects were assigned to each of the early and late alarm timing conditions. Each condition comprised two sessions; a session without alarms and a session with alarms. Each session included six potential collision events with 0.8g deceleration of the leading vehicle with illumination of the stoplights until the vehicle came to a stop. Three different driving speeds (40, 60, 70 mile/h) and two different time headways (1.7 and 2.2 s) were implemented as driving conditions. Accordingly, in combination these gave 6 treatment conditions (1.7 s/ 40 mile/h; 2.2 s/40 mile/h; 1.7 s/60 mile/h; 2.2 s/60 mile/h; 1.7 s/70 mile/h; 2.2 s/70 mile/h). The order of driving conditions was counterbalanced (Figure 5-1) and the order of trials within each session were also counterbalanced across the subjects.

The braking events occurred irregularly to prevent drivers from predicting their occurrence. Furthermore, in situations where a collision event occurred, one of the driving conditions discussed above was obtained. The required conditions were achieved by (1) ensuring that subjects drove at the target speed with a tolerance of

A session without alarms



A session with alarms:

early or late alarms were provided according to experimental conditions



Session order was counterbalanced

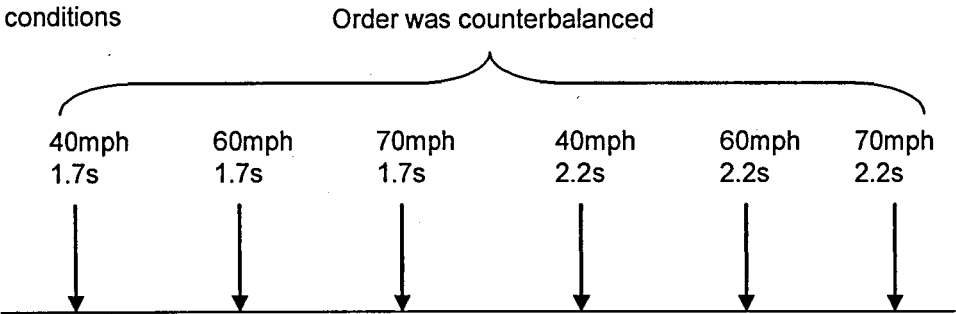


Figure 5-1 Driving conditions for each session

$\pm 5\%$ and (2) by adjusting the speed of the leading vehicle to provide the correct headway. The time headway between the leading and following vehicle was fixed by manipulating the leading vehicle's speed in response to the following vehicle's speed. Accordingly the time headway was nearly the same for all drivers immediately before the occurrence of potential collision events.

5.3.3 Procedure

All participants were required to complete an informed consent form and were briefed on task requirements by the experimenter. Each participant was then given a 10-min practice drive to familiarise themselves with the simulator and to experience the lead vehicle decelerations that would be involved in the experimental trials. After a 5-minute break, the regular trials were started. All participants were given two objectives in the regular trials. One was to keep their own speed at a target speed as directed by the experimenter (40, 60, or 70 mph) and the other was to follow the leading vehicle but to avoid rear-end collisions. The drivers were directed to only use the brakes to avoid an imminent collision with the lead vehicle, rather than to change lanes. About 8 second after each braking event, the leading vehicle gradually began accelerating again. Subjects were instructed to gradually accelerate until they reached the target speed. The participants had a 5-minute break between sessions.

5.3.4 Dependent measures

Five dependent measures describing the driver's braking response and one dependent measure describing driver trust in the system were recorded:

- *Braking event to brake onset time*
- *Braking event to accelerator release time*
- *Accelerator release to brake onset time*
- *Maximum deceleration*
- *Driver subjective rating of trust*

The definition of each variable is given in chapter 3.

5.4 Results and discussion

In the subsequent statistical analyses an ANOVA was used in order to investigate differences between factors, however several nonparametric tests were used in response to experimental conditions when homogeneity of variance was not present. In this experiment none of the subjects suffered collisions and so the effect of collision events on driver behaviour could be ignored.

5.4.1 Driver performance without alarms in response to driving conditions

This analysis focuses on driver behaviour without the aid of alarms in order to clarify inherent driver reaction to imminent collision situations in different driving conditions; three levels of driving speed and two levels of time headways.

Table 5-1 presents braking event to brake onset time in response to different driving conditions. A two-way ANOVA with the driving speed and the headway time as within-subjects independent variables showed no significant main effects and no significant interactions between factors.

Table 5-2 presents braking event to accelerator release time in response to different driving conditions. A two-way ANOVA of driving speed and time headway found no significant main effects and no significant interactions between factors.

Table 5-1 Summary of braking event to brake onset time in response to driving conditions

		Velocity		
		40 mile/h	60 mile/h	70 mile/h
Time headway	Long (2.2 s)	1.06 (0.41)	1.06 (0.34)	1.06 (0.37)
	Short (1.7 s)	1.02 (0.41)	0.99 (0.28)	1.10 (0.44)

Table 5-2 Summary of braking event to accelerator release time according to driving conditions

		Velocity		
		40 mile/h	60 mile/h	70 mile/h
Time headway	Long (2.2 s)	0.74 (0.38)	0.70 (0.28)	0.70 (0.36)
	Short (1.7 s)	0.71 (0.43)	0.68 (0.27)	0.81 (0.43)

Driver braking effort was considered next. Figure 5-2 illustrates mean values of maximum deceleration for avoiding imminent collision situations in response to different driving conditions. Generally speaking, short headways seem to induce greater braking effort than longer headways. A two-way ANOVA of driving speed and headway time showed no significant interaction between factors but a significant main effect on headway time, $F(1, 126)=11.01$, $p<0.01$, (long: $M=7.61$, $SD=1.18$, short: $M=8.24$, $SD=0.94$). The results suggest that drivers may adjust braking effort according to time headways.

To sum up, driver braking reaction time was not influenced by driving conditions but was consistent. This result may derive from consistent accelerator release timing in collision situations as a consequence of the illumination of the brake lights of a leading vehicle. When drivers give full attention to the forward view, it is likely that the brake lights of a leading vehicle may help trigger the braking response. In this study, driver reaction to the onset of the lead vehicle's brake lights triggered release of the accelerator in a consistent manner. This is predictable because brake light illumination does not indicate the rate of deceleration of a leading vehicle and to avoid a potential collision, drivers would have to assume that all brake illuminations were associated with maximum deceleration. However braking effort may vary according to headway with longer time headways leading to more gentle braking

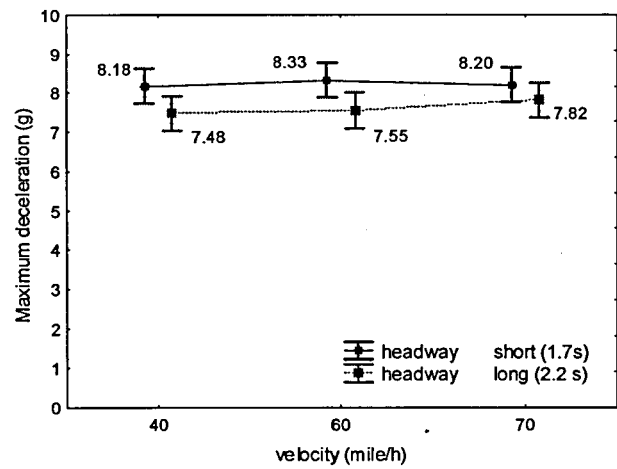


Figure 5-2 Maximum decelerations in response to time headways

effort than shorter time headways. It can also be concluded that in this experiment the drivers were well motivated to complete the driving task and responded to the imminent collision situations according to the driving conditions.

5.4.2 Driver braking performance in imminent collision situations with alarms

Here the effect of the presentation of alarms on driver braking performance was considered in order to gain a comprehensive understanding of alarm impact on imminent collision situations.

In this study two different alarm timings (relatively early alarm timing and relatively late alarm timing) were achieved by manipulating the alarm trigger parameters. In the following analysis of driver behaviour, alarm time (i.e. the elapsed time from when the leading vehicle begins to brake to when the alarm is presented) was also considered as a contributing factor in determining driver behaviour. Table 5-3 presents mean alarm times (and standard deviations) for the actual values achieved in the different experimental conditions. It can be clearly seen that vehicle speed has a much smaller influence on alarm time compared with headway values.

Table 5-3 Summary of alarm time for each driving condition

		Velocity		
		40 mile/h	60 mile/h	70 mile/h
Time headway	long (2.2 s)	Early: 0.641 (0.071)	Early: 0.533 (0.105)	Early: 0.498 (0.103)
		Late: 1.104 (0.126)	Late: 1.442 (0.262)	Late: 1.484 (0.439)
	Short (1.7 s)	Early: 0.190 (0.078)	Early: 0.182 (0.081)	Early: 0.074 (0.056)
		Late: 0.661 (0.081)	Late: 0.782 (0.080)	Late: 0.859 (0.110)

5.4.2.1 Braking event to brake onset time

Braking event to brake onset time was analysed in order to estimate the effect of the presentation of alarms on net reaction to imminent collision situations.

First, the effect of early alarm timing with respect to time headways was investigated. Figure 5-3 illustrates mean values for braking event to brake onset time for the 'early alarm' and 'no alarm' conditions when driving with short time headways. It appears that braking event to brake onset time tends to decrease when an alarm is provided. The standard deviation for the early alarm timing condition is also smaller than that for the no alarm condition. There was a significant difference in variance between the two conditions, $F(1, 64)=8.42$, $p<0.01$. With respect to the mean values, a signed rank sum test showed that there was a significant difference between the two conditions ($Z=2.09$, $p<0.05$).

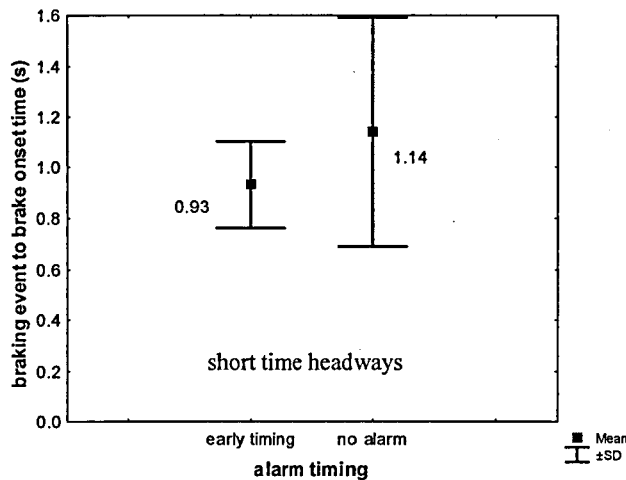


Figure 5-3 The impact of the presentation of early alarm timing on braking event to brake onset time for short time headways

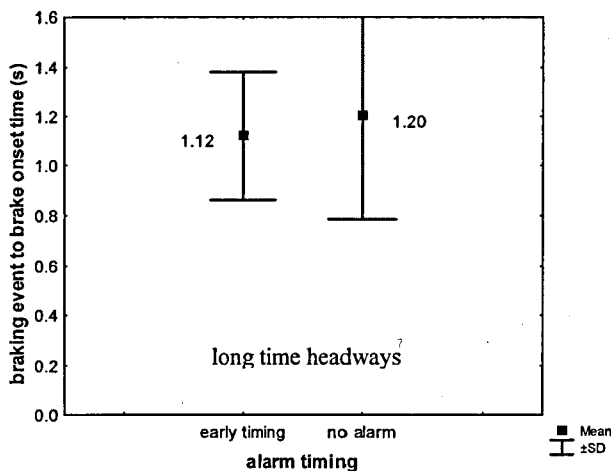


Figure 5-4 The impact of the presentation of early alarm timing on braking event to brake onset time for long time headways

Figure 5-4 illustrates the difference in mean values between the two conditions when driving with the longer time headways. There was no significant difference between the conditions. However it appeared that compared to the late alarm timing condition, the transition time for the no alarm condition varied widely. In fact, there was a significant difference in deviation among two conditions, $F(1, 64)=4.72, p<0.05$.

With respect to interactions between driving speed and the presentation of alarms, no statistically significant interactions were observed.

Figure 5-5 illustrates a frequency distribution of braking event to brake onset time for the no alarm and early alarm timing conditions. It appeared that, compared to the early alarm timing condition, the transition time for the no alarm condition varied widely. There was a significant difference in standard deviation among two conditions (No alarm: Mean=0.32, early alarms: Mean=0.19), $F(1, 10)=7.39$, $p<0.05$.

To sum up, the results suggest that the effect of the presentation of alarms may vary according to driving conditions even if the same alarm trigger logic is used. The explanation for this phenomenon may derive from the timing of the alarm presentation in response to driving conditions. In other words, if alarms are presented at the mean value of alarm time for relatively early alarms in short time headways driving (i.e. 0.149s) then these alarms may slow braking reaction compared to the no alarm condition. However if alarms are presented at the mean value of alarm time for relatively early alarms in long time headways driving (i.e. 0.557s) these alarms have no potential to decrease braking reaction. Furthermore with respect to the overall effects of alarms on driver behaviour, the presentation of alarms at the mean value of alarm time for relatively early alarms for all driving conditions (i.e. 0.353 s) may lead to more consistent braking reaction to imminent collision situations than no presentation of alarms.

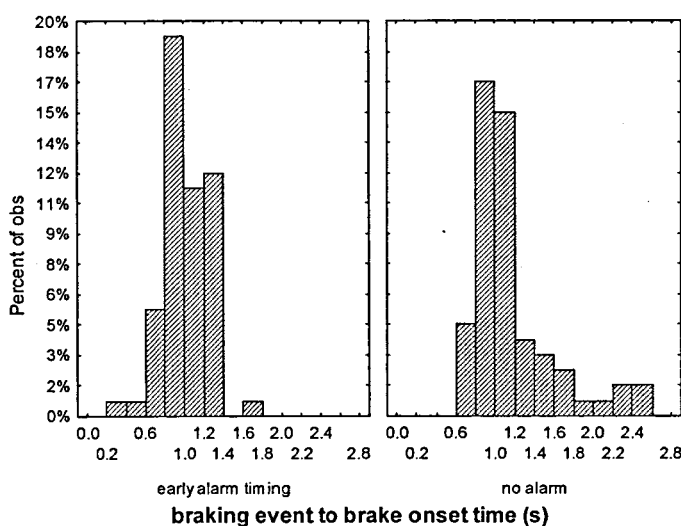


Figure 5-5 The impact of the presentation of early alarm timing on braking event to brake onset time

The effect of late alarm timing is considered next. Figure 5-6 illustrates braking event to brake onset time for relatively late and no alarm conditions when driving with short time headways. There is no significant difference between the two conditions. Figure 5-7 illustrates the difference in the transition time when driving with long time headways. A statistically significant difference was observed, $F(1, 53) = 5.32$, $p < 0.05$). With respect to interactions between driving speed and the presentation of alarms, no statistically significant interactions were observed.

The results suggest that the presentation of late alarms has no potential to improve driver braking reaction time to imminent collision situations and with longer time headways, a later alarm timing may actually lead to an increase in braking event to brake onset time.

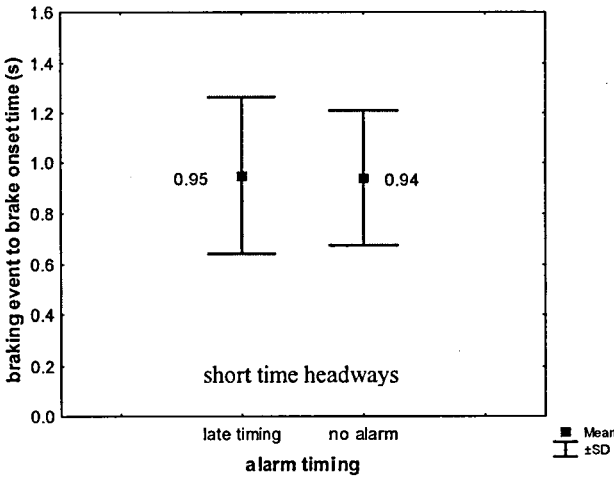


Figure 5-6 The impact of the late timing of the alarms on braking event to brake onset time for short time headways

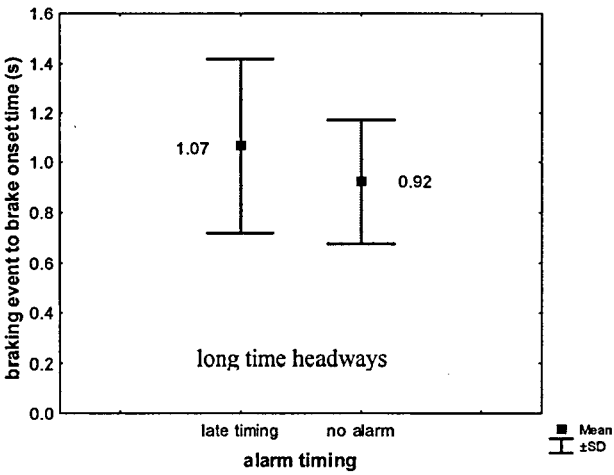


Figure 5-7 The impact of the late timing of the alarms on braking event to brake onset time for the long time headways

5.4.2.2 The timing of accelerator release

Changes in the timing of release of the accelerator in response to the timing of the alarms are considered next. First the effect of early alarm timing with respect to different time headways was investigated. Figure 5-8 illustrates braking event to accelerator release time for ‘early alarms’ and ‘no alarm’ conditions when driving with short time headways. A signed rank sum test showed that there was a significant difference between the two conditions ($Z=2.09$, $p<0.05$). With respect to long time headways, the presentation of alarms did not affect the timing of release of the accelerator (early: Mean=0.81 s, SD=0.23 s, no alarm: Mean=0.81 s, SD=0.42 s). No statistically significant interactions between driving speed and the presentation of alarms were observed.

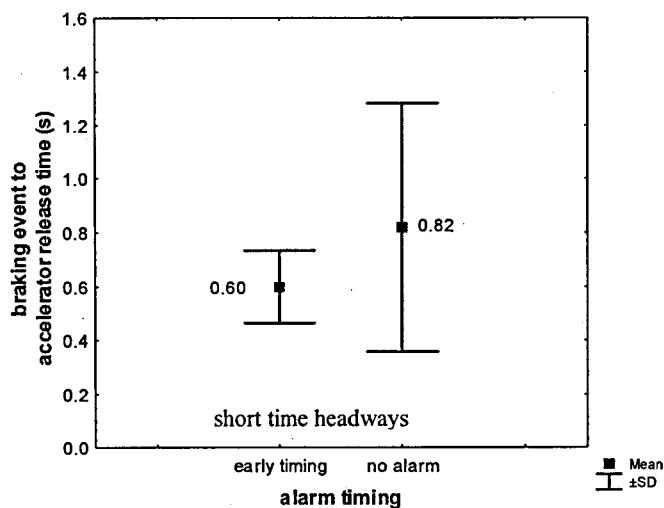


Figure 5-8 The impact of the early timing of the alarms on braking event to accelerator release time for short time headways

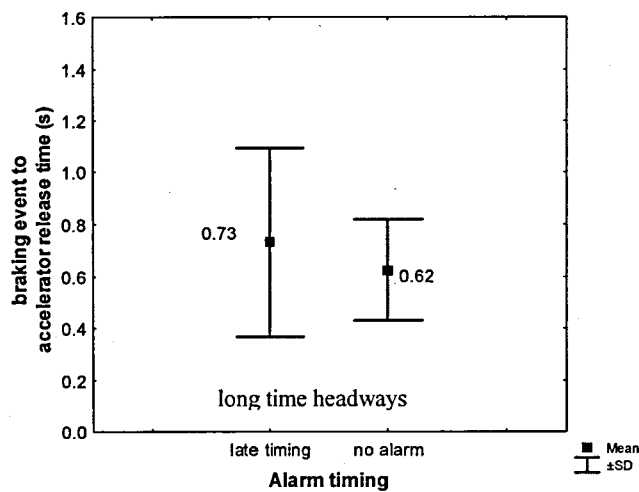


Figure 5-9 The impact of the late timing of the alarms on braking event to accelerator release time for long time headways

Figure 5-9 presents the effect of the presentation of late alarms on braking event to accelerator release time when driving with long time headways. It appeared that, compared with the no alarm condition, the transition time for the late alarms condition varied widely. A Levene’s test revealed that there was a significant difference in variance between the two conditions $F(1, 36)=8.10, p<0.01$. However there was no significant difference in mean values among two conditions. With respect to the effect of late alarms with short time headways, no statistically significant differences were observed (late alarms for short time headways: Mean=0.65 s, SD=0.25 s, no

alarm for short time headways; Mean=0.65 s, SD=0.26 s). No statistically significant interactions between driving speed and the presentation of alarms were observed.

These results are partly consistent with the earlier results related to driver braking response. That is, decreased braking event to brake onset time may derive from prompt release of the accelerator, depending on the timing of the alarms. Furthermore it is possible that the increased variation in accelerator release timing associated with late alarms when driving with long time headways may be linked to delayed driver braking response.

How should driver performance with late alarms when driving with relatively long time headways be interpreted? In relatively low severity car-following situations, for example with long time headways, drivers have more time to decide when to start braking compared with short time headways driving. Furthermore, drivers who know alarms will be provided in imminent collision situations, may expect to respond on the presentation of alarms. Late alarms may therefore induce increased variation in accelerator release timing, resulting in longer braking reaction time.

5.4.2.3 Accelerator release to brake onset time

Table 5-4 and table 5-5 present results for the effect of early and late alarms on accelerator release to brake onset time with different time headways respectively. No statistically significant differences were observed between the two alarm conditions and time headways. It can be said that the presentation of alarms may have no particular potential to impact on driver braking response after release of the accelerator.

Table 5-4 Summary of mean (SD) values of accelerator release to brake onset time for early alarm timing

	No alarm	Early alarms
Short time headways	0.32 (0.09)	0.33 (0.11)
Long time headways	0.40 (0.23)	0.33 (0.13)

Table 5-5 Summary of mean (SD) values of accelerator release to brake onset time for late alarm timing

	No alarm	Late alarms
Short time headways	0.30 (0.11)	0.30 (0.17)
Long time headways	0.30 (0.14)	0.34 (0.17)

5.4.3 Driver trust according to driving conditions

Figure 5-10 shows the effect of time headways on driver trust for early and late alarm timings. It appeared that ratings of trust for early alarm timing were similar for both short and long time headways. However with respect to late alarm timing, it seemed that trust ratings for long time headways was lower than those for short time headways. A one-way ANOVA found a significant main effect for time headways with respect to late alarm timing, $F(1, 50)=4.67, p<0.05$.

The results suggest that trust in early alarms was higher irrespective of time headways. Furthermore, time headways may affect driver judgement of trust with late alarms. Driving speed did not affect ratings of trust.

An explanation of these results can be provided by consideration of the timing of the presentation of alarms. Specifically, with respect to early alarms, when driving at short time headways, the timing of the presentation of alarm was 0.14s from the beginning of deceleration of the leading vehicle. On the other hand, when driving with long time headways, alarm timing was 0.56s. With respect to relatively late alarms, the timings of the presentation of alarms for the long and short headway time conditions were 1.34s and 0.76s respectively. Consequently there is a possibility that driver subjective ratings of trust may be influenced by perceived differences in alarm timing. That is, there is a possibility that trust towards alarms presented with a 0.76s alarm time is maintained at a relatively high level (over 5.0) but trust towards alarms with a 1.34s timing is reduced.

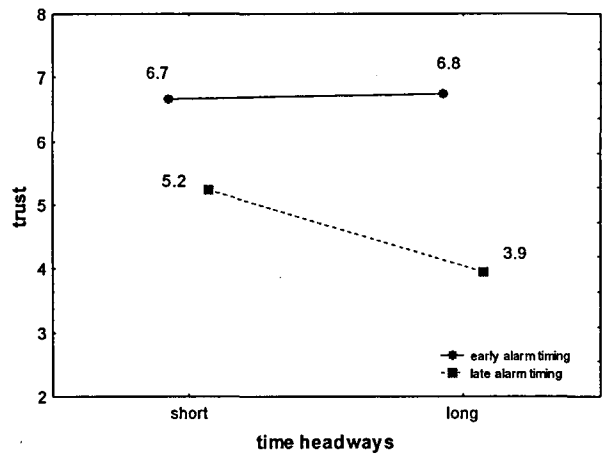


Figure 5-10 The effect of time headways on trust according to alarm timing

5.4.4 Driver perceived alarm timing and its relation to trust and alarm time

The relationship between driver perceived alarm timing and subjective ratings of trust will now be considered. First the relationship between pre-determined alarm timing (early and late alarm timing) and perceived alarm timing (Table 5-6) is confirmed. As can be seen in this table, early alarm timing had a tendency to be perceived as correct timing while late alarm timing was perceived as late in the driving conditions used in this study.

Figure 5-11 illustrates ratings of trust in alarms which were estimated as having correct or late timing. In this trial, one alarm viewed as a perceived early timing by one subject was omitted from this statistical analysis. There was a significant difference between the two trust values, $F(1,115)=118.32$, $p<0.01$. The result suggests that driver perception of alarm timing reflects ratings of trust and, more specifically, trust in alarms which were judged as late was lower than trust in alarms judged as having correct timing.

