

# Ergonomics of intelligent vehicle braking systems 

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A Doctoral Thesis
Submitted in partial fulfilment of the requirements for the award of Philosophiae Doctor of Loughborough University

## Acknowledgements

This document must start with acknowledgements. For it would not exist without the active involvement of volunteers during the administration of the studies behind it. First of all, the name of Dr Mostapha Al-Dah must be quoted for his kind offer to provide his vehicle and himself as the confederate driver and marshal for the closed-road study. His time and effort is very much appreciated. So is the time and effort of Mr Andrew Weeks, Dr lain Darker and Mr Michael Gregoriades who covered for Dr Al-Dah when he was unable to take part. Additionally, this study would be impaired in the absence of Ms Yan Chen, Ms Lindsey Cooper, Dr Moi-Hoo Yap, Ms Lauren Morgan and Ms Teresa Lyssiotou as passengers, when the participant was a female driver.

Special note must be made of Mr Edward Packe-Drowry-Lane for his exceptional generosity to offer the airfield, where the emergency-test took place. It is hugely motivating to find people so kind and keen on supporting research in road safety.

More people need to be acknowledged for their help and advice during the development of the equipment used in the studies that follow. The author is thankful to Dr Pauli Komi, Mr Mathavan Senthan and Dr Pinar Boyraz for their advice during the instrumentation of the vehicle used in two studies; Mr Yves Page and Dr Mohamed Kassagi for inspiring and supporting during the initial phase of the project; Dr Neil Mansfield and Ms Lauren Morgan for their active involvement during testing of the trailer's (see chapter 5) properties.

Mr John Richardson must also be noted; because his discreet supervision and continuous support in difficult times made this document possible.

Last but not least, special thanks go to a special girl who laughed out loud when, 10 years ago, she heard that a psychology graduate aimed at a career in automotive research. She has made up for it by standing by the author during the long process that led to this Thesis.


#### Abstract

The present thesis examines the quantitative characteristics of driver braking and pedal operation and discusses the implications for the design of braking support systems for vehicles. After the current status of the relevant research is presented through a literature review, three different methods are employed to examine driver braking microscopically, supplemented by a fourth method challenging the potential to apply the results in an adaptive brake assist system.


First, 30 drivers drove an instrumented vehicle for a day each. Pedal inputs were constantly monitored through force, position sensors and a video camera. Results suggested a range of normal braking inputs in terms of brake-pedal force, initial brake-pedal displacement and throttle-release ("throttle-off") rate. The inter-personal and intra-personal variability on the main variables was also prominent.

Then, 48 drivers drove the instrumented vehicle on a predetermined course on a public-road section before encountering an emergency brake test on a closed-road section. This study allowed for the comparison and the exploration of relationships of the main parameters between normal and emergency braking. Results supported the pre-established theoretical distinction between normal and emergency braking and provided evidence of relationships between normal and emergency braking parameters.

One of those relationships was selected to be incorporated to a virtual adaptive brake assist system. The behaviour of the system was tested using data from the real trips of 25 drivers. The study indicated the superiority of the
particular system specification over conventional non-adaptive specifications. However, results suggested weaknesses of the system to adapt to driverbraking style quickly enough under certain circumstances, and therefore, the need to improve its specification further.

The accident study provided the actual context within which driver braking and interaction with braking systems becomes critical. The road-userinteractions file of 301 cases where "failure to stop" was identified as the precipitating factor (1099 interactions) and 39 cases where "sudden braking" was identified as the precipitating factor (152 interactions) were examined. Results suggested that longitudinal control and support systems like the proposed system address some of the contributing factors to this type of accidents; however, there are many more factors that are not addressed by such systems or other conventional active safety systems. Therefore, new streams of research and development within road safety need to be established.

In parallel, if the full potential of technological advancements is to be harvested and accidents to be mitigated, current streams, such as the one followed by the present research, need to grow and evolve.

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## Chapter 1: Introduction

The purpose of this chapter is double: first, it clarifies the theme of this thesis and prepares the reader for the chapters that follow. Second, it underlines the main ideas the reader should have in mind when browsing the latter chapters. This should enhance comprehension of the results and the function of the suggested system in the end.

## What do we mean by "ergonomics of intelligent vehicle brake

## systems"?



Figure 1: A semantic analysis of the title

Ergonomics or human factors (term used in the US predominantly) is a multidisciplinary science that focuses on the human needs and capabilities in the design of products, processes and technological systems. A large number of different, though overlapping, definitions of ergonomics/human factors now
exist (Wogalter, Hancock, \& Dempsey, 1998). The combination of scientific characteristics (fundamental information/knowledge) with technological characteristics (application of this knowledge to problems of design/engineering in their wider sense) is a common ingredient of most definitions (Wilson, 2005). The ergonomics/human factors sphere contains all elements of human-environment interaction, be it interaction with hardware, software or other people. The International Ergonomics Association (IEA - the international ergonomics association.) defines ergonomics as the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theoretical principles, data and methods to design in order to optimise human well-being and overall system performance.

Key words in this definition are "interactions", "humans" and "systems". Ergonomics is about human-system interaction and is associated with 3 main criteria - efficiency, comfort and safety. This is the first element of this thesis title (figure 1). The ideas in this document must tend towards improving the human-system interaction in terms of efficiency, comfort and safety.

The second element of the title is "intelligent systems". Within the framework of ergonomics, intelligent systems are human-centred systems, which have not only the capability to sense, process information and "make decisions" or change status, but are also engineered to match human capabilities and adapt to human variability. As every human being is unique, individual differences are one of the major problems to engineers and designers. The "common sense" of using simple averages to accommodate users is a fundamental fallacy (Pheasant, 1996). There are two ways to
overcome this. The first is to customise design to each user. This is ideal as it directly eliminates the problem at its heart; each product/system is designed for each individual specifically. In reality though, there are only a handful of instances when this is applicable. With the exception of users involved in high-end technology projects with virtually unlimited budgets (space exploration program, special army units), no projects can support the financial and human resources necessary to support such a design approach. The second solution to deal with the individual differences of the user population is to make use of the "smart" electronics technology and utilise it in a design that adapts to each user's characteristics. In the case of this thesis, the users are road vehicle drivers.

The system of interest in this case is the vehicle braking system. This is the third element of the thesis title. It is the group of mechanical and electronic devices installed in a road vehicle in order to achieve negative deceleration, when activated. Without dismissing completely the mechanical/electronics part of the system, the current document focuses on the interaction with the driver, the ergonomics. There is a constant momentum in brake engineering (materials, mechanics, electronics) since the birth of automobiles, however as we shall see in the following chapters, little has been done to improve the interaction with the driver. The latter deserves particular attention as it is associated with two of the three elements of a safe road system (safe driver safe vehicle - safe road environment). Successful communication between driver and vehicle could contribute further towards the achievement of the ultimate goal; accident mitigation. For the moment, this goal is some way in the distance.

## Road accidents as a global epidemic

"An automobile is a convenient means of private transportation, but it is also a prime killer of both passengers and pedestrians" (Bennet, Degan, \& Spiegel, 1963)


Figure 2: estimated road fatalities with under reporting adjustments per region

The exact number of global traffic accidents is unknown and so are the exact figures of fatalities and injuries. What is known is that the estimated values are long numbers with more than six digits. Common estimations are based on hospital and insurance data (Ghee, Silcock, Astrop, \& Jacobs, 1997). However, data for most countries in the world are full of gaps and some are inaccessible. At the same time hospital and police accident records
have a lot of mismatches (Cercarelli, Rosman, \& Ryan, 1996) indicating that the problem of under-reporting is global (Laumon \& Martin, 2002). To address the issue of inconsistency the World Bank and the Department for International Development UK (DFID) funded a project with the Transport Research Laboratory (TRL) aiming to provide accurate numbers of global fatalities (G. D. Jacobs \& Aeron-Thomas, 2000). Figure 2 presents the main outputs of this: data from 192 countries are assigned to six major regional groups, namely highly motorised countries (HMC), Africa, Central and Eastern Europe, Asia and Pacific countries, Latin America, Middle East and North Africa (MENA). Accordingly a realistic number for global road deaths is estimated between 750000 and 880000 for the year 1999.

Although we tend to think of "drivers" as the main road victims, quite a significant part of road casualties consists of non-drivers. $38 \%$ of those killed in a traffic accident are not the vehicle driver (Fatality analysis reporting system (FARS) web-based encyclopedia. data files and procedures to analyse them.2005). A basic distinction of road victims is based on their location at the time of the accident: of all traffic fatalities, $86.51 \%$ are vehicle occupants, and $13.49 \%$ are outside the vehicle environment. Of the vehicle occupants, $61.59 \%$ are drivers and $24.91 \%$ are passengers. The non-vehicle occupants are predominantly pedestrians (11.59\%) and the rest 1.9\% consists of cyclists in majority. The group of drivers can be analysed into car drivers (32.89\%), light truck/van drivers (19.20\%), truck drivers (1.45\%), motorcycle riders (6.85\%), bus drivers (0.03\%) and "other" drivers (1.18\%). Within the passenger victims, $15.16 \%$ are car occupants, $8.56 \%$ are van occupants, $0.27 \%$ are truck occupants, $0.56 \%$ are motorcycle co-riders,
$0.05 \%$ are bus passengers and $0.32 \%$ are passengers in "other" type vehicles.

Road traffic fatalities data are abundant in European and North American literature, but also can be found in many national statistics globally. Underneath those data lie injury and non-injury accidents with higher monetary costs (L. Evans, 2004; J. D. Lee, 2006) and impact in quality of life (Barnes, 2006). Non-fatal accidents cost more and in many different ways to the society. Table 1 presents the frequency of different types of vehicle collisions and an estimate of the annual economic cost of each.

Table 1: Frequency and Severity of Major Crash Types (adapted from Wang, Knipling, \&

| Blincoe, 1999) |  |  |
| :--- | :--- | :--- |
| Crash type | Frequency, Number per Year <br> and Percentage of Total | Severity, Economic <br> Cost per Year ${ }^{1}$ |
| Rear-end | $1,454,000(23 \%)$ | 33.8 billion $\$$ |
| Single-vehicle/roadway <br> departure | $1,310,000(21 \%)$ | 33.2 billion $\$$ |
| Intersection | 27.4 billion $\$$ |  |
| Left turn across path | $396,000(6 \%)$ | 11.9 billion $\$$ |
| Lane change/merge | $234,000(4 \%)$ | 4.1 billion $\$$ |
| Opposite direction | $190,000(3 \%)$ | 12.7 billion \$ |
| Pedestrian | $176,000(3 \%)$ | 2.7 billion \$ billion \$ |
| Backing | $171,000(3 \%)$ | 164.4 billion \$ |
| Total | $6,261,000(100 \%)$ |  |

[^0]What is apparent from a quick look at the table is prevalence of rear-end collisions and road departures, both in terms of frequency and monetary cost. Further examination of the table indicates proportionately high economic costs for "opposite direction" collisions and those involving pedestrians. It should be noted however, that the values presented in the table do not include consequential costs in quality of life, which in the case of non-fatal accidents as rear-end collisions commonly are - multiply the figures significantly (Wang et al., 1999). The main problem is that it is hard to find information about "minor"-injury cases and even harder to know or estimate the impact of this accident in the life of those involved and their families.

In one of the few studies that addressed this issue (Barnes, 2006), participants with relatively minor injury had significant physical problems compared to the population norms for the health outcome measures particularly in the first 6 months post injury. At 12 months all participants had returned to work with both physical and mental health rated similar or worse than the population norms (Barnes, 2006). Adding this evidence to the widely acknowledged predominance of rear-end collisions in road accidents (L. Evans, 1991; L. Evans, 2004; J. D. Lee, 2006; National Safety Council, 1996; Parker, West, Stradling, \& Manstead, 1995), the impact of those accidents to the society can be seen differently. Rear-end collisions are no longer as innocent as one might think based on fatality rates. Therefore, it is worth investigating non-fatal accident cases and investing in resources that aim at the amelioration of such accidents.

There are three main areas where developments aim at minimising road accidents: road environment, vehicle and driver. The three-agent systematic
approach has been adopted formally by the Swedish Road Administration and has been validated as an effective generic approach (Stigson, Krafft, \& Tingvall, 2008). The vehicle branch of this model has seen significant developments in the recent years with the introduction of active safety technologies in the vehicle. These consist of electro-mechanical systems engineered to mitigate accidents.

## Safety Technology

Vehicle safety technology was first implemented with the introduction of seat belt in cars during the sixties, based on a concept developed at the beginning of the century. After that, harness systems have been continuously developed and airbags were added later. Frontal airbags began initially as alternatives to seat belts in the US, however the their suspected contribution to some fatalities (Airbagcrash, 2001) soon shifted their use to supplementary to seat-belts. In the '90s side-airbags and anti-whiplash seats were introduced by Autoliv (Autoliv, 2009). In the new millennium, knee airbags were introduced and the first car to include them as standard received excellent marks in leg protection during crash-tests (Euroncap, 2003). All these systems are based on the notion that accidents are inevitable and the focus was on mitigation of their consequences.

However, as cars become faster and faster, the physical limits of how kinetic energy can be dissipated will soon be reached (Evans, 2004), and the example of aerospace industry needs to be followed. As had been the case with aeroplanes in the middle of the $20^{\text {th }}$ century (De Haven, 2000), road
vehicle development creates more and more powerful cars and a setting where the effect of passive safety will be limited. Thus, more and more it is acknowledged in the automotive world that the focus should shift from "minimal casualties" to "no accidents". Under this notion a new trend in vehicle technology was born, commonly named "active safety" technologies.

Table 2: Haddon's matrix with examples of how human, vehicle and roadway environment measures can contribute to crash avoidance, injury minimisation and mitigation of consequences

|  | Human | Vehicle | Environment |
| :--- | :--- | :--- | :--- |
| Pre- | Training, | Collision warning/mitigation | Roadway design, |
| crash | traffic law | systems, ABS, ESC, In-vehicle | availability of |
| phase | enforcement | information systems | other modes of |
|  |  |  | transportation |
| Crash | Bracing | Seat-belts, Pre-tentioners, | Barriers and lane |
| phase | action | Airbags, | separation |
| Post- | Emergency | Automatic emergency call | Emergency |
| crash | call |  | services |
| phase |  |  | response |

Already since the early '70s, Haddon's matrix (Haddon, 1970) provided the theoretical background for additional safety measures that target the precrash phase and reduce the opportunities for an accident to occur in the first place (table 2). Starting with the Antilock Braking System (ABS) developed by Bosch in 1978, a series of vehicle control systems has been developed in order to either support the driver or acquire control and prevent accident occurrence. First, the ABS aimed at preventing the wheels from locking and
allowing steering to be possible when full brakes are applied. After that, many systems claim that they allow controllability in many different situations, although essentially most of them are based on the same concept as ABS preventing wheels from locking.

Generally, there are four main types of systems already in production. These are: systems that support or take over control of headway (e.g. Collision Warning/ Collision Mitigation Systems), Stability Control Systems [e.g. Electronic Stability Program (ESP), Vehicle Stability Control (VSC) etc.], lateral support or automatic control systems [Lane Change Support (LCS)], and systems that augment driver input to the brake pedal [Brake Assist System (BAS) or Emergency Brake Assist (EBA)].

The Collision Mitigation Brake System (CMBS) is a contemporary example of headway-based safety system. Based on previous collision warning and headway controlling systems is viewed as a promising solution to rear-end collisions. CMBS uses a long range radar or lidar (light detection and sensing) sensors to detect target vehicles in front and adjusts the vehicle speed and gap accordingly. CMBS automatically decelerates or accelerates the vehicle according to the desired speed and distance settings established by the driver or by default (figure 3). When the system detects an imminent collision, it even applies brakes automatically to avoid or mitigate the consequences of the crash. Almost every car manufacturer and every system developer offers its own version of such system using a different label to name it. Essentially however systems like Delphi's Smart Cruise Control (Delphi active safety products for automotive manufacturers.), Honda's

Collision Mitigation Brake System (Honda safety - active safety.), and TRW's
Collision Warning System (Adaptive cruise control.) fall in this category.


Figure 3: Collision Mitigation Brake System (CMBS) (Honda safety - active safety.)

Electronic Stability Program (ESP) was originally developed by Bosch (BOSCH, 2000; Society for Automotive Engineers, 1999) as a promising system to mitigate roadway departures and rollover accidents. Based on ABS and traction control, the system identifies differences in wheel spin during road curve driving and brakes each wheel as necessary in order to maximise friction (the original ESP braked the front in- or outside wheel only, depending whether the tendency is towards under- or oversteering). Significant evolution followed, names and specification changed slightly (Electronic Stability Control, Vehicle Stability Control, Dynamic Stability Control and Vehicle Dynamics Control, to name few) but the notion behind the system remained the same; maximise friction by controlling wheel spin.

Lane Change Support systems aim to assist the driver in controlling lateral position of the vehicle and completing the typical task of lane changing. They support the driver and assist in preventing unintentional lane departures. Utilizing a forward-looking video camera that continuously monitors the
vehicle's lane (figure 4) the system can determine whether or not a driver is unintentionally drifting from their lane or the road. If the driver unintentionally begins to wander out of their lane, the system alerts the driver visually, audibly or by vibrating the steering wheel-specifications vary by manufacturer. When integrated with Electrically Powered Steering, some specifications of the system are also capable of providing a light steering input, helping the driver keep the vehicle within its lane.


Figure 4: TRW Guide System (Adaptive cruise control.)

Emergency Brake Assist (Breuer, Faulhaber, Frank, \& Gleissner, 2007) supports the drivers who do not apply brakes vigorously enough in an emergency situation. The function of the system is presented in figure 5. Based on findings regarding the inability of most drivers to use the full potential of the vehicle brakes (Kiesewitter, Klinkner, Reichelt, \& Steiner, 1997) the system applies full brakes when quick brake reaction by the driver is detected. The system uses pedal application speed as an indicator of emergency situations. If an unusually high pedal speed is detected, the system infers an emergency situation and applies full brakes, rather than the
typically limited braking force applied via the brake pedal. Wheel lock is prevented through ABS and the system function is terminated as soon as the driver lifts their foot off the brake pedal.


Figure 5: the general function of Emergency Brake Assist

Apart from the above basic system categories there is a huge pool of ideas and applications coming from the automotive industry as well as academia. Building on the systems described above and some other components system developers suggest new integrated systems that combine active and passive safety elements. Figure 6 presents the components of the Active Passive Integration Approach (APIA) by Continental (Continental automotive systems -APIA: Active passive integration approach.). A similar integration is being developed by Bosch aiming at predicting an accident based on driver behaviour and vehicle factors (BoschLive.). Of course, each one of the systems comes with a series of
ergonomics issues to be addressed. The introduction of automation and the transfer of control away from the driver is an issue identified across the spectrum, as happens with automation in other domains (Dixon \& Wickens, 2006; Gao, Lee, \& Zhang, 2006; J. D. Lee \& Moray, 1994; Miller \& Parasuraman, 2007; R. Parasuraman \& Mouloua, 1996; Riley, 1996; Rovira, McGarry, \& Parasuraman, 2007), however possible problems with each system need to be addressed separately and in depth.

Figure 6 shows an additional characteristic of many modern active safety systems; they consist of previous systems or share elements with previous systems. For example, the APIA system by Continental includes Adaptive Cruise Control, Electronic Brake System (as an EBA system would have) and Electronically Controlled Steering (as a Lane Departure Warning/Avoidance system would have). Marketing and sales pressure has possibly led to the regular bombardment of the vehicle market with new acronyms, without necessarily corresponding to new technologies. There are exceptions of course, when a new acronym is the name of a system with new functions and offers a new accident mitigation opportunity. Such was probably the ABS when first introduced and the early Collision Warning systems. The majority of systems however, probably follow the example of APIA. This approach is not necessarily wrong or disapproved. On contrary, practice indicates this is the safest method to come around accident mitigation through technology. The next section describes some of the system groups and the prominent ergonomics issues associated to them.


Figure 6: The APIA system (Continental automotive systems -APIA: Active passive integration approach.)

## Driver support and automation



Figure 7: The topology of common active safety systems in relation to automation level and type of control

Automation and human-machine allocation of function has been a concern since the post World War II era and the formalisation of human factors/ergonomics as a discipline (Fitts \& Posner, 1967). Initially a concern in high-hazard (nuclear/chemical) industry and aviation (R. Parasuraman \& Mouloua, 1996), automation became noticeable in automobiles relatively recently with the introduction of systems like those described in the previous section. On one hand automating aspects of driving is seen as a beneficial development that relieves the driver of certain tasks and thus decreases his/her workload (Walker, Stanton, \& Young, 2001), on the other hand it transforms driving into a monotonous monitoring task. Furthermore, the human-machine system performance is threatened by the additional operator workload imposed by the deliberation whether and when to use automation
(R. Parasuraman \& Riley, 1997), by overreliance on automation (J. D. Lee \& Moray, 1994), or even by mental "underload", if the task-demand falls occasionally (M. S. Young \& Stanton, 2002).

All active safety systems introduce some sort of automation in the vehicle. Figure 7 indicates the position of the systems presented in the previous section relative to their level of automation and the type of vehicle control they refer to. Thus, Lane Change Support (LCS) refers more to a lateral control task and introduces a high level of automation in the task, as it tends to be combined with force feedback or small inputs from the steering wheel. The system does not acquire complete control, but contributes to "correct" steering, when a lane deviation is sensed. Electronic Stability Program or Control (ESP/ESC) controls wheel-spinning of individual wheels when understeer or oversteer of the vehicle is identified. It does not intervene directly to the basic control task (steering and braking/accelerating) and does not assume any type of control over the vehicle. For this reason the level of automation introduced is relatively low. ESP aims at lateral control during curve negotiation; however, its intervention is on a longitudinal control parameter (i.e. individual wheel speed). Therefore, although basically a system pertinent to lateral control, it has some association with longitudinal control as well. Adaptive Cruise Control (ACC) on the other hand is almost an exclusive longitudinal control system. It introduces very high levels of automation, as it acquires control of headway and stopping before obstacles, the major parts of longitudinal control. This fact has raised significant concerns, analogous to those encountered in other domains high automation entered (J. D. Lee \& See, 2004; Lees \& Lee, 2007; Rajaonah, Anceaux, \&

Vienne, 2006). Still though, probably because of the litigation issues caused otherwise, ACC is marketed as a "comfort" system rather than a "safety" system, as the manufacturers do not want to assume responsibility for the proportion of control that corresponds to the system. Therefore, the benefits of the system could be limited in practice by the issues quoted above (transfer of workload into monitoring tasks, complacency on automation and underload). Emergency Brake Assist (EBA) or just Brake Assist is also predominantly a longitudinal control system. Its function is directly effective on braking and thus on longitudinal control. In practice of course, it can be also associated with longitudinal control, as its "augmented braking" effect is accompanied by ABS when an emergency stop takes place. Thus, it enhances steering control during the event. Introduced automation is relatively low, as the system is probably rarely activated and mainly acts as additive force to certain driver reaction, rather than automatic control with limited contribution of the driver. Therefore, it is acts as a "support" rather than as an "automatic control" system.

As braking/accelerating is longitudinal control it is easy to see its importance in the (effective) operation and function of active safety systems that are closer to longitudinal control on the $x$ axis in figure 7. However, as braking affects speed control, which is so central to driver safety (Summala, 1996), then braking has indirect effect on the other types of active safety systems. Thus, the next chapter is dedicated on its study so far.

## Summary

Chapter 1 acted as the introduction to the theme of the Thesis. The title was analysed to its three key elements: ergonomics, intelligent systems and vehicle braking. Then, the real-world context and the relative epidemic against which vehicle systems should be effective was described. Global roadaccident statistics were presented and the predominant type and consequences of accidents in terms of frequency, loss of life, and monetary cost were briefly discussed.

Then, contemporary counter-accident/active safety technologies were presented. The general characteristics of each family of active-safety systems were described (headway-control, stability-control, lane-change support, and augmented braking). Example instantiations of each type were presented and then positioned on Cartesian plane, with respect to the level of automation each induces and their pertinence to either lateral or longitudinal vehicle control. Thus, a theoretical link was created between systems and the type of accidents and failures they refer to.

## Chapter 2: Literature review

This chapter describes both general and braking-specific driver models before moving on to detailed description of previous studies of driver-braking and implications for assistive technology. It is expected that the driver models will help the reader understand the general framework of driver ergonomics, before the braking-specific studies provide an image of the current status of directly relevant research. Following a particular stream of research in the area, the research questions for this Thesis are set out at the end of this chapter and challenged in the chapters that follow.

## A description of the general driver models

Research and observation in the field of driving has produced a series of characteristics commonly found during performance of the task; those efforts contributed or explicitly suggested three models describing the driving task. On a theoretical level, driving has been suggested as "threat-avoidance" and control of speed and direction through the "safe field of travel". On a more practical level, literature has pointed out a time-based description of the driving task, where both longitudinal and lateral control is controlled by relative distances to possible obstacles in the road environment. Finally, models of driving as a multi-level control task provided a more holistic and integrated view of the task. The main literature behind those models is presented in the following section.

## Driving as "threat-avoidance"

Possibly the earliest attempt to introduce a theoretical model of the driving task is sourced in the work of Gibson and Crooks (1938). In their model drivers adjust their speed and direction avoiding hazards and moving towards their destination. The roadway and other vehicles define the field of safe travel - the total of unimpeded paths that the vehicle can take (Gibson \& Crooks, 1938). The driver adjusts the steering wheel in order to maintain a course relatively on the central line of the safe path, however any trajectory within the safe field is possible, as long as it is satisfactorily safe (figure 8).


Figure 8: Examples of the safe field of travel (adapted from Gibson \& Crooks, 1938)

Speed is also influenced by the field of safe travel. The distance required to stop the vehicle and driver's intention to decelerate is defined by the minimum stopping distance. As the stopping zone approaches the end of the
safe field of travel, the drivers decelerate proportionally. The ratio of depth of the field of safe travel to the minimum stopping zone defines the index of cautiousness. Smaller safety margins are accepted, thus the index decreases, when drivers are in a hurry.

The field theoretic description of driving suggests driving as an interaction between perceptual cues and vehicle dynamics for avoiding obstacles while moving toward a destination, while location and direction of other vehicles influence the field of safe travel. Thus the theory underlines some important characteristics of driver behaviour (J. D. Lee, 2006):

- Driver and vehicle characteristics cannot be considered separately. Drivers adapt to improved vehicle characteristics by increasing speed and closer following distances. This hints of the risk homeostasis theory that appeared many years later (Wilde, 1986; Wilde, 1989).
- Adverse weather, traffic or sharp curves are dangerous only to the extent to which they lead drivers to misperceive a field of safe travel or minimum stopping zone. Roadway conditions can jeopardise safety only if the driver fails to perceive and adjust to them.


## Time-based models

The field theory of driving implies that drivers are continuously monitoring the roadway. However we now know that people in vehicles engage in a range of activities related or unrelated to the driving task (Neale, Dingus, Klauer, Sedweeks, \& Goodman, 2005). People adjust and listen to radio, talk on the phone, eat, drink, talk to other passengers and interact with navigation and computer devices. A series of experiments and a mathematical model
sought to quantify this phenomenon (Senders, Kristofferson, Levison, Dietrich, \& Ward, 1967). This was the start of a trend to describe the driving task or parts of it using time-related measures. Two measures that arose in the late 70s/early 80s aspired to describe the driving task based on measurable time criteria: Time to Lane Crossing (TLC) and Time To Collision (TTC). TLC provides a direct estimate of the amount of time the driver has available before crossing the lane or the roadway limits (Godthelp, Milgram, \& Blaauw, 1984). It is calculated by dividing the distance to the lane boundary by the lateral velocity of the vehicle. Relatively recently, the element of road curvature has been also added in the calculation (W. van Winsum, Brookhuis, \& de Waard, 2000). Time-To-Collision (TTC) and Time-Headway are the most basic measures of longitudinal control. Both measures seem to be shaping factors of driving behaviour in the car-following context. TTC is the distance between the vehicles divided by the relative velocity of the vehicles. Timeheadway is the distance between the vehicles divided by the velocity of the following vehicle only and essentially it represents the time available for the following driver to respond to the deceleration of the leading vehicle - officially the time available for the following vehicle to match the acceleration (usually negative values matter) of the leading vehicle. Evidence is available that drivers' preferred time headway is independent of speed and distance (W. van Winsum \& Heino, 1996; W. van Winsum \& Brouwer, 1997). The authors of these studies suggest some numerical formulae which are supported as an estimate of the tendency by the data presented, however of high importance is the qualitative result that time headway is the safety margin that controls driver's following behaviour. Furthermore, although individual differences and
preferences are significant, experimental evidence is available that suggests that preferred time-headway is correlated with the driver's skill to transform visual information to an action in driving - reaction skills in effect $(\mathrm{W}$. van Winsum, 1998). Preferred time-headway is not only defined by individual skills, but also by the driver state and visual conditions (W. van Winsum, 1999). Van der Hulst (van der Hulst, 1999) demonstrated that fatigue leads to increased headways. Another experiment by Van der Hulst (van der Hulst, 1999), suggests that drivers adopted longer headways as result of a foggy environment. This was not the case with drivers in a hurry - leading back to the important issue of driver motivation. TTC on the other hand, guides the response to dangerous situations by triggering and modulating braking behaviour (W. van Winsum \& Godthelp, 1996).

Another, slightly different time-related parameter in driving control is Tau ( $\tau$ ), proposed by Prof Lee from Edinburgh University (Lee, D. N., 1976)). Lee argued that the time a driver applies brakes to control a vehicle is affected by the perceived visual information they have about the vehicle's TTC to the lead vehicle. His theory was expanded to the control of locomotion outside the driving setting (Lee, D.N., 2004). Lee suggested a mathematical description of how drivers control the timing of their braking inputs based on TTC change and he named it tau. Tau is a temporal variable that represents the time-toclosure of a motion-gap at its current closure rate (Lee, D.N., 2004). In the driving setting, tau is the perceived TTC according to the information provided by the visual field of the driver. Tau is perceived directly from the changing visual properties of the stimulus, more specifically the ratio between image size and its rate of change. In simple words, the rate by which the size of the
back of the car in front is changing in the driver's retina affects the time they will apply brakes during approach. Similar vision-based descriptions of driving control have been suggested on steering (Land \& Lee, D. N., 1994).


Figure 9: Graphic illustration of the time-based driving model

The time-measures quoted above are commonly employed as measures driving performance and behaviour. Time-headway for example, is measured as an indication of risk-taking behaviour (e.g. Fuller, 1981; Heino et al., 1996) and TLC as an indication of driving performance and lateral control (e.g. Gkikas \& Richardson, 2007). In parallel, the relevant literature behind those measures provided the parts of a synthetic model to describe the driving task
(figure 9). Using the observed patterns with regards to the annotated driving measures, driving can be described as a control-task regulated by time-based variables. Thus, drivers drive to their destination while engaging the necessary steering and braking to retain between $2.5-5$ s headway to the lead vehicle, TTC above 1.5 s and TLC above 3 s ,

Nevertheless, because of the generalisation of driving in the developed world and the volume of traffic on the roads, instances outside the time-limits in the model above are not uncommon in practice. Although the time-based description describes the driving reality for the majority of drivers during the majority of circumstances, it is limited to such cases only, and ignores cases outside those borders. Concurrently, it is a rather superficial model for driving, as it is confined to a descriptive level of driving based on a handful of variables and fails to examine underlying explanations/justifications for the observed control-behaviour of the drivers. This is an issue another league of driving literature attempted to address: the multi-level control approach to the driving task.

## Driving as multi-level control task

Parallel to the development of time-based descriptions of the driving task and driver behaviour, another stream of research focussed on driving as a multi-level control task. Allen, Lunenfeld and Alexander (1971) used a taskanalysis method originally developed in the military domain to analyse the driving task. Data was obtained through verbal observations during one long (interstate, US) trip and several short trips in urban roads. The result was 1,000 feet of tape-recorded material. The analysis and categorisation of the
data into subtasks supported the development of the driving model in figure 9 (Allen, Lunenfeld, \& Alexander, 1971).