Table 5-6 Summary of perceived alarm timing and pre-determined alarm timing

	Early (perceived)	Correct (perceived)	Late (perceived)
Early alarm timing	1 (2%)	43 (65%)	22 (33%)
Late alarm timing	-	18 (34%)	35 (66%)

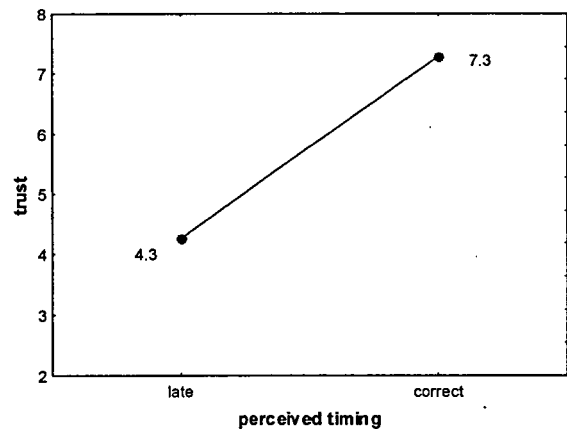


Figure 5-11 Trust ratings for perceived late and correct timing

Figure 5-12 presents the relationship between perceived alarm timing and actual alarm time. In this figure the dotted line represents the mean value of time for the release of the accelerator when no alarms were given. Interestingly there is a possibility that if alarms are presented later, compared with a driver's own performance in releasing the accelerator without the aid of alarms, then alarms will be viewed as being late. Given driver subjective ratings of trust for perceived alarm timing then it should be expected that alarms which are provided later than the timing of driver release of the accelerator without the aid of alarms may affect driver ratings of trust.

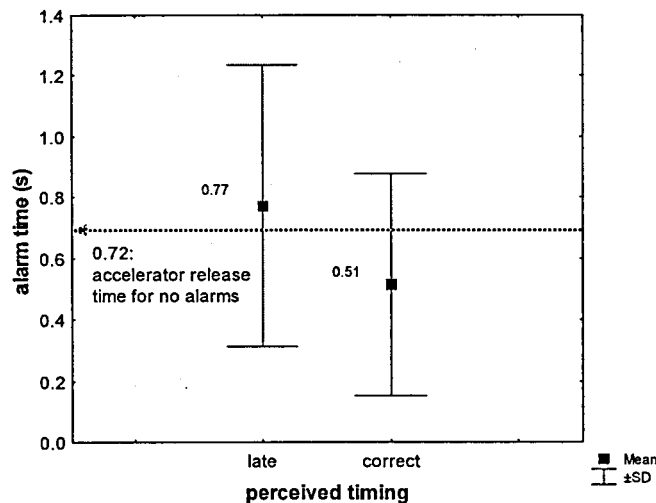


Figure 5-12 The relationship between perceived alarm timing and actual alarm time

5.4.5 The relationship between driver trust and alarm timing

Driver trust and its relation to alarm time will now be considered in more detail. With respect to ratings of trust, a transformation was implemented using Z-scores in order to minimise differences in judgement of trust between individuals and emphasize variation in judgement of trust. Z-scores were used as a measure of subjective driver response. A distribution value x being determined by its mean μ and standard deviation σ is converted into its value z by the formula below.

$$z = \frac{x - \mu}{\sigma}$$

The use of this transformation minimises differences in judgement of trust between individuals and emphasizes variation in judgements of trust. Accordingly, the Z-scores represent how far each subject's trust estimation is different from the centre of distribution of ratings of trust.

Figure 5-13 comprises a scatter plot showing alarm time and trust Z-scores. A negative correlation was found ($R=-0.47$, $p<0.01$). The result suggests that as an overall trend, as alarms are provided earlier driver trust is higher.

Next data which were not consistent with the overall trend (i.e. as alarms are provided earlier driver trust is higher) were considered in order to understand the relationship between alarm time and trust in more detail. The horizontal dotted line represents the mean trust value in terms of Z-score (i.e. zero). The vertical dotted line indicates mean value of braking event to brake onset time without the aid of alarms. As can be seen in this figure, all plotted points are assigned to the 4 zones which are created by the two dotted lines. For the plotted points which are involved in Zone A and Zone C, alarm time and its relation to trust is reasonably understandable as these data can be interpreted using the last analysis of correlation. That is, the earlier the alarm true the higher the trust rating.

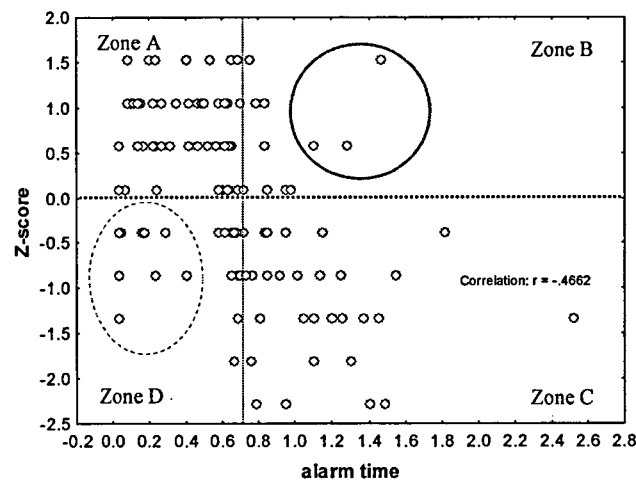


Figure 5-13 The relationship between alarm time and trust

However the data in Zones B and D requires further consideration since it appears to fall outside the overall trend. Some data showed relatively late alarms associated with relatively high trust values and the opposite was also true. The three data points which are enclosed by a solid circle and 10 data which are enclosed by a dotted circle are relatively big error data compared with the overall trend. Table 5-7 classifies the error data in terms of their speed/ headway conditions. In Zone B, 3 data points were all associated with long time headways. In Zone D, 8 data points (80 %) were associated with short time headways.

These data suggest that in situations where driving demand is relatively low (i.e. when driving with long time headways) driver subjective ratings of trust may exhibit 'tolerance' i.e. trust is relatively high even though alarms are relatively late. Conversely in situations where driving demand is relatively high i.e. when driving at high speed with short time headways, driver ratings of trust may be 'intolerant' i.e. trust is relatively low even though alarms are relatively early.

Table 5-7 Summary of characteristics for error data

Zone B		Zone D	
Driving condition (Speed/headway time)	Number of times observed data	Driving condition (Speed/headway time)	Number of times of observed data
70/long	2	70/short	5
40/long	1	60/short	2
		40/short	1
		70/long	1
		60/long	1

5.4.6 The dynamics of trust in alarms

In the previous analysis a static relationship was proposed among the timing of alarms, driver trust and perceived alarm timing. Now the dynamic nature of trust in alarms is considered. In chapter 4 a trust model using multiple regression analysis was proposed and this method of analysis will now be used again. The difference between braking event to accelerator release time without the aid of alarms and alarm time (i.e. the elapsed time between the leading vehicle begins to brake and when the alarm is presented) was used as a causal variable, (termed (RAT-AT)). Furthermore, the subjects' trust ratings which were measured immediately before the present ratings of trust were used as a causal variable. A multiple regression analysis using both causal variables gives the following trust model.

$T_n=0.231(RAT-AT)_n+0.534T_{n-1}$ ($r^2=0.43$), where T is the rating of trust, (RAT-AT) is the remainder of the mean value of braking event to accelerator release time before the introduction of the warning system for each subject and alarm time for each braking event. The subscripts (n and n-1) indicate the current trial and the previous trial. The resulting regression model was reasonably reliable, $F(2, 93)=36.79$, $p<0.01$.

The result corresponds reasonably with the previous model (section 4.4.4.2 in chapter 4), indicating that the relationship between alarm time and the timing of release of the accelerator for the no alarm condition may play an important role in the determination of driver trust. Furthermore, in this study driver objective data were obtained under a variety of driving conditions, therefore this model of the dynamics of trust not only

validates the previous model but is also relevant to a broader range of driving situations.

5.4.7 Alarm time, driver performance, and trust

In this section, the analyses of alarm time, driver braking performance, trust and their interactions will be integrated in order to provide a human factors perspective on the design of FCWS. Although many factors influence the occurrence of collision events in real traffic only the sudden deceleration of the leading vehicle was used to create potential collision events in the scenarios employed in this study. Accordingly the following argument can only be applied to these limited collision situations.

It was found that the timing of alarms (i.e. when alarms are activated) is an important contributing factor in determining driver performance, trust and the perception of alarm timing. In this study two predetermined alarm timings were generated by manipulating parameters of the alarm trigger logic (SDA), however the actual alarm timing varied according to driving conditions (3 driving speeds and 2 time headways). Accordingly, the variation in alarm timing may impact on driver object and subjective data. In other words, even when the same predetermined alarm timings were used the transition time from a braking event's onset to arriving at the warning distance varied in response to the driving conditions. In particular it was found that time headways may have more potential to influence alarm timing than driving speeds. That is, compared with the differences in driving speeds, the differences in time headways may lead to greater variation in alarm time with the same alarm trigger logic.

When driving with short time headways the presentation of early alarms (mean alarm time 0.149s) reduces driver braking response time as well as leading to a more consistent braking response. Furthermore, trust in these alarms is relatively high. When driving with long time headways, however, early alarms generated by the same trigger logic with the same parameter exhibit a different effect on driver behaviour; there is no improved driver braking response. Interestingly trust in these alarms (mean alarm time 0.557s) is also relatively high.

The research evidence suggests that improved driver performance with alarms is not always necessary in order to gain relatively high trust ratings and alarm timing may be a more important factor in determining driver trust. As to the overall trend of trust, if alarms are presented earlier trust is higher. However some data may exhibit 'tolerance', that is trust is high even when alarms are late when driving with long time headways. Moreover some data may exhibit 'intolerance' that is trust is low even when alarms are early when driving with short time headways.

Another result from this study indicates that it is possible that the timing of release of the accelerator without alarms i.e. driver baseline performance (mean value 0.72 s), may have the potential to determine driver perception of alarm timing i.e. correct timing or late timing, and their relation to driver ratings of trust. That is whether alarms are actuated before this timing is an important determinant of driver ratings of trust.

An explanation of this phenomenon was obtained from the post trial free discussion about FCWS with participants. Some participants commented that FCWS should be used as a backup alert or confirmation alert to encourage drivers to start braking. This may mean that these drivers are satisfied with alarms which simply act to confirm driver decisions. These alarms could be called 'confirmation alarms'. It is expected that for 'confirmation alarms' the presentation of alarms should be consistent with the driver's own decision to implement action to avoid an imminent collision.

However, other participants commented that alarms should be provided as early as possible in order to give drivers more time to respond to critical situations. This may mean that these drivers are satisfied with alarms which are provided in anticipation of potential collision events (before the driver is aware of them). These alarms could be called 'collision anticipation alarms'. Defining an alarm timing that always precedes a driver's awareness of an imminent collision situation is difficult due to variation in driver attention to the road environment. For drivers who are distracted or not attending alarms may function as collision anticipation alarms even when these are presented relatively late. In this study a sudden deceleration of a leading vehicle was used as a potential collision event with relatively high attention. Accordingly only relatively early alarms function to prompt earlier braking response times and the

timing of accelerator release may be a threshold for the determination of driver perception of alarm timing.

5.5 Concluding remarks

This study considered six different driving conditions according to speed and time headways and investigated their effect on driver behaviour and trust in the presentation of alarms. The results support the following conclusions:

1. With respect to driver baseline performance without the aid of alarms, differences in driving speed and time headway do not affect driver braking response time when a leading vehicle decreases its speed suddenly.
2. Differences in driving conditions induce variation in alarm time; the elapsed time from when the leading vehicle begins to brake to when the alarm is presented. This results in different alarm effectiveness and driver perception of alarm timing even if the same pre-determined parameters for triggering alarms are employed.
3. Variation in alarm time mainly derives from differences in time headway rather than from driving speed. Accordingly time headways have a greater influence on the effect of the alarm's presentation on driver performance and perception of alarms.
4. The relationship between trust in alarms and improved performance is not always correlated but alarm timing is an important factor in maintaining ratings of trust. In this study it can be concluded that an alarm time of about 0.56s may have the potential to maintain relatively high ratings of trust even though these alarms exhibit no improvement in driver performance compared with a 'no alarm' condition.
5. In particular, when driving with long time headways, drivers' adaptation to late alarms may induce a longer response to the brakes compared to the 'no alarm' condition, possibly resulting in impaired driver behaviour.

5. Driver perception of alarm timing reflects driver subjective rating of trust in these alarms relatively well. Accordingly, trust in perceived late alarms is lower than trust in perceived correct alarms. There is a possibility that a threshold between perceived late and correct alarm timings derives from the timing of release of the accelerator for avoiding collisions without the aid of a warning system. That is, when alarms are provided after this timing they may be perceived as late alarms.

6. Overall a positive correlation between alarm promptness and driver ratings of trust was found. However some data may exhibit another trend describing driver trust and alarm timing and their interactions with driving conditions. Specifically when driving with long time headways, driver trust in a relatively late timing was not decreased. On the other hand, when driving with short time headways, driver trust in relatively early timing was decreased.

7. The development of trust in alarms can be described as a function of the difference between braking event to accelerator release time without the aid of alarms and alarm time and the subjects' trust ratings which were measured immediately before the present ratings of trust.

Chapter 6: Driver performance and trust in alarms when driving at low speed

6.1 Introduction

In the last two chapters the timing of alarms and their influence on driver trust and driver performance in imminent collision situations were investigated. Although a number of important recommendations related to the design of forward collision warning systems (FCWS) were provided, these studies were implemented in conditions where drivers drove at relatively high speed (>40 mile/h).

Previous research suggests that approach velocity may affect accuracy of collision estimation (Sidaway et al., 1996). This finding indicates that driving speed may influence driver response to imminent collisions and driver performance with alarms may vary according to driving speed. Driving speed may affect driving demand or motivation to respond to critical events. Compared with high speed driving, there is a possibility that drivers compensate in their response to critical situations during low speed driving, resulting in different driver performance in imminent collision situations.

Although the urgency of response required may be different, it does not mean that the frequency of occurrence of potential collision events themselves will be decreased when driving at relatively low speed. Previous studies suggest that braking reaction time may be modulated by perceived urgency due to the degree of deceleration of a leading vehicle (Green, 2000, Summala, 1990). It is not surprising that driver performance in imminent collision situations varies in response to the deceleration of the leading vehicle since the rate of lead vehicle deceleration provides a strong

indication of the required urgency of driver response. In contrast, a relatively low deceleration of the leading vehicle has a reduced potential to induce serious accidents in low speed driving and, as a consequence, driver motivation to respond to alarms may be relatively low.

The study reported in this chapter focused on low speed driving conditions and also the difference in driving demand resulting from variable deceleration of a leading vehicle. These factors were not covered in the previous study and their consideration allows recommendations regarding system design to be made for a more broad range of driving conditions.

6.2 The aim of this study

The purpose of this study was to investigate driver response to alarms according to the degree of the deceleration of the leading vehicle and alarm timing when driving at relatively low speed. The study also considered the impact of these factors on driver trust.

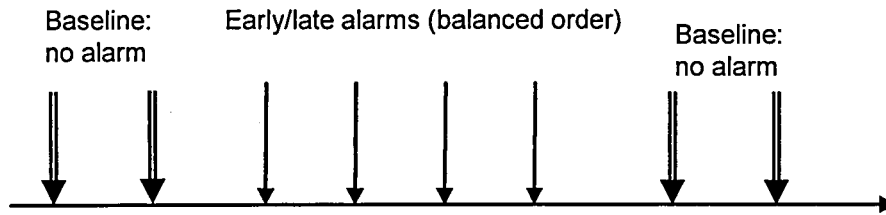
6.3 Method

6.3.1 Subjects and experimental design

Twenty four participants (12 women and 12 men) ranging in age from 21 to 55 took part in the experiment. Each received a financial compensation of £10 for their participation.

The experiment comprised a 3 x 2 factorial within/between-subjects design. Deceleration of the leading vehicle (high/low) was the between-subjects variable and alarm timing (early/late/no alarms) was the within-subjects variable. The participants were randomly assigned to two groups, with 12 in each group.

High deceleration group



Low deceleration group

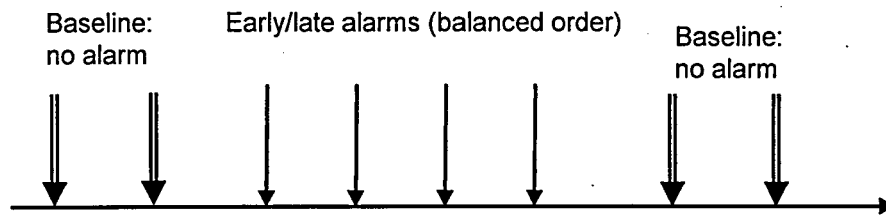


Figure 6-1 The procedure of experiment

In one group the leading vehicle decreased its speed quickly with 0.8g deceleration (high deceleration) and in the other group the leading vehicle decreased its speed gently with 0.4g deceleration (low deceleration). Each group experienced 8 potential collision events. Each potential collision event, with deceleration of the leading vehicle according to the two conditions discussed above, required a driver response to the brakes to avoid collision. In the first and last two events no alarms were provided, allowing driver baseline performance in response to be measured. In the other four events, late or early alarms were provided. The order of presentation of alarm timing was counterbalanced across the participants. The entire flow of the experiment can be seen in Figure 6-1.

6.3.2 Apparatus

Data were collected using the Leeds Advanced Driving Simulator (see chapter 3). In this study a simulated urban road environment with single carriageway was created. The urban road environment included buildings beside the road, pedestrians, the occasional appearance of oncoming vehicles, and a leading vehicle.

The following vehicle, 'driven' by the subjects, was equipped with a simulated FCWS incorporating a Stop-Distance-Algorithm (SDA). The detail of the SDA is given in chapter 3.

This study examined driver response to two different values of alarm timing (late/early) produced by manipulating one of parameters which was involved in the SDA. Specifically two D_f levels, 0.75g and 0.35g were prepared for the late and early timing of the alarm respectively. The other parameters had the same value in all conditions; $RT=1.25s$ and $D_f=0.5g$. The same parameters as used in the study described in chapter 4 were chosen where relatively high driving speed (45 mph) was implemented in order to gain knowledge about the effect of the difference in driving speeds on alarm effectiveness. A pilot trial was undertaken to determine parameter values that would be sufficiently different in promptness to be reliably discriminated by participants in the two conditions.

Potential collisions occurred at intervals that varied between one and two minutes. The occurrence of critical events was also dependent on whether the driving speed was 30 mph (48.3 kph) with a tolerance of $\pm 5\%$ of 30 mph or not. Thus alarm onset could not be predicted from time passage. In situations where potential collision occurred a stoplight of the leading vehicle was turned on, followed by deceleration (depending on experimental condition) until the leading vehicle came to stop. The time headway between the leading and following vehicle was fixed at 2.0s by manipulating the leading vehicle's speed in response to the following vehicle's speed. Accordingly the time headway was nearly the same for all drivers immediately before the occurrence of potential collision events.

The warning system provided drivers with a simple auditory buzzer alarm when the distance headway reached the pre-determined warning distance. The auditory tone lasted approximately 2.0 s and the prominent frequency was 4000 Hz.

Table 6-1 Summary of the experimental conditions

Condition	Initial Velocity (km/h)	Lead Vehicle Deceleration (g)	Initial Headway (s)	Algorithm Parameter	Mean Value of Alarm Time (s)
Early Alarm	48.3	0.8	2.0	RT=1.25g D _f =0.5g D _f =0.35g	0.13
	48.3	0.4	2.0	RT=1.25g D _f =0.5g D _f =0.35g	0.21
Late Alarm	48.3	0.8	2.0	RT=1.25g D _f =0.5g D _f =0.75g	0.85
	48.3	0.4	2.0	RT=1.25g D _f =0.5g D _f =0.75g	1.35

The timing of each alarm was dependent on the pre-determined parameters and on a common start point: the onset of deceleration of the leading vehicle. In Table 6-1 the parameters for each of the experimental conditions are summarised. Alarm time in Table 6-1 is defined as the elapsed time from when the leading vehicle began to brake to when the alarm was presented.

6.3.3 Procedure

All participants were required to complete an informed consent form and were briefed on task requirements by the experimenter. Each participant was then given a 10-minute practice drive to familiarise themselves with the simulator and to experience the lead vehicle decelerations that would be involved in the experimental trials with the test road used in the experimental trial. After a 5-minute break, the experimental trials were started. All participants were given two objectives in the regular trial. One was to keep their own speed at 30 mph (48.3 km/h). The other objective was to follow the leading vehicle but to avoid rear-end collisions. Drivers had to take appropriate action when the leading vehicle decelerated. However, the drivers were directed to only use the brakes to avoid an imminent collision with the lead vehicle, rather than implement lane changes. About 8 seconds after each braking event, the

leading vehicle gradually began accelerating again. Subjects were instructed to gradually accelerate until they reached the target speed.

6.3.4 Dependent variables

Five dependent variables describing the driver's braking performance and one dependent variable describing driver trust in the system were recorded.

- *Braking event to brake onset time*
- *Braking event to accelerator release time*
- *Accelerator release to brake onset time*
- *Alarm to brake onset time*
- *Maximum deceleration*
- *Driver subjective rating of trust*

The definition of each variable is given in chapter 3.

6.4 Results and discussion

In this experiment none of the subjects suffered collisions and so the effect of collision events on driver behaviour could be ignored.

In the subsequent statistical analyses an ANOVA was used in order to confirm significant differences between factors, however several nonparametric tests were used in response to experimental conditions when homogeneity of variance was not guaranteed.

6.4.1 Driver baseline braking performance in response to imminent collisions

Driver braking performance without the aid of alarms was considered in order to identify differences in driver behaviour only attributable to the degree of deceleration of the leading vehicle. Figure 6-2 illustrates mean values of braking event to brake onset time for low and high decelerations of the leading vehicle. There were no significant differences among conditions. Next, Figure 6-3 illustrates mean values of

maximum deceleration of the following vehicle associated with high and low decelerations of the leading vehicle. It appeared that the mean value in the high deceleration condition was greater than that in the low deceleration condition. Furthermore it seemed that variance in the low deceleration condition was greater than that for high decelerations. A Levene's test showed a significant difference among deceleration conditions, $F(1, 94)=24.93$, $p<0.01$. As for mean values, a Mann-Whitney test revealed a significant difference among deceleration conditions, $z=5.82$, $p<0.01$.

These results suggest that although there is no difference in the timing of driver braking response according to deceleration of the leading vehicle, drivers do adjust the strength of their braking efforts. More specifically, drivers brake harder in the high deceleration condition but in the low deceleration condition the variation in values for each driver tends to be higher.

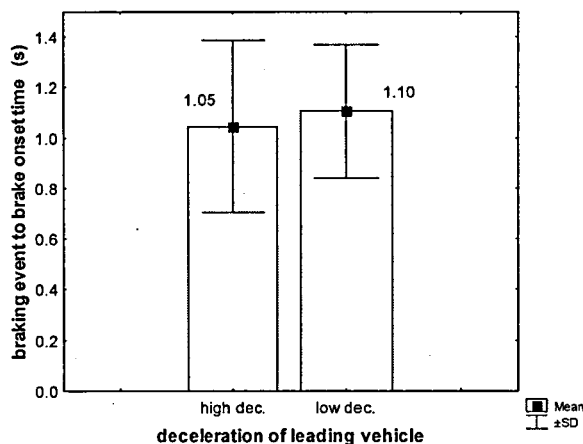


Figure 6-2 Comparison of braking event to brake onset time between high and low decelerations for driver baseline performance

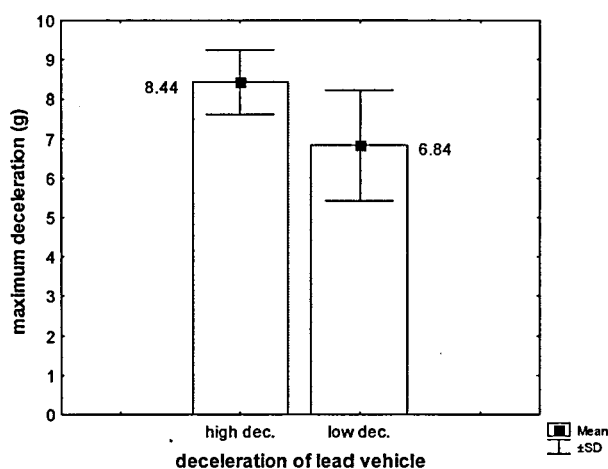


Figure 6-3 Comparison of braking effort between high and low deceleration for driver baseline performance

6.4.2 Driver braking process with alarms

In this experiment, the provision of alarms was based on predetermined parameters. In other words, there were no intended missed or false alarms caused by system malfunction. However as alarm generation was dependent on driver behaviour and drivers were given a degree of discretion in their vehicle control i.e. their speed adjustment and braking force, it was not possible to ensure that every subject experienced all the intended alarms. Thus, some intended alarms were not triggered by some subjects. These alarms were termed “untriggered alarms”.

Phenomenologically, untriggered alarms are similar to missed alarms for the driver. In both cases alarms are not provided in response to potential collision situations. Missed alarms are generally the results of a mechanical or electrical fault even when alarm trigger conditions are achieved. However, with untriggered alarms drivers anticipate a potential collision event and adjust their behaviour accordingly; as a result the headway does not achieve the warning distance. For drivers, missed alarms will be viewed as alarms which were not provided when necessary, but for untriggered alarms this perception may not always apply. A more detailed investigation will be given later (in section 6.4.3.).