Figure 10: A description of the driving task (adapted from Allen et al., 1971)

When driving, the driver performs a series of subtasks. These subtasks are interrelated and a hierarchy can be developed according to the time scale and the level of cognitive activity of the driver. Some tasks, like steering, are performed within fractions of a second, while others, like journey route decision-making, might take hours to complete. In addition, the cognitive activity required to perform an over-learned task such as turning the steering wheel is minimal compared to the task of route finding which requires mental processes in terms of abstract symbols, maps and language. The "microperformance" part of driving in figure 10 corresponds to driving at a detailed level, basic control tasks like steering, changing gears, accelerating, decelerating/braking etc. The "macroperformance" part corresponds to tasks
at a highly cognitive level, like navigational decisions, which are on the high end of the hierarchy. The remaining subtasks in between have to do with responses/adaptation to roadway and traffic situations and are defined as "situational performance". Tasks on a lower level of the scale are part of tasks on a higher level. For example, steering is necessary in order to navigate to the desired destination and speed choice is instantiated though the amount of acceleration (both positive and negative) the drivers utilise.

The model has another dimension: primacy. Objectively tasks in the lower levels of the scale are more important for the safety of the journey, and therefore when there is a perturbation there, tasks on a higher level can be suspended or cancelled in order to devote mental resources to the critical tasks. For example, when there is a puncture in one of the tyres, the driver is expected to stop considering which route is the fastest and focus on the basic steering/decelerating control tasks, in order to pull over safely and change the wheel. Primacy is also subjective; the driver can choose where to focus attention and does not necessarily focus his/her mental resources where expected.

Contemporarily with Allen, Lunenfeld and Alexander, another team of researchers focussed on the control level of the driving task ("microperformance" according to Allen et al., 1971). Influenced by the models of aircraft manual control, Weir and McRuer (1970) attempted to quantify driver steering. To achieve this, they modelled steering as part of a closedloop control structure. Figure 11 presents the layout of the system. It depicts how the driver interacts with the vehicle and how the driver/vehicle system interacts with the roadway. The controlled element consists of the vehicle
dynamics, the steering system and the geometry of the visual field from which the driver extracts information for guidance and control. The roadway environment provides inputs both in terms of commands to be followed as well as disturbances to be avoided. The key elements in the system are the two "Quasilinear Compensatory Control" blocks. This is because all feedback loops from vehicle movement end here and thus these are the factors of steering wheel angle that change continuously. This means that steering is a continuous compensatory task, where drivers compensate to any disturbances of their desired path through steering wheel movements. The researchers went on quantifying the relationship between driver-steering and vehicle lateral-control parameters like heading angle (Weir \& Mcruer, 1973).


Figure 11: Steering as a closed-loop control system (adapted from Weir \& Mcruer, 1970)

The multi-level performance model was adopted, developed (Hale, Stoop, \& Hommels, 1990; Michon, 1985; Michon, 1993; Summala, 1996) and
adapted to explain specific facets of interaction with technology (J. D. Lee \& Strayer, 2004; J. D. Lee, 2006). Michon $(1985 ; 1993)$ renamed microperformance, situational performance and macroperformance into "operational", "tactical" and "strategic" control level. Hale et al. (1990) positioned Rasmussen's (Rasmussen, 1983) skill-rule-knowledge framework against Michon's control hierarchy (table 3). Although for most drivers in most cases strategic, tactical and operational control correspond to knowledge, rule and skill- based behaviour, there are instances where this is not the case (i.e. novice drivers, or unfamiliarity/exceptional familiarity with the route). A firsttime driver might have to adapt knowledge-based behaviour in order to shift gears and even an experienced driver might have to adapt rule-based behaviour temporarily when driving a new vehicle for the first time.

Table 3: Michon's control classification against Rasmussen's skill-rule-knowledge behaviour model (adapted from Hale et al., 1990)

|  | Strategic | Tactical | Operational |
| :--- | :--- | :--- | :--- |
| Knowledge | Navigating in <br> unfamiliar area | Controlling skid | Novice on first <br> lesson |
| Rule | Choice between <br> familiar routes | Overtaking other <br> vehicles | Driving unfamiliar <br> vehicle |
| Skill | Route used for <br> daily commute | Negotiating <br> familiar <br> intersection | Vehicle handling <br> on curves |

Summala (1996) expanded the three-level model in order to explain behavioural adaptation and risk homeostasis (Wilde, 1988; Wilde, 1989) on
driving safety. To achieve this, he added two more dimensions of driving as a complete human behaviour. The result is the driver task cube (figure 12). The model was originally developed as a driver-based accident-causation model. The functional hierarchy corresponds to Michon's control model (1993) and Allen's (1972) three-level performance description of driving. The functional taxonomy consists of the major categories of continuous lane and headway control, control of conflicting flows at crossings and specific manoeuvres such as lane changing and overtaking, based on the taxonomy by McKnight \& Adams (1972). The third dimension (level of psychological processing) is closely associated with Rasmussen's framework (1983), however directly applied to the driving setting. It focuses on the distinction between the automated motor control and the conscious decision-making and monitoring element of driving, while attention control is in between. Attention control is sometimes closer to conscious processes (e.g. when a driver chooses to pay attention to sports news on radio while driving) and other times it is more of a semi-automatic response to a stimulus (e.g. when a driver shifts attention back on the road when a sudden storm starts).

Speed control is underlined as the central task (Summala, 1996). Speed and time control determine mobility, the basic goal in transportation. Increased speed capability enlarges the area of reach and this affects trip decisions. Trip decisions themselves together with driving costs and speed limits set the approximated desired speed level (Summala, 1989). The desired speed determines lower-level decisions like overtaking.


Figure 12: The Driver Task Cube (Summala, 1996)

With the introduction of multiple in-vehicle information/communication devices, there was a shift towards models that explain/predict possible effects on the driving task and driving safety. Such models can be found in J. D. Lee \& Strayer (2004); J. D. Lee (2006); Sheridan (2004). Figure 13 shows three levels of control while interacting with a telematics device like a navigation system or a cell phone (J. D. Lee \& Strayer, 2004). The top section describes driving in terms of strategic behaviour, where driving and in-vehicle activities occur at a very molar level with a time scale of minutes to days. Tactical behaviour describes driving and in-vehicle activities at a finer level, with a time scale of 5-60 seconds. At the bottom of the figure, operational behaviour describes the micro-level activity with a time scale of 0.5 to 5 seconds. The conceptual model described in the figure captures several critical elements that govern driving safety (Lee, 2006):

- It shows that failures of control at any of the several levels can compromise safety.
- Behaviour at the higher levels imposes performance requirements on the lower levels.
- It shows that the parallel demands of driving and non driving tasks compete for driver's attention.
- It demonstrates that these demands evolve and that drivers adapt to these demands with time constants ranging from seconds to days. This means that the drivers can always compensate for limits at one level by adapting at another.


Figure 13: Driving as multi-level control task that is shared between the main task and other in-vehicle tasks (adapted from J. D. Lee \& Strayer, 2004)

Most of the presented models have been criticised for too much focus on accidents and safety (Ranney, 1994). As accidents are rather rare occurrence, driving models should explain facets of driving, other than safe (and unsafe) driving. Nevertheless, the reality remains that safety is of
paramount importance to driving. Without safety, every other goal of driving is at risk. To arrive quickly, first one needs to arrive...

Where does braking control fit in all this?
All the models described so far include, a basic vehicle control element, which in turn consists of longitudinal and lateral control. In Gibson and Cooks (1938), drivers "adjust speed" and "direction" in order to reach their destination "avoiding hazards and obstacles". The time-related measures are essentially vehicle control-related measures. TLC is a measure of lateral control and TTC and time-headway refer to longitudinal control. "Microperformance" (Allen et al., 1971) is vehicle (longitudinal and lateral) control. Weir and McRuer's work (1970) on steering is basically a study of driver/vehicle lateral control. Then, Michon (1985) explicitly suggests a basic control level of driving and so does Summala (1996). Furthermore, the "driving task cube" includes the functions of headway and lane control in its "Functional Taxonomy" (figure 12).


Figure 14: Basic vehicle control

In line with the aforementioned distinction between lateral and longitudinal control, figure 14 presents the components of basic vehicle control. Lateral control is instantiated through steering and longitudinal control is instantiated through acceleration. Acceleration can be both positive and negative. The typical vehicle control instruments are the steering wheel for lateral control and the pedals (+ the gearshift for manually transmissioned vehicles) for longitudinal control. Focussing on longitudinal control, as illustrated on figure 15, positive acceleration is initiated by the depression of the throttle-pedal while negative acceleration commences by the depression of brake pedal in principle. In practice however, negative acceleration is initiated by the release of the throttle and/or the change of gear as well. It is not uncommon that people refer only to the depression of the brake pedal when using the term "braking", however literally brake is "an apparatus for retarding the motion of a wheel" (Oxford english dictionary brake, n.7.) and
thus "braking" could be identified with any control-reaction of the driver that results in negative deceleration of the vehicle; be it brake pedal depression, throttle pedal release or gearing down. There are two objectives of driver braking; brake to decelerate (before a corner, adjusting headway etc.) and brake to stop (and avoid collision with a stationary object). The existence of the former is supported by Gibson and Crook's model (drivers decelerate proportionally) and the distinction with the latter (brake to stop) is backed by previous studies described in the next section and will be challenged by the original studies described in the later chapters of this thesis.


Figure 15: Longitudinal vehicle control in practice

## Braking-specific studies

In this section, the main studies where driver braking was examined in some detail are presented. The review of driver-braking studies is split between studies that examined the timing of the braking input in relation to other driving variables (e.g. headway to the lead vehicle or type of warning)
and a second group examining the quantifiable characteristics of the braking input itself. Both groups are described in detail before further attention is paid to the "braking-input" studies. The latter will lead to the development of the main research questions of the Thesis, before the following chapter explores the methods that can be employed to address them.

## Focus on the timing of braking

Literature on and the timing of braking has been rich since the early ' 90 s.
Two factors contributed to this trend: first, the development of time-based descriptions about driving as described in the previous chapter (Godthelp et al., 1984; Godthelp, 1986; Senders et al., 1967). Within this framework, driving control can be described in terms of Time to Lane Crossing (lateral control) and Time to Collision (longitudinal control). Second, the various sensors necessary were integrated into collision avoidance or cruise control systems and by 1993 "Full systems for autonomous intelligent cruise control" were expected (Emberger, 1993). Such systems needed data about the "natural" timing of driver braking for their successful HMI (Human-Machine Interface) specification.

Among other publications that addressed timing of braking, two Doctoral Theses examined the phenomenon in detail. Van der Horst (1990) used TTC and related measures to describe road user behaviour in normal and critical encounters. Through the use of video recorders close to signalised road junctions and grade railway junctions, he estimated and compared the relative time-measures (Time To Intersection predominantly) of drivers. With regards to braking, the author concludes that TTC values below 1.5 s rarely do appear
and the average in all intersections was about 2.5 s . Furthermore, in the penultimate chapter of that thesis, an experimental study was presented where participants were asked to drive towards a stationary object and either brake hard at the latest moment they thought possible to stop or brake normally at the latest point they thought they could stop in front of the object. Testing at $30 \mathrm{kmh}, 50 \mathrm{kmh}$ and 70 kmh indicated that speed had an effect on the time of the onset of braking after both normal and hard-braking instructions although considerable differences among subjects were found. Achieved vehicle decelerations ranged from 3.5 to $5 \mathrm{~ms}^{-2}$ for normal braking and between 5.5 and $7 \mathrm{~ms}^{-2}$ for hard braking instances. The respective values for minimum TTC ranged approximately from 2.5 s to 1 s for normal and between 2 s and 1 s for hard braking. Although this was not the main purpose of that thesis, the studies support a minimum TTC of 1.1 s acceptable and a desirable TTC $_{\text {min }}$ of about 1.5 s for the specification of Adaptive Cruise Control (ACC) systems. Most importantly - and this was within the purpose of that thesis - they established measurable/quantitative differences between normal and critical encounters. This was accomplished through the use of timerelated measures of vehicle behaviour.

Gap acceptance and adaptive control of safety margins was the explicit topic of another thesis (van der Hulst, 1999). In the fourth chapter of van der Hulst's thesis, a study is presented where time-headway was measured during driving on a simulated rural roadway with opposite coming traffic. Twenty participants' car-following behaviour and reaction to expected and unexpected deceleration of the lead vehicle were tested. The lead vehicle had a constant speed of 80 kmh , except during the decelerating phase, when the
speed would drop at a rate of either $1 \mathrm{~ms}^{-2}$ (slow) or $2 \mathrm{~ms}^{-2}$ (fast) down to 60 kmh for 3 seconds. Taking time-headways over 5 s out of the calculation, average time-headway during driving was 2.6 s . At the onset of lead vehicle's deceleration mean time-headway was almost 3s for fast-expected, 2.7s for slow-expected, 2.4 s for both fast and slow-expected deceleration. Mean reaction times ranged between 3.5 s for expected-fast deceleration and 6.2 s for the unexpected slow deceleration scenario.

The fifth chapter of van der Hulst's thesis examines time-headway in reduced-visibility conditions based on two experimental studies. The same driving simulator was used (Van Wolffelaar \& Van Winsum, 1992) to test the hypotheses that (a) drivers choose a longer time-headway at lower speeds, (b) adaptation of time-headway is smaller, when time-pressure is also present, (c) and lead vehicle deceleration results in more conflicts (as per van der Horst, 1990) in the foggy condition compared to the clear-visibility condition. Twenty-four participants completed the two studies, although 4 participants were excluded from the analysis of the first study due to their "extremely safe" driving (very low speed/long headways). Results indicated that during steady-state driving, time-headway is longer and during the deceleration of the lead vehicle, the minimum time-headway is significantly longer under foggy than under clear conditions. The second experiment indicated reduced speed behaviour and longer time-headways in foggy conditions, while the introduction of time-pressure increased speed under clear visibility but not under foggy conditions. Regarding the last hypothesis (d), results indicated that drivers compensated for the limited visibility under
foggy conditions by driving slower and increasing the safety margin. Thus, contrary to the hypothesis, less conflicts (TTC<1.5s) took place.

The penultimate chapter of the thesis is based on a study on prolonged driving and collision-avoidance performance. Again, the same simulator was used (Van Wolffelaar \& Van Winsum, 1992) and twenty-four drivers participated. Car-following behaviour was measured in two 30-minute rides, with a route-memorisation experiment in-between. This involved the memorisation of complex routes while driving through built-up areas and lasted an hour and fifteen minutes approximately. Again, time-pressure was introduced to one group of participants while another factor was visibility (clear/fog). Results did not confirm the hypothesis that prolonged task execution results in longer headway. Again though, time-pressure resulted in shorter time-headway, higher speed and lower minimum TTC irrespective to the visibility conditions.

Van Winsum and Heino (1996) were the first to combine the study of carfollowing with that of detailed driver braking. The study examined drivers' preferred headway and its relation to brake reaction-time, braking intensity and quality of braking control. Braking intensity was indicated by percentage of brake pressure. The harder the drivers braked, the greater percentage of the brake system's pressure capabilities they employed. Quality of brake control was indicated by the absolute time interval between the instant of maximum vehicle deceleration and the instant TTC is minimum. Effectively this is the time it took the drivers to achieve maximum vehicle deceleration since the moment they got "closest" to the lead vehicle. Experiments were carried out in the same driving simulator as van der Hulst's studies (Van

Wolffelaar \& Van Winsum, 1992). Participants were asked to drive "safe" but reach the leading vehicle as soon as possible abiding to the 80 kmh limit. The protocol included a 10-minute familiarisation pre-session. In the first part, lead vehicles had a constant velocity of $40,50,60$ or 70 kmh . Vehicles merged in front of the participant's car and controlled their speed so that they were 100 m in front of the participant's car every time he was 50 m from an intersection. In the second part of the study, vehicles merged in front of the participant and held speeds of 60 kmh or 50 kmh . When headway was 50 m , the lead vehicle would decelerate at a rate of $2 \mathrm{~ms}^{-2}$ to 40 kmh or 30 kmh respectively ( -20 kmh ). 54 male driver with an average age of 29 years participated in the study. Four of them failed to reach a stable speed at the 70 kmh condition and further two of them failed to display a clear braking response in the two braking conditions. Results suggested that preferred time-headway remains constant over different speeds per individual, while individuals differ on their preference in time-headway.

The studies described so far, shaped the human element of car-following and (safe) headway keeping. Van der Horst (1990) suggested an average TTC of 2.5 s in car following and a desirable TTC $_{\min }$ of 1.5 s . He also distinguished normal and hard braking quantitatively; achieved vehicle decelerations were between 3.5 and $5 \mathrm{~ms}^{-2}$ for the former and between 5.5 and $7 \mathrm{~ms}^{-2}$ for the latter group. Regarding time-headway during car-following, van der Hulst (1999) suggests a 2.6 s as typical value. Van Winsum and Heino (1996) suggested that preferred time-headway is constant over different speeds per individual. At the same time, there are individual differences to deal with. Last but not least, there is behavioural adaptation to
be taken into account, both at adopted time-headways as well as at brake reaction times and braking intensity (van Winsum \& Brouwer, 1998). These parameters set the ergonomics basis for any type of longitudinal control support; however, the introduction of support systems may change the previously observed patterns in timing of driver braking. Another major study addressed this issue within the context of the "complex issues surrounding the appropriate design of headway maintenance and rear-end collision warning systems" (Dingus et al., 1997).

Dingus et al. (1997) carried out three on-road studies; the first study concentrated on the naïve user and the design of an appropriate collision avoidance system. The second experiment compared the relative merit of different display modalities (visual-auditory) for collision warning. The third experiment explored the effects of false alarms on driver behaviour and trust in automation. The instrumented vehicle used was equipped an infrared laser range finder system that detected the car in-front and calculated the headway.

Fifty-four male and fifty-four female drivers participated in the first study. They were told they were performing a marketing assessment of a prototype information-system and asked to follow another (confederate) vehicle on a 40 km rural and residential route. The confederate driver was instructed to avoid any abrupt braking for safety purposes. The lead vehicle was described to the participants as another participant testing a new navigational system. During each trial, one of the following displays was fitted on the dashboard: a car icon display, a bars display or a blinking blocks display. The first two (figures 16,17 ) included grades of criticality while the third (figure 18) one provided only imminent warning information. Maximum, minimum and
average time-headway were the variables of interest. Results indicated that both the car icon and the bar display resulted in longer maximum timeheadway and the bar icon display had the edge over the other two in the mean time-headway criterion by 0.4 s . Also, with bars and icons display the frequency of instances when time-headway was below 2 s was significantly lower. Overall the results supported superiority of graded warnings and headway information in supporting driver headway maintenance.


Figure 16: The car icon display. Adapted from Dingus et al. (1997)


Figure 17: The Bars display. Adapted from Dingus et al. (1997)


Figure 18: The blinking blocks display. Adapted from Dingus et al. (1997)

The second study aimed to compare different modalities of collisionwarning display. Sixteen young (aged 18-24) drivers participated in the study
and drove the instrumented vehicle equipped with visual only, visual/auditory combination or auditory only warning. Results indicated that the combined visual/auditory warning led to longer headways. Results were congruent both during coupling with another vehicle and during braking events. The final experiment tested the effect of false alarms on forty participants. The collision warning was the combination of visual bars (figure19) with an auditory warning. Four false-alarm rates were compared to each other and to a baseline no-warning condition. Results suggested that younger drivers drove closer to the lead vehicle; however with the introduction of false alarms they increased their headway more than the older drivers - up to the 60\% falsealarm rate. After that point their trust in the system fell dramatically. The authors concluded that overall results indicate a beneficial effect of collision warning devices in headway maintenance. This conclusion has been supported by additional studies (Shinar \& Schechtman, 2002).

Driver's trust in automation - as the Dingus et al (1997) study indicated is one of the key issues in the effectiveness of headway -support/collisionavoidance systems. Another doctoral thesis attempted to tackle this issue (Abe, 2005). That thesis includes five original simulator-studies on drivers' trust in collision warning systems. Three of these investigated the relationship between alarm timing and driver performance in a range of driving conditions. Results indicated that an early alarm-timing leads to quick brake reaction-time and higher level of trust, while a late alarm-timing can delay braking response when driving with long time-headway. The fourth study examined the nature of trust in forward collision warning systems (FCWS). The effect of false and missing alarms was tested and it was found that trust has two separate
aspects; one related to individual alarms and another related to system integrity. The former was correlated to false alarms, the latter to missing alarms. The final study suggested that previous exposure to early alarmtiming resulted to negative driver-reactions during alarm failures. This was not the case with drivers exposed to late alarm-timing.

As reported in the previous chapter, the motor industry has already developed fully-automated headway-control systems named after various acronyms. Although research on ergonomic issues must have started earlier (at least by the system developers), it is only recently that system-specific research was published (Hoedemaeker \& Brookhuis, 1998; Pauwelussen \& Minderhoud, 2008; Rudin-Brown \& Parker, 2004; M. S. Young \& Stanton, 2007) with Adaptive Cruise Control (ACC under the limelight). The major issue examined was behavioural adaptation to the system, due to its strong automation element.

Hoedemaeker and Brookhuis (1998) used a driving simulator to explore this issue. Twenty-five male and thirteen female participants, aged between 25 and 60 years completed a Driver Style Questionnaire (DSQ; West, Elander, \& French, 1992). Accordingly, they were split in groups based on two driving style dimensions (Speed and Focus). The virtual ACC system tested was configured to 1 s time-headway, 1.5 s time-headway or the preferred headway selected by the driver. Also, two versions of the system were tested: one which the driver could overrule by pressing either the throttle or brakepedal, and one which they could not overrule. In both versions the ACC system was always able to stop the vehicle avoiding any collision without the intervention of the driver. Thus, system failure was not examined in this study.

Results suggested that although acceptance of the system was generally satisfactory, fast drivers rated significantly lower. Furthermore, low-speed drivers performed significantly higher maximum brake effort when an emergency stop was required. Generally, participants experienced less workload when driving with ACC rather than driving without it and particularly the overrule-able version was preferred by most participants. However the encouraging results, authors stressed the fact that the system might not have the expected benefits in practice. Drivers in the study tended to drive more frequently on the fast lane and weave from one lane to the other. Also, shortfollowing occurred more frequently when the system was engaged.

Hoedemaeker and Brookhuis' (1998) concerns are shared by another two researchers who examined behavioural adaptation to ACC, using a testtrack study instead (Rudin-Brown \& Parker, 2004). Eighteen experienced drivers drove an instrumented vehicle following another vehicle in a closed road track. The experimental design included three conditions: no ACC (2s target time-headway), ACC short-headway setting (1.4s time-headway), and ACC long-headway setting (2.4s time-headway). Results indicated that participants drove faster with the ACC, and as in the previous study spent more time on the fast lane and weaving than without the system. Also, during the emergency-stop in low-speed scenario, where the ACC's deceleration properties were far exceeded, drivers brake reaction time (BRT) was longer, maximum brake force was higher and the minimum headway shorter. Nevertheless, no matter the issues in the above scenarios, participants rated positively the system for its comfort attributes, a result the authors found encouraging for the market of such systems.

The effect of ACC on brake reaction times was revisited by another study (M. S. Young \& Stanton, 2007). In this study, 20 learner and 24 expert drivers drove a car with ACC in the virtual environment of the Brunel University Driving Simulator. They were asked to follow a lead vehicle and made aware that it would brake periodically. Two conditions were examined; one where ACC was supplemented by Active Steering (keeping the vehicle in the middle of the lane until overruled by driver input) and one where only ACC was active. An automation failure took place short before the end of each trial and drivers' response was measured. Results indicated that BRT is extensively affected by automation (average BRT was 2 s longer than the BRT quoted by Liebermann, Bendavid, Schweitzer, Apter, \& Parush (1995). The authors conclude that it is ironic that the safety benefit of the controlled headway provided by ACC is accompanied by the necessity for increased headways and time, in order to react to emergencies. Furthermore, it is worrying that the common configuration of ACC between 1 and $2 s$ is not enough to satisfy the required reaction times.

Probably the boldest attempt to explore issues with ACC is the Field Operational Trial/Test (FOT) commenced in the Netherlands (Pauwelussen \& Minderhoud, 2008). During the 6-month period of the trial, 19 participants drove an instrumented vehicle equipped with ACC and Lane Departure Warning (LDW). Results indicated a decrease in time-headway during disengagement of the system, similar to the one quoted in the above simulator and test-track studies (Hoedemaeker \& Brookhuis, 1998; RudinBrown \& Parker, 2004). Behaviourally, participants tended to deactivate the system during urban driving and speeds between $20-40 \mathrm{kmh}$. The authors
support that there are two categories of ACC deactivation: the mandatory deactivation, when the situation urges vehicle speed/acceleration out of the system's boundaries. In such case, the system requests the driver to take over. The second category is the discretionary deactivation, when the driver disengages the system temporarily by depressing the throttle of brake pedal. This was associated with lane-changing.

Very recently, Sommer and Engeln (2009) explored effects of automatic braking on driver behaviour. 46 drivers experienced autonomous emergency brake (AEB) activation driving a vehicle on a closed test track. A correct and an incorrect activation of AEB took place while driving on the test track. The correct activation took place when an obstacle was erected during the test drive. The incorrect activation was initiated by the experimenter, while the driver attempted to swerve and avoid another vehicle on the track. Based on the results, the authors claim that they developed two algorithms that recognise driver intent to overrule the system or undertake an emergency brake manoeuvre. If they are as successful as the authors claim, these algorithms could be integrated to ACC and Collision Avoidance systems.

The proposed characteristics of braking with regards to timing
In summary, the Headway Control-related studies presented above suggested the following with regards to the timing of braking:

- Typical time-headway is around 2.6 s and braking inputs occur while trying to maintain the desired headway
- "Normal" braking inputs tend to take place when the TTC approaches 2.5 s and heavier inputs tend to take place when TTC falls to 1.5 s .
- Drivers control their speed (through braking) when approaching an intersection with another vehicle, in order to retain TTI about 2.5 s .
- Visibility is a factor affecting time-headway - drivers tend to increase headway to the lead vehicle, when visibility deteriorates.
- Time-pressure is associated with shorter time-headways under clear weather conditions. This effect is cancelled under poor visibility.
- Drivers adopting shorter time-headways, tend to compensate by means of stronger inputs to the brake pedal.
- Driver-support technology affects the timing of driver braking.
- The use of graded warning by collision warning systems is beneficial both to the timing of braking and the length of the adopted headway.
- Auditory modes have beneficial effects to the timing of driver braking, when used in conjunction with visual modes.
- The timing of the warning itself can have an effect on driver's trust - earlier warnings can cause more distrust than later warnings.
- Headway-control systems, such as ACC, are generally acceptable by drivers; however, the option to override the system through the application of the brake-pedal should be provided.
- Headway-control systems are susceptible to side effects caused by behavioural adaptation; drivers driver faster with the ACC on, and perform longer reaction times.
- Drivers prefer to deactivate ACC when vehicle speed is between 20 and 40 kmh .


## Focus on the braking input itself

Van Winsum and Heino (1996), as described in the previous section, examined the timing of the onset of braking in tandem with the intensity of the braking input itself. The intensity (force, effort applied on the pedal) is one the main characteristics of driver's braking inputs, however not the only one. The input is characterised by the speed of pedal movement, the speed the feet move between pedals etc. A series of studies investigated such variables under various circumstances. Initially, the aim was to define the operational properties of (brake) pedals; however, within the active safety and driversupport framework, the plausibility of identifying the urgency for augmented braking through the aforementioned variables has recently been examined. The general notion is that if enough information is known about the quantifiable properties of driver-braking input, these could be exploited by brake-assist systems that decrease realistic stopping distances. A description of the major relevant studies follows.

Probably the earliest published attempt to quantify driver braking is the work commenced by Eaton and Dittmeier (1970). In a period when "improvements in automotive braking and steering systems generally reflect refinement of mechanical design" (Eaton \& Dittmeier, 1970), the authors
instrumented two vehicles with the means of the time (mainly strain gauges) to measure the effort capabilities of drivers when they operate vehicle controls. Specifically for the brake-effort study, 48 female drivers drove an "intermediate-sized" and a "full-size" sedan in a test track. Both were altered, so that an experimenter could vent the power brake booster and cause a power-assist "failure". As they would drive around performing various manoeuvres, they would have to come to a "dead end" formed by pylonbarrier. They were asked to stop as close to the barrier as possible, after adopting a 35 mph speed. The participant would reverse and continue their lap performing this stop three times before the experimenter would activate the recorder and deactivate the brake power booster for the fourth stop. Results indicated a mean 708 N force for the "full sedan" and 620 N force for the "intermediate sedan". A T-test comparison indicated the difference between the two vehicles to be statistically significant ( $p<0.05$ ). The authors suggested that the difference is explained by the considerable difference in the decelerating properties of the two vehicles under brake-boost failure. For the typical maximum brake force applied in the intermediate sedan, the full-sedan would generate less than half the deceleration. For this reason and because of the tendency to exert only the force perceived necessary to stop in time, the authors claim that the results with the larger car are more realistic. The authors conclude that the results represent the maximum abilities of female drivers in surprise failure situations.

Table 4: Maximum brake pedal forces in a surprise brake-failure test, adapted from Eaton \& Dittmeier (1970)
Full size sedan
Intermediate size sedan

| Mean | 708 N | 620 N |
| :--- | :--- | :--- |
| SD | 139 N | 125 N |

Many years later, a similar experimental design was used to investigate drivers' reaction to a servo or circuit failure (Curry, Southall, Jamson, \& Smith, 2003). For this purpose 48 drivers experienced both types of failure in their brake system while driving an instrumented vehicle in a closed test track. Results indicated that while everybody managed to bring the vehicle from an initial 64 kmh speed to a stop within 58 m distance, only 17 of them did so under a circuit failure and only 14 under a servo failure. Gender comparison indicated the expected superiority of male drivers in terms of the physical strength in their response to the failure (especially in the servo failure) and also in maintaining their strong input for longer. Also, during the tests when prior information about the system-failure was available, males improved their performance while female drivers performed worse. The closed-track study was complemented by a simulator-study where 48 drivers encountered an "unexpected" failure. Half of the drivers were given extracts of an artificial handbook referring to different failures of the brake system. Results indicated an improved performance of these drivers compared to the other half in terms of stopping the vehicle during the brake system failure. However, the information provided to the first group must have also reduced the surprise element of the system failure.

An alternative scenario was adopted by researchers at the Laboratoire d'Accidentologique, Biomecanique et facteur humain (LAB). Perron, Kassaagi, \& Brissart, (2001) commenced a closed-track study for the
specification of active safety systems that comply with driver behaviour during an emergency. The study was supported by two manufacturers and yielded data out of more than 100 participants. 114 drivers drove and instrumented vehicle, following another vehicle with a trailer on the test track. The emergency was triggered by the release of the trailer. This took place at a relative distance of 17 m and at a speed of $70 \mathrm{~km} / \mathrm{h}$. The trailer braked with a deceleration of $7 \mathrm{~m} / \mathrm{s}^{2}$. Gas pedal travel, brake pedal travel and force, and steering wheel angle were the driver-related variables measured. Results showed that although all drivers braked, only half of them braked strong enough to trigger the ABS. 85\% of the drivers who swerved avoided the crash, but only $20 \%$ of those that brake strong enough to activate the ABS, take advantage of it by swerving. $65 \%$ of those who swerved, braked before swerving. The typical effective (release to start of deceleration) reaction time was 1.7 s . No significant genders differences were reported, while driving experience had an effect on throttle release speed and brake pedal force.

The published paper (Perron et al., 2001) included a section dedicated to Emergency Brake Assist (EBA). The ABS was not activated in 50\% of trials because the drivers did not press the brake pedal hard enough to do so. Moreover, for $85 \%$ of drivers the maximum braking was delayed because of a plateau phase during braking. Therefore, the authors suggest that the EBA could significantly enhance driver braking by enabling them to reach maximum deceleration quicker. They suggest that the data from the study can be used for the specification of such systems. For example, the threshold value for triggering such systems can be based on the comparative analysis
of the brake pedal speed distribution in normal and emergency conditions (figure 19).


Figure 19: Distribution of brake pedal speed in normal and critical conditions, adapted from Perron et al. (2001)

LAB researchers went a step further and run a simulation of all cases including a virtual EBA. Results of the simulation suggest that up to $40 \%$ of collisions would have been avoided. Additionally, in another $30 \%$ of cases the impact speed would have been reduced by more than 15 kmh . Further simulations of a conceptual EBA that would activate brakes as soon as the throttle was released, suggested that over $70 \%$ of crashes would have been avoided. The analytical procedure followed for those studies can be found in a confidential PhD thesis (Kassaagi, 2001).