Table 6-2 Number of untriggered alarm events according to driving condition

The degree of deceleration	Early timing	Late timing
High	0	0
Low	0	14(58%)

Table 6-1 shows the frequency of untriggered alarms across the potential collision events. All the untriggered alarms occurred under the same treatment condition (low deceleration and late alarm timing). When driving at relatively low speed drivers were less likely to achieve the speed and headway conditions necessary to trigger a deceleration event.

In the subsequent analyses the driver objective performance data for untriggered alarm events were also included as the effect of late alarm timing on driver behaviour. However driver subjective trust ratings for untriggered alarms and triggered late alarms probably have different meanings, therefore trust data for each situation were treated separately in the analysis of driver trust.

6.4.2.1 Braking event to brake onset time

Braking event to brake onset time was analysed in order to explore net driver performance in collision situations according to alarm timing and deceleration of the leading vehicle.

Figure 6-4 illustrates mean values of braking event to brake onset time for early and late alarm timings and baseline performance according to the deceleration of the leading vehicle. The left and right sides of this figure represent driver braking response for high and low deceleration conditions respectively. In the low deceleration condition, the presentation of alarms did not influence the transition time, furthermore the variance in the transition time for each alarm timing was almost the same. However, in the high deceleration condition, it appeared that the mean values varied according to alarm timing. Interestingly, the variance in early and late alarm timing data was smaller than that for the baseline performance. A Levene's test showed a significant difference in variance values, $F(2, 93)=3.08$, $p=0.05$. A

Friedman test revealed that there was a difference in mean values among conditions, $\chi^2(2)=4.66$, $p=0.096$. A post-hoc Sing test revealed a significant difference between the early timing and the baseline condition, ($p<0.05$).

These results indicate that when driving at low speed, even if the same trigger logic is used, the effect of alarm timing on driver braking reaction time may vary in response to the degree of deceleration of the leading vehicle. More specifically, if the leading vehicle decelerates rapidly, an early alarm may tend to lead to a decreased braking response time and the presentation of early alarms may contribute to decreased variation in driver response. This is not the case in the low deceleration condition.

6.4.2.2 Braking event to accelerator release time

In order to investigate driver performance in imminent collision situations in more detail, braking strategies were divided into two groups according to the time elapsed. Braking event to accelerator release time was considered first. Figure 6-5 illustrates mean values of this transition time according to alarm timing. The left and right sides of this figure represent high and low decelerations of the leading vehicle respectively. For the low deceleration condition there is no significant difference in values of the transition time. However, in the high deceleration condition it appeared that the transition time varied according to alarm timing and variances for early and late alarms were short, compared with variance for the baseline performance. Although a Levene's test failed to show a significant difference among conditions for mean values, $F(2, 76)=2.04$, $p=0.13$, a Friedman test showed a difference in mean values among conditions, $\chi^2(2)=3.45$, $p=0.072$. A post-hoc Sing test revealed significant difference between the early alarm and the baseline conditions, $p=0.07$.

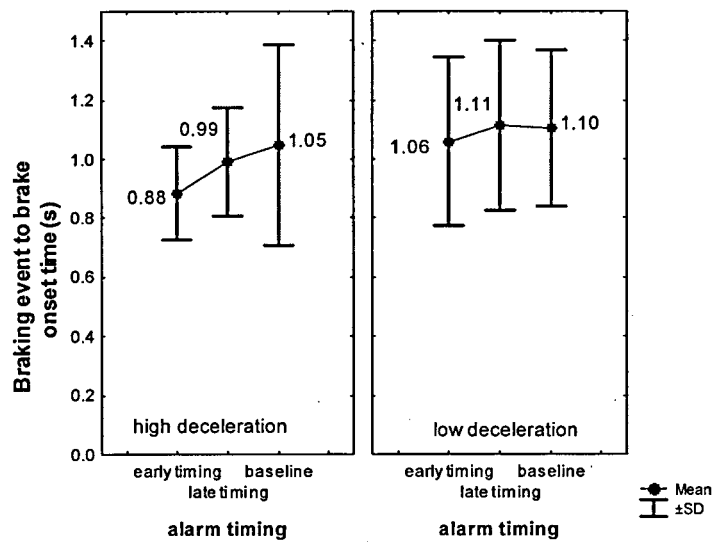


Figure 6-4 The effect of deceleration of the leading vehicle and alarm timing on braking event to brake onset time

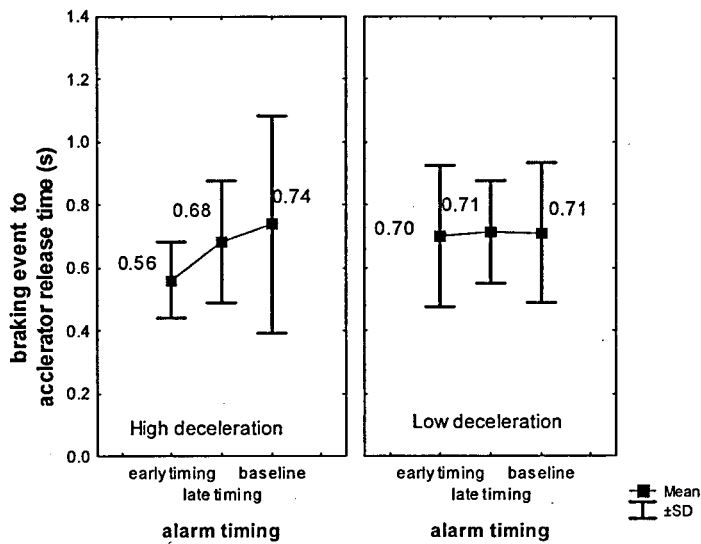


Figure 6-5 The effect of deceleration of the leading vehicle and alarm timing on braking event to accelerator release time

These results indicate that for the high deceleration condition, an early alarm timing tends to induce more rapid release of the accelerator. As for the low deceleration condition, the presentation of alarms has no particular contribution to driver performance in releasing the accelerator when collision events occur.

6.4.2.3 Accelerator release to brake onset time

Accelerator release to brake onset time was considered next. This variable corresponds to the time between the driver's release of the accelerator and application of the brakes. Figure 6-6 illustrates mean values of accelerator release to brake onset time for the early timing, late timing and the baseline condition. The left and right sides of this figure represent high and low decelerations of the leading vehicle respectively. Interestingly, for high deceleration events, the mean values of the transition time were almost the same across conditions. However, for the low deceleration condition, it appeared that the variance in the late alarm data was relatively high, compared with the other conditions. A Levene's test was conducted but the difference in variance among conditions did not achieve a traditional significant value, $F(2, 69)=2.02$, $p=0.14$. There was also no statistically significant difference between the mean values of the transition time for the low deceleration condition.

These results suggest that for low speed driving, the presentation of alarms may not affect accelerator release to brake onset time when the leading vehicle decreases its speed rapidly. For the low deceleration condition, however, careful consideration is required when attempting to assist driver behaviour through the use of alarms. As can be seen in the right side of this figure, compared with the values of standard deviation of the transition time for the late alarm timing and baseline conditions, the value for the early alarm timing condition is reduced.

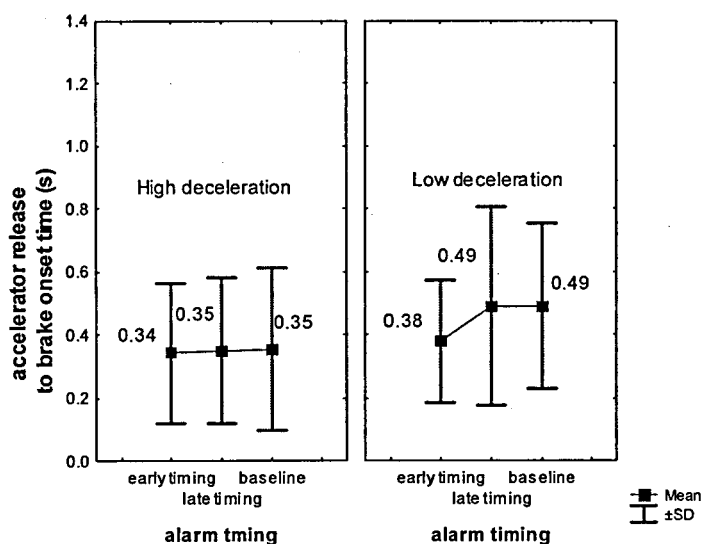


Figure 6-6 The effect of deceleration of the leading vehicle and alarm timing on accelerator release to brake onset time

This phenomenon might derive from driving demand and alarm timing. That is, when driving at relatively slow speed and when deceleration of a leading vehicle is relatively gentle, prompt braking reaction is not necessary, allowing the driver a relatively long period in which to decide to start to brake. Furthermore, some drivers may brake quickly after releasing the accelerator and others may brake relatively slowly due to individual differences in performance. Accordingly drivers exhibit a relatively wide variation of braking response after releasing the accelerator.

The data suggest that an early alarm might tend to encourage a faster braking response after accelerator release in low demanding driving conditions, inducing more stable braking strategies. Certainly these results are not strongly supported by statistically significant results but this phenomenon has potentially important implications for the design of alarm timing and such trends were not observed in the high deceleration condition.

6.4.2.4 Alarm to brake onset time

In order to investigate driver behaviour before and after the presentation of alarms in more detail, alarm to brake onset time was considered. As mentioned earlier, in this trial there were some untriggered alarms associated with low deceleration of the leading vehicle and alarm to brake onset time could not be measured in these cases.

The data associated with untriggered alarms was omitted from the analysis. Figure 6-7 illustrates mean values of alarm to brake onset time for the early and late alarm timing conditions. The solid and dotted lines refer to high and low decelerations of the leading vehicle respectively. A negative mean value indicates that drivers implemented the brakes before the presentation of alarms. A two-way ANOVA showed a significant interaction between alarm timing and deceleration of the leading vehicle, $F(1, 39)=6.47$, $p<0.05$. A Newman-Keuls post-hoc test revealed a significant difference in mean values for late alarm timings between the two deceleration conditions ($p<0.01$).

The results indicate that driver response to alarm presentation may vary according to alarm timing and the degree of deceleration of the leading vehicle. That is, drivers may respond to early alarms with a similar timing regardless of the degree of deceleration of the leading vehicle. It is likely that driver braking strategy is coincident with the presentation of alarms, that is early alarm timings for the high and low deceleration of the leading vehicle (mean value of each alarm time was 0.13 s and 0.21 s respectively) are consistent with driver braking action or have the potential to encourage driver braking action in order to avoid imminent collisions. However, for the late alarm timing condition, it can not be safely concluded that driver braking strategy is coincident with the presentation of alarms (mean values of alarm time for the high and low deceleration conditions were 0.85 s and 1.35 s respectively). This is because, with respect to the low deceleration condition, some drivers tended to start braking before the presentation of alarms. In such situations the alarm provided no obvious warning benefit to the driver.

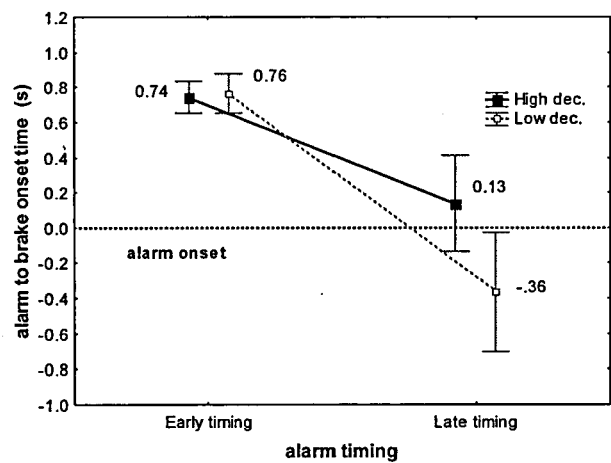


Figure 6-7 The effect of alarm timing on alarm to brake onset time

6.4.2.5 Maximum deceleration

The effect of alarm presentation on maximum deceleration was considered here. Figure 6-8 presents maximum deceleration for the early, late and no alarm conditions in response to deceleration of the leading vehicle. There was a trend that maximum deceleration for the condition of high deceleration of the leading vehicle was greater than that for the low deceleration condition. However the presentation of alarms did not affect maximum deceleration.

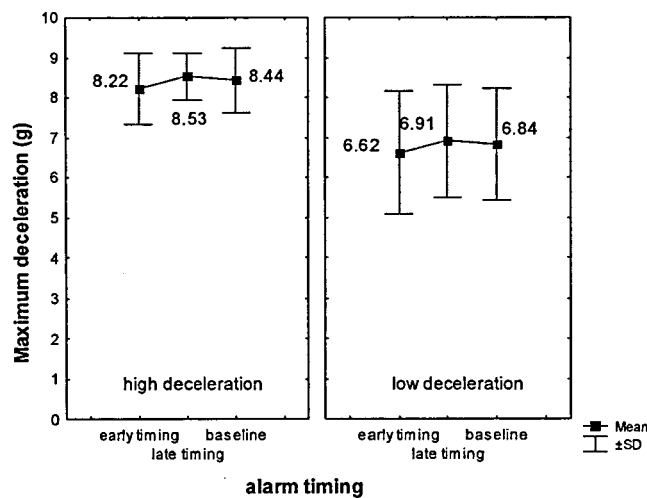


Figure 6-8 The effect of deceleration of the leading vehicle and alarm timing on braking effort

These results suggest that driver braking effort is not influenced by the occurrence of alarms or their timing.

6.4.3 Driver trust in alarms

Here, differences in driver trust arising from early and late alarm timings and different rates of deceleration of the leading vehicle are considered. Figure 6-9 illustrates mean values of subjective ratings of trust for early and late alarm timings with high deceleration of the leading vehicle. There was a significant difference between alarm timings, $F(1, 35)=45.72$, $p<0.01$. Figure 6-10 illustrates mean values of trust with low deceleration of the leading vehicle. The trust data for the untriggered alarm trials were omitted as these alarms may have a different meaning for drivers compared with trust in triggered alarms. A detailed analysis of this data was implemented separately. A statistically significant difference between late and early alarms was found $F(1, 21)=7.13$, $p<0.05$. These results suggest that trust in early alarms is higher than in late alarms regardless of the degree of deceleration of the leading vehicle.

As mentioned above, with respect to the low deceleration condition, some trials resulted in untriggered alarms. The effect of untriggered alarms on driver subjective ratings of trust was considered in order to understand differences in trust ratings associated with triggered late alarms and untriggered alarms. Figure 6-11 illustrates mean values of trust in triggered late alarms and untriggered alarms. The results showed that trust in untriggered alarms was lower than trust in triggered late alarms, $F(1, 11)=27.00$, $p<0.01$.

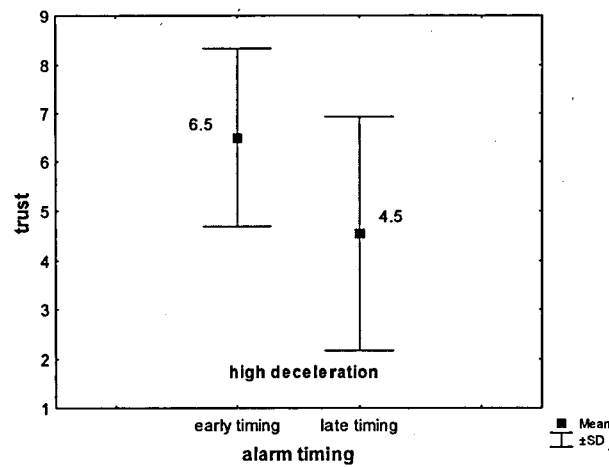


Figure 6-9 The effect of alarm timing on trust for high deceleration of the leading vehicle

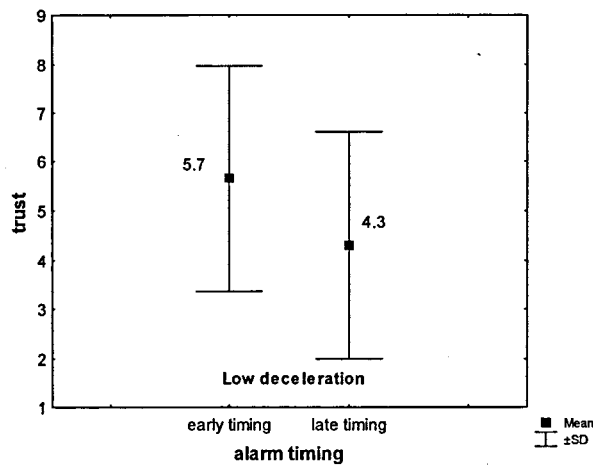


Figure 6-10 The effect of alarm timing on trust for low deceleration of the leading vehicle

This result may indicate an important characteristic of driver trust. If trust in triggered alarms is interpreted as the driver’s estimation of alarm effectiveness for avoiding imminent collision situations then trust in untriggered alarms may represent the degree to which drivers expect that FCWS should be reliable or, more specifically, should have provided an alarm in an untriggered alarm condition, both being relevant to system reliability. Although the drivers were able to avoid collisions without the assistance of an alarm in the untriggered alarm condition, drivers might reasonably expect that alarms should be activated when they are needed. It is crucial for the design of alarm timing that the presentation of alarms is consistent with driver expectation. The result provides a possibility that untriggered alarms also have the

potential to decrease trust due to inconsistency between the presentation of alarms and driver expectation in some situations.

The above statement also suggests that the nature of trust in FCWS might vary according to alarm performance. That is, it is possible that driver trust in FCWS may have different aspects which can be influenced by different components of system behaviour i.e. alarm timing and alarm reliability. From the drivers' perspective some alarms may be perceived as late alarms and drivers who experience a late alarm may start braking before the presentation of the alarm. Accordingly late alarms are consistent with the concept of the 'perceived false alarm' proposed by Wheeler et al., (1998). On the other hand, some drivers who are exposed to an untriggered alarm may regard these alarms as missed alarms if alarm performance is not consistent with a driver's expectation.

If this driver perspective on trust in triggered and untriggered alarms is correct then it is possible that decreased trust in triggered late alarms may be interpreted as reduced 'trust in alarm performance' and decreased trust in untriggered alarms may be interpreted as reduced 'trust in alarm systems', implying that driver trust in FCWS comprises two different components. Although any interpretation of the above arguments must be treated with caution due to the assumptions involved it suggests that there may be a case for considering the nature of driver trust in more detail. More specific arguments regarding nature of trust in FCWS will be developed in the following chapters.

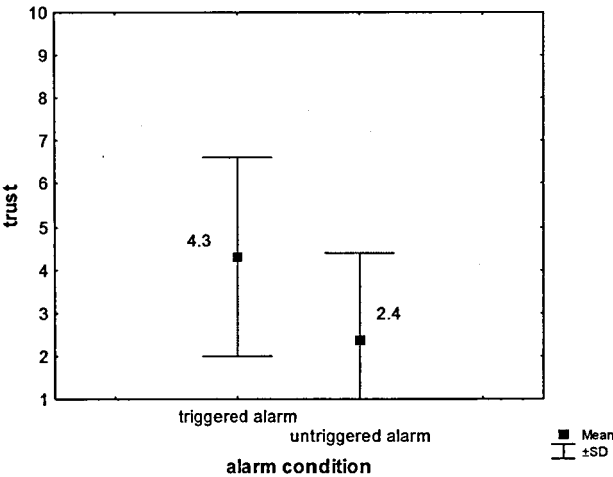


Figure 6-11 Comparison of trust between triggered and untriggered alarms

6.5 The relationship between trust and driver behaviour

In this section driver objective performance data is integrated with driver subjective ratings of trust in order to interpret driver trust from the viewpoint of driver performance.

With respect to early alarm timing, it has been established that the effect of alarm presentation on driver performance may depend on the degree of deceleration of the leading vehicle. However driver trust in early alarms is higher than that in late alarms despite differences in deceleration of the leading vehicle. On the other hand with respect to late alarm timing, it was established that the presentation of alarms may not help drivers to avoid collision situations because some drivers may start braking before the presentation of alarms, resulting in decreased trust. Taking all these results into consideration, it can be said that the presentation of alarms with a relatively early timing may play an important role in maintaining driver trust at appropriate levels despite the fact that these alarms do not always lead to improved driver performance.

6.6 Concluding remarks

This study focused on driver behaviour when driving at relatively low speed (30 mph) and investigated the effect of alarm timing and driving demand on driver braking strategies in collision situations. Three kinds of alarm timing condition (early, late alarm timings, and no alarms) and two kinds of driving demand (high and low decelerations of the leading vehicle) were considered. The results support the following conclusions which have considerable significance for alarm system design.

1. First, in the case of driver baseline performance in imminent collision situations without the aid of alarms, we can conclude that driving demand does not affect driver response time. However, drivers do adjust the strength of their braking efforts according to driving demand. Specifically, drivers brake more gently when the deceleration of the leading vehicle is relatively low.

2. Trust in late alarms is lower than trust in early alarms.
 3. Late alarm timing may have the potential to decrease trust in system reliability caused by untriggered alarms associated with inconsistency between driver expectation to alarm systems and actual presentation of alarms.
 4. In situations where the deceleration of the leading vehicle is low, the presentation of alarms does not affect braking reaction time. However, in situations where the leading vehicle decelerates rapidly, early alarm timing has the potential to reduce braking reaction time and also to reduce variation in braking reaction time, resulting in a more stable response, compared with baseline performance.
 5. From the subsequent analyses of driver braking strategies from the braking event to the application of the brakes, we can conclude that for the condition where the deceleration of the leading vehicle is high, there is a trend that early alarms may induce quicker release of the accelerator as a collision avoidance action, compared with the baseline condition (no alarms given). However for the condition involving low deceleration of the leading vehicle, the presentation of alarms does not affect the timing of the release of the accelerator.
- Furthermore, when driving with relatively low demand, for the conditions involving low deceleration of a leading vehicle, early alarms may have the potential to lead to more consistent braking than late alarms (or no alarms) after accelerator release.
6. Finally, from the analysis of driver behaviour before and after the presentation of alarms, it can be concluded that for the condition involving high deceleration of the leading vehicle, early alarms may encourage or be coincident with driver action to avoid collisions, resulting in high trust ratings. However, for the condition of low deceleration of the leading vehicle, late alarms may not always encourage driver action to avoid collisions and it is likely that drivers may tend to implement braking earlier, compared with the presentation of late alarms, resulting in low trust ratings.

Chapter 7: Driver response to false and missing alarms: The role of driver trust

7.1 Introduction

In the last three chapters, we focused on alarm timing and its influence on driver trust and performance with alarms. As mentioned earlier, another important issue in the design of forward collision warning systems (FCWS) is driver response to alarm failure.

In a failure mode analysis, alarm failure, i.e. the generation of false alarms or missing alarms, is a common problem in the domain of warning systems. The fundamental issue in setting the alarm trigger threshold is a trade-off between the cost of a missing and a false alarm. Parasuraman et al. (1997) insisted that if a system is designed to minimise the rate of missed alarms, then an increase in the number of false alarms becomes almost inevitable. Furthermore, the possibility of occurrence of false and missed alarms does not simply result from theoretical considerations but from system failures related to mechanical or electrical problems (i.e. sensor failure or data processing under-performance). Therefore, it is necessary to consider the effect of both missing alarms and false alarms on driver behaviour if system effectiveness is to be maximised.

In chapter 6, initial evidence was presented that trust in FCWS may have different aspects and may be influenced by alarm failure in different ways. This chapter will focus on the nature of driver trust and explore how false and missing alarms can affect driver trust.

7.2 The aim of this study

The primary aim of this study was to understand the nature of driver trust in warning systems and to address its relation to driver behaviour with respect to false and missing alarms. A model of driver trust in warning systems is proposed that supports the generation of several hypotheses relating to driver trust and performance. Finally the trust model will be validated using driving simulator experiments to test the hypotheses.

7.3 A model of trust in warning systems and its relation to driver behaviour

Figure 7-1 depicts a schematic model for driver trust in warning systems and its relation to driver behaviour, how alarm malfunction affects driver trust and how impaired trust influences driver behaviour. The model is divided into three conceptual factors, namely “system behaviour”, “trust in warning systems” and “driver behaviour”. Moreover it is assumed that an upper hierarchical stage may influence a lower hierarchical stage (i.e. system behaviour influences trust in warning systems).

Several authors have observed that operator trust in automated systems is not a simple construct but has several dimensions (Muir, 1987; Muir, 1994; Zuboff, 1988). Meyer (2001) distinguished between two types of operator trust in relation to warning systems that are subtly but significantly different; one he termed compliance and the other reliance. In compliance the operator responds to alarms promptly, assuming that they reliably indicate a hazard or fault condition. However, in the absence of an alarm (‘green light’ condition) the operator assumes that there is **probably** no hazard and proceeds with caution. In reliance the operator assumes that there will be no hazard unless the alarm is given; the green light condition **reliably** indicating a lack of hazard.