However exciting and promising this result is, it is based on the assumption that EBA is always activated when needed. This might be ideal, but far from reality. As the authors admit in the paper (Perron et al., 2001), due to the significant overlap of braking parameter distributions between normal conditions and emergency situations, triggering criteria based on a single braking parameter cannot both detect all emergency braking actions and never activate the assistance in situations in which it is not absolutely
necessary". Both false-positives (unintended activation) and false-negatives (non-activation when in fact needed) can have negative consequences. It is obvious that if the system is not activated when intended by the driver, then any claimed safety benefit is gone. In practice, the driver will have the same longitudinal collisions they would in the absence of the system. On the other hand, if the system is activated when the driver does not intend to, then this could be an automation surprise for the driver, and also other road users would have to deal with a vehicle that decelerates at its maximum capability for no apparent reason.

In an attempt to overcome this problem, researchers in LAB employed hybrid neural networks and genetic algorithm (Genetic programming wikipedia, the free encyclopedia.2009) methodology in order to find parameters that could be used in combination to distinguish emergency situations from normal braking (Bouslimi, Kassaagi, Lourdeaux, \& Fuchs, 2005). The study presented in this paper was part of another confidential PhD thesis attempted to tackle the problem within the general sense of shaping a model for driver behaviour in emergency situations (Bouslimi, Kassaagi, Lourdeaux, \& Fuchs, 2005). Data was collected through another series of critical situations replicated in the test track. 95 drivers (59 male - 36 female) took part in the study. Also, improved trailer and released mechanism were used to increase the internal validity of the study. After extensive analysis of driver parameters and their ability to distinguish between normal and emergency situations, Bouslimi used Bayesian neural networks to create a model that predicts the criticality of the situation. The aim was to combine the quantitative properties of Bayesian logic with the qualitative properties
(Yes/No, A/B, etc.) of neural networks. The final model came down to 26 variables that were used to predict the presence of an emergency. The major limitation was that some of those variables referred to post-critical-event parameters, such as the "emergency manoeuvre result". Therefore, although highly efficient in theory, the model is rendered inapplicable in practice.

Contemporary to Bouslimi's thesis, another group of researchers based in Germany employed Fuzzy-Logic technique to improve EBA (Schmitt \& Färber, 2005). Based on this method, Schmitt and Färber (2005) developed a model that distinguishes between normal and emergency brake inputs by the driver. Their model is based on three parameters of throttle-pedal operation: change of radius, jerk, and foot displacement time (from throttle to brake pedal). Data for this study was collected through the CAN bus of the vehicle 54 participants drove in a test-track study. Speed was restricted to $60 \mathrm{~km} / \mathrm{h}$ and the obstacle appeared on-route about 35 m before the vehicle. Authors claim that their model predicts correctly $85 \%$ of emergency braking and $97 \%$ of braking before a corner, against 77\% emergency braking and 99\% braking before a bend correctly predicted by a system with a fixed trigger-level.

Recently, McCall and Trivedi (McCall \& Trivedi, 2007) utilised Bayesian networks to fuse driver behavioural information with vehicle/environment information to predict an emergency or non-emergency situation. Inputs to the system include time-headway (from lidar sensor), wheel speed, brake pressure, accelerator position, steering angle, vehicle longitudinal and lateral acceleration, yaw rate, steering angle and gaze and face expressions through cameras. The authors provided data supportive of the effectiveness of the system in predicting critical situations; however they admitted that the main
problem was the number of false positives (undesired system activation). This was the case particularly when drivers covered the brake pedal but eventually decided not to brake. Although titled "brake support" by its authors, the model aims more towards "brake automation" - automatic braking rather than augmented braking.

The properties of driver-braking input, as suggested by the literature In summary, the aforementioned studies on the characteristics of driver input to the pedals under braking suggested the following:

- The typical maximum effort capability of drivers is about 620 N , and the standard deviation is 125 N .
- There is a slight effect of vehicle size on the numbers above - greater forces were witnessed in larger vehicles.
- During an emergency-brake situation only $50 \%$ of drivers apply brakes hard enough to engage the ABS. $85 \%$ of drivers also swerve to avoid collision and 65\% of those brake before swerving.
- $85 \%$ of drivers' braking exhibit a plateau phase, where the braking force remains constant for the middle part of the input.
- Up to $40 \%$ of collisions could be avoided if a system successfully identifies an emergency-brake input.
- If the emergency could be identified from the throttle-release phase, then more than $70 \%$ of crashes could have been avoided.
- However, in practice, there is significant overlap between normal and emergency braking inputs.
- If a constant level of a variable is utilised to trigger the Brake-Assist System, then both false-positive and false-negative activation of the system is possible.
- Methodologies such as neural networks, genetic algorithms and fuzzy logic have provided improved results in distinguishing between normal and emergency inputs; however, in many cases, such methods are inapplicable in practice.
- Automatic Emergency Braking solutions, although promising for the future, exhibit even more weaknesses at their current status.


## The scope and the research questions of this thesis

In the first section of this chapter a series of studies in the area of timebased vehicle-control parameters and the timing of the onset of braking were presented. The relative merits and problems with the associated technology were discussed by some studies. The human element in the main variables of interest (TTC and time-headway) for such systems specification was reasonably delivered. Simulation (Hoedemaeker \& Brookhuis, 1998; Rajaonah et al., 2006) and even FOT studies (Dingus et al., 1997; Pauwelussen \& Minderhoud, 2008) explored behavioural issues with the implementation of such. The main problems were:

- the behavioural adaptation to the system - drivers drive faster, change lane more frequently and adapt shorter headways (Hoedemaeker \& Brookhuis, 1998; Pauwelussen \& Minderhoud, 2008)
- Complacency to automation - during automation failures driving control deteriorates as increased BRTs (Hoedemaeker \& Brookhuis, 1998; M. S. Young \& Stanton, 2007) indicates and driver workload increases (Wille, Röwenstruck \& Debus, 2008)
- The legislative framework - as blame is a key issue of any failure within our society, the manufacturers would do everything to avoid liability in case of an accident. Therefore, such systems are still marketed as "comfort" rather than "safety" systems.

The studies of the driver braking input, on the other hand, focussed on parameters of driving/braking that correspond predominantly to the primary level control in the hierarchy of the driving task (Allen et al., 1971; Michon, 1985). The study of braking at this operational/control level is only a part of the whole multi-level task, however according to the principle of "primacy" (Allen et al., 1971), the operational/control level of driving is objectively prioritised over the tactical and strategic level. This is because failures at the basic level of control, unless recovered, result directly to accidents, while failures/unsafe decisions in the higher levels do not have immediate effects. Similarly, it is worth examining the operational level of braking control for a future with enhanced driver safety.

Additionally, driver-support technology can enhance driver control by augmenting driver input when needed, without abstracting control out of him/her. Perron et al (2001) simulation provided exciting numbers of crash amelioration, if driver's emergency braking could be detected directly from throttle pedal release. As mentioned earlier though, systems' intervention "when needed" is a complex objective to achieve. This is among the main
aims of this thesis and an improvement the author is hoping to be achieved by the end of it.

Last but not least, driver support systems can be - and actually are implemented to road vehicles in the short term. The applications of relative research can contribute to road safety at the present and near future. Furthermore, they can serve as an intermediate level between manual driving and semi or fully automated driving in the future, preparing gradually the drivers of tomorrow for the technology being developed today. In the "technology" section of the introduction, we encountered some of the latest developments in the area. With a careful read-through, one could notice that new systems are either evolution of previous or integration of multiple other systems. Thus, familiarisation with low levels of automation found in previous systems could mitigate the surprise element when transiting to a future highlyautomated vehicle. This approach is in line with a proposed roadmap for the cognitive car of the future (figure20).


Figure 20: The roadmap of the cognitive car (RWTH Aachen, 2004)

For a complete examination of the ergonomics of braking, the examination of driver braking should not be limited to critical conditions but should also include field studies, where the most typical/normal instantiation can be found. The braking literature encountered so far emphasises the longitudinal control behaviour during the onset of a critical event, but little information of the quantitative characteristics of driver braking in "normal" driving is available. This "normal" needs numbers attached to it. A field study of driver braking could provide this.

Regarding the emergency-brake studies themselves, there is still room for improvement, especially on the external-validity side of them. Eaton et al. (1971) made a basic assumption that maximum pedal effort equals pedal effort in an emergency. Curry et al (2001) focussed on the nature of driver reaction when a brake system fails and had no intention to replicate
emergency braking in their studies. Even the LAB studies (Bouslimi, 2006; Kassaagi, 2001) used data from simulation and test track experiments to measure emergency and normal brake pedal inputs. As they conclude in one of their publications (Bouslimi et al., 2005), their results could be supplemented by field data too. The same applies to Schmitt and Färber's (2005) study. This thesis will attempt to combine data collection methods, in order to improve data-quality. However, there is another worthy goal partially achieved by three most recent of the above studies: to examine relationships and successfully identify the emergency brake input.

Therefore, the research questions this thesis attempts to address are:

- What constitutes normal braking and how it can be defined quantitatively? Typical brake pedal operation and its characteristics.
- Are there distinctive characteristics between "normal" and "emergency" brake application? Further validation of the quantitative differences quoted by Kassagi (2001), Bouslimi (2006), Schmitt \& Färber (2005).
- More importantly, is there a constant relationship between "normal" and emergency brake application, per individual? If great variability is found regarding the previous question (Perron et al., 2001; Schmitt \& Färber, 2005), it is important for any prospective application to know whether people that are harder on brakes in the first condition (typical/normal), are hard on brakes in the second (emergency) as well.
- Is it possible to use the relationships above to design an intelligent brake system that "learns" from the driver and adapts to his/her braking characteristics?

It is surprising how quickly the previously quoted literature (Bouslimi et al., 2005; Bouslimi, 2006; Kassaagi, 2001; McCall \& Trivedi, 2007; Perron et al., 2001; Schmitt \& Färber, 2005) overlooked the first question. No attempt was made to provide even a practical definition. Instead, the "non-emergency" measurements either on the track (Bouslimi et al., 2005; Kassaagi, 2001; Perron et al., 2001) or on the road (McCall \& Trivedi, 2007) were taken as "common sense" would direct. Again, however, in order to have a meaningful definition of "non-emergency" we need to have one for the "emergency".

It is therefore necessary to at least attempt a working definition of emergency braking at this stage. For the purpose of this thesis, driver emergency braking is defined as the driver's reactive operation of vehicle pedals in response to the sudden appearance of a perceived obstacle, with which the vehicle will collide unless the reactive pedal operation takes place. This definition includes three key elements. a)The surprise element ("sudden appearance"): previous studies where the drivers were aware they would have to respond to the appearance of an obstacle or were just prompted to press hard a brake lever, did not replicate emergency braking. b)The importance of driver perception ("perceived obstacle"): no matter whether the danger is real or not, the consequent pedal-operation is emergency braking, if the driver perceives the situation as such. c) The imminent collision with this perceived obstacle ("vehicle will collide unless..."): instances when the collision is avoidable without any pedal-reaction by the driver (longitudinal control), do not constitute emergency braking.

Regarding normal braking, if we try to avoid it being defined qualitatively as "non-emergency braking", we should look towards a statistical definition.

The statistical definition in turn, first requires the quantification of braking input, as some form of quantification is a required for statistical analyses. Such issues, however, as the methods to be employed in the present attempt to address the research questions are discussed in the following chapter, titled Methods.

## Summary

Chapter 2 presented the prominent theories and models about the driving task and the literature with regards to the ergonomic aspects of driver braking in normal and emergency situations. Driver and driving models were grouped according to the facet of the task they focused on. First, early theories of driving as threat-avoidance (Gibson \& Crooks, 1938) were described, before moving on to the time-based descriptions and the model this literature collectively implied. Then, models of driving as a multi-level control task were presented and the most popular among them were described in detail.

After a brief discussion of the role of driver braking within the driving task and vehicle control, the second part of the chapter presented the literature of driver-braking studies: first, the studies aiming at the timing of driver braking inputs, followed by the studies which aimed at the braking input itself and its quantifiable characteristics. The latter group of studies set the background for the research questions and the context for the studies presented in the following chapters of the present Thesis. The four research questions and the associated objectives are: the provision of a functional definition for "normal" driver braking, the examination of the differences between normal and
emergency braking input, the exploration for exploitable characteristics and relationships between driver-braking parameters, and finally, the examination of the plausibility for such relationships to be integrated to an intelligent/adaptive braking system.

## Chapter 3: Methods

For the research questions to be answered satisfactorily, the appropriate methods need to be employed. The purpose of this chapter is to provide the appropriate and realistically plausible methods to be employed within this framework. The methodology commonly employed in driving-related research will be described and discussed here, and the rationale behind the selection of the finally adopted methods will be given.

There is a variety of measures and techniques employed in driver-ergonomics/driving-safety research. They range from high-tech (and cost) equipment such as advanced driving simulators, which are capable of measuring a range of driving performance measures in a secure and controlled environment, to relatively "low-tech" (and less costly) measures designed to measure specific aspects of distraction, such as the visual occlusion technique. The relative merits of driving research methods can be presented as being dependent on two variables, one being extrinsic validity (realism) and the other being control over the environment - and confounding variables (figure 21). The major methods for measuring distraction are presented and their relative merits are discussed in this section.

On a generic level, methods could be distinguished between laboratorybased studies and field-based studies. Studies employing all sorts of driving simulators fall under the first category, and studies which examine driving in a closed or open road section fall under the second category. Within each group however, there are further differences regarding the level of control, the level of realism provided and costs involved. A description of those methods,
starting with driving simulation and moving on to instrumented-vehicle based studies and accident investigation follows.

| $\begin{array}{\|l} \text { Increasing } \\ \text { control } \end{array}$ | - Laboratory testing (e.g. PC simulation) <br> - Low-cost driving simulator <br> - Advanced graphics, fixed base simulation <br> - Advanced, dynamic simulation <br> - Test track trials <br> - Road trials <br> - Naturalistic driving <br> - Accident investigation | Increasing realism |
| :---: | :---: | :---: |

Figure 21: Extrinsic and intrinsic validity of common methods used in driving research

## Driving Simulators

Driver ergonomics are often examined using driving simulators to reflect a controlled version of the traffic environment. The first important merit of using them is that they provide a safe driving environment, where driver errors and failures do not have severe consequences. Phenomena with inherent risk of injury or damage in the real world can be examined in simulated environments. As such, simulators have been commonly used to test effects of distraction on driver performance (Gkikas \& Richardson, 2007; Jamson, Westerman, Hockey, \& Carsten, Winter 2004; Salvucci \& Macuga, 2002), driver complacency to ACC and other vehicle automation (Abe \& Richardson,

2006; Hoedemaeker \& Brookhuis, 1998; Lin, Hwang, Su, \& Chen, 2008; R. Ma \& Kaber, 2007; Rajaonah et al., 2006; Rajaonah et al., 2006) and driver braking in critical situations (Curry et al., 2003; Kassaagi, 2001). Realism and fidelity varies from simulator to simulator. High-fidelity simulators offer a realistic driving environment, complete with realistic components and layout, a coloured, textured visual scene with roadside objects, trees, signposts. Some of them are motion-based; the whole chamber where the simulation takes place moves in accordance with vehicle movement in the simulated environment, effectively simulating acceleration via vestibular stimuli. Lowfidelity instantiations offer less realistic environments and are fixed-based.

The advantages of simulators over on-road and test-track studies are:

- Simulators provide a safe environment to conduct research that is too dangerous to be conducted on the road. A research design where distraction is a core element, can be too dangerous to be tested in naturalistic driving conditions. Although test-tracks can be used to examine driver behaviour using single vehicle scenarios, multiple vehicle scenarios are hazardous in such conditions. On the contrary, driving simulators offer a safe environment for the examination of such issues.
- Simulation includes the key element of control; greater experimental control compared to on-road studies can be applied.

Simulation allows the experimenter to specify the type and difficulty of the driving task and eliminate confounding variables such as environmental conditions.

- The cost of modifying the in-vehicle environment to address different research questions may be significant less than modifying an actual vehicle and ensuring that the modifications meet the design rules.
- Driving simulators offer the capability to examine a large number of measures, from speed control and lateral position on the road, to eye-movements and glance-behaviour.
- Test conditions (night, day, weather, roads) can be manipulated and administered relatively easy. Such conditions could include hazardous situations that would be difficult or dangerous to generate under real driving conditions.