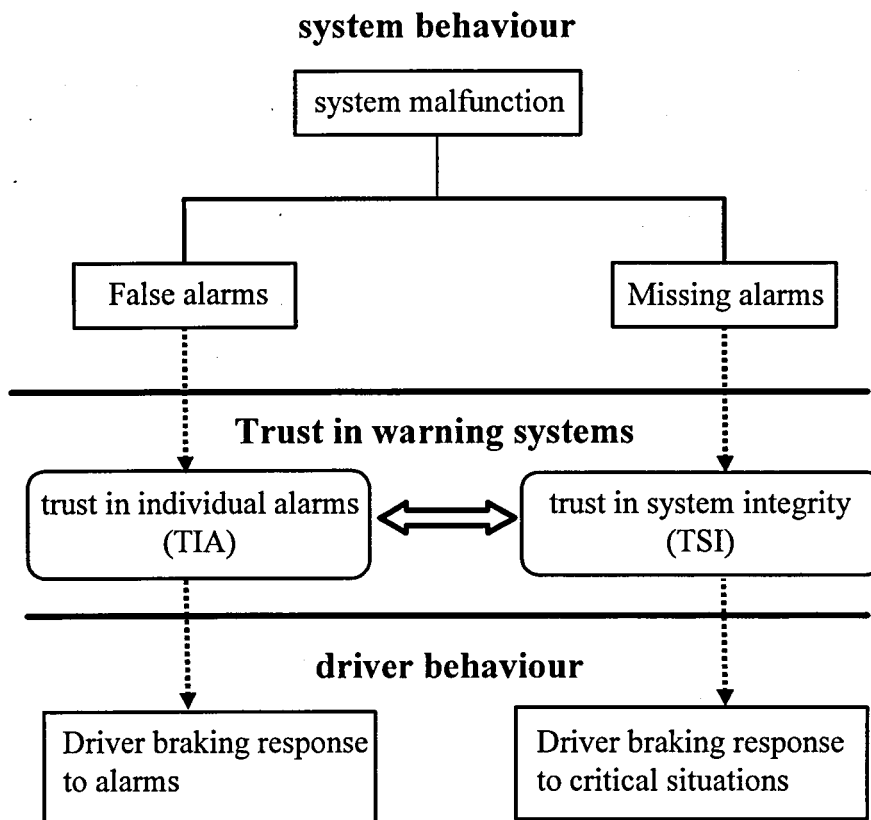


Figure 7-1 Conceptual model showing among system behaviour, trust, and driver behaviour

In the current study, the proposed trust model for warning systems also involves two different aspects of trust; “trust in individual alarms (TIA)” and “trust in system integrity (TSI)”. TIA is defined as driver trust which is determined by individual alarm performance and TIA strongly influences a driver’s judgement as to whether specific alarms are valid or not, whether alarm timing is appropriate or not and so on. TSI is defined as driver trust which is determined by system reliability and TSI has a strong influence on driver judgement as to whether or not a system is reliable and consistent with past performance.

TIA is therefore influenced by individual episodes while TSI is influenced by relatively longer term experience than TIA. The relative strengths of TIA and TSI in overall trust are a consequence of a driver’s cumulative experience of alarms. In a driver’s early experience with a warning system each individual alarm (and hence TIA) can be expected to have a greater influence on driver behaviour than TSI. The driver has simply had insufficient experience to enable the development of TSI.

However, as experience increases, and providing the alarm system operates efficiently and consistently, it is likely that TSI will become more influential, possibly at the expense of TIA.

Consequently, it can be argued that trust in warning systems may represent the combined influence of TIA and TSI and it is necessary to interpret driver behaviour as a response to both factors to achieve a comprehensive understanding of driver response to alarm failures. The influence of system failure on driver trust in warning systems will now be considered.

In this study, system behaviour (top stage in Figure 7-1) is limited to situations in which system malfunction occurs. Two types of alarm malfunction, "false alarms" and "missing alarms", were considered as factors that have the potential to impair system effectiveness. Alarm malfunction may lead to decreased trust in warning systems as it is well established that faults in automated systems contribute to decreased trust. However, false and missing alarms are distinctly different phenomena with very different consequences for driver safety and it is possible that the two types of alarm malfunction may influence driver trust in warning systems in different ways. It is suggested that false alarms may decrease TIA and missing alarms decrease TSI. The experience of false alarms is likely to reduce driver perception of alarm performance, resulting in impaired TIA. However the experience of missing alarms may inevitably reduce an expectation of system reliability (i.e. that warning systems will always produce an alarm in critical situations) resulting in impaired TSI.

The proposed trust model also takes account of decreased trust and its influence on driver performance. This is represented in the bottom of figure 7-1. First, with respect to driver response to false alarms, if false alarms decrease TIA then drivers could reasonably believe that any given alarm might be invalid. Consequently drivers may be reluctant to respond promptly to alarms presented after experiencing false alarms.

A different viewpoint must be taken with respect to driver response to missing alarms where the level of TSI is an important factor in understanding driver performance. If TSI is high then drivers would reasonably expect alarms to be presented when

hazardous situations occur. As a result, driver response to imminent collision situations may be delayed when a missing alarm occurs. However, if missing alarms decrease TSI then drivers may have reduced expectations of warning systems in critical situations. Consequently, any delayed response to critical situations caused by the experience of a missing alarm, would be improved in subsequent missing alarms conditions. Furthermore if trust in warning systems has two different aspects then impaired TSI caused by missing alarms would not affect driver response to a true alarm after the presentation of missing alarms.

Accordingly it is possible that TIA and TSI may conceptually correspond to compliance and reliance respectively as proposed by Meyer (2001). That is, TIA may play an important role in determining compliance with presented alarms, particularly with respect to false alarms. When TIA is high drivers will tend to respond positively to a false alarm. On the other hand, TSI may be strongly relevant to reliance and drivers may assume that there will be no hazard unless an alarm is given if TSI is high.

The discussion above suggests four hypotheses describing the impact on driver behaviour caused by false and missing alarms.

- (i) The experience of false alarms will impair TIA and this will reduce the speed of driver response to subsequent true alarms.
- (ii) If TSI is high, following the experience of valid alarms, then missing alarms will lead to delayed response to critical situations.
- (iii) If TSI is impaired, following the experience of a first missing alarm, then the response to subsequent missing alarms will be quicker.
- (iv) After missing alarms have been experienced driver response to a true alarm will not be delayed because missing alarms will not directly affect TIA.

As a way of testing these hypotheses, two experiments were completed using a driving simulator with a forward collision warning system. The details of these experiments are given in the following sections.

7.4 Experiment I

The purpose of experiment I was to investigate the effect of alarm malfunction on driver behaviour and trust. In this study a false alarm was defined as an alarm issued in the absence of an imminent collision situation.

7.4.1 Apparatus

The experiments were undertaken using a Driving Simulator owned by the Japan Automobile Research Institute (JARI). The detail of this simulator can be seen in chapter 3. The road conditions comprised a straight, two-lane freeway. There were no other vehicles or pedestrians in the simulated environment except for a leading vehicle.

The following vehicle, 'driven' by the subjects, was equipped with a simulated FCWS. Although several algorithms have been used for alarm trigger logics, a Stop-Distance-Algorithm (SDA) was used in this experiment. The detailed description of the SDA is given in chapter 3.

The warning system provided drivers with a simple auditory tone alarm. The alarm was activated when the headway distance between the lead and following vehicle corresponded with the warning distance. In this experiment the parameter values were defined as 1.0s, 0.6 g and 0.6 g for RT , D_f and D_l respectively. The values of these parameters were chosen to reflect realistic values for the deceleration level of the following vehicle and driver braking response time. Moreover a pilot trial was undertaken in order to confirm that alarms were reasonably effective for drivers to avoid collisions.

7.4.2 Subject and experimental design

Eight JARI volunteer employees (5 males and 3 females) participated in this study.

The experiment comprised 15 trials with 12 normal alarms events and 3 false alarm events. Itoh et al. (1999) found that while discrete system failures may not impede

human interactions with automated systems, continuous malfunctions significantly influence human behaviour and ratings of trust in the systems. The primary aim of this experiment was to investigate changes in driver behaviour and trust when false alarms occur and so false alarms were provided for the 7th, 8th, and 9th “events” when the leading vehicle did not decelerate. In the other braking events, the system worked correctly (Figure 7-2). A potential collision event involving a sudden 0.6g deceleration occurred about once every three minutes, however, the exact timing of the speed reduction was always at random in order to prevent drivers from anticipating the need to brake. In situations where the braking event occurred the headway distance between the leading and the following vehicle was always fixed at 2.0s.

7.4.3 Procedure

After being given complete verbal instructions and having any questions answered, each subject completed a practice session lasting eight minutes in order to familiarize themselves with the simulator dynamics, possible system actions, the way in which the warning system triggered alarms, how to avoid an accident and so forth. The purpose of this study was to estimate the effect of alarm malfunction on driver behaviour and trust and as it was hypothesised that this effect could depend on the experience of previous false or missing alarms, the warning system operated correctly in the practice trial.

All participants were given two tasks. One was to keep their own vehicle speed at 50 mile/h (80km/h) and to follow the leading vehicle. The other was to avoid rear-end collisions with the leading vehicle. In order to avoid imminent collision situations, the drivers were required to brake when the leading vehicle decreased its speed

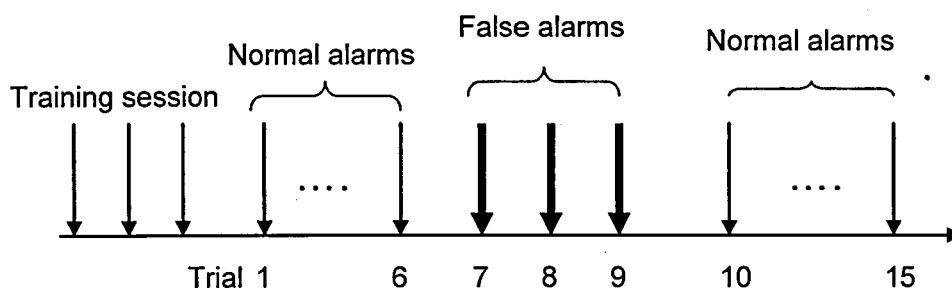


Figure 7-2 The procedure of experiment I

It was assumed that drivers would recognise the deceleration of the leading vehicle from a change in the relative distance between their own vehicle and the leading vehicle. The illumination of a leading vehicle's stoplights provides variable additional information about that vehicle's possible behaviour, but does not necessarily indicate prompt deceleration. The stoplights will be illuminated if the driver touches the brakes (no deceleration) or brakes hard. Thus the stoplight of the leading vehicle provides ambiguous information on the leading vehicle. However, as the focus of this study was driver response to prompt deceleration of the leading vehicle with and without a warning system, the stoplight display on the leading vehicle was turned off across all trials in order to reduce the influence of other factors on the driver braking process. The subjects were therefore required to decide whether braking was needed by observing changes in headway.

After a two minute break, the subjects began the experimental session comprising 15 potential collision events. Each participant was given a 3-minute break at the end of the fourth and 11th braking events.

7.4.4 Dependent measures

The two following variables were recorded as measures of driver braking performance and driver trust.

- *Alarm to brake onset time*
- *Driver subjective rating of trust.*

The definition of each variable is given in chapter 3. A possible interpretation for trust ratings will be given based on the relationship between trust ratings and driver response to alarms failures in the following sections.

7.4.5 Results and discussion

Figure 7-3 illustrates the trend in mean values of alarm to brake onset time across successive trials. The transition time increased following the presentation of three false alarms from trial 7 onwards. Interestingly, alarm to brake onset time was longest in trial 10 where a true alarm was presented after the presentation of three

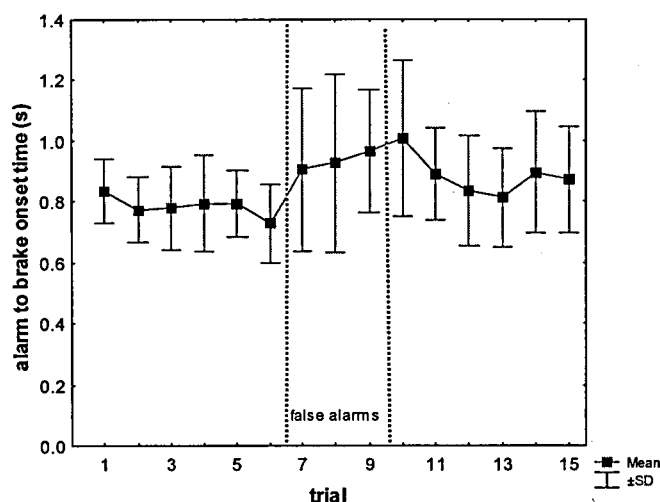


Figure 7-3 The effect of false alarms on alarm to brake onset time

false alarms. Furthermore reaction time did not recover to the pre-malfunction level. A one-way ANOVA showed a significant main effect among trials, $F(14, 94)=2.34$, $p<.01$.

Figure 7-4 illustrates mean values of subjective ratings of trust for each trial. As can be seen, trust gradually increased during the first 6 trials and decreased rapidly following the presentation of false alarms from trial 7. Following trial 9, trust increased gradually, however it did not immediately recover to the pre-malfunction level. A one-way ANOVA on the subjective rating of trust showed a significant main effect among trials, $F(14, 98)=9.09$, $p<.01$.

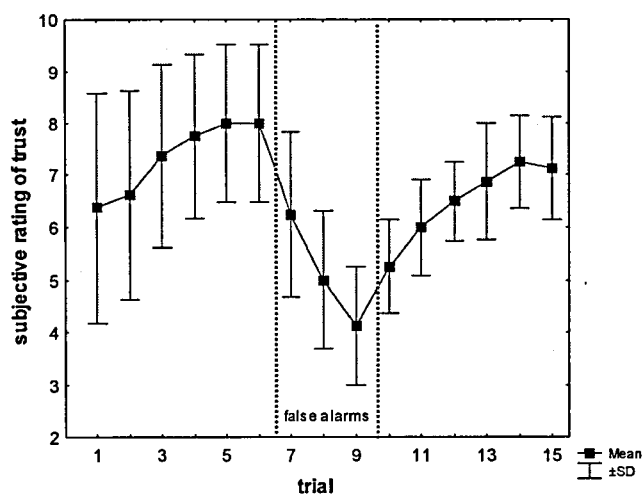


Figure 7-4 The effect of false alarms on driver trust

Taking our proposed trust model for warning systems into consideration, a possible explanation for these phenomena representing driver performance in false alarms is proposed. Decreased TIA caused by false alarms induced a response bias, resulting in delayed response to the following false alarms. Furthermore, the significant delayed response to a true alarm issued immediately after the three false alarms is consistent with the influence of decreased TIA. Consequently the results reasonably support the proposed trust model for warning systems and the hypotheses regarding driver response to false alarms.

7.5 Experiment II

The effect of false alarms on driver trust and its influence on driver behaviour towards alarms were investigated in experiment I. The effect of missing alarms on driver response to imminent collision situations was considered in experiment II.

7.5.1 Apparatus

Exactly the same apparatus as experiment I was used in experiment II.

7.5.2 Subject, experimental design and procedure

Nine JARI employees (5 males and 4 females) participated in experiment II. They had not participated in experiment I. The method of this experiment was exactly the same as experiment I with the exception that missing alarms were 'presented' on the seventh to ninth braking events. After the trials with alarms all subjects completed 3 post-session trials without the warning system in order to measure driver unassisted performance in critical situations. The subjects took a 3-minute break after the 15th trial. It was assumed that the data obtained in the post-session trial represented the drivers' most effective braking performance without alarms fully informed by the experiencing critical situations without the support of an alarm. The entire design of this study can be seen in Figure 7-5.

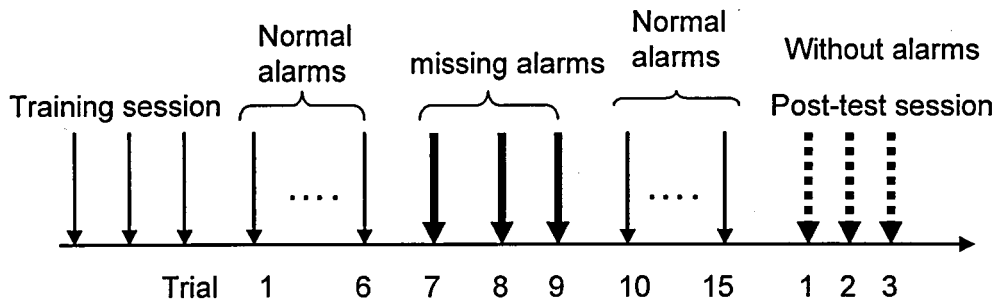


Figure 7-5 The procedure of experiment II

7.5.3 Dependent measures

- *Braking event to brake onset time*
 - *Driver subjective rating of trust.* This measure was the same as in experiment I
- The definition of each variable is given in chapter 3.

7.5.4 Result and discussion

7.5.4.1 Dynamics of braking event to brake onset time

Figure 7-6 illustrates the trend in mean values of braking event to brake onset time for each trial. The results showed that the transition times for trials 7, 8 and 9 were much longer than those for any other trial, furthermore, the first exposure to a missing alarm led to the longest braking reaction time. However, the delay in response to the potential collision situations for trials 8 and 9, where the subjects have already experienced a missing alarm, was reduced compared with trial 7 and braking event to brake onset time recovered to the pre-malfunction levels when the system returned to correct functioning from trial 10. A one-way ANOVA showed a significant main effect among trials, $F(14,112)=9.73$, $p<.01$.

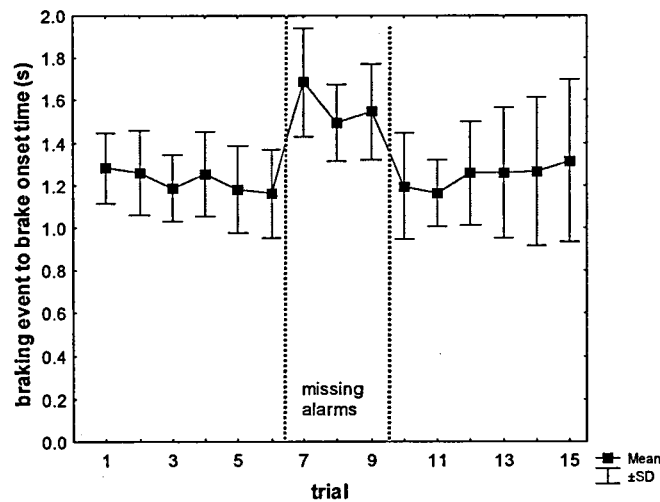


Figure 7-6 The effect of missing alarms on braking event to brake onset time

7.5.4.2 Delay in response to the brakes according to driver's experience of missing alarms

Here braking event to brake onset time is compared with and without the aid of the FCWS. The braking data collected from drivers in the absence of the FCWS can be regarded as optimal performance since it was informed by the immediately preceding experience of responding to critical events. Accordingly the comparison may reasonably indicate the differences in driver performance caused by the introduction of the FCWS.

Figure 7-7 illustrates mean values of the transition time for trials 7, 8, and 9 and the no alarm condition. A one-way ANOVA showed a significant difference among conditions ($F(3, 24)=4.28, p<0.05$).

In conditions where a missing alarm occurs the response required to avoid a collision is exactly the same as the no alarm condition except that drivers have recently experienced a true alarm, possibly resulting in some expectation that an alarm will be provided in further critical situations. However, these results indicate that the first exposure to a missing alarm may be associated with a significant delay in braking response. Furthermore, the delay in braking reaction following the first exposure to a missing alarm is significantly longer than the no alarm condition value. Interestingly,

braking event to brake onset time for the subsequent missing alarms was found to recover to the levels found in the no alarm trials.

7.5.4.3 Decreased trust caused by two types of malfunction

Experiment I found that false alarms decreased driver trust and the decreased trust did not recover immediately when only valid alarms were presented. In order to clarify the differences in the dynamics of trust resulting from the two types of alarm malfunction a regression analysis was conducted.

The dotted and solid lines in Figure 7-8 illustrate trends in mean values of subjective ratings of trust for all trials in experiments I (for false alarms) and II (for missing alarms) respectively. As can be seen in this figure, missing alarms led to a more substantial reduction in driver trust compared with false alarms.

The occurrence of false or missing alarms appears to be the most important causal variable. Moray et al. (2000) found that when investigating the dynamics of trust in automated systems in a time series, the value of subjective ratings of trust for the previous trial may contribute to increased validity for the trust model. Following this research, the previous trust value was used as a causal variable. Trust values for trials 1 to 9 were used to create a regression model for the decreased trust caused by alarm malfunction. The results were as follows. For the dynamics of trust resulting from false missing alarm, $T_n = -0.43F_n + 0.755T_{n-1}$ ($r^2 = 0.89$), where T is the rating of trust and F is the occurrence of false alarms. F is treated as a discrete (0,1) variable ($F=1$ if there is a false alarm, otherwise $F=0$). The subscripts (n and $n-1$) indicate the current trial and the previous trial. For the dynamics of trust resulting from missing alarms, $T_n = -0.72M_n + 0.296T_{n-1}$ ($r^2 = 0.87$), where T is the rating of trust and M is the occurrence of missing alarms. M is treated as a discrete (0,1) variable ($M=1$ if there is a missing alarm, otherwise $M=0$). Again, n and $n-1$ are trial subscripts.

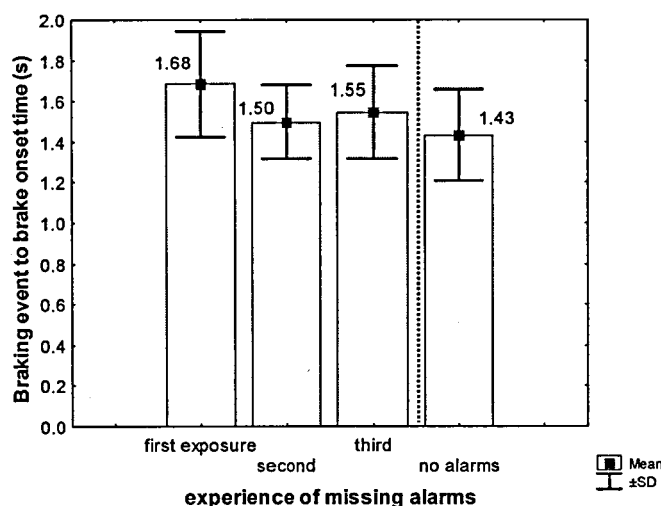


Figure 7-7 The comparison of braking event to brake onset time according to the difference in experience of missing alarms

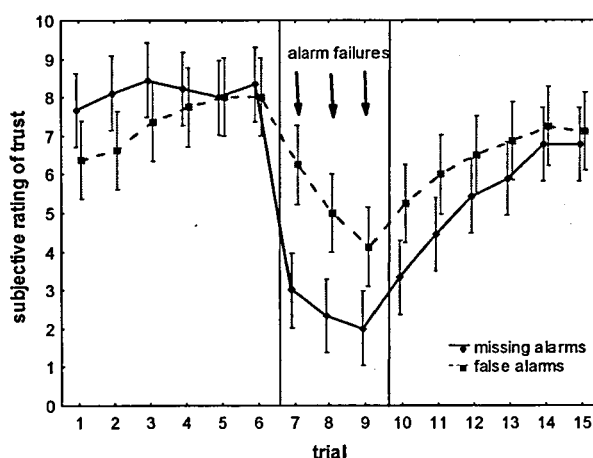


Figure 7-8 The differences in decreased trust between false and missing alarms

These models indicate that the level of trust for the previous trial may have an impact on present level of trust, moreover the relative insensitivity of the dynamics of trust to the occurrence of false alarms is reflected in the small coefficient of F_n compared with M_n ; the occurrence of missing alarms.

7.5.4.4 Relationships between driver trust and response to imminent collisions

The data regarding driver response to missing alarms showed that driver response to the brakes was significantly delayed following the first exposure to a missing alarm,

however subsequent braking reaction time with missing alarms recovered to the level for no alarm. A possible explanation for this phenomenon may lie in two aspects of trust in the warning system.

As already mentioned, if a driver has past experience with reliable and effective alarms, TSI may dominate trust in warning systems. Accordingly drivers may expect that the warning system will always provide reliable alarms to help them avoid collisions in critical situations. Therefore a significant delay in response to the brakes becomes obvious when an alarm is missed. The data is consistent with this position since it showed that trust was relatively high immediately before the first exposure to a missing alarm. However the trust model states that missing alarms may impair TSI, resulting in reduced expectations of system reliability. That is, drivers realise that there is a possibility that the warning system might provide missing alarms through the experience of missing alarms. It is likely, therefore, that driver braking reaction performance would only recover to the no alarm condition level in the subsequent missing alarm trials. In fact, driver trust was significantly reduced following the first missing alarm. Furthermore, as for a quick recovery of driver response to the brakes after missing alarms, the data suggests that trust in the warning systems has two aspects and missing alarms do not directly affect TIA. As a result, drivers tend to respond to valid alarms without any delayed response.

The results obtained from experiment II provide broad support for the proposed trust model and the hypotheses regarding driver response to missing alarms.

7.6 Concluding remarks

This study focused on driver trust in warning systems and proposed a model of driver trust in order to estimate the effect of alarm malfunction on driver behaviour. The proposed model was tested in two experiments using a driving simulator with a FCWS. The results support the following important conclusions.

First, with respect to the nature of driver trust, the proposed interpretation of trust in warning systems is reasonably supported. More specifically, changes in overall trust

in warning systems following two types of alarm malfunction, false and missing alarms, can be explained by the influence of TIA and TSI. False and missing alarms impair TIA and TSI respectively. A regression analysis to determine the difference in sensitivity between TIA and TSI to alarm malfunction confirmed that TSI is more sensitive to alarm malfunction than TIA.

Second, as for alarm malfunction and its influence on driver behaviour, the hypotheses are also reasonably validated. Impaired TIA caused by false alarms leads to a delayed response to alarms. In particular, a significant delay in response to a true alarm occurs immediately after the presentation of false alarms. On the other hand, a significant delay in response to the brakes occurs on the first exposure to a missing alarm if TSI is relatively high. However a missing alarm also affects TSI, resulting in reduced expectations of system reliability. Thus driver braking response is improved on subsequent missing alarms. Furthermore, missing alarms tend to act only on TSI, therefore, driver response to true alarms recovers to the pre-malfunction levels after the presentation of missing alarms.

This study offers an important increase in our understanding of the nature of driver performance with, and trust in, warning systems that are inevitably imperfect. Furthermore false and missing alarms are common problems for every kind of warning system and the results provide insight regarding general human response to alarm failure.

Chapter 8: The influence of alarm timing on driver response to forward collision warning systems following system failure

8.1 Introduction

In chapter 7 the effects of false and missing alarms on driver trust were considered. The nature of trust in forward collision warning systems and the different aspects of trust that influence driver response to alarm failure, resulting in impaired system effectiveness were identified. It was argued that false alarms may affect driver trust in individual alarms (TIA) and missing alarms may affect driver trust in system integrity (TSI) and the nature of trust can be applied to not only the design of FCWS, but also the design of warning systems in general. However, the study reported in chapter 7 did not consider another factor which may play an important role in alarm malfunction and its influence on driver behaviour; alarm timing.

As already mentioned, alarm timing has been recognized as an important factor that can affect system effectiveness, (Janssen and Nilsson 1993; Lee et al. 2002). When considering driver response to alarm failure, it should be stressed that alarm timing not only affects alarm effectiveness but also driver behaviour following alarm malfunction. This is because alarm timing itself may determine driver perception of warning systems. For example, it is possible that for drivers some alarm timings are associated with perception of reliability while others (e.g. late alarms) result in perceptions that a system is unhelpful, resulting in different driver responses to the warning system. The study in chapter 7 was concerned with a fixed alarm timing, thus the question remains as to whether or not drivers respond to alarm failure in the same way with different regimes of alarm timing.

Driver performance with alarms may also be influenced by different mental models for FCWS or driver trust (Wickens et al., 1998), therefore this chapter does not simply explore the phenomenon of driver response to alarm failure but considers factors which may have the potential to determine the effect of alarm failure on driver behaviour by proposing a driver mental model showing the relationship between driver trust and alarm timing.

8.2 The aim of this study

The purpose of the research reported in this chapter was to investigate the effect of false and missing alarms on driver behaviour in response to alarm timing from the viewpoint of driver trust. In this study false and missed alarms were defined respectively as alarms which were provided without critical events and those which were not provided although critical situations had occurred.

8.3 Driver response to alarm failures according to alarm timing and driver trust

8.3.1 Conceptual models for examining alarm timing and its relation to trust and event awareness

Parasuraman and Riley (1997) provide a broad understanding of human use, misuse and disuse of automated systems and assert that trust in automated systems will affect how automated systems are used. Muir (1994) provides a comprehensive theory of human trust in automated systems which integrates two theories of trust between humans proposed by Barber (1983) and Rempel et al. (1985). Moreover trust in automated systems is a key factor in determining human reliance or dependence on such systems (Bliss and Acton 2003; Gupta et al. 2002; Lee and Moray 1992; Moray et al. 2000; Muir 1987; Muir and Moray 1996). These results indicate that driver trust in alarm systems may play an important role in determining driver response to alarm failure.

In order to estimate the effect of false and missing alarms on driver behaviour, a conceptual model is proposed describing the relationship between alarm timing and trust and its influence on driver response to alarm failure, followed by hypotheses regarding driver response to alarm failure. Figure 8-1 shows a framework for understanding driver event awareness for imminent collisions when alarms are provided and its relation to driver trust in the alarms according to alarm timing.

In this figure the horizontal line refers to alarm timing and a possible alarm zone is defined as the time period between onset of potential collision events (i.e. sudden deceleration of a leading vehicle) and the latest alarm moment (the latest alarm moment can be derived from driver reaction time to alarms; Δt , and the timing of the latest action required to avoid a collision). Hence the period of time which is valid for the presentation of alarms starts at the occurrence of potential collision events and extends to the latest alarm moment. In this time zone early and late alarm timings are labels for alarms which are provided relatively close to the moment of occurrence of potential collision events and the latest alarm moment respectively.

The vertical line to the left of the figure refers to the drivers' trust in an alarm. Research evidence shows that early and middle alarm timings may lead to increased trust compared with late alarm timing (Abe and Richardson 2003). Therefore it is reasonable to assume that, as delay in alarm timing increases, trust may gradually reduce (the solid curve in Figure 8-1). The other vertical line refers to event awareness with respect to an imminent collision when a collision warning system is available to provide support. This is largely dependent on information obtained from system behaviour during an individual critical event rather than accumulated information regarding alarm performance. The diagonal dotted line represents the relationship between alarm timing and a driver's event awareness. The model assumes that event awareness is directly linked to the driver's understanding of alarm performance in an imminent collision situation, therefore alarm timing is crucial in determining event awareness. Specifically, as the timing increases, the quantity of information available to the driver about the developing situations grows and event awareness becomes sufficient for an informed decision. The reverse is also potentially true. While the perception of alarm timing (i.e. early or late) has an

important influence on driver perception of alarm quality, in this model we are more concerned with the impact of alarm timing on the information available to the driver. A late alarm may provide the driver with less time in which to react but allows the driver more time to perceive the critical event.

Next, the proposed conceptual model suggests that there can be significant discrepancies between the degree of driver trust in alarms and the event awareness, except at the point where the dotted and the solid lines cross each other. In particular, when alarm timing is early or late, the gaps between solid and dotted lines are relatively large. For example when alarms are early and trust is relatively high even though event awareness is relatively limited. This gap is termed "blind faith" in the model. Previous research has suggested that human trust in automated systems may approach faith when operators do not have enough behavioural evidence generated by an automated system (Muir 1994). Furthermore Itoh (2003) notes that human operators may have a positive bias towards automated systems and this can lead to the rejection of safety critical information which is not consistent with alarm output. Thus driver trust can be relatively high even if event awareness is relatively limited.

In contrast, trust may be relatively low even when event awareness is sufficient. As the timing of an alarm is delayed, the time available to the driver to perceive the developing critical event is increased and, as a result, sufficient event awareness becomes available to inform a rational judgement of system behaviour. However when alarms are provided too late, it is possible for drivers to judge them as unnecessary for avoiding a potential collision event. In this model this situation is referred to as 'rational mistrust'.

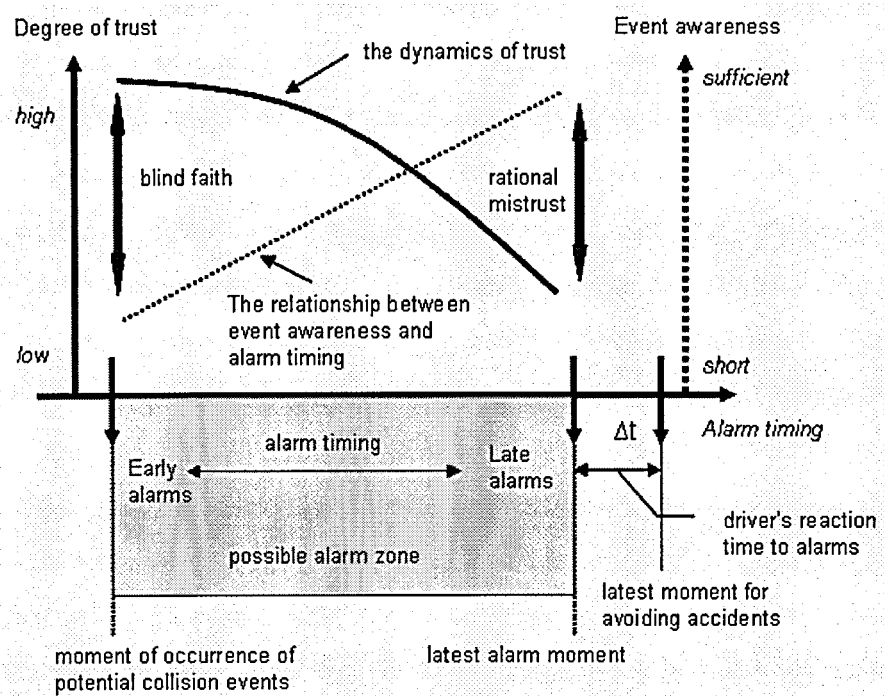


Figure 8-1 The conceptual model showing the relationship among alarm timing, ratings of trust and event awareness

8.3.2 The proposed hypotheses

On the basis of the proposed model, two sets of hypotheses regarding driver response to alarm failure are proposed.

First, when alarm timing is relatively early, blind faith may affect system effectiveness when missed alarms occur. One potential consequence of blind faith is complacent behaviour, resulting in delayed response to imminent collisions. The term automation-induced complacency has been used as an accident inducing behaviour in the aviation domain (Sign et al. 1993), although a specific definition has not yet been agreed (Satchell 1998). However research evidence suggests that human operators who are supported by highly developed automated systems tend to experience decreased vigilance, resulting in failure to detect system malfunction (Molloy and Parasuraman 1996). This phenomenon may also occur in the vehicle domain. If drivers believe that a collision warning system is very reliable then trust in alarms can become high, resulting in an expectation that alarms will always be provided when a critical event occurs. Consequently there is a possibility that the introduction of

FCWS in road vehicles may also cause complacency when drivers experience certain alarm timings.

In this study it was hypothesised that drivers who experience early alarms will exhibit a delayed response to an imminent collision when a missing alarm happens due to the influence of blind faith. However, when alarm timing is relatively late a delayed response to an imminent collision caused by a missing alarm will not occur and this may result from a rational mistrust of the alarm system.

Second, drivers who experience early alarms will be more prone to blind faith and will tend to respond to all alarms including false alarms. However, drivers who experience late alarms will tend to respond to alarms according to their perceived validity. In the current study the hypotheses were tested by measuring driver objective performance in imminent collision situations and driver subjective ratings of trust in alarms.

8.4 Method

8.4.1 Apparatus

The research was completed using The Leeds Advanced Driving Simulator (see chapter 3). The visual scene was a computer generated environment which included other vehicles, buildings and pedestrians. In this study a simulated rural road environment was created with a single carriageway, a leading vehicle, and the occasional appearance of oncoming vehicles.

The following vehicle, 'driven' by the subjects, was equipped with a simulated FCWS. The Stop Distance Algorithm (SDA), as described in chapter 3, was also use in this study.

This study examined driver response to different values of the assumed deceleration of the following vehicle (D_f), in order to estimate the effect of two different alarm timings on driver response to alarm failure. Two different timing characteristics of

the alarm timing (late/early) were prepared by manipulating D_f (0.75g for late, 0.35g for early). The other parameters had the same value in all conditions ($RT=1.25\text{sec}$, $D_f=0.5\text{g}$). The values of these parameters for early and late alarm timings were the same as those used in chapter 4. The warning system provided drivers with a simple auditory alarm. The alarm lasted approximately 2.0 s and the prominent frequency of the auditory tone was 4000 Hz.

8.4.2 Subjects and experimental design

Twenty four participants (12 women and 12 men) ranging in age from 21 to 55 years ($M=31.4$, $SD=8.2$) took part in the experiment. All were licensed drivers with driving experience of two years or more. Each received a financial compensation of £10 for their participation.

All participants were assigned to two alarm timing conditions; early or late. Each condition comprised 11 potential collision events with a missing alarm event and a false alarm event (Figure 8-2). In the first and last two potential collision events braking performance without the aid of alarms was measured with the participants being instructed to avoid potential collision events, relying only on their driving skill. These data were regarded as indicators of driver baseline performance without the warning system. In the other trials drivers were instructed that alarms would be available although there would be a possibility of alarm failure. In the 6th and the 9th braking events false and missing alarms occurred respectively but true alarms were provided in all the other braking events according to the experimental conditions. Here a false alarm meant an alarm was presented with no potential braking event and a missing alarm meant that a potential braking event had occurred but no alarm was issued.

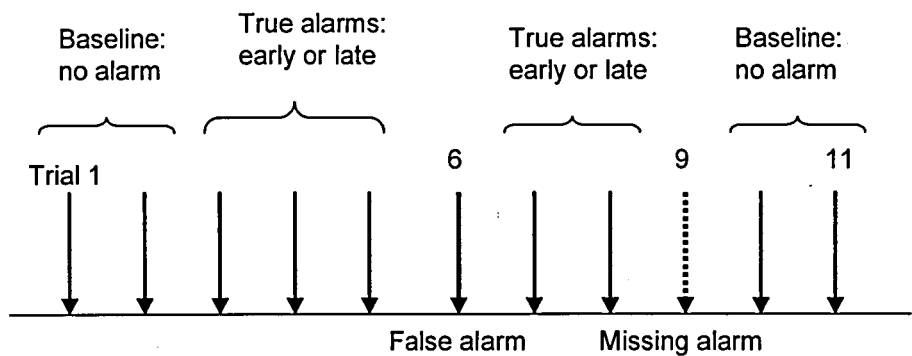


Figure 8-2 The procedure of experiment

In each potential collision event the leading vehicle decreased its speed with 0.8g deceleration with illumination of the stoplights until the vehicle came to a stop. A potential collision event occurred once every two minutes but dependent on whether the driving speed was 60 mph (96.6km/h) with a tolerance of $\pm 5\%$, so that alarm onset could not be predicted from time passage. The time headway between the lead and following vehicle was maintained at 2.0 s by manipulating the leading vehicle's speed in response to the following vehicle's speed. Accordingly all participants had nearly the same headway time immediately before all braking events. Table 1 contains a summary of the specific experimental conditions. Alarm time in Table 8-1 was defined as the elapsed time between when the lead vehicle began to brake (i.e. a braking event occurs) and when the alarm was issued.

Table 8-1 Summary of experimental conditions

Condition	Initial Velocity (km/h)	Lead Vehicle Deceleration (g)	Initial Headway (s)	Algorithm Parameter	Mean Value of Alarm Time (s)
Early Alarm Timing	96.6	0.8	2.0	$RT=1.25g$ $D_f=0.5g$ $D_f=0.35g$	0.02
Late Alarm Timing	96.6	0.8	2.0	$RT=1.25g$ $D_f=0.5g$ $D_f=0.75g$	1.20

8.4.3 Procedure

All participants were required to complete an informed consent form and were briefed on task requirements by the experimenter. Each participant was then given a 10-min practice drive to familiarise themselves with the simulator and to experience the lead vehicle decelerations that would be involved in the experimental trials. After a 5-minute break, the regular trials were started. All participants were given two objectives in the regular trials. One was to keep their own speed at 60 mph (96.6km/h) and the other was to follow the leading vehicle but to avoid rear-end collisions. The drivers were directed to only use the brakes to avoid a collision with the lead vehicle, rather than implement lane changes. About 8 second after each braking event, the leading vehicle gradually began accelerating again. Subjects were instructed to gradually accelerate until they reached the target speed.

8.4.4 Dependent variables

Two dependent variables describing the drivers' braking performance in response to imminent collisions and one dependent variable describing driver trust in the system were recorded.

- *Braking event to brake onset time*
- *Maximum deceleration*
- *Driver subjective rating of trust*

The definition of each variable is given in chapter 3.

8.5 Results and discussion

The data regarding driver objective performance in imminent collision situations were examined along with an analysis of driver ratings of trust. Driver response to false alarms was investigated with respect to regimes in which drivers experienced either early or late alarms. In this experiment none of the subjects suffered collisions and so the effect of collision events on driver behaviour could be ignored.

8.5.1 Driver performance according to alarm timing: the analysis of braking event to brake onset time

In this experiment all participants experienced a false alarm in which no potential collision events occurred. As the driving task in a false alarm condition was different to that in all the other conditions the driver braking performance data were considered separately.

First, the differences in braking reaction time between early and late alarm timings were considered in order to estimate their effect on driver performance in imminent collision events. Figure 8-3 illustrates mean values of braking reaction time for early and late alarm timings. There was a significant effect for alarm timing, $F(1,118)=13.48$, $p<0.01$. The result suggests that alarm timing may impact on driver braking reaction, that is, the early alarm timing has the potential to reduce braking reaction to potential collision events.

Next, in order to estimate the effects of a false alarm on driver braking reaction and to investigate how driver response to a missing alarm may vary according to alarm timing, all trials were divided into four sessions, namely: baseline trials, trials before a false alarm, trials after a false alarm and a trial with a missing alarm. The baseline trials session comprised braking reaction time with no warning systems. The trials before a false alarm comprised the first three trials before the presentation of a false alarm, the session of trials after a false alarm comprised the two trials following a false alarm and a missing alarm event was the last trial in the session where no alarm was given.

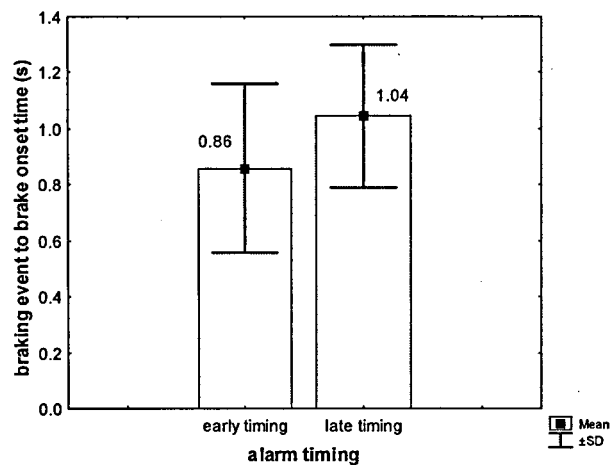


Figure 8-3 The effect of alarm timing on braking event to brake onset time

Figure 8-4 illustrates the dynamics of braking reaction times in response to early and late alarm timings. For the late alarm timing, a one-way ANOVA showed that there were no significant main effects among sessions. For the early alarm timing, however, a one-way ANOVA showed a significant difference among sessions $F(3,105)=15.12$, $p<0.01$. More specifically a Newman-Keuls post-hoc test revealed braking reaction time for trials after a false alarm was longer than that for trials before a false alarm ($p=0.10$). Furthermore, braking reaction time for the missing alarm trial was longer than that for the baseline trials ($p<0.01$). These results indicate that for drivers who experience early alarms, false alarms and missing alarms may affect driver braking reaction time. This is not the case with late alarms where false and missing alarms have relatively little impact on driver braking response.

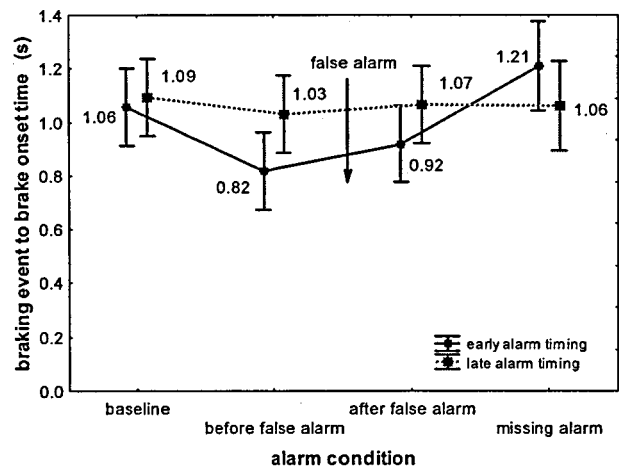


Figure 8-4 Changes in braking event to brake onset time in response to trial-by-trial

8.5.2 Driver trust

The purpose of this analysis was to clarify how driver trust may vary according to alarm timing and system failure.

First, ratings of trust for early and late alarm timings were compared. Figure 8-5 illustrates mean values of trust for the early and late alarm timing conditions with true alarms (i.e. where alarms were presented correctly). The results show that trust for the early alarm timing was higher than that for the late alarm timing, $F(1,118)=116.33$, $p<0.01$.

Next, in order to investigate the dynamics of trust in response to variations in alarm performance, the trials were divided into five sessions, namely: trials before a false alarm, a false alarm trial, trials after a false alarm and a trial with a missing alarm. The session comprising trials before a false alarm involved the first three braking events with true alarms before the presentation of a false alarm. The false alarm trial session represented the subjects' judgments of trust with a false alarm. The session of trials after a false alarm involved two braking events with true alarms after the presentation of a false alarm. The missing alarm trial session represented subjects' judgements of trust with a missing alarm. The solid and dotted lines in Figure 8-6 represent the dynamics of trust for the early and late alarm timings respectively.

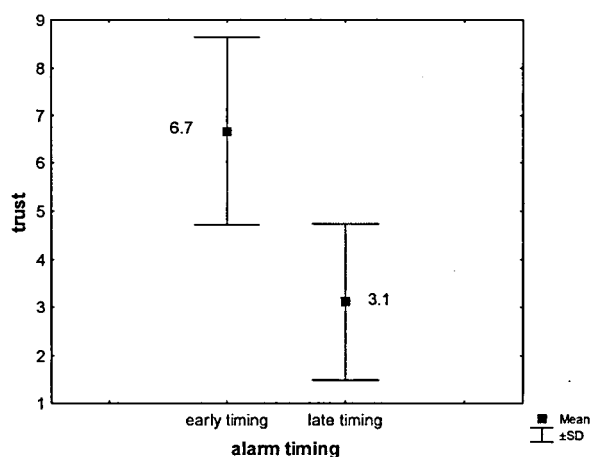


Figure 8-5 The effect of alarm timing on driver trust

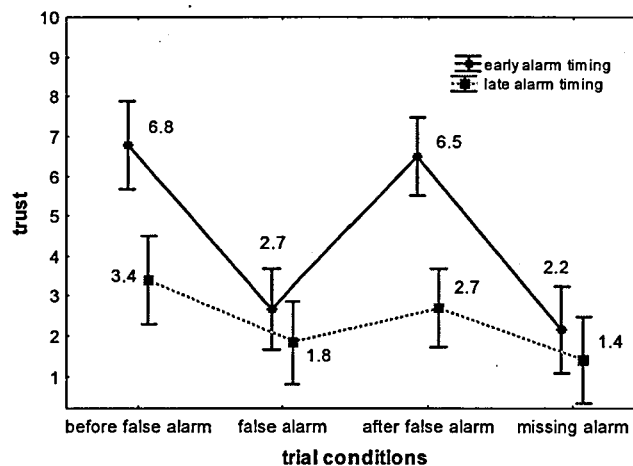


Figure 8-6 Changes in trust ratings in response to trial-by-trial

For the late alarm timing condition, there were no significant differences in trust ratings. As can be seen in this figure, trust in true alarms is relatively low and as a result, the level of trust was not depressed by the occurrence of alarm malfunctions. However a one-way ANOVA on the sessions showed that the mean values of ratings of trust for the early alarm timing were not consistent but varied widely according to the experience of false and missing alarms, $F(3,69)=43.78$, $p<0.01$. Furthermore, trust values after a false alarm recovered to the pre-malfunction level. This result suggests that although false and missing alarms may induce decreased trust, the impact of the alarm on judgement of trust caused by one discrete false alarm may be temporary, and trust may recover quickly.

8.5.3 The relationship between driver performance and trust in the missing alarm condition

Driver response to a missing alarm was considered from the viewpoint of driver trust in the warning system. In conditions where a missing alarm occurs, the response required to avoid a collision is exactly the same as the baseline condition except that drivers have recently experienced a true alarm, possibly resulting in an increased expectation that an alarm will be provided in critical situations. However the results showed two different phenomena regarding driver braking reaction in the missing alarm condition according to alarm timing.

With respect to the late alarm timing, braking reaction time for a missing alarm was not significantly delayed compared with baseline performance. A possible reason for this phenomenon concerns the different level of trust associated with early and late alarm timings. With a late alarm timing, the drivers' judgement of trust immediately before a missing alarm was relatively low suggesting that drivers may depend less on the warning system. The low level of trust in late alarms can be interpreted as rational mistrust and consequently, the missing alarm has relatively little impact on braking performance. However, in the case of early alarm timing, driver trust was relatively high immediately before a missing alarm occurred, indicating more dependence on the warning system. The high level of trust in early alarms can be interpreted as blind faith and this may lead to a longer response to an imminent collision, compared with the baseline level.

In order to identify the quantitative differences in driver performance resulting from missing alarms a regression analysis was conducted. Figure 8-7 is a scatter plot showing the delay in braking response, and level of trust obtained, immediately before a missing alarm for each participant. Here the delayed response time was defined as the difference between braking reaction time for the missing alarm condition and braking reaction time for the baseline condition. Positive values mean that braking reaction time for the missing alarm condition was longer than that for the baseline condition. As previously mentioned, positive values indicate complacent behaviour, that is, a delay in response to the brakes resulting from a lack of vigilance.

As can be seen in Figure 8-7 drivers who indicate high levels of trust tend to show longer delayed response times and conversely drivers whose trust is relatively low tend to show shorter delays or no delays. A positive correlation ($r=0.37$, $p=0.07$) was found between trust and driver braking performance. Although any interpretation of these results must be treated with caution due to the relatively small correlation, the result suggests that driver response to missing alarms may vary according to trust level. Furthermore, given the assumption regarding complacent behaviour discussed above, when trust is higher drivers may become complacent.