## Instrumented-vehicle based approaches

On-road evaluation studies are one of the most realistic methods that have been employed to measure driver behaviour and driver performance characteristics. With this method, data loggers are used to gather driving performance data while drivers drive an instrumented vehicle for a specified period of time. This time period varies from a lap on a test track up to months of continuous monitoring (see naturalistic studies below). Even though this method yields huge amounts of data in real-like conditions, it can be timeconsuming (needs months or years to complete analysis) and expensive, and thus is less common than simulator-based methods in driver studies. Shortduration on-road evaluations or test-track studies also represent real world driving and are often used to examine the effects of technologies. They appear typically in studies with manufacturers' involvement (Reymond,

Kemeny, Droulez, \& Berthoz, 2001; Yoshida, Mouri, Sato, \& Nagai, 2006; K. L. Young et al., 2008), because they provide in-depth vehicle-centred data quickly and cost-efficiently to them.

Typically, an instrumented vehicle is equipped with sensors on the vehicle controls, monitoring pedal and steering wheel operation by the driver and computers to store the data electronically. Depending on the scope of the study, cameras can be used to measure the immediate road environment and driver behaviour qualitatively, eye-tracking facilities to monitor visual attention, Global Positioning Systems (GPS) to monitor vehicle position or sensors on the wheels and chassis to monitor vehicle dynamics, velocity, accelerations etc. Examples of various types of vehicle instrumentation can be found in Bener, Lajunen, Ơzkan, \& Haigney (2006); Blaauw (1982); X. Ma \& Andreasson (2007); McCall \& Trivedi (2007); Reed \& Green (1999); Zheng, McDonald, \& Wu (2006); Arakawa, Matsuo, \& Kinoshita (2006); Dingus et al. (1997). Participants are asked to drive an instrumented vehicle on a test route, on actual roads or on a closed test track. While participants are driving the vehicle, data is collected either by a logger and/or by an observer. This is a method with high extrinsic validity, reflecting real world driving, and especially in the case of closed test track - minimises safety risks associated with driving on actual roads. However, biases can be induced by learning and adapting to the environment, the nature of the course, or the fact that the participant is being observed. For example, if the course is relatively short and there is little or no traffic or obstacles, then the drivers may not perform the driving task as they would on actual roads.

## Naturalistic studies

Naturalistic studies are an extreme case of instrumented-vehicle based method. Evolution of sensors and data acquisition technology has made monitoring driver behaviour in the real-world for prolonged periods of time feasible. Now, it is possible to collect data from people driving vehicles on the public road network doing their everyday routine for months or years without interruptions. It is even possible to use participants' own vehicles for the purpose. This method offers maximum external validity and at the same time microscopic data. The vast amounts of data generated are a two-edged sword: on the one hand, researchers have access to virtually unlimited depth of data on one hand; on the other, there is strong need for data cleaning and huge resources for analysis. The Virginia Tech 100-car Naturalistic Driving Study (Neale et al., 2005) was anticipated with enthusiasm by the research community. Since this method uses empirical tools to measure phenomena in the field, it tends not to have a specific focus. It attempts to measure "everything" instead, a goal very difficult to be achieved. Although this is not inherent to the conception of the method, in practice it turns out necessary in order to justify the immense cost involved. In the end however, it is only possible for the research team to use parts of the data to support arguments regarding specific issues. In the case of the annotated study, that was road accidents and "near-misses". Then again, as road accidents are rare occurrences, analysis focused on the "near-miss" instances, which although helpful in confirming the "accident pyramid" (Heinrich, 1936) are not quite the same as actual accidents.

However, it is still early, both for this study and the naturalistic driving method in general, to be judged definitely, as this was the first study of its kind. It has been five years since the study commenced (2004) and data are still being analysed and results are to be published. The method is still quite new and the cost-benefits have still to be fully assessed.

## Accident Investigation

Accident investigation is a traditional method used to tackle road safety problems. Its merit lies in the fact that it refers to the problem - i.e. accident in a direct way. All data collected are real-world data. Therefore, if it were to be in figure 20, it would be on the lower rung of the "ladder", where maximum realism but limited control lies. This is its main limitation as a method; there is no control over the event studied and thus there is variance and limited depth in the data - especially the "human" data.

Data on road accidents in the UK has been collected since 1909 (Hillard, Logan, \& Fildes, 2005). However, it was not until 1949 that a nationwide system for accident data collection was introduced, namely STATS19. The original system collected both objective factors (speed limit, time, weather etc.) as well as contributory factors, i.e. the factors which the reporting officer on the accident scene believed contributed to the accident's occurrence. The system has been reviewed and improved every five years since its introduction. After some arguments about the reliability of the subjective nature of contributory factors, such data ceased to be a national requirement in the 1959 review. Collection and central collation of objective data continued as before. However, in 1994 half the country's police forces still used some kind of contributory factors in accident data collection (Broughton, 1997).

This subjective dataset is both an advantage and disadvantage of this method. This is because it provides information about otherwise unapproachable facets of accidents, but on the other hand it relies heavily on expert judgement and is very hard to validate objectively. Thus, it can be extremely useful in practical terms (road design, policy advice, etc.) but it allows room for arguments in an academic setting.

In an effort to compensate for that limitation, the On-The-Spot (OTS) accident study commenced in 2000 in the UK, building upon the long experience from retrospective examination of police files (STATS19) and previous on-the-spot studies (Mackay, 1969; Sabey \& Staughton, 1975) and concurrent work in Germany (Otte, 1999) and France (Girard, 1993). Against the traditional retrospective studies, where accident data is collected several days after an accident occurred, the OTS offers the ability to collect invaluable data which would otherwise be lost such as vehicle rest position, debris locations, weather conditions, road surface conditions, tyre pressures, temporary changes in the road environment at the time of impact, immediate driver and witness descriptions. In addition to this, it includes data which is collected retrospectively in days or months after the accident (road signs, impact damage on vehicles, road dimensions etc.).The project has been operational since the year 2000 and is now in its third phase. More information about OTS can be found in the following chapter.

The relative strengths and weaknesses of each method

| Method | Strengths | Weaknesses |
| :---: | :---: | :---: |
| Driving Simulators | Control over the road environment | Low level of realism usually. Can be improved, but this process comes at a high price. |
| Test-Track trials | Reasonable control over the road environment. Reasonable level of realism. | Inappropriate for examination of longterm (strategic) driver behaviour issues. |
| Road Trials | Highly realistic road environment. | Can be expensive and logistically demanding. |
| Naturalistic Studies | Maximum achievable realism. | Expensive, logistically most demanding, data analysis can be very long. |
| Accident Data | Maximum achievable realism. | Limited to cases that accidents did happen. Depth of data is superficial and partly subjective compared to the other methods. |

The aforementioned methods exhibit relative strengths and weaknesses. Each one of them can be appropriate or inappropriate, depending on the framework within which they are employed and the detailed issues they attempt to tackle. In general, however their comparative characteristics are such as described on table 5.

Starting with the simulation-based methods, their greatest strength is the virtually infinite control over the simulated environment they exhibit. Road and vehicle parameters can be pre-set according to the desired specification. Thus, the variance of the variables of interest can be studies while controlling variables, which could otherwise become confounding. In addition to the level of control available, simulation-based studies tend to take place in confined spaces (e.g. laboratories); therefore, it is not only the variables in the simulation which can be controlled, but also the real physical environment in which the participants are exposed is easier to control. The risk assessment and control for such studies tend to be a lot easier than for studies in open road environments.

Although the safety of participants tends to be a key factor in the selection of the method over other alternatives, it can also be the greatest weakness of this method. Risk and sense of danger are important characteristics of the driving task in a real world setting, and the dismissal of both alters the nature of the driving task that is tested in a virtual environment (Goodman et al., 1997). A driver's behaviour and the amount of cognitive resources he/she devotes to performing concurrent tasks while in the simulator may differ significantly from his/her behaviour in real cars on actual roads because there are no serious consequences that result from driving errors in the simulator.

Because their safety is not compromised, a driver may look away from the road or move his/her hands off the steering wheel for greater lengths of time in the simulator than he would do in the real world. This is a basic issue in simulator research and raises the issue of the validity of simulation as a tool for human factors research (Blaauw, 1982; Blana \& Golias, Summer 2002; Brown, 1976; K. Young, Reegan, \& Hammer, 2003). Other weaknesses of the method include learning effects from simulator use (Moraal \& Poll, 1979) and any other concurrent task, and the amount of resources necessary to construct and operate state-of-the-art, high-fidelity simulators. Finally, simulation discomfort and sickness is an issue sometimes encountered (Goodman et al., 1997) and is particularly common among older and female drivers.

Above all, validity is the main concern in the case of using driving simulators. Blaauw (1982) proposed two aspects of simulation validity. The first is the physical correspondence between the simulator's components, control layout, and its response characteristics, with its real-world counterpart. This has been labelled physical validity or simulator fidelity. A simulator that offers a realistic visual scene with a coloured and textured background has greater fidelity than one, which offers a black and white representation of the environment, with only major road line markings visible. Similarly, a simulator that has a motion-base and can simulate kinaesthetic and motion cues present in real world driving would be considered to have greater fidelity than a fixed-base simulator (Reed \& Green, 1999).

The second aspect of simulation validity is behavioural validity and concerns the correspondence between the ways in which the driver or the
operator behaves in the simulator and in actual vehicles (Blaauw, 1982). Ideally, the method that determines the behavioural validity is to compare driving performance in the simulator to driving performance in real vehicles using the same driving tasks. Behavioural validity has two levels: absolute validity and relative validity. Absolute validity is achieved when the numerical values for certain tasks obtained from the simulator match with those from actual vehicles. Relative validity is achieved when variations in driving tasks have a similar impact on driving performance in both simulator and real vehicles. Generally, simulators demonstrate good relative behavioural validity for many driving performance measures (Carsten, Groeger, Blana, \& Jamson, 1997), though absolute validity is rarely the case (Blana \& Golias, Summer 2002). The comparative study by Reed \& Green (1999) using a low cost driving simulator and an instrumented vehicle revealed that mean speeds were similar in both conditions, while lane-keeping was less precise in the simulator than in the instrumented vehicle. The authors concluded that the simulator demonstrated good absolute validity for speed measurements and good relative validity for the effects of a distraction source on driving. However this result does not guarantee that every simulator has the same characteristics with the one Reed and Green tested.

The above issues with behavioural validity can be mitigated through the use of an instrumented actual vehicle instead of a simulated one. Since the vehicle dynamics and the objective feedback to the driver correspond to a real vehicle. The use of a real vehicle for the study of driving, however, necessitates the use of real road-section as well. If that road-section is limited to a closed test-track, then much of the control over variables encountered in
simulation studies can be retained. Variables such as the nature of the route travelled, the presence of other vehicles, and the behaviour of other actors can be controlled during a test-track study. In parallel, the limited and controlled road environment comes with limited ecological validity. The road environment tends to be locally and temporarily different to the real road environment. A session with a participant on a test-track takes place in a relatively sterile environment and lasts for a few miles distance and a few minutes time. Real driving on the contrary, rarely takes place on roads and environments free of other road users, pedestrians or other human activity. In addition, temporarily and locally it is not subject to the limitations imposed to a test-track study.

The above weakness can be mitigated through the use of an open roadsection instead of a closed track. Thus, the road environment becomes less sterile and includes many more elements of the natural road environment. In terms of length, on-road studies can benefit from the virtually unlimited length of the road network. Nevertheless, control over environmental variables decreases in proportion to the increase in realism, while the temporal limitations of the test-track studies still apply. The latter can be further raised, if the necessary resources are available to turn the on-road study into a naturalistic study, as described in the previous section. In such case, maximum realism is possible through the study of participants longitudinally over a period of time, when they commence their normal driving routine, on the road environments of their choice. The resources necessary to support such a study are beyond the limits of many research projects, on the other hand, and control of confounding variables can be a real challenge from the
conceptual stage all the way up to the administration of the study and the data analysis.

Data collection from road accidents can be equally demanding in terms of resources - especially if microscopic data re to be collected. Nevertheless, accident investigation is often part of the law enforcement authorities and enjoys political support. Therefore, as long as cooperation with the respective authority is established, in practice the logistics are not as demanding as those in the case of a naturalistic study. In addition the ecological validity of the data is sound, as these are collected directly from the real road environment, without any interference from the researcher. Nevertheless, there are two key weaknesses: first, all the data collected refer to phenomena and behaviours that took place immediately before, during and after an accident. By definition, information regarding driving parameters outside that window is excluded. It is therefore impossible to produce evidence regarding driving in a "normal" framework. Second, even in the case of "microscopic" studies, accident investigation provides relatively superficial data. In the absence of in-depth measures and apparatus to provide accurate quantitative data regarding drivers' input and vehicle's feedback, significant part of accident databases consists of qualitative information inferred through the measurements available to the accident investigator during the assessment of an accident scene. Furthermore, as mentioned above, data tend to be collected by police forces rather than research teams. Accordingly, the focus has traditionally been on enforcement policies and attribution of blame, rather than the in-depth analysis of driving behaviour and performance. Therefore,
the quality of data yielded by accident-studies tends to be quite different to those yielded by the other methods discussed previously.

Overall, this section discussed the relative merits of each of the methods commonly employed in driving research. The following step is to discuss them in relation to the research questions in particular, before the most appropriate of those applicable, are selected to formulate the methodology of the Thesis. This discussion takes place in the following section.

## The methods to be used for the purpose of the present Thesis

As described so far, each method has its pros and cons and different research questions favour different methods. The first research question in this thesis, the examination of the constitution of normal driver braking, requires microscopic, numerical data, such as those collected using simulators and instrumented vehicles in controlled environments; however, at the same time the nature of the examined phenomenon - "normal" braking demands maximum ecologic validity. This can be provided only in a naturalistic environment.

The second and third research questions, comparison and examination of relationships between normal and emergency braking, require the same type of microscopic, numerical data and realistic environment, however, due to the safety-critical element of emergency braking and for ethical reasons, more control is needed over the environment. Therefore, the naturalistic setting needs to be somewhat compromised for the safety requirement to be in place.

A combination of a naturalistic environment for the "normal" part and the controlled environment of a closed road section for the "emergency" part can fulfil such requirements. A simulator could also be employed alternatively, but it would probably compromise ecological validity further.

The fourth research question has multiple prerequisites before a method is employed to provide relative evidence. The above naturalistic and controlled methods have to be used first, and provided useful results and exploitable characteristics indicated. Then, unless resources are available for the integration of the results to a system prototype and the commencement of field operational trials (FOT) of the system on public roads, the system needs at least to be simulated. Real-world data can be provided from the previous naturalistic and controlled studies.

No matter how good one method is in dealing with a particular research question, there are always weaknesses. The employment of several methods in conjunction can compensate for the weaknesses of one method. The rationale is that the relative merits of each can be used to compensate for the weaknesses of the other. A full-scale naturalistic study seems ideal for the purpose of this research; however the required budget and resources exceed the context of the PhD project. Accident-studies provide direct access to realworld data; however the depth of these data is comparatively limited.

Simulation can be used for maximum control and access to the desired depth of data; however application of results to the real-world can only be indirect through analogies. This is the issue of ecological validity mentioned previously. In general, there are two, often conflicting, conditions this project is attempting to fulfil: internal validity and external validity.

Validity refers to the degree to which what we measure is actually what we think we are measuring. For example the degree to which an index developed to measure workload is actually measuring workload instead of attention, perception or something else. Internal validity refers to the degree to which the design of the study and the resulted measures are accurately measuring the desired variables. For example in an experiment, how accurately the measurements taken replicate the results of the processes that took place. Thus, it is closely associated with reliability. External validity is about the degree to which what we measure has a reference in the real world. For example, if we measure response times to a stimulus in the laboratory, how accurately our measures reflect the participant's response times to the same stimulus in the real-world (Carmines \& Zeller, 1979; J. Evans, 2007).

In the current project, both controlled and realistic methods will be used in order to maximise both internal and external validity. In general, the employment of an accident study and/or a naturalistic study will improve external validity, while the use of a controlled/empirical study will allow for the measurement of the exact variables of interest and increase internal validity. With the focus on brake-assistive technology, these would be pedal-operation parameters, including speed, force and pressure during pedal-operation, a.k.a. "pedipulation" (Oxford english dictionary pedipulate, v.). Furthermore, additional measures for each method to be used will help decrease the impact of the inherent weaknesses of each of them.