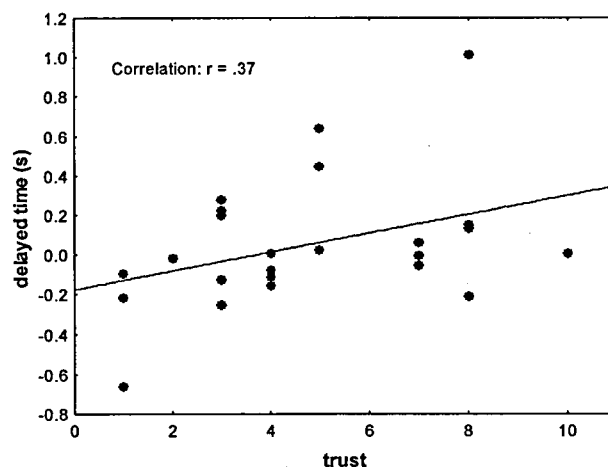


Figure 8-7 The relationship between driver subjective and objective data

To sum up, driver response to system failure may vary according to system characteristics, such as alarm timing. The effects of false and missing alarms on human response to alarm systems have been identified as factors which have the potential to impair system efficiency and it is necessary to minimize their impact. Our results indicate that manipulating alarm timing might be a possible countermeasure to minimize the decreased driver performance caused by missing alarms.

8.5.4 Driver behaviour and false alarms

8.5.4.1 Driver response to false alarm and its relation to trust

The analysis discussed above focused on the effect of a missing on driver behaviour and explored its impacts on braking reaction time and driver trust.

Here driver response to a false alarm will be considered according to previous driver experience with early and late alarm timings. First, the number of participants responding to a false alarm was summarised, see Table 8-2 with “braking” or “no braking” meaning that participants responded to, or did not respond to, a false alarm respectively. The results show that almost all the participants (11) who were assigned to the early alarm timing condition responded to a false alarm. On the other hand, half the participants (6) who were assigned to the late alarm timing condition did not brake on a false alarm. This indicates that driver behaviour towards false alarms may vary in response to alarm timing. More specifically, early alarms may lead to an

“automated response” to all presented alarms regardless of alarm validity. Conversely drivers who experience late alarms may tend to decide whether presented alarms are trustworthy or not and brake accordingly.

Next, the influence of ratings of trust on driver response to a false alarm was investigated. Figure 8-8 illustrates mean values of trust for participants who responded to a false alarm (braking) and those who did not (no braking). Here each trust rating represents the value which was obtained immediately before a false alarm event (at the 3rd braking event). There was a significant difference between mean trust values, $F(1, 22)=3.95, p=0.059$. The result suggests that there is a tendency for drivers who respond to a false alarm to have relatively high trust and drivers who do not brake to have relatively low trust.

Table 8-2 The difference in response to a false alarm according to alarm timing

Alarm timing	Early timing		Late timing	
"Braking" or "No braking"	Braking	No braking	Braking	No braking
Number	11 (92%)	1 (8%)	6 (50%)	6 (50%)

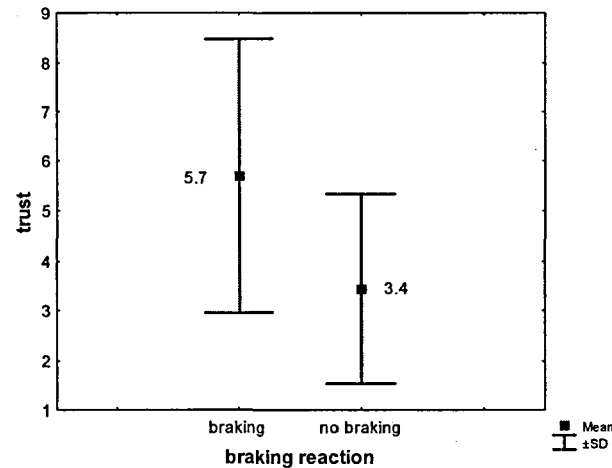


Figure 8-8 The effect of trust ratings on driver response to a false alarm

8.5.4.2 Driver braking effort for false alarms

The previous analysis explored the possibility that low levels of trust may lead to a decision not to brake when false alarms occur. However it is possible that there could be other differences in driver performance influenced by alarm timing. Here maximum deceleration in the false alarm condition was investigated in order to explore differences in driver behaviour toward a false alarm with respect to early and late alarm timings.

Figure 8-9 illustrates the dynamics of maximum deceleration according to trial conditions. It was expected that maximum deceleration can be indicative of the strength of the drivers' braking response, i.e. their sense of urgency. All trials were divided into five sessions on the basis of the same rule which was used in the analysis of the dynamics of trust. For participants who did not brake, values of deceleration achieved by engine braking were used in this analysis. The solid and dotted lines represent the trends of mean values of maximum deceleration for the early and late alarm timings respectively. It appears that, with the exception of the false alarm condition, all values of maximum deceleration were similar. A two-way ANOVA showed a significant interaction between alarm timing and trial conditions, $F(4, 88)=2.36$, $p=0.059$. Post-hoc analysis, using a Newman-Keuls test showed a significant difference between early and late alarm timings in the false alarm condition ($p<0.01$). This result indicates that false alarms may lead to decreased maximum deceleration, that is, alarm timing may affect braking efforts for a false alarm.

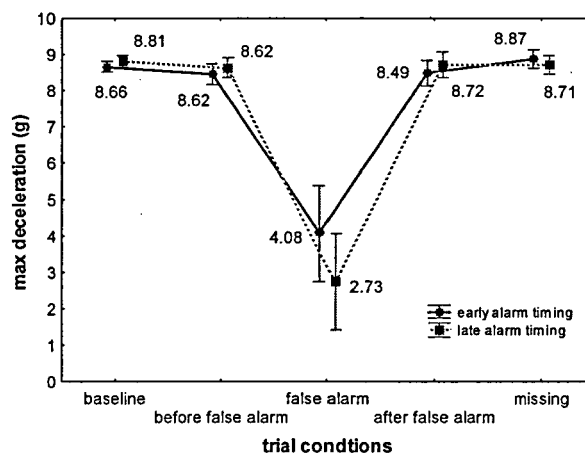


Figure 8-9 The effect of a false alarm on braking effort

8.6 Validity of the proposed model

The validity of the proposed model is now assessed by considering the relationship between driver overall trust and alarm timing based on the driver's mental model of the collision warning system.

With respect to driver trust, trust in early alarms was higher than that in late alarms. On the other hand, driver performance data representing responses to alarm failure showed that drivers who experienced early alarms had a delayed braking response when missing alarms occurred and tended to respond to false alarms. However drivers who experienced late alarms exhibited robust behaviour in response to alarm failure. There was no delayed response to imminent collision situations when missing alarms occurred and they tended to only respond to valid alarms.

Taking driver subjective and objective data regarding driver response to alarm timing together, it can be said that the proposed model and following hypotheses are reasonably validated. That is, driver trust in early alarms is relatively high even though event awareness is inherently limited, i.e. when alarms are provided early, the amount of information available to the driver about the reason for an alarm being generated is limited. Accordingly it is possible that the driver's perception of alarm timing might be a crucial factor in inducing increased trust. However this type of trust may lead to blind faith due to the gap between event awareness and the degree of trust in alarms, resulting in delayed response to imminent collisions when missing alarms occur. Moreover it is likely that blind faith may lead to an "automated response" to alarms, including false alarms. These phenomena result in impaired system effectiveness.

On the other hand, trust in late alarms, where drivers have more adequate information about alarm behaviour, is relatively low, resulting in rational mistrust. Consequently, this kind of limited trust enabled drivers to respond to alarms according to their validity. Drivers may tend to respond only to valid alarms, even when false alarms occur, and their response to missing alarm is consistent with their response to valid alarms.

The issue of alarm timing and its influence on driver response to alarm failure may be linked to the trade-off between driver subjective trust ratings and the quantity of information available to the driver about system behaviour. Certainly low trust in alarms may have the potential to lead to disuse of alarm systems. On the other hand, appropriate driver reaction to alarm failure may play an important role in maintaining safe driving. The proposed model can predict that some alarm timings possibly provide appropriate event awareness with reasonable ratings of trust and drivers who experience these alarms may show a robust response to alarm failure.

8.7 Concluding remarks

This study focused on driver response to system failures comprising false and missing alarms and investigated how false and missing alarms can influence driver behaviour in response to alarm timing. Furthermore driver behaviour was investigated in terms of the relationship between alarm timing and the level of driver trust in the warning systems. The results support the following conclusions.

1. Early alarms lead to a quicker response to the brakes than late alarms.
2. For drivers who experience late alarms, alarm failure does not affect braking reaction time.
3. Drivers who experience early alarms tend to exhibit longer braking reaction time to a true alarm immediately after a false alarms. A missing alarm leads to a delayed braking response.
4. Trust in early alarms is higher than trust in late alarms.
5. The dynamics of trust in late alarms is not influenced by alarm failure.
6. The dynamics of trust in early alarms vary in response to alarm failure. Specifically, a false alarm and a missing alarm lead to decreased trust. However the

decreased trust caused by a false alarm recovers to the pre-malfunction level when true alarms are restored.

7. With respect to the relationship between trust and delayed response to imminent collisions, drivers whose judgement of trust is relatively high, may exhibit a delayed braking response, compared with drivers who estimate their trust at low levels when missing alarms occur.

8. Drivers who experience late alarms tend not to respond to false alarms. On the other hand, drivers who experience early alarms tend to respond to false alarms.

9. Due to the differences in driver braking response to false alarms with respect to alarm timing, maximum vehicle deceleration for the late alarm timing is smaller than that for the early alarm timing.

To sum up, the following final suggestions are made. An early alarm timing has the potential to lead to timely braking response to imminent collisions, however drivers who always experience early alarms may respond inappropriately if the system fails. If it is accepted that the occurrence of false and missing alarms is inevitable, the delayed response to imminent collisions following a missed alarm may result in decreased system efficiency. Furthermore unnecessary braking caused by a braking response to false alarms may provide another potential collision event for following vehicles. The late alarm timing, on the other hand, does not contribute to a quick response to imminent collisions but drivers who experience late alarms still adjust their performance to alarm failure, resulting in compensation for system malfunction.

Although late alarms decrease trust, resulting in less dependence on warning systems, these results suggest that sufficient information regarding the sequence of potential collision events including alarm generation gained through the time period between a occurrence of a potential collision event and alarm onset, is crucial in order to maintain event awareness, resulting in appropriate behaviour following system failure. If a swift response to a potential collision event is not required for alarm design then manipulating alarm timing with reasonable ratings of trust is a possible strategy to

keep the balance between maximization of alarm effectiveness for true alarms and minimisation of system impairment caused by alarm failure.

Chapter 9: Overview results: Towards the integration of trust into alarm design

9.1 Introduction

The previous chapters have described and discussed the results of a series of empirical studies. In particular, driver trust has been investigated experimentally in order to understand the nature of driver trust in FCWS and to clarify the relationship between driver trust and alarm timing and their influence on driver behaviour. This chapter aims to synthesise the research findings in order to gain knowledge about the nature of driver trust for alarm system design. Accordingly this chapter will consider the alarm benefits associated with different alarm timings and the trade-off problems between alarm timing and driver response to alarm failure from the viewpoint of driver trust. Finally, recommendations for alarm timing in the design of FCWS will be given.

In this thesis, two descriptions of alarm timing were employed. One represents relative differences in alarm timing; early, middle, or late alarms, in order to discuss the relative differences in driver behaviour in response to alarm timing. The other represents absolute values of the alarm time; the elapsed time from when a leading vehicle begins to brake to when the alarm is presented. In this chapter these two terms will be used depending on the context of the discussion.

9.2 alarm contribution to safe driving

In chapters 4, 5 and 6, several benefits for safe driving were found when an alarm indicates that a leading vehicle has suddenly decreased its speed. A relatively early alarm timing may lead to prompt driver response to the brakes. This benefit of alarm presentation may reduce collision accidents by providing enough time for the driver to implement appropriate actions to avoid collisions. Moreover the presentation of alarms may have the potential to decrease variation in driver braking response, resulting in a reduction in delayed braking response. A middle alarm timing also reduced variation in braking response time.

It was also found that a decreased braking response following the presentation of an alarm may derive from the prompt release of the accelerator. This means that the presentation of alarms may help drivers recognise imminent collision situations earlier than unassisted drivers.

If we describe driver behaviour at the most basic level, it can be said that drivers implement three tasks continuously, namely recognition, decision, and control (Dingus et al., 1998). Recognition refers to the first stage for driving safely, where drivers need to identify threats which have the potential to affect their safe driving. Decision refers to the second stage, where drivers need to decide what they should do in response to the threats which they have recognized. Finally, control refers to specific vehicle control based on driver decision.

Considering these three tasks based in situations where drivers must avoid imminent collisions, the following interpretation can be given. Drivers must recognize the deceleration of a leading vehicle and then decide whether they need to implement an action to avoid a collision. Finally drivers implement an action i.e. steering, accelerator release, braking, or a combination of all three. Viewing the current results from this perspective it can be argued that appropriate alarms may improve recognition of imminent collision situations and lead to a more prompt release of the accelerator, resulting in a decreased braking response time (Figure 9-1). In other

words, following the introduction of alarms, drivers can implement collision avoidance actions with longer headway times (Figure 9-2).

Dingus et al. (1998) note that recognition error is the dominant factor in accidents where driver failure results in a crashes and it is expected that the introduction of FCWS may achieve their intended effort by the reduction of recognition errors.

It should be stressed here that the effect of SDA determined alarm presentation on driver behaviour may vary according to driving conditions, driving speeds, time headway, or degree of deceleration of a leading vehicle even if the same pre-determined alarm trigger logic is used. That is, even if the pre-determined alarm trigger logic is the same in different driving conditions, the timing to achieve the warning distance for triggering alarms from the beginning of the potential collision events may vary.

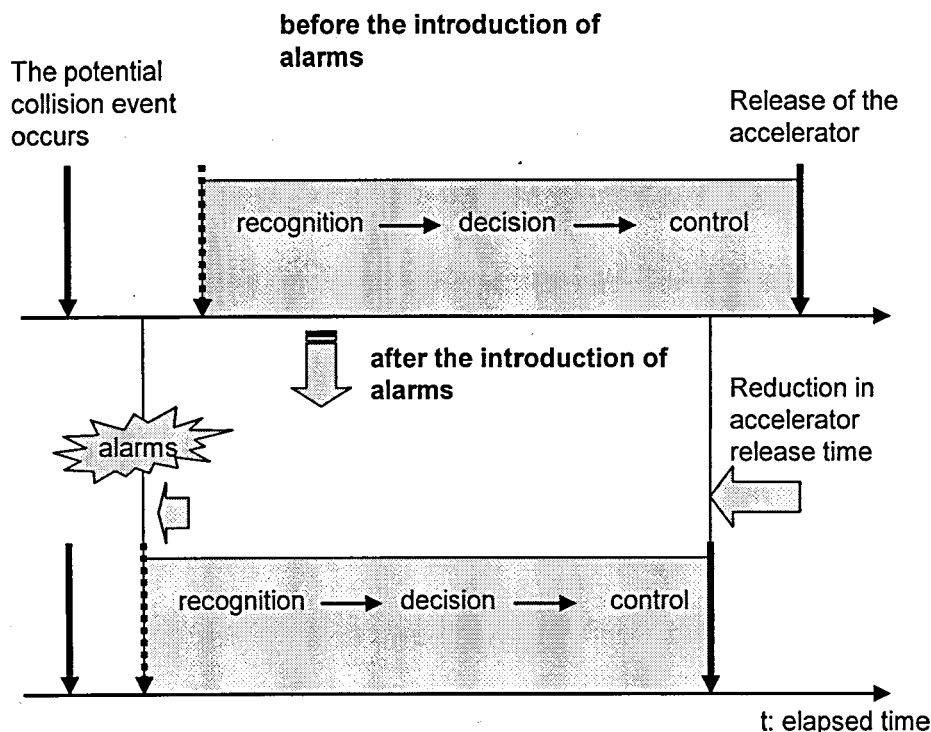


Figure 9-1 The conceptual figure showing changes in driver performance in collision situations due to the introduction of alarms

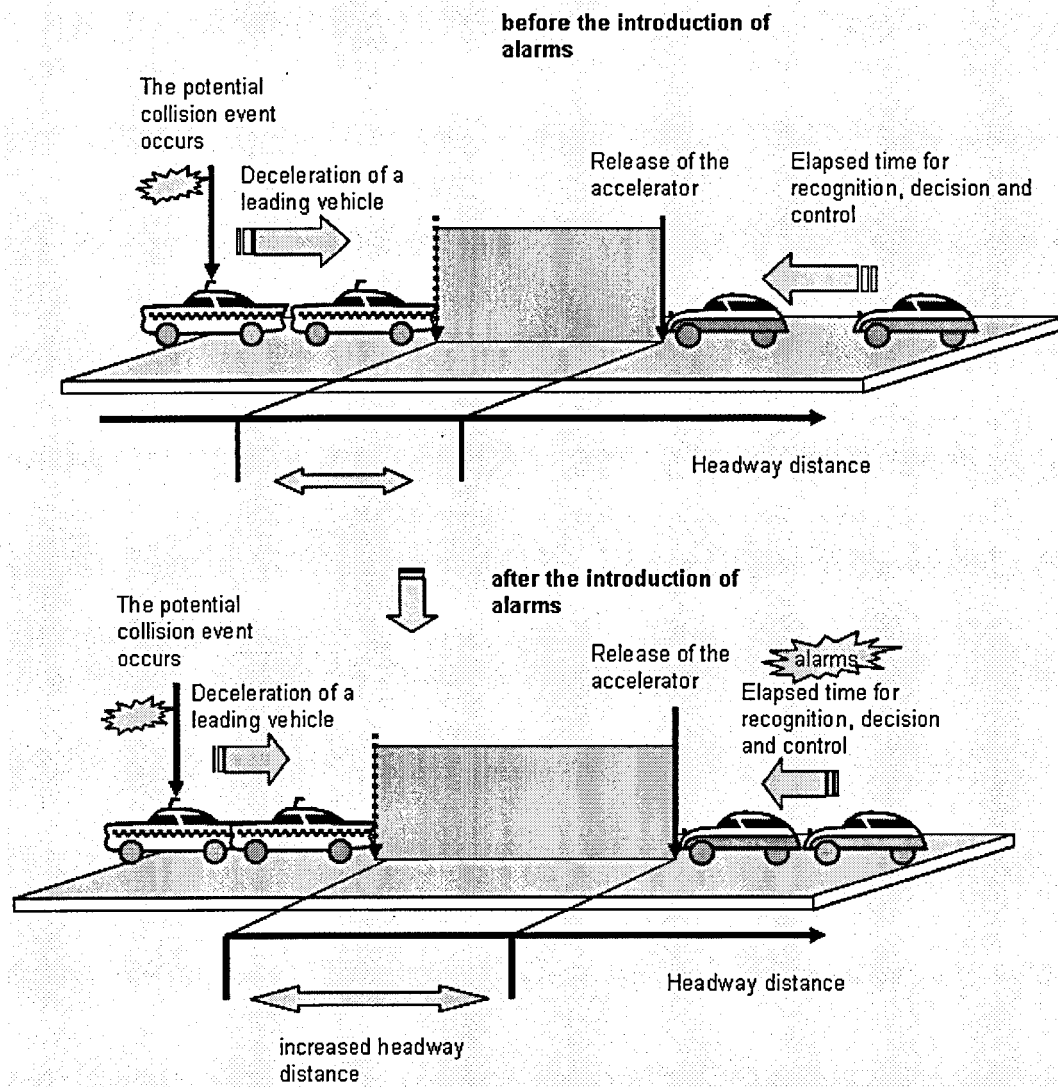


Figure 9-2 The impact of introducing alarms on headway

The results of chapters 4, 5 and 6 established that the timing of alarm presentation strongly impacts on alarm effectiveness for safe driving in a variety of driving conditions. Moreover time headways and deceleration of the leading vehicle affect alarm timing more importantly than driving speed. Specifically alarm times of up to 0.15 s for sudden deceleration of the leading vehicle lead to prompt response to the brakes. Alarm times with a range of 0.35 s and 0.64 s may have the potential to decrease variation in response to the brakes in some situations. Alarm times of over 1.00 s do not influence driver response to the brakes.

However, in the experiments the collision events and alarms were presented in the absence of driver distraction and it must be assumed that the drivers had a high

expectation for both. As a result the above arguments regarding driver performance with alarms will be reliable in this limited situation.

It is obvious that prompt recognition of critical events due to the introduction of warning systems may be helpful for drivers by providing sufficient time for them to brake, resulting in accident avoidance. However consistent response time resulting from the presentation of alarms may also contribute to safe driving. This is because some delayed responses to imminent collision events which are included in the wide range of variation in braking response times may be associated with greater risk of collisions. Thus, if drivers respond to imminent collision situations in a consistent way, every time, this may also result in a decrease in the number of collision accidents.

The results of chapter 5 raised an important human factors perspective for late alarms. As an overall trend of the effect of late alarm timing of driver behaviour, driver braking response is not influenced by late alarms. It does not seem that late alarms impair safe driving but careful attention is needed when driving with long time headways. This is because a late alarm timing induces longer braking response time, compared with driving without the aid of alarms when driving with long time headways. This phenomenon might drive from changes in driver attitude due to the introduction of FCWS.

These studies indicate that it is possible that the introduction of FCWS may induce less cautious driving. Furthermore, relatively long time headways may allow drivers to take longer to decide to implement a collision avoidance action, compared with short headways. Accordingly late alarms may induce delayed braking response time, compound these effects. The results of this thesis show that a late alarm timing may lead to a delay in releasing the accelerator in some situations.

9.3 The timing of the alarms and trust

The primary aim of this thesis was to understand the nature of driver trust in FCWS and to apply the concept of trust dynamics to alarm system design. As mentioned earlier driver trust may play an important role in determining driver acceptance of

FCWS and also influence driver performance with alarms. It is necessary to consider not only alarm benefit related to safe driving but also how the timing of the alarms may influence driver trust. Accordingly this section will discuss alarm timing and its influence on driver trust.

9.3.1 A static relationship between alarm timing and driver trust

First, the overall trends for alarm timing and trust indicates that, compared with relatively late alarms, trust in relatively early alarms is high. This result applied to relatively low (30 mile/h) and high (70 mile/h) driving speeds.

In chapter 5, alarm time and its relation to driver trust was generalized using a regression analysis and the results indicated that as alarms are provided earlier, trust in alarms increases. However, some data exhibit a different trend to the overall trend. That is, when driving with relatively long time headways i.e. when driving demand is relatively low, trust may not be decreased even if alarms are triggered relatively late. This effect was termed the 'tolerance'. On the contrary, when driving with relatively short time headways i.e. when driving demand is high, drivers may give relatively low trust ratings even when alarms are provided early. This effect was termed 'intolerance'. This result might suggest that with respect to relatively high demand driving (e.g. high speed and short time headways) it is necessary to provide alarms as early as possible in order not to decrease driver trust.

9.3.2 Driver expectation and alarm performance

The static analyses regarding driver trust successfully indicate that there are relative differences in driver subjective ratings of trust associated with different alarm timings but there is still uncertainty over what aspects alarm timing can influence variability in trust. One possible factor will now be considered.

Takahashi and Kuroda (2000) state that driver expectation of system behaviour and actual system behaviour plays an important role in determining driver trust in such systems. If driver expectation is not consistent with system performance then driver trust will be impaired. They focused on automated braking assistance systems and

demonstrated that the automated controller's timing for starting the braking action could influence driver trust. They found that drivers tended to prefer systems which began to brake before their own manual operation of the brakes, compared to systems which implemented the brakes after the driver's own timing.

Their results are relevant to the development of arguments regarding alarm timing and its relation to driver trust in this thesis. It is possible that driver expectation and alarm performance will play an important role in determining driver trust when taking driver trust into the design of alarm timing. It is necessary to consider alarm timings which are consistent with driver expectation of alarm timing rather than alarm timings which can induce prompt braking response. If this argument is accepted then a question immediately arises; what is the driver expectation of alarm timing.

9.3.3 Perceived alarm timing

In chapter five, driver perceived alarm timing, i.e. early, correct, or late, was considered. The timing of release of the accelerator in imminent collision situations without the aid of alarms (RAT) may play an important role in determining driver perception of alarm timing. It was found that alarms which were triggered before RAT were viewed as perceived correct alarms. In contrast, alarms which were triggered after RAT were viewed as perceived late alarms. The results are consistent with the interpretation that alarms act to improve accelerator release. That is, it is likely that drivers may expect that alarms should be triggered before, or at least at the same timing as, they recognize a critical situation and decide to release the accelerator. Thus alarms which are provided after RAT may be regarded as late alarms.

Interestingly, with respect to the relationship between driver behaviour and trust, the results suggest that improved driver performance due to the presentation of alarms is not directly connected to driver trust. That is, even though alarms may not directly improve driver performance in imminent collision situations, there is a possibility that trust in these alarms may be maintained at relatively high levels if driver expectation is not impaired.

9.3.4 The dynamics of driver trust in FCWS

In chapters 4 and 5 two models describing the dynamics of trust in alarms in response to alarm timings were proposed. These models suggest that driver trust has a dynamic nature which can be described as a function of several causal variables.