For this reason, an accident study of real-world relevant accident files will be based on accident files from the OTS accident investigation. This dataset is currently the most microscopic accident data available in the UK. As
braking/decelerating is essentially longitudinal control (figures 14, 15), the focus will be on longitudinal control failures. Additionally, to test reliability, results will be compared to results using the National Statistics (STATS19) files for the same accidents (Figure 23). The combination of microscopic data use with comparative analysis of the same accidents using another database should increase internal validity. In the case of the naturalistic study, there is not much space for improvement as in this case the internal validity is the external validity - i.e. the experimental measurements are at the same time field measurements; "the field is a laboratory". This stands as long as the study is appropriately designed. This is the main advantage of this method, as it allows for maximum depth of data through the use of instrumentation, while at the same time it is as realistic as a study can be. Accidents and emergency reactions are comparatively rare though, and the risk of acquiring only a few useable data from emergency brake reactions is very high. So, while this method is ideal for the study of "normal"/"natural"l"common", average braking, it would not provide enough instants of emergency braking and any attempt to induce such in the open road could render the study unethical. This is where the empirical study comes in, allowing for an ethical and safe data collection measure and maximum internal validity. The latter is enhanced through the use of repeated measures and a strict experimental protocol (figure 22).


Figure 22: Rationale aiming at internal validity

Regarding overall external validity, two of the three methods to be used (accident study and naturalistic study) are strong in this type of validity. The "normal" part of the controlled study described in a following chapter, is validated by comparison with the naturalistic study (figure 23). Identical measurements can be taken during both studies and compared directly. Due to the nature of the emergency part, replicating this parallelism for the emergency-braking study is much more challenging; it is very hard to validate it directly with real-world emergency-brake inputs, simply because these data do not exist. So far researchers do not have direct access to the ECU units of vehicles which recorded data from emergency brake reactions (before accidents or near misses). However, the study design will opt for realism and parameters will be compared with the reaction-variables from the OTS cases.

The comprehensive description of each study can be found in the relevant chapters (4-7)


Figure 23: Rationale aiming at external validity

To conclude, individual methods are employed to provide the evidence regarding the research questions of this thesis, but also combined methods are used to supplement and compensate for the weaknesses of individual methods. A naturalistic braking study is employed to provide evidence regarding the issue of normal braking. A controlled study using an instrumented vehicle on both public and closed roads is employed to provide evidence regarding the differentiation between normal and emergency braking and then the presence of relationships between braking parameters in these two instances. Results are then integrated into an "adaptive brake assist" concept and the respective system is tested virtually using simulation
software. The simulation study is expected to provide evidence of the exploitability of the results by an intelligent brake system, the final research question. Ultimately, the naturalistic study complements the normal-braking part of the controlled study, and a detailed accident study complements the emergency-braking part of the same study.

## Summary

The purpose of the chapter 3 was to present the most common methods employed in road-driving research and identify the appropriate methods to address the research questions, as these were set out in the previous chapter. The range of methods used in driving research was presented; from lab-based low-cost methods of driving simulation to studies on the test track or the public highway, and even methods employing road-accident data.

The relative merits of each methodology were then discussed with regards to the level of control and realism offered by each and their suitability for the established research questions. A hybrid methodological plan was developed to incorporate the advantages of each method and compensate for the individual weaknesses of each method within. With realism as priority, an accident-study in conjunction with a controlled road-study, a test-track study and a "naturalistic" study will form the core hybrid methodology. Depending on the results from the core methods, a supplementary simulation-study will be used to indicate the practical potential and limitations of the results.

## Chapter 4: The in-depth accident study ${ }^{2}$

As accident mitigation is the ultimate goal of any safety technology; any vehicle system should incorporate the demands of the accident characteristics to its design. Additionally, as explained in the "Methods" chapter, it is beneficial to any empirical evidence to be supplemented by real-world data. This chapter describes a study based on the analysis of accident files from cases pertinent to longitudinal vehicle control and driver braking in particular. The most in-depth accident data available, the road-user interactions file, from 3024 road accidents in Thames Valley and Nottinghamshire in the UK were analysed. The focus was on the interactions where "failure to stop" or "sudden braking" on behalf of a user was the precipitating factor of the accident. Main variables of interest were the contributing factors to the precipitating factor and the reactions of each user during the accident occurrence. Results indicate that both automated braking and brake assist technologies can only address some of the factors and the development of other measures and technologies is necessary in order to achieve accident-free longitudinal control.

[^1]
## Rationale

As described in the Methods chapter, there are two main reasons behind a study of accident cases pertinent to longitudinal control failures. First, although attempts to examine driver control microscopically are necessary for the specification of safety technologies, there is always room to miss the target of accident mitigation, if their results are used in isolation. The integration of empirical with road accident data still remains to be successfully accomplished. The main studies for the specification of successful brake assist systems (Bouslimi, 2006; Kassaagi, 2001; Perron et al., 2001; Schmitt \& Färber, 2005) previously described almost took no account of the accidents these systems are supposed to mitigate, other than the general notion that "since most drivers don't operate the pedal effectively, there is a need to augment driver braking" Second, it is part of the methodology in this Thesis to employee in-depth accident data in tandem with empirical methods in order to maximise overall ecologic validity, without compromising internal validity (See figure 23 in chapter 3). Thus, any solution or application yielded by this three-year research project can benefit from integrated data at its inception level. In this case such application would be an ergonomical/driver-centred brake system.

To achieve this and succeed the systems approach of Ergonomics
(Wilson, 2005), the environment and circumstances, under which such system is expected to operate and achieve its target, need to be investigated. Such an approach will allow for important parameters outside the basic control-level driver reactions (Allen et al., 1971; J. D. Lee \& Strayer, 2004; Michon, 1985; Summala, 1996) to be identified. If nothing more, it is expected that this study
will provide the framework in which the system described later in the "system simulation" chapter should operate and the qualitative data to support its further development.

However, the nature of traditional accident data is quite different from the data presented so far. Integration and comparison of accident data to empirical data is therefore not straightforward. The major challenge is the difference in depth; the accident data usually being too "shallow" and the empirical data being too "deep"; essentially another expression of the methodological pros and cons described in chapter 3 (pp 72-74). A way to tackle this problem is to use the most microscopic accident data available. These data are available from a relatively recent accident investigation project titled On-The-Spot Accident Study (OTS), which since the year 2000 collects the most detailed data from road accidents in the UK (Hill, Thomas, Smith, \& Byard, 2006). As the shift in type of data in the following chapters is significant, a section on its background is presented before the main part of the OTS data analysis. This section can be skipped by readers familiar with in-depth accident investigation methods.

## Background - Recording the Causes of Accidents in the

## British National Data

Data on road accidents has been collected since at least 1909 (Hillard et al., 2005). However, it was not until 1949 that a nationwide system for accident data collection was introduced, namely STATS19. The original system collected both objective factors (speed limit, time, weather etc.) as well as contributory factors, i.e. the factors which the reporting officer on the
accident scene believed had contributed to accident occurrence. The system has been reviewed and improved every five years since its introduction. After some debate about the reliability of the subjective nature of contributory factors, such data ceased to be a national requirement following a review in 1959. However, in 1994 half the country's police forces still used some kind of contributory factors coding in accident data collection (Broughton, 1997).

The report by Maycock (Maycock, 1995) classifies in three broad groups the contributory data collected by the police forces at the time. Some police forces opted to record a simple list of causes, while others preferred to use a list of contributory factors tailored to the level of flexibility considered necessary for individual local users. Devon and Cornwall police forces used one of the more systematic and comprehensive systems: the causation factor could be selected from seven broad categories, namely: driver error, pedestrian error, passenger error, vehicle defect, highway defect, weather conditions and animal/object involvement. One of those broad factors was supplemented then with up to two qualifiers, from a list of twenty six (figure 24).


Figure 24: classification system used by Devon \& Cornwall police forces

That report persuaded the Department for Transport to commission the Transport Research Laboratory (TRL) to develop and test a prototype system for the collection of contributory factors data. TRL elaborated on the previous hierarchical system and presented a "new system for recording contributory factors in road accidents" (Broughton, 1997). The suggested system was an amalgam of the theoretical model suggested by a team of researchers at Leeds University during the late 80's (Carsten, Tight, Southwell, \& Plows, 1989), plus the aggregated experience and practical needs indicated by the police forces. Therefore, a two-level hierarchy with the following terminology was developed:

- Precipitating factors are the failures and manoeuvres that immediately led to the accident.
- Contributory factors are the causes for these failures and manoeuvres. A recorded contributory factor always relates to a precipitating factor that has already been recorded.

In its early version, the system was flexible enough to allow up to three precipitating factors to be chosen and up to three contributory factors per precipitating factor. Factors had also to be entered in decreasing order of importance. The authors suggested that the hierarchical model has the advantage that it allows for the same factors to be recorded as in the case of a single tier approach, however in application it imposes a discipline upon the investigator and thus leads to a more reliable coding.

Police involvement was substantial in the development as well as in the support of the project. During the first stage of its development police accident files were examined to decide whether such system was applicable in real world incidents. This was followed up by interviewing and consultation with police officers.

The new system should:

- be comprehensive enough to accommodate within standard codes the majority of road accidents
- be simple and compatible with operational procedures
- be self-explanatory and minimising the need for extensive training
- encourage the collection of high-quality data.

The finally tested version allowed for only one precipitating factor to be selected, as only a few of the accident files revisited in the previous step included more than one precipitating factor and thus, the design of the form becomes simpler. The option "other" was introduced to allow flexibility and
also check the completeness of the coverage in the current form. This allowed for new factors to be incorporated within the rapidly changing transport environment. The final innovation introduced was the "definite, probable, possible" option for the investigator to rate each contributory factor he/she so chooses.

After consecutive reviews in the year 2000 (Neilson \& Condon, 2000) and 2002 (Wilding, 2002) suggested itemised amendments and especially the latter acknowledged the internal "blame machine" of the system, as it tended to lay blame on an individual and was totally inappropriate for accidents where there was contribution from multiple road users. The issues identified in the review in conjunction with the previous paper by Neilson and Condon (2000) lead the Department for Transport to commission the Transportation Research Group in Southampton University to go one step further and make suggestions to the Standing Committee on Road Accident Statistics (SCRAS) for the improvement of the contributory system. The subsequent report (Hickford \& Hall, 2004), among other recommendations, suggested a revised form for collecting contributory data. However for ease of use, after consultation with the local authorities and the police, a different layout was adopted by SCRAS. The outcome of that work was the STATS19 contributory factors form now in use, including seventy-six contributory factors and also an option to report "other factor" by text description. The factors are grouped in five main categories: road environment contributed (nine factors); vehicle defects (six factors); driver/rider only (forty-seven factors); pedestrian only (ten factors); and four factors for special codes (stolen vehicle, vehicle in course of crime, emergency vehicle on call, vehicle door open/closed
negligently). The driver/rider category is further subdivided into five subcategories: injudicious action, error or reaction, impairment or distraction, behaviour or inexperience and vision affected (by). The reporting officer can select up to six factors from the grid, relevant to the accident. Previously suggested three and four-point scales of confidence are now substituted by a simple two-point scale: the officer indicates for each factor whether he/she considers it "very likely" or just "possible". The system allows for more than one factor to be related to the same road user and for the same factor to be related to more than one road user, if appropriate. This allows the police officer sufficient flexibility to include the necessary details and in a concise manner.

## In-depth OTS Causation Studies

The current On-The-Spot (OTS) accident research study commenced in the UK in the year 2000. Unlike the more traditional retrospective research studies, where accident data is collected several days after an accident occurred, the OTS study offers the ability to collect invaluable data which would otherwise be lost such as vehicle rest position, debris locations, weather conditions, road surface conditions, tyre pressures, temporary changes in the road environment at the time of impact, immediate driver and witness descriptions. Expert research teams attend the scene of road accidents, typically within 20 minutes of the incident occurring to make an indepth investigation that includes the highway, vehicles and human factors present. In addition, it includes data which is collected retrospectively in days
or months after the accident (road signs, impact damage on vehicles, road dimensions, injury details, etc.).

The procedure starts with the arrival of the investigation team at the scene of an accident. The serving police officer on the OTS team makes contact with the police officer in charge of the accident scene and briefs him/her about the intended activities of the investigators. After fulfilment of protocols and safety requirements, the team makes contact with the people and the various elements involved in the crash. Data is coded in a library of some 200 forms with over 3000 individual variables. More details about the OTS method and protocols can be found in Hill et al., 2001.

OTS investigators analyse the causes of accidents in detail and record their findings using a suite of causation coding systems. National contributory factors forms [both the current (Hickford \& Hall, 2004) and previous (Broughton, 1997) forms, as described above] are routinely coded for all OTS cases according to the same protocols followed by police officers. Thus accident causation is coded in two levels: a precipitating factor and up to six contributory ones.

OTS cases are further analysed to determine more complex descriptions of accident causation in terms of possible interactions between the active road users. A system called "interactions" has been developed to allow analysis and recording of one or more interactions between each road user and his/her environment to provide a description of pre-crash events at any degree of necessary complexity. All information is held on an anonymous accident database and does not include personal identifying details or other similar documentation.

## Methodology

Accident cases were studied from Phase 2 of the OTS project covering the period from September 2003 to October 2006 and include detailed, disaggregated data from 3024 accidents in the Thames Valley and South Nottinghamshire regions. This study selected accidents where "failure to stop" or "sudden braking" had been coded as the factor initiating the accident sequence. While other precipitating factors are also relevant for the study of longitudinal control failures, those two factors were considered to be of prime interest within the scope of the current study.

It should be noted that "failure to stop" here defines a very specific set of accidents where that is the single, precipitating factor causing the accident. Clearly all accidents are in some way the result of a failure to stop before the collision occurs, but the sub-set under study here represent drivers who were considered to be the predominate, precipitating cause of their accident by failing to stop their vehicle in time. Each "failure to stop" will have been assigned as the precipitating factor following an accident investigation to eliminate other possible precipitating factors, such as for example, the driver travelling too fast, or a pedestrian stepping into the road. This is therefore a set of drivers who were not able to stop for a variety of personal psychological or other reasons. There will of course be other drivers who did not stop before collision (all the other drivers in the database). This study, focuses, however, on the unique group for which "failed to stop" was the precipitating factor (together with the additional "sudden braking" group, as explained above).

This study cannot therefore attempt to consider all possible reasons for drivers failing to stop in time to avoid their accident.

Case selection resulted in 301 cases involving "failure to stop" and 39 cases involving "sudden braking". The study went on to analyse precipitating and causal factors in the context of driver behaviour and longitudinal control of the vehicle. Case analyses focused on the more detailed OTS road-user Interactions coding system, as has been described above. The Interactions file included 1099 interactions in "failure to stop" accidents and 152 interactions in "sudden braking" accidents. Thus, the level of detail goes deep down to analyses per interaction, per road user, per case. To the author's awareness, this is the most detailed level of accident data available in the UK. The database has been compared against the national data for Great Britain (STATS19) and validated as broadly representative of accidents occurring over Great Britain (Hill et al., 2006). The first section of results is based on the accident causation form of these cases completed by the police and included in the STATS19 database. The second section supplements these results with data from the additional OTS causation form, which is completed by the OTS accident investigators on the spot of the respective accidents. All results presented hereafter have been tested for asymptotic significance (chi-square test) and found below the criterion $\mathrm{a}=0.01$.

Results (Contributory Factors 2005 data)

[^2]Failure of a driver or vehicle to stop in time to avoid a collision with another road user or object is identified as the precipitating factor in 301 cases investigated by the OTS team (Phase 2). However, these cases were the result of interactions of more than one road users at a time. Browsing through the cases one by one, it is very rare - and naïve - to attribute accidents to a single factor. This is in accordance with experience of accident investigation in high-hazard industry, aerospace and space applications (Columbia Accident Investigation Board, 2003; Kirwan, 1994; Reason, 1990; Whittingham, 2004). Therefore it is necessary to look further into the factors that contributed to the precipitating factor.

Collision types resulting from "failure to stop" are shown in table 6. One might expect junction overshoots and rear-end collisions to predominate, however the OTS cases show a wider variety of collisions. Common collision types associated with such accidents include crossing, merging, turning, and others.