It should be remembered that the difference between braking event to accelerator transition time without the aid of alarms and alarm time (RAT-AT) has a positive coefficient. Consequently, as the time period between alarm onset and accelerator release without the warning system increases trust increases. Moreover, the occurrence of alarm presentations after drivers have started to brake (Discouragement) has a negative coefficient. These results indicate that gaining knowledge about the nature of driver's baseline performance in releasing accelerator in response to a variety of driving conditions and considering those data in the design of alarm timing are important in maintaining appropriate levels of trust. Moreover, if drivers have already responded to the brakes then it might be necessary to inhibit the presentation of alarms in order to prevent driver trust from decreasing. This result supports the arguments regarding inconsistency between driver expectation of alarm performance and actual alarm timing. This inconsistency corresponds to Discouragement and has the potential to impair trust.

In chapter 7 another model of trust describing the impact of false and missing alarms on driver trust was proposed. The model indicates that missing alarms have more potential to decrease driver trust than false alarms. This phenomenon may derive from differences in fault consequence. Missing alarms have the potential to induce more serious results than false alarms.

As already described in chapter 2, Lee and Moray (1992) and Moray et al., (2000) have proposed multiple regression models of trust dynamics and found several important contributing factors including system reliability, fault size, and conflict between operator's and automated system's fault diagnosis. In general trust was found to increase with system reliability. In their model Fault size, which referred to the magnitude of the fault and corresponded to the difference between the system's potential performance and the actual performance, affected trust. Greater magnitudes

of fault in system components may result in more serious problems in system control, resulting in reduced trust. Furthermore the disagreement between the operator and the automation as to the diagnosis also impairs trust. That is, with respect to fault diagnosis, if the decision making of automated systems is not consistent with the view of the operator then trust decreases.

The model proposed in this thesis, which accounts for subjective ratings of trust may also be able to integrate past results to identify the characteristics of driver trust in FCWS. For example the current research found that driver trust towards FCWS varies in response to alarm timing, an original finding when describing trust development. On the other hand, some similarities with existing models can be found. One is relevant to the kinds of fault found with mechanical systems.

Past studies have established that quantitative differences in the magnitude of faults affect trust and the research reported in this thesis established that differences in system failure mode, i.e. false and missed alarms affect the dynamics of trust. It is possible that perceived fault seriousness can affect human trust in mechanical systems. The other similarity is relevant to human conflict with mechanical systems. Synthesising the current trust models with previous trust models, it can be said that in order to gain human trust in machines it is crucial to avoid conflict between human expectations of systems performance regarding how fast alarms should be triggered or fault diagnosis performance and actual system behaviour, even when systems work correctly or provide correct information. It is necessary to incorporate operator expectations regarding system performance into the design.

As already mentioned earlier several different aspects dominate trust. Although identifying which aspects may influence driver trust in FCWS was not the purpose of this study, it is possible to interpret driver subjective ratings as a measure of the technical competence of a FCWS. This is because alarm timings and alarm failure derive from technical capability and reliability points of view. A fundamental goal was to assess the feasibility of studying the construct of relationships between trust and alarm timing. Importantly the quantitative analyses indicate that alarm timing plays an important role in determining trust ratings and differences in ratings are related to driver response to alarms.

9.4 The trade-off between alarm timing and system robustness against alarm failure: An assessment from the viewpoint of driver trust

In chapters 7 and 8, driver response to alarm failure was considered and a model for driver trust in FCWS with particular relevance to the differences in the effect of false and missing alarms on trust, was proposed. Furthermore, another trust model relating to alarm timing and its influence on trust from the viewpoint of event awareness was proposed. In this section alarm timing and its relation to driver response to alarm failure is discussed based on the two proposed trust models in order to provide a comprehensive understanding of alarm timing, trust, and driver response to alarm failure.

9.4.1 The effect of alarm failure on driver trust

First we found that driver overall trust in FCWS has two different aspects and alarm failures (i.e. false and missing alarms) affect these different aspects. In this thesis two aspects of trust were proposed; trust in individual alarms (TIA) and trust in system integrity (TSI). Both aspects of trust are important components of overall trust. However our model suggests that the relative strengths of TIA and TSI in overall trust are a consequence of a driver's cumulative experience of alarms. In a driver's early experience with a warning system each individual alarm (and hence TIA) can be expected to have a greater influence on driver behaviour than TSI. The driver has simply had insufficient experience to enable the development of TSI. However, as experience increases, and providing the alarm system operates efficiently and consistently, it is likely that TSI will become more influential, possibly at the expense of TIA. Furthermore false alarms affect TIA and missing alarms affect TSI.

As already described in chapter 2, the issue of driver response to alarm failures (such as false and missing alarms) is well established as a factor that may impair system effectiveness. Furthermore, although specific phenomena of driver response to alarm failure have been investigated, we need to incorporate appropriate alarm presentation

strategies into the design of alarm systems in order to optimise alarm capability in all alarm conditions.

The concept of driver trust proposed here is useful in understanding driver response to alarm failure and driver response to FCWS. That is, the current trust model provides new interpretations of the effect of false and missing alarms on driver behaviour that have been investigated in previous research. As more specific aspects of trust are considered, more specific countermeasure for alarm failure can be proposed. Specifically, if false alarms occur then it is necessary for TIA to be restored in order to prevent drivers from making delayed responses to subsequent true alarms. On the other hand, if missing alarms occur then it is crucial to restore impaired TSI in order to maintain driver's use of alarm systems.

9.4.2 Alarm timings and their influence on driver response to alarm failure

Integrating the results of chapter 8 suggests that manipulating alarm timing is one countermeasure that can minimize the negative impact of alarm malfunction on driver behaviour. In chapter 8 it was established that driver response to alarm failure may vary in response to alarm timing. The differences in driver response to alarm failure derived from the alarm timing and its relation to driver trust and event awareness. Here event awareness is directly linked to the driver's understanding of alarm performance in an imminent collision situation, therefore alarm timing has a major influence on event awareness. Specifically, as the alarm timing increases, the quantity of information available to the driver about the developing situation grows and event awareness becomes sufficient for an informed decision. The reverse is also potentially true.

The conceptual model showing how alarm timing may influence trust and event awareness proposed in this chapter suggests that early alarm timing leads to higher subjective ratings of trust but, at the same time, may induce blind faith due to a lack of event awareness. Consequently when missing alarms occur, driver response to imminent collisions is delayed. On the other hand late alarm timing leads to lower subjective ratings of trust, however event awareness is sufficient, resulting in rational mistrust. Consequently drivers who experience late alarm timing exhibit robust

behaviour in the face of alarm failure, that is, driver response to imminent collision situations is not delayed even if missing alarms occur. These results indicate that it is necessary for drivers to experience alarm behaviour for some period of time in order to gain appropriate event awareness.

9.4.3 Synthesising the two models regarding driver trust

Here a conceptual model showing the nature of trust proposed in chapter 7 and another conceptual model showing the relationship between driver trust and alarm timing proposed in chapter 8 will be integrated in order to provide a comprehensive understanding of the relationship between the two models.

The differences in ratings of trust according to alarm timings shown in chapter 8 can be interpreted in terms of the differences in levels of TIA that were proposed in chapter 7. That is, TIA may vary according to driver judgements as to whether specific alarms are valid or not for avoiding imminent collision situations. Typically TIA for a late alarm timing is lower than TIA for an early alarm timing. Moreover, low subjective trust ratings resulting in rational mistrust and high subjective ratings resulting in blind faith can be interpreted as differential development of TSI according to alarm timing. As already mentioned in chapter 7, TSI is dominated by perceived system reliability. Thus it can be said that blind faith may derive from excessive TSI and rational mistrust may result from underdeveloped TSI.

This interpretation suggests an important conclusion which must be emphasised. TSI is developed based on driver experiences with alarms depending on levels of TIA. It is impossible for TSI to develop individually without the existence of appropriately high levels of TIA. In other words, low TIA does not have the potential to develop TSI. On the other hand, high TIA does have sufficient potential to develop TSI. Given that a late alarm timing does not affect driver behaviour and an early alarm timing contributes to safe driving, it should be emphasised that alarm timing can play an important role in the development of TSI.

9.4.4 Trade off between safe and unsafe behaviour resulting in alarm timings

The argument up to now includes a trade-off between alarm benefit for safe driving depending on alarm timing and driver response to alarm malfunction. That is, early alarms have great potential to lead to prompt responses to the brakes but also result in impaired response to the brakes following alarm failure. With respect to late alarms, the effect of alarm failure on driver performance may be very limited, however the results of chapters 4, 5, and 6 indicate that late alarms do not have the potential to improve driver performance in braking response.

When considering the design of FCWS, it is very important to optimise alarm timing from the viewpoint of system performance including alarm failure. Accordingly it is necessary to consider TIA, TSI and event awareness with respect to alarm timing in order to design appropriate alarm timing for overcoming the trade off issues. Furthermore, given that trust has a multidimensional aspect that varies in response to levels of experience it is likely that, even though the same alarm timing is used, the differences in short and long term experience may influence the development of trust aspects such as predictability, dependability and faith, resulting in different response to alarm failure. This study showed relatively short term effects of alarm failure and further research is required to assess the long terms effects.

Human factors research has indicated that new technology can contribute to solving problems and simultaneously create new problems (for example Kantowitz, 2000; Hancock and Parasuraman, 1992; Hancock and Verwey, 1997). The results of the research reported in this thesis include situations where the promise of increased safety offered by FCWS would be undermined if the system design was inadequate.

9.5 What is the most appropriate alarm timing?

While this question is possibly the most interesting one for every reader it is the most challenging one to provide with a specific answer because 'appropriate' alarm timing is influenced by multiple factors; driving conditions, driver distraction, and so on. It is very difficult to argue this issue in a generalised manner that would be relevant to all driving contexts, including the more hazardous situations. Furthermore, in the

experiments reported in this thesis the sudden deceleration of a leading vehicle was implemented with little possibility of the driver being distracted and thus application of the results requires caution. However this section will try to explore possible recommendations for the design of alarm timings which may have the potential to optimise driver performance by integrating the findings from the experiments. Figure 9-3 illustrates a full integration of the factors undertaken in the experiments and their influences on driver objective and subjective data. The following conclusions will be offered based on the results regarding alarm timing and its relation to trust and braking performance, the effects of false and missing alarms on trust and braking performance, and behavioural robustness for alarm failure in response to alarm timing.

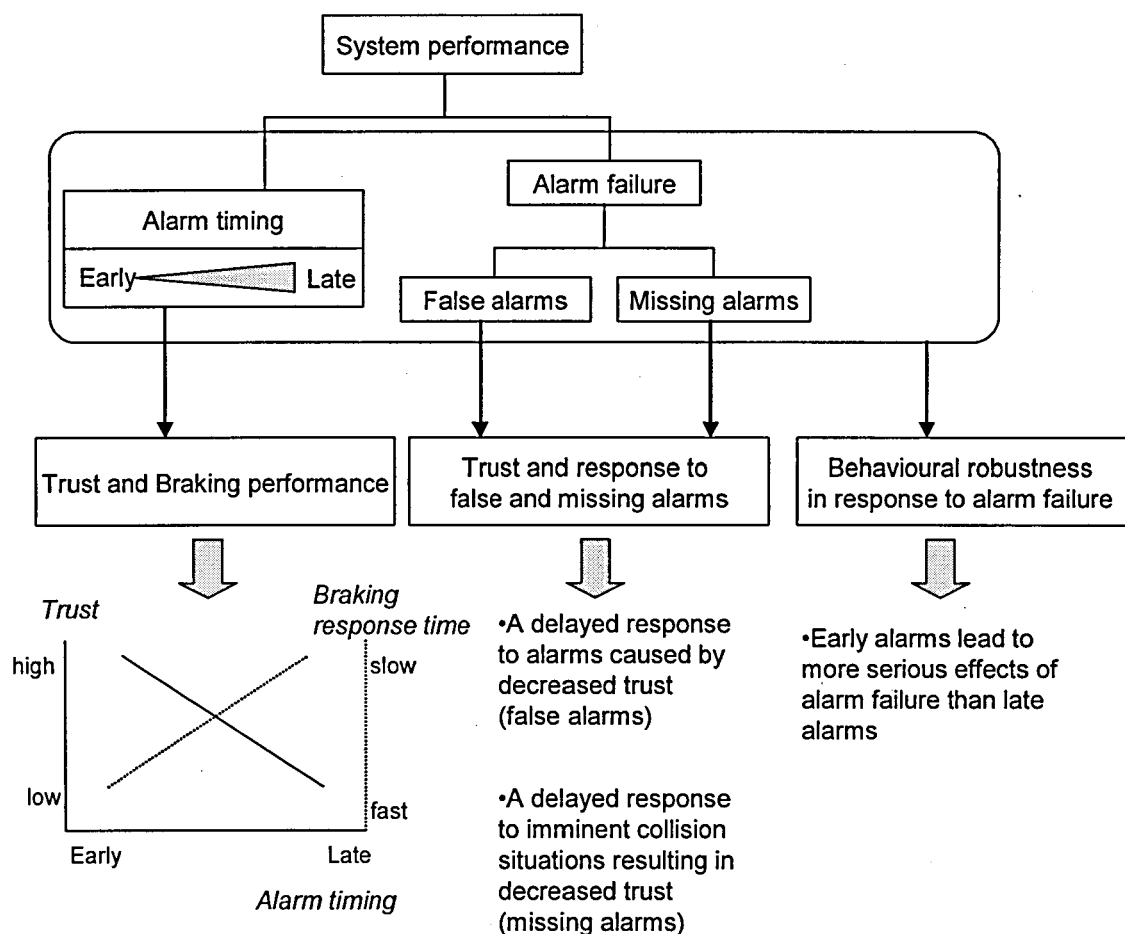


Figure 9-3 An integration of findings from the experiments

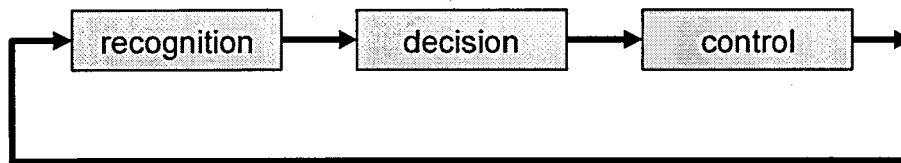
9.5.1 The driver's mental model

People develop mental models of complex systems to predict future performance, thus mental models significantly influence interaction with complex systems (Lee and Kantowitz, 1998; Moray, 1988). This strongly suggests that, mental models may play an important role in the driver's response to FCWS and in determining alarm effectiveness.

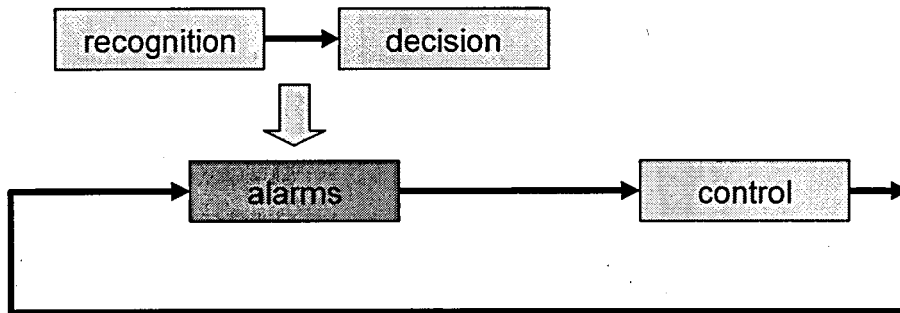
First, driver's mental models of FCWS and their relation to driver behaviour are considered by integrating the results of the thesis. Figure 9-4 illustrates four possible types of interactions between driver's mental models and alarm systems.

Type I interaction refers to a 'basic' driver mental model in which drivers are responsible for implementing all three tasks for avoiding collisions with assistance themselves. Type II shows a change in the driver mental model caused by the introduction of alarms. Here the presentation of alarms replaces recognition and decision tasks. In this situation it is possible that alarms themselves may function as a trigger for the implementation of a control task. However such a replacement has the potential to lead to impaired driver performance when alarms are missed in critical situations. Evidence that the above explanation is plausible can be seen in the results of chapter 8 and 9. There it was shown that drivers who experience early alarms may show a delayed response to imminent collision events when missing alarms occur. In other words early alarms may tend to replace driver recognition and decision tasks and, as a result, the presentation of alarms may directly influence control actions. This effect might not be obvious while alarm systems work correctly but has a potential to decrease system effectiveness.

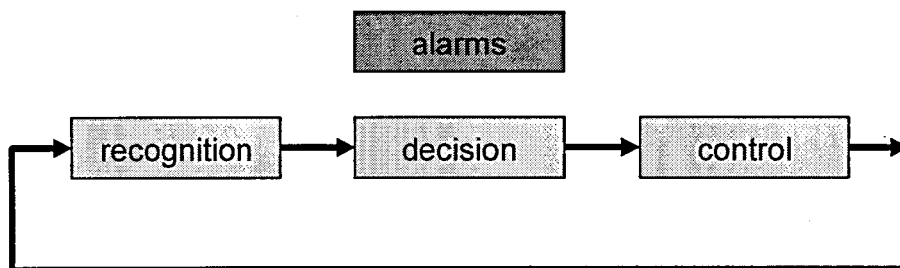
Type III refers to the situation where alarms are 'out of the loop' with respect to the driver's mental model. In this situation alarms influence none of the driver's tasks. Thus changes in driver performance with alarms are not observed. Evidence that the above explanation is acceptable can be seen in the results of chapters 4, 5, and 6. Late alarms have no potential to improve driver performance and these alarms do not function as useful facilities.



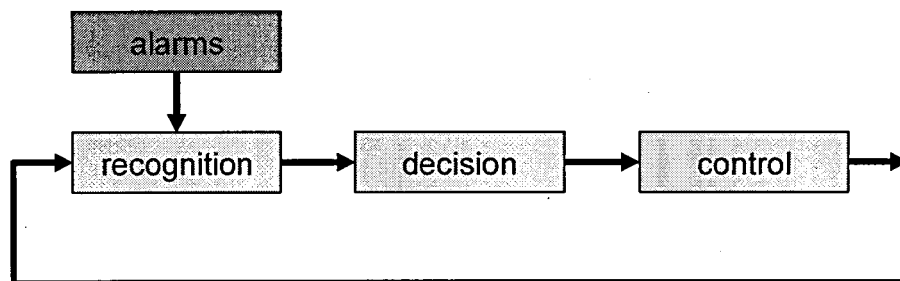
Type I: Before the introduction of alarms



Type II: Replacing aspects of the driver's task



Type III: Out of the driver's task loop



Type IV: Supporting or encouraging the driver's task

Figure 9-4 The differences in driver mental model according to alarm timing

Finally Type IV interaction possibly refers to an ideal driver response towards FCWS. In this context drivers have a mental model that requires them to be ready to implement all driver tasks with assistance with alarms functioning as a support or encouragement to the driver's recognition task. de Waard et al. (1999); Wickens

(1992); Ward (1996) argue that shifting the driver out of the control loop may lead to reduced responsiveness to critical events. That is, in general drivers are poor “process monitors” (e.g. Molloy and Parasuraman, 1996) and if parts of the driver task are replaced or affected by driver support systems (e.g. FCWS), there is a possibility that safe driving might be impaired due to decreased situation awareness. It is necessary for drivers to remain in the loop all the time, even if FCWS are introduced. Thus, this ideal type of mental model may exhibit a robust behaviour against all system conditions and contribute to the achievement of the intended alarm effect.

The arguments regarding driver mental models discussed in this section are relevant to task allocation between drivers and automated systems. As technology advances, the issues of function allocation to humans or machines are more crucial for system design (Hancock and Scallen, 1996,) in order to optimise total system safety. In the vehicle domain the introduction of in-vehicle control systems such adaptive cruise control systems also necessitates consideration of which functions to allocate to the driver and to the system (Stanton and Marsden, 1996). The allocation of functions to person or machine should be determined by considering task efficiency and responsibility for action.

With respect to in-vehicle information systems such a FCWS, Janssen and Nilsson (1993) suggest that before collision avoidance systems can be safely implemented it is necessary to satisfactorily answer the following question; ‘how is the responsibility for action to be divided between the system and the driver?’ It might reasonably be expected that warnings would only function as aids to driving when necessary and that the introduction of a FCWS would not directly replace driver tasks. However, the current research suggests that it is necessary to induce an appropriate mental model for driver tasks and alarm roles when determining alarm timing.

9.5.2 Most appropriate alarm timing

In order to define timings which correspond to the conditions for ideal alarm timing discussed above, alarm timing and its relation to driver performance with alarms and subjective ratings of trust were summarised (Table 9-1). Although the data summarised in this table was collected in the limited situations manipulated in the

experimental conditions used in the current research, possible appropriate alarm timings will be considered in this section.

When discussing appropriate alarm timing, the objectives given priority for FCWS will influence the required alarm timing. For example, whether alarms should lead to a prompt response to the brakes or not plays an important role in determining alarm timing. Although the primary objective of alarms is to prevent collision accidents, there are other requirements to be satisfied in order to achieve the primary objective.

First of all, appropriate driver trust is a crucial factor in ensuring a good partnership between driver and alarm system. Second, driver response to alarm failure is also an important consideration for alarm timing. If imperfect system reliability is inevitable for FCWS it is necessary to find alarm timings which mitigate the effect of alarm failure on driver behaviour. Although improved driver response to imminent collision situations is an inherent purpose of FCWS, how driver performance is actually enhanced is a more interesting challenge for the alarm design. It should be remembered that a reduction of braking response time is not the only positive alarm effect, decreased variation in braking response time is also beneficial. Driver braking performance without alarms may vary according to the degree of driver attention to forward vision. If appropriate alerts can lead to more consistent braking response time, resulting in compensation for delayed responses to the brakes due to some distraction then the purpose of alarms would be partly achieved.

Table 9-1 Summary of alarm effectiveness, trust in alarms and response to alarm failures according to alarm timing

Alarm timing	Benefit	trust	Response to alarm failure
Relatively early	Reduction in braking response time. Decreased variation in braking response time.	high	Delayed braking response
Middle	Possibly Decreased variation in braking response time	Relatively high	<i>It was not considered in this thesis</i>
Relatively late	No benefit	low	No impact on driver response to alarm failure

Taking all the data obtained from the current research and all the considerations discussed into account, late alarms should be avoided because of their negative impact on driver trust and driver performance. Unless the serious problem relating to delayed response to missed alarms can be overcome, early alarms should also be avoided. However, there are no standard guidelines regarding the definition of an early alarm. As a minimum requirement alarms should have the potential to recover delayed recognition to imminent collision situations caused by driver inattention, in addition to providing a benefit to drivers applying a 'normal' level of attention in an unanticipated collision situation.

Based on the results reported in this thesis an alarm time of between 0.3-0.6s may provide the best target value. Although a specific alarm time is a value that varies in response to driving conditions, recommended values are useful for the design of default alarm timings. This value may be moderated if the system is capable of sensing contextual factors (e.g. driver alertness).

It can be anticipated that advances in technology will allow the provision of significant driver assistance (i.e. speed and headway under automatic control) in addition to FCWS. When these systems are available driving conditions will be more similar to the conditions which applied in the experimental scenarios (i.e. sudden deceleration of a leading vehicle occurs when driving with constant speed and time headways). Although it is necessary to consider another human factor issue regarding driver interaction with automated vehicle control systems, target values could be applied to alarm timing with confidence when this situation is achieved.

Chapter 10: Thesis conclusions

10.1 Final conclusions

This thesis has described research undertaken to investigate the effect of alarm timing on driver response to FCWS and its relation to driver trust and also proposed trust models describing the nature of trust in FCWS. A literature review was conducted and a series of experimental studies performed. The main conclusions of this thesis were:

- an early alarm timing leads to prompt braking response to potential collision events
- an early alarm timing leads to prompt accelerator release
- the presentation of an early and a middle alarm timings leads to decreased variation in braking response
- generally, a late alarm timing does not affect driver braking response
- when driving under relatively low demand (relatively long time headways) a late alarm timing induces later braking responses
- trust in early alarm timing is higher than that in late alarm timing
- driving demand; driving speed or time headway, may influence driver's estimation of trust in FCWS
- alarms which are presented after drivers have already begun braking can impair trust
- the timing of accelerator release in unassisted driver performance may play an important role in determining driver subjective ratings of trust.
- actual alarm performance should be consistent with driver expectation of alarm performance and if it is not then trust is impaired

- although an SDA type trigger logic may have the pre-determined alarm timings by manipulating alarm trigger parameters the alarm timing achieved may be affected by driving conditions (i.e. headway time or degree of deceleration of a leading vehicle), resulting in variable alarm effectiveness.
- trust towards FCWS comprises two components; trust in individual alarm (TIA) and trust in system integrity (TSI) and false and missing alarms affect TIS and TSI respectively
- driver response to alarm failures (false alarm and missed alarms) varies in response to alarm timing.

10.2 Contribution to knowledge

This doctoral research has investigated the issues surrounding the effect of alarm timing on driver braking response and trust, and driver response to alarm failure and its influence on alarm timing was investigated from the viewpoint of trust.

The relationship between trust and alarm timing was quantified, moreover the nature of driver trust towards FCWS was explored. The impact of alarm timing on driver behaviour has been recognised as an important factor in determining alarm effectiveness and has been considered in several studies (for example, Lee et al., 2002). However this study provides important new insights on the effect of driver cognition on driver response to FCWS. This new knowledge has important implications for system design in order to construct appropriate cooperation between drivers and FCWS for improving safe driving. Moreover the nature of driver trust and its relation to driver response to FCWS was explored through the experiments regarding false and missing alarms. Countermeasures for alarm malfunction must be thoroughly assessed before being launched in the market place in order to ensure the desired safety benefit is achieved. The findings of the research reported here suggest a knowledge how to mitigate the negative effect of alarm malfunction on driver behaviour.

In this thesis the concept of 'appropriate alarm timing' has been proposed by incorporating driver trust into the design of alarm timing. The comprehensive

understanding of driver behaviour in response to alarm timing and its influence on driver trust has enabled a specific alarm timing (between 0.3-0.6s) to be proposed as a target value.

The results should help strategy for the definition of optimised alarm timings from the view point of driver-centred design.

10.3 Further research

The following section presents some of the issues which required further consideration and possible experimental investigation and which mainly derive from the limitations of the experimental methods employed in the current work.

- The experimental work conducted in this research was concerned with driver behaviour over relatively short time periods. The drivers were exposed to alarms frequently and this inevitably induced high levels of expectation. Accordingly, the data represents the short-term effect of alarm timing on driver behaviour and attitudes. It is possible that driver experience with FCWS accumulated over long periods of driving may influence driver behaviour significantly. It is also necessary to consider the long-term effects in order to clarify how driver mental models of FCWS develop with long-term experience. These issues can only be fully resolved with longitudinal field trials.
- Potential collision events may occur due to multiple factors; driving conditions, degree of driver attention, road design and so on. The experimental scenarios provided in these experiments represented one limited cause of potential collisions. Specifically the sudden deceleration of a leading vehicle was employed in order to give drivers potential collision events without any secondary tasks which might induce driver distraction. Alarm effectiveness may be affected by the driver's state of attention. Thus it is necessary to consider a variety of collision causes in order to establish strategies of system design in response to such situations.

- With respect to the effect of alarm timing on driver response to alarm failure, it was found that there is a possibility that the negative effect of alarm failure can be moderated by alarm timing. A further investigation would be needed in order to find an optimal alarm timing for maintaining alarm effectiveness and also mitigating impairments to system effectiveness caused by alarm failure.
- Driver trust was a particular focus of this thesis and was proposed as an important contributing factor in determining appropriate cooperation between drivers and FCWS. However, it is likely that other factors which could not be considered in the thesis also need to be incorporated into the design of alarm timing. It is necessary to identify other factors which have the potential to influence driver response to FCWS (for example driver self-confidence as proposed by Lee and Kantowitz, 1998) and identify their specific effects on system effectiveness in order to establish comprehensive guidance on alarm system design.
- With respect to warning efficiency, the assignment of sensory modalities for alarm presentation must be considered (Hirst and Graham, 1996). Visual, tactile, or auditory information are available for alerting drivers to potential collision situations. In this study auditory warnings such as simple buzzers were used in order to investigate driver response to FCWS. Auditory warnings lead to more prompt reaction times than those presented visually (Colavita, 1974) and such alarms are generally recommended in situations where a swift response to a safety-critical situation is required. However, any design process leading to the introduction of a specific vehicle system would need to complete a thorough human factors investigation to determine the most appropriate alarm design (modality, location, characteristics) in order to maximise effectiveness. This may mean that alarm timing and its relation to driver behaviour must be considered in response to alarm types. Moreover, it is possible that the differences in alarm types might influence trust in FCWS. Accordingly it is necessary to establish guidelines of alarm timing design in response to alarm modalities.

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Appendix A. Chapter 4 Instructions and Data Forms of subjective ratings of trust

Study Description Presented to the subjects

General instruction for this experiment

In this study you have two tasks. One is to drive at 45 miles/h while following another car. It is very important that you try and drive in that same way as you would drive a real car in this task. Please try not to experiment with the simulator. The other is to avoid rear-end collisions. Whilst you are driving 45 miles/h journey, the leading vehicle may suddenly decrease its speed because of a problem on the road ahead. Hence you have to be ready to brake so as to avoid a rear-end collisions.

This experiment involves two sessions. In the first session you have to avoid collisions by relying on your driving skills. In the second session the simulated car you will be driving is equipped with a collision warning systems. However, like any real life system, the warning system is subject to some reliability problems and occasionally the timing of the alarms, which alert drivers to the critical situations, may be variable.

You will drive the simulated car for a total 45 minutes. Make yourself familiar with driving the vehicle in the simulator before starting session I. During the training period the supervisor will be available to help you. After the training phase there will be a short brake followed by the experimental phase. While you are driving we will ask you to complete some questionnaires but we will try not to disturb your driving. The purpose of this study is to understand more about warning systems and it is not a test of your driving skills. It is very helpful for us if you would drive in the same manner as you would drive your own car.

Any questions?

Introduction to subjective rating

In this study we are interested in your trust in the rear-end collision warning system. We will record your trust in the warning system when alarms are presented using a simple rating scale. Specifically we want you to perform the following rating.

How much did you trust in the rear-end collision warning system?

Not at all completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

You will be asked to respond to the question and give your rating using a 10 point scale; 1 indicating “not at all” and 10 indicating “completely” after each braking event.

There are no “right” answers. We are interested in how you feel about the warning system. Your answers will help us in our research on how to improve interactions between driver and warning systems.

Data forms of subjective ratings of trust

Questionnaires

How much did you trust in the rear-end collision warning system?

Trial one

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Trial two

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Trial three

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Trial four

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Trial five

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Trial six

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Appendix B. Chapter 5 Instructions and data forms of subjective ratings of trust and perceived alarm timing

Study Description Presented to the subjects

General instruction for this experiment

In this study you have two tasks. The first is to drive at a particular speed, namely 40 miles/h, 60miles/h, or 70miles/h while following another car. The experimenter will tell you which speed (40, 60, or 70mile) to drive. Although the driving speed required will change please follow the instructions carefully and drive as close to the required speed as possible. It is very important that you try and drive in the same way as you would drive a real car in this task. Please try not to experiment with the simulator.

The second task is to avoid rear-end collisions. Whilst you are driving, the leading vehicle may suddenly decrease its speed because of a problem on the road ahead. You have to be ready to brake so as to avoid a forward collision.

This experiment will consist of two sessions with a number of potential collision events in each session. In one session you have to avoid collisions by relying on your driving skills alone. In the other session alarms will be provided in order to help you avoid collisions. An experimenter will let you know which session (no alarm session or alarm session) you are driving first before starting the experiment. A 3-minute break will be available between sessions.

You will drive the simulator car for a total of 45 minutes and you will have a chance to make yourself familiar with driving the vehicle before starting your trial. During the training period the supervisor will be available to help you.

After the training phase there will be a short break followed by the experimental phase. While you are driving we will ask you some questions but we will try not to disturb your driving. The purpose of this study is to understand more about warning systems and it is not a test of your driving skills. It would be very helpful for us if you were to drive in the same manner as you would drive your own car.

Any questions?

Introduction to subjective rating

In this study we are interested in how much you trust the warning system. We will record your trust when alarms are presented using a simple rating scale. Specifically we want you to perform the following rating.

How much did you trust in the warning system?

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

You will be asked to respond to the question and give your rating using a 10 point scale; 1 indicating "not at all" and 10 indicating "completely" after each braking event. You can give your judgement by saying the number aloud.

We also interested in how you perceive the alarm timing. We will record your ratings of alarm timing using a 3 point rating. Specifically we want you to perform the following question.

How would you rate the alarm timing?

You will be asked to respond to the question and give your rating using a 3 rating scale; **Early, Correct or Late.**

There are no "right" answers. We are interested in how you feel about the alarms. Your answers will help us in our research on how to improve interactions between driver and warning systems.

Data forms of subjective ratings of trust and perceived alarm timing

Questionnaires: How much did you trust in the rear-end collision warning system? and How would you rate the alarm timing?

Subject number:

Trial one
Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Early Correct Late

Trial two
Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Early Correct Late

Trial three
Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Early Correct Late

Trial four
Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Early Correct Late

Trial five
Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Appendix C. Chapter 6 Instructions and data forms of subjective ratings of trust

Study Description Presented to the Subjects

General instruction for this experiment

In this study you have two tasks. The first is to drive at 30 miles/h while following another car. It is very important that you try and drive in the same way as you would drive a real car in this task. Please try not to experiment with the simulator. The second task is to avoid rear-end collisions. Whilst you are driving, the leading vehicle may suddenly decrease its speed because of a problem on the road ahead. Hence you have to be ready to brake so as to avoid a forward collision.

In this trial you will drive at 30 miles/h on an urban road. This trial includes a number of potential collision events. You have to avoid collisions by relying on your driving skills in the first and last 2 events. In the other events alarms will be provided at some timing in order to help you avoid collisions.

However, like any real life system, the warning system is subject to some reliability problems and occasionally the timing of the alarms, which alert drivers to the critical situations, may be unreliable.

You will drive the simulated car for a total of 30 minutes and you will have a chance to make yourself familiar with driving the vehicle in the simulator before starting your trial. During the training period the supervisor will be available to help you. After the training phase there will be a short break followed by the experimental phase. While you are driving we will ask you

some questions but we will try not to disturb your driving. The purpose of this study is to understand more about warning systems and it is not a test of your driving skills. It would be very helpful for us if you were to drive in the same manner as you would drive your own car.

Any questions?

Introduction to subjective rating

In this study we are interested in your trust the warning system. We will record your trust when alarms are presented using a simple rating scale. Specifically we want you to perform the following rating.

How much did you trust in the warning system?

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

You will be asked to respond to the question and give your rating using a 10 point scale; 1 indicating “not at all” and 10 indicating “completely” after each braking event. You can answer your judgement with saying aloud.

There are no “right” answers. We are interested in how you feel about alarms. Your answers will help us in our research on how to improve interactions between driver and warning systems.

Data Forms of subjective ratings of trust

Questionnaires: How much did you trust in the rear-end collision warning system?

Subject number:

(30miles/h, low/high deceleration)

Trial three

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Trial four

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Trial five

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Trial six

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Appendix D. Chapter 8 Instructions and data forms of subjective ratings of trust

Study Description Presented to the Subjects

General instruction for this experiment

In this study you have two tasks. The first is to drive at 60miles/h while following another car. It is very important that you try and drive in the same way as you would drive a real car in this task. Please try not to experiment with the simulator. The second task is to avoid rear-end collisions. Whilst you are driving, the leading vehicle may suddenly decrease its speed because of a problem on the road ahead. Hence you have to be ready to brake so as to avoid a forward collision.

In this trial you will drive at 60 miles/h on a rural road. This trial includes a number of potential collision events. You have to avoid collisions by relying on your driving skills in the first and last 2 events. In the other events alarms will be provided to help you avoid collisions.

However, like any real life system, the warning system is subject to some reliability problems and occasionally the timing of the alarms, which alert drivers to the critical situations, may be unreliable.

You will drive the simulated car for a total of 30 minutes and you will have a chance to make yourself familiar with driving the vehicle in the simulator before starting your trial. During the training period the supervisor will be available to help you. After the training phase there will be a short break followed by the experimental phase. While you are driving we will ask you

some questions but we will try not to disturb your driving. The purpose of this study is to understand more about warning systems and it is not a test of your driving skills. It would be very helpful for us if you were to drive in the same manner as you would drive your own car.

Any questions?

Introduction to subjective rating

In this study we are interested in your trust the warning system. We will record your trust when alarms are presented using a simple rating scale. Specifically we want you to perform the following rating.

How much did you trust in the warning system?

Not at all completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

You will be asked to respond to the question and give your rating using a 10 point scale; 1 indicating “not at all” and 10 indicating “completely” after each braking event. You can answer your judgement with saying aloud.

There are no “right” answers. We are interested in how you feel about alarms. Your answers will help us in our research on how to improve interactions between driver and warning systems.

Data Forms of subjective ratings of trust

Questionnaires: How much did you trust in the rear-end collision warning system?

Subject number:

Session II (60miles/h, early/late alarm timing)

Trial three

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Trial four

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Trial five

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Trial six (false alarm)

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Trial seven

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Trial eight

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Trial nine (missing alarm)

Not at all

completely

1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	----

Appendix E. Subject Consent and Payment Forms



Volunteer Consent Form (Driving simulation Study)



Thank you very much for agreeing to take part in this research looking at driver behaviour. The purpose of this form is to make sure that you are happy to take part in the research and that you know what is involved. Signing this form does not commit you to anything you do not wish to do.

Have you read the Participant Briefing Sheet? YES NO

Have you had the opportunity to ask questions and discuss the study? YES NO

If you had asked questions, have you had satisfactory answers? YES NO

Do you understand that you are free to withdraw from the study at any time and without having to give a reason for withdrawing? YES NO

Do you agree to take part in the study? YES NO

Name in block letters _____

Signed _____ Date _____

Date of birth _____

Annual mileage _____

Number of years driving experience _____

I acknowledge receipt of £ for participation in this study.

Signature _____

Date _____

Appendix F. Summary of experimental data

Table F-1 Summary of driver response to alarms and trust ratings (from chapter 4)

	Alarm timing (non-consistent alarm timing)				F value	p value
	Early	Middle	Late	Before introducing alarms		
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)		
Trust	6.7 (1.95)	6.6 (1.99)	4.9 (2.22)	no record	F(2,48)=9.679	0.0029
Braking event to brake onset time	0.95 (0.19)	1.18 (0.32)	1.18 (0.29)	1.21 (0.36)	F(3,70)=3.707	0.0154
Braking event to accelerator release time	0.58 (0.22)	0.79 (0.38)	0.82 (0.32)	0.79 (0.42)	F(3,70)=1.923	0.1336
Accelerator release to brake onset time	0.37 (0.14)	0.39 (0.24)	0.36 (0.14)	0.41 (0.30)	F(3,70)=0.424	0.7361

Table F-2 Summary of regression analysis (from chapter 4)

Regression Equation	R^2	F Value	p value
	Model		
$T_n=0.32(RAT-AT)_n-0.44(Discouragement)_n+0.576T_{n-1}$	0.62	$F(4,43)=17.17$	$p<0.001$

Table F-3 Summary of alarm onset to accelerator release time (from chapter 4)

	Alarm timing (non-consistent alarm timing)		
	Early	Middle	Late
	Mean (SD)	Mean (SD)	Mean (SD)
Alarm onset to accelerator release time	0.54 (0.22)	0.15 (0.40)	-0.15 (0.35)

Table F-4 Summary of braking efforts without alarms in response to different speeds and time headways (from chapter 5)

	Velocity(mph)		
	40	60	70
Time headways			
Short: Mean (SD)	8.18 (0.98)	8.33 (0.94)	8.20 (0.93)
Long: Mean (SD)	7.48 (1.34)	7.55 (1.22)	7.82 (0.97)

Table F-5 Summary of braking efforts without alarms in response to time headways (from chapter 5)

Time headway		
Short : Mean (SD)	Long: Mean (SD)	Statistical test
8.24 (0.94)	7.61 (1.18)	F(1,126)=11.01,p=0.0011

Table F-6 Summary of driver response to early alarms in response to time headways (from chapter 5)

	Alarm conditions		
	Time headways	Early timing	No alarms
Braking event to brake onset time	Short: Mean (SD)	0.93 (0.17)	1.14 (0.45)
	Long: Mean (SD)	1.12 (0.26)	1.20 (0.42)
			Statistical test
			Z=2.088, p=0.0367
			F(1,64)=4.720, p=0.033
Braking event to accelerator release time	Short: Mean (SD)	0.60 (0.14)	0.82 (0.46)
	Long: Mean (SD)	0.81 (0.23)	0.81 (0.42)
			Statistical test
			Z=2.088, p=0.0367
			N.S

Table F-7 Summary of driver response to late alarms in response to time headways (from chapter 5)

		Alarm conditions		Statistical test
	Time headways	Late timing	No alarms	
Braking event to onset time	Short: Mean (SD)	0.95 (0.31)	0.94 (0.27)	F (1,53)=5.318, p=0.025
	Long: Mean (SD)	1.07 (0.35)	0.92 (0.25)	
Braking event to accelerator release time	Short; Mean (SD)	0.65 (0.25)	0.65 (0.26)	F(1,36)=8.102, p=0.0059
	Long: Mean (SD)	0.62 (0.19)	0.73 (0.36)	

Table F-8 Summary of trust ratings of alarm timings response to time headways (from chapter 5)

		Time headways		Statistical test
	Alarm timing	Short	Long	
Trust	Early: Mean (SD)	6.7 (1.55)	6.8 (1.56)	F (1,50)=4.668, p=0.355
	Late: Mean (SD)	5.2 (2.18)	3.9 (2.07)	

Table F-9 Summary of trust ratings in response to perceived alarm timings (from chapter 5)

		Perceived alarm timing		Statistical test
	Correct	Late		
Trust:				
Mean	7.3	4.3		
(SD)	(1.28)	(1.70)	F(1,115)=118.32, p<0.001	

Table F-10 Summary of perceived alarm timings and alarm time(from chapter 5)

	Perceived alarm timing	
	Correct	Late
Alarm time:		
Mean	0.51	0.77
(SD)	(0.36)	(0.46)

Table F-11 Summary of regression analyses of the development of trust (from chapter 5)

Regression Equation	R^2 Model	F Value	p value
$T_n = 0.231(RAT-AT)_n + 0.534T_{n-1}$	0.43	F (2,93)=36.79	p<0.001

Table F-12 Summary of driver baseline performance with collision events (from chapter 6)

	Decelerations of the leading vehicle (baseline)		Statistical test
	High	Low	
	Mean (SD)	Mean (SD)	
Maximum deceleration of the following vehicle	8.44 (0.81)	6.84 (1.40)	z=5.825, p<0.001
Braking event to brake onset time	1.05 (0.34)	1.10 (0.26)	F(1,94)=0.905,p=0.344

Table F-13 Summary of driver performance with collision events in response to alarm timings (from chapter 6)

Dependent valuable	Deceleration	Alarm conditions			Statistical test
		Early	Late	Baseline	
		Mean (SD)	Mean (SD)	Mean (SD)	
Braking event to brake onset time	High	0.88 (0.16)	0.99 (0.18)	1.05 (0.34)	$\chi^2(2)=4.66$, p=0.096
	Low	1.06 (0.29)	1.11 (0.29)	1.10 (0.26)	N.S
Braking event to accelerator release time	High	0.56 (0.12)	0.68 (0.19)	0.74 (0.34)	$\chi^2(2)=3.45$, p=0.072
	Low	0.70 (0.22)	0.71 (0.16)	0.71 (0.22)	N.S
Accelerator release to brake onset time	High	0.34 (0.22)	0.35 (0.23)	0.35 (0.26)	N.S
	Low	0.38 (0.19)	0.49 (0.31)	0.49 (0.26)	$F(2,45)=1.213$, p=0.306
Maximum deceleration	High	8.22 (0.88)	8.53 (0.58)	8.44 (0.82)	N.S
	Low	6.61 (1.54)	6.91 (1.41)	6.84 (1.40)	N.S
Alarm to brake onset time	High	0.74 (0.14)	0.13 (0.15)	no record	$F(1,39)=6.471$, p=0.01504
	Low	0.76 (0.15)	-0.36 (0.70)	no record	

Table F-14 Summary of trust ratings in response to alarm timings (from chapter 6)

	Deceleration	Alarm conditions		Statistical test
		Early	Late	
		Mean (SD)	Mean (SD)	
Trust	High	6.5 (1.81)	4.5 (2.38)	$F(1,35)=45.721$, p<0.001
	Low	5.7 (2.30)	4.3 (2.31)	$F(1,21)=7.130$, p=0.0143

Table F-15 Summary of trust ratings in triggered and untriggered alarms(from chapter 6)

	Alarm conditions		Statistical test
	Triggered	Untriggered	
	Mean (SD)	Mean (SD)	
Trust	4.3 (2.31)	2.4 (2.02)	F(1,11)=27.00, p=0.0003

Table F-16 Summary of driver response to false alarms (from chapter 7)

Trials(false alarms)																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	statistical test
Alarm to brake onset time: Mean (SD)	0.84 (0.11)	0.77 (0.11)	0.78 (0.14)	0.80 (0.16)	0.79 (0.11)	0.73 (0.13)	0.91 (0.27)	0.93 (0.29)	0.96 (0.20)	1.01 (0.26)	0.98 (0.15)	0.84 (0.18)	0.81 (0.16)	0.90 (0.20)	0.87 (0.18)	F(14,94)=2.336, p=0.0815
Trust: Mean (SD)	6.4 (2.20)	6.6 (2.00)	7.4 (1.77)	7.8 (1.58)	8.0 (1.51)	8.0 (1.51)	6.3 (1.58)	5.0 (1.31)	4.1 (1.13)	5.3 (0.89)	6.0 (0.93)	6.5 (0.76)	6.9 (1.13)	7.3 (0.89)	7.1 (0.99)	F(14,98)=9.087, p<0.0001

Table F-17 Summary of driver response to missing alarms (from chapter 7)

Trials(missing alarms)																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Statistical test
Braking event to brake onset time: Mean (SD)	1.28 (0.16)	1.26 (0.20)	1.19 (0.16)	1.25 (0.20)	1.18 (0.21)	1.16 (0.21)	1.68 (0.26)	1.50 (0.18)	1.55 (0.23)	1.19 (0.25)	1.16 (0.16)	1.26 (0.24)	1.26 (0.31)	1.27 (0.35)	1.32 (0.38)	F(14,112)=9.727, p<0.001
Trust	7.7 (1.50)	8.1 (1.17)	8.4 (0.73)	8.2 (1.09)	8.0 (1.22)	8.3 (1.12)	3.0 (2.06)	2.3 (1.66)	2.0 (1.50)	3.3 (1.80)	4.4 (1.51)	5.4 (1.67)	5.9 (1.62)	6.8 (1.79)	6.8 (1.64)	F(14,120)=21.749, p<0.001

Table F-18 Summary of driver response to collision events in response to experiences of missing alarms (from chapter 7)

	Experiences of missing alarms				Statistical analysis
	First exposure	Second	Third	No alarms (baseline)	
Braking event to brake onset time: Mean (SD)	1.68 (0.26)	1.50 (0.18)	1.55 (0.23)	1.43 (0.22)	F(3,24)=4.276, p=0.0149

Table F-19 Summary of regression analyses of the influence of false alarms on trust (from chapter 7)

Regression Equation	R^2 Model	F Value	p value
$T_n = -0.43F_n + 0.755T_{n-1}$	0.89	F(2,61)=251.841	p<0.001

Table F-20 Summary of regression analyses of the influence of missing alarms on trust (from chapter 7)

Regression Equation	R^2 Model	F Value	p value
$T_n = -0.72M_n + 0.296T_{n-1}$	0.87	F(2,69)=229.40	p<0.001

Table F-21 Summary of trust ratings in response to alarm timings (from chapter 8)

	alarm timing		Statistical test
	Early	Late	
Trust: Mean (SD)	6.7 (1.96)	3.1 (1.63)	F(1,118)=116.33, p<0.001

**Table F-22 Summary of braking response times in response to alarm timings
(from chapter 8)**

	alarm timing		Statistical test
	Early	Late	
Braking event to brake onset time: Mean (SD)	0.86 (0.30)	1.04 (0.26)	F(1,118)=13.47, p=0.00036

Table F-23 The influence of alarm failures on braking response times in response to alarm timings (from chapter 8)

Alarm timing	Alarm conditions				Statistical test
	Before a false alarm	After a false alarm	Missing alarm	Baseline	
Early timing: Mean (SD)	0.82 (0.30)	0.92 (0.30)	1.21 (0.30)	1.06 (0.33)	F(3,105)=15.120, p<0.001
Late timing: Mean (SD)	1.03 (0.28)	1.07 (0.22)	1.06 (0.26)	1.09 (0.37)	N.S

Table F-24 The influence of alarm failures on trust in response to alarm timings (from chapter 8)

Alarm timing	Alarm conditions				Statistical test
	Before a false alarm	False alarm	After a false alarm	Missing alarm	
Early timing: Mean (SD)	6.8 (1.96)	2.7 (2.02)	6.5 (2.00)	2.2 (2.37)	F(3,69)=43.780, p<0.001
Late timing: Mean (SD)	3.4 (1.80)	1.8 (1.34)	2.7 (1.23)	1.4 (0.90)	N.S

Table F-25 The influence of alarm failures on braking efforts in response to alarm timings (from chapter 8)

Alarm timing	Alarm conditions					Statistical test
	Baseline	Before a false alarm	False alarm	After a false alarm	Missing alarm	
Early timing:						
Mean	8.66	8.46		8.49	8.87	
(SD)	(0.32)	(0.53)	4.08 (1.35)	(0.75)	(0.15)	
Late timing:						
Mean	8.81	8.62		8.72	8.71	F(4,88)=2.356, p=0.0597
(SD)	(0.14)	(0.53)	2.73 (2.82)	(0.39)	(0.56)	

Table F-26 The influence of trust ratings on driver response to a false alarm (from chapter 8)

	Drivers' response to the brakes		
	Braking	No braking	Statistical test
Trust:			
Mean	5.7		F(1,22)=3.949, p<0.0594
(SD)	(2.76)	3.4 (1.90)	