Table 6: Collision type as a result of failure to stop compared to general accident data

|  | General <br> (all accidents) | Failure to stop |
| :--- | :---: | :---: |
| rear-end | $20.6 \%$ | $65.3 \%$ |
| cornering | $12.4 \%$ | $0 \%$ |
| lost control or off-road | $10.4 \%$ | $0.7 \%$ |
| (straight roads) | $10.4 \%$ | $0 \%$ |
| overtaking and lane change |  |  |


| collision with obstruction | $3.1 \%$ | $1.4 \%$ |
| :--- | :---: | :---: |
| head on | $5.5 \%$ | $1.7 \%$ |
| turning versus same | $3.2 \%$ | $0.9 \%$ |
| direction | $6.1 \%$ |  |
| crossing (no turns) | $8.5 \%$ | $15.9 \%$ |
| crossing (vehicle turning) | $3.4 \%$ | $3.1 \%$ |
| merging | $5.5 \%$ | $3.3 \%$ |
| right turn against | $2.6 \%$ | $3.5 \%$ |
| manoeuvring | $6.3 \%$ | $0 \%$ |
| pedestrians crossing road | $0.5 \%$ | $1.9 \%$ |
| pedestrians other | $0.6 \%$ | $0 \%$ |
| miscellaneous |  | $0 \%$ |

Table 6 also makes a comparison with the overall collision-type frequency distribution from the OTS database and that comparison underlines differences in the result of failure to stop in particular collisions. Apart from the widely acknowledged predominance of rear-end collisions (+44.7\%), crossing without turning is particularly common ( $+9.8 \%$ ), while cornering, overtaking, manoeuvring do not appear at all, and pedestrian crossings are less common (-4.4\%).

In terms of contributory factors (Table 7) drivers' "too close" car-following strategy is identified as the most common contributory factor, followed by nonadherence to automatic traffic signals and speeding. Cognitive failures - to look and to judge others' paths - and inappropriate reactions - sudden braking - are also commonly found in such accidents. Comparing that with
the general OTS distribution (table 7), "too close" car-following behaviour is more frequent as a contributor (+16.81\%), non-adherence to automatic traffic signals is more common in failures to stop (14.06\%), while too-fast driving is more frequent (+7.33) and psychological parameters (reckless/in hurry) more common $(+7.30 \%)$ in failures to stop. On the contrary, non-adherence to giveway signals is less common factor (-9.03) and failure to judge other paths is somewhat less frequent (-2.71\%).

Table 7: Common contributors in failure to stop compared to general

| accident data |  |  |
| :--- | :---: | :---: |
|  | failure to | general (all |
| stop | accident cases) |  |
| following too close | $22.93 \%$ | $6.12 \%$ |
| disobeyed automatic traffic signal | $16.65 \%$ | $2.59 \%$ |
| careless, reckless or in a hurry | $13.74 \%$ | $6.44 \%$ |
| travelling too fast for conditions | $12.01 \%$ | $4.68 \%$ |
| failed to look properly | $6.19 \%$ | $5.15 \%$ |
| exceeded speed limit | $4.19 \%$ | $5.10 \%$ |
| failed to judge other person's | $4.19 \%$ | $6.90 \%$ |
| path or speed |  |  |
| sudden braking | $2.37 \%$ | $1.01 \%$ |
| special codes: stolen vehicle | $2.37 \%$ | $0.73 \%$ |
| slippery road (due to weather) | $1.55 \%$ | $2.06 \%$ |
| disobeyed give-way or stop-sign | $1.36 \%$ | $10.40 \%$ |
| or markings |  |  |


| impaired by alcohol | $1.36 \%$ | $2.08 \%$ |
| :--- | :---: | :---: |

To make the picture clearer, it is necessary to check the type of road users involved in such accidents (table 8). About 80\% of road users are car occupants, 3.5\% are Light Goods Vehicle (LGV) occupants and 3.1\% are Heavy Goods Vehicle occupants. Motorcyclists and bus occupants each constitute about $1 \%$ of the road users involved in such accidents. Sensitive road-users comprise $3 \%$ in total, $1.3 \%$ are pedestrians and $1.7 \%$ are pedal cyclists.

Table 8: The distribution of road user involvement in "failure to stop"


## "Sudden braking"

"Inappropriate reaction-sudden braking" is identified as the precipitating factor in 39 cases investigated by the OTS team. The interaction-files of those cases include 152 road-user interactions. 73\% of those involved are car
occupants, while 9.2\% are Light Goods Vehicle (LGV) and 6.6\% are Heavy Goods Vehicle (HGV) occupants. Bus occupants and cyclists each consist $2.6 \%$ of total road users and motorcyclists are $5.9 \%$.

Table 9: The distribution of road users involved in "sudden braking


Compared to "failure to stop" cases, there is more frequent involvement of LGVs and HGVs and motorcyclists (more than 6 times more common). On the other hand, there have been, as might be expected, no pedestrians involved in this type of accident (compared to $1.3 \%$ in failures to stop), and differences below $1 \%$ exist in bus occupant and cyclist involvement.

Comparison of collision types in "sudden braking" cases with the general and the "failure to stop" cases reveals some interesting differences (table 10). While the predominance of rear-end collisions is there, collisions commonly associated with lateral control such as overtaking, cornering and loss of
control collisions are initiated by a sudden-braking reaction. Furthermore, miscellaneous collisions (with a trailer mostly) are common results of suddenbraking, unlike other precipitating factors. On the other hand, collisions while crossing and collisions with pedestrians are not found at all in "sudden braking" accidents, unlike "failure to stop" accidents and the database in general.

Table 10: Collision-type relative frequencies in "sudden braking",
"failure to stop" and general accident data

|  | sudden | general | failure to |
| :--- | :---: | :---: | :---: |
| braking |  | stop |  |
| rear end | 62.5 | 20.6 | 65.3 |
| overtaking and lane change | 7.9 | 10.4 | 0 |
| Cornering | 7.9 | 12.4 | 0 |
| lost control or off road | 7.2 | 10.4 | 0.7 |
| Miscellaneous | 5.9 | 0.6 | 0 |
| turning versus same direction | 3.9 | 3.2 | 0.9 |
| head on | 2.6 | 5.5 | 1.7 |
| collision with obstruction | 2 | 3.1 | 1.4 |
| crossing(no turns) | 0 | 6.7 | 15.9 |
| crossing (vehicle turning) | 0 | 8.5 | 3.1 |
| Merging | 0 | 3.3 | 3.7 |
| right turn against | 0 | 5.5 | 3.5 |
| Manoeuvring | 0 | 2.6 | 0 |
| pedestrians crossing road | 0 | 6.3 | 1.9 |


| pedestrians other | 0 | 0.5 | 0 |
| :--- | :--- | :--- | :--- |

Examination of the contributory factors in accidents initiated by a sudden-braking reaction indicated a "wave effect" of sudden braking reaction in response to one or more other drivers also braking suddenly to be the most common factor (table 11). Similarly with "failure to stop", close car-following behaviour is a major contributor to this type of accident. Failures of judgement and masked road markings and signs are among the most common contributors as well as distraction. However failure to look properly, junction overshooting and cyclists' intrusions are not common as in "failure to stop" cases.

Table 11: Comparison of contributors in "sudden braking" and general accident data (percentage values)

|  | sudden <br> braking | general (all <br> cases) |
| :--- | :---: | :---: |
| sudden braking | 35.53 | 1 |
| following too close | 24.34 | 6.1 |
| failed to judge other person's path or speed | 7.89 | 6.9 |
| inadequate or masked signs or road markings | 4.61 | 0.4 |
| careless, reckless or in a hurry | 4.61 | 6.44 |
| exceeded speed limit | 3.29 | 5.10 |
| road layout (e.g. bend, hill, narrow carriageway) | 2.63 | 6.1 |
| travelling too fast for conditions | 2.63 | 4.68 |
| distraction outside vehicle | 2.63 | 0.9 |


| aggressive driving | 2.63 | 0.3 |
| :--- | :--- | :--- |
| slippery road (due to weather) | 1.97 | 2.1 |
| animal or object in carriageway | 1.97 | 0.5 |
| junction overshoot | 1.97 | 0.5 |
| vision affected by road layout (e.g. bend, winding <br> road, hill crest) | 1.97 | 0.4 |
| cyclist entering road from footway | 0.66 | 0.3 |
| failed to look properly | 0.66 | 5.2 |

## Results (OTS causation data)

All the above results are based on the Contributory Factors 2005 forms of each accident case completed by the police officer. The OTS database benefits from an additional causation system based on the forms completed by independent accident investigators on the scene of an accident.

Examination of the data coded by OTS investigators in the accident causation files reveals a more detailed picture. Additional contribution is founded in psychological factors such as distraction, panic behaviour, nervousness and inattention (tables12, 13).

Table 12: Contribution of cognitive failures in "failure to stop" accidents

|  | \% Definitely |  |  |  |
| :--- | :---: | :---: | :---: | :---: |
| causative | \% Probably | \% Possibly | Total |  |
|  | 19.5 | 30.6 | 23.2 | 73.3 |
| Inattention | 15.8 | 8.8 | 7 | 31.6 |
| Failure to judge other |  |  |  |  |
| person's path or speed | 5.6 | 8.7 | 14.4 | 28.7 |
| Failure to look | 7.8 | 7.4 | 11.5 | 26.7 |
| Lack of judgement of |  |  |  |  |
| own path | 2.2 | 7.4 | 14.5 | 24.1 |
| Look but did not see |  |  |  |  |

Table 13: Contribution of emotional factors in "failure to stop" accidents

|  | \% Definitely <br> causative | \% Probably <br> causative | \% Possibly <br> causative | Total |
| :--- | :---: | :---: | :---: | :---: |
| Aggressive driving | 0.6 | 3.6 | 4.2 | 8.4 |
| In a hurry | 1.7 | 8.8 | 8.8 | 19.3 |
| Carelessness, reckless | 18.6 | 17.7 | 14.1 | 50.4 |
| or thoughtless |  |  |  |  |

## Sudden braking

In terms of injury outcomes, as was the case in "failure to stop", sudden braking initiates accidents with small amount of fatalities and serious injuries.

The biggest part of road users remains uninjured or leave the crash scene with minor injuries. However this does not include any long-term effects of the
accident occurrence (Barnes \& Thomas, 2006). Further examination of the cases by OTS investigators reveals increased contribution of emotional (table 14) and cognitive factors (table 15), while contribution of close following and speed behaviour (table 16) is about the same level as in the National Causation data.

Carelessness/recklessness/thoughtlessness was found contributing between $15.8 \%-32.2 \%$ of interactions, panic behaviour between $7.2 \%$ and $23.6 \%$, aggressive driving between $13.2 \%-15.8 \%$, while nervousness/uncertainty contributed from $2 \%$ to 11.9\%. Inattention was a major factor not immediately identified in the Contributory Factors (STATS19) 2005 form. Its contribution was found between $9.2 \%-42 \%$. Failure to judge other road users' path or speed had a contribution between $15.1 \%$ and 29.6\%, higher than the STATS19 form suggests, while lack of judgement for own path ranged between 2.6 and 11.2 percent, and "look but did not see" failures had a $0-8.5 \%$ contribution. The important contribution of too close carfollowing found previously (table 7 ) was confirmed ( $16.4 \%-34.8 \%$ ) as well as the contribution of speeding (5.9\%-14.4\%).

Table 14: Relative contribution of emotional factors in "sudden-braking" accidents

|  | \%definitely <br> \%probably | \%possibly total <br> causative | causative | causative |  |
| :--- | :---: | :---: | :---: | :---: | :---: |
| careless/reckless/thoughtless | 15.8 | 3.3 | 13.2 | 32.3 |  |
| Panic behaviour | 7.2 | 7.2 | 9.2 | 23.6 |  |
| aggressive driving | 13.2 | 0 | 2.6 | 15.8 |  |


| nervous or uncertain | 2 | 5.3 | 4.6 | 11.9 |
| :--- | :--- | :--- | :--- | :--- |

Table 15: Relative contribution of cognitive failures in "sudden-
braking" accidents

|  | \%definitely <br> causative | causative <br> cably | \%possibly <br> causative |  |
| :--- | :---: | :---: | :---: | :---: |
| Inattention | 9.2 | 16.4 | 16.4 | 42 |
| failure to judge others path <br> or speed | 15.1 | 7.9 | 6.6 | 29.6 |
| lack of judgement of own <br> path | 2.6 | 0 | 8.6 | 11.2 |
| look, but did not see | 0 | 2.6 | 5.9 | 8.5 |

Table 16: Relative contribution of tactical/strategic-level behaviour in
"sudden-braking" accidents

|  | \%definitely <br> causative | \%probably <br> causative | \%possibly <br> causative |  |
| :--- | :---: | :---: | :---: | :---: | :---: |
| following too close | 16.4 | 12.5 | 5.9 | 34.8 |
| excessive speed | 5.9 | 4.6 | 3.9 | 14.4 |

## Road user reaction

Taking into account how critical the human input is in the driver-vehicleroad environment system, road-user reaction is a necessary bit of information, very hard to extract accurately though. In "failure to stop" cases, almost half
the road users have no significant reaction as the accident phase commences (table 17).

Table 17: Percentage distribution of road users' reaction in "failure to stop" cases

|  | Frequency | Percent | Valid <br> Percent |
| :---: | :---: | :---: | :---: |
| No significant braking, steering or accelerating | 518 | 47.1 | 48.2 |
| Accelerated (also steering somewhat to the Right) | 9 | . 8 | . 8 |
| Steered Right (also Accelerating somewhat) | 3 | . 3 | . 3 |
| Steered Right without significant braking or acceleration | 10 | . 9 | . 9 |
| Steered Right (also Braking somewhat) | 13 | 1.2 | 1.2 |
| Braked (also steering somewhat to the | 29 | 2.6 | 2.7 |
| Right) |  |  |  |
| Braked without significant change in steering | 399 | 36.3 | 37.1 |
| Braked (also steering somewhat to the | 34 | 3.1 | 3.2 |
| Left) |  |  |  |
| Steered Left (also Braking somewhat) | 13 | 1.2 | 1.2 |
| Steered Left without significant braking or acceleration | 2 | . 2 | . 2 |


| Steered Left (also Accelerating | 3 | .3 | .3 |
| :--- | :--- | :--- | :--- |
| somewhat) | 12 | 1.1 | 1.1 |
| Accelerated (also steering somewhat to <br> the Left) | 25 | .5 | .5 |
| Accelerated without significant change in | 5 | 2.3 | 2.3 |
| steering | 25 | 97.8 | 100.0 |
| Unknown | 1075 | 2.2 |  |
| Total | 1099 | 100.0 |  |
| Missing System |  |  |  |

In "sudden braking" cases the proportion of road users that applied brakes is much greater than in the previous cases. Combined steering and braking inputs consist about $15 \%$ of reactions while steering only reactions are minimal (table 18).

Table 18: Percentage distribution of road users' reaction in "sudden braking" cases

|  | Frequency | Percent | Valid Percent |
| :--- | :---: | :---: | :---: |
| No sig brkng, strng or acc: | 37 | 24.3 | 24.7 |
| stayd clse to orig line or |  |  |  |
| curve |  |  |  |


| Steered Right (also | 2 | 1.3 | 1.3 |
| :--- | :--- | :--- | :--- |
| Braking somewhat) <br> Braked (also steering <br> somewhat to the Right) | 11 | 7.2 | 7.3 |
| Braked without significant | 92 | 60.5 | 61.3 |
| change in steering <br> Braked (also steering | 3 | 2.0 |  |
| somewhat to the Left) <br> Steered Left (also Braking <br> somewhat) | 1 | .7 | 2.0 |
| Steered Left without | 2 | 1.3 | 1.3 |
| significant braking or | 4 | 2.6 | 2.6 |
| acceleration | 152 | 100.0 | 100.0 |
| Unknown/missing data |  |  |  |
| Total |  |  |  |

## Discussion

Earlier in the introduction, the Emergency Brake Assist (EBA) system was presented, a system supposed to identify the instances when full-brake application is needed and avoid engaging when the need is not there. Failure to succeed on those two objectives leads to false-negatives and falsepositives. The dangerous consequence of a false-negative is the failure to stop the vehicle, when necessary to avoid collision. Respectively, the relevant
accident-case of a false-positive is a "sudden-braking" accident. Thus, the system function is pertinent to this type of accidents and its successful operation can mitigate these accidents. On the contrary, inaccurate engagement of the system can exacerbate the occurrence of this type of accidents. The results of the accident study indicated a few more patterns that should be taken into account when designing any active safety system.

Close following, as expected, was found as one of the common contributors to longitudinal control failures. More than 20\% in "failure to stop" and more than $24 \%$ contribution in sudden braking cases was attributed to road users' close-following behaviour. As following distance is not included in the system simulated in the previous chapter, there are two ways to account for that. Either the proposed adaptive brake system should incorporate a timeheadway parameter or it should be integrated with an ACC system. In both cases the notion is the same: "take into account headway". In practice one of them might be more practical.

The road user reaction data (tables 17-18) point out another limitation of the EBA system: even if the system adapts perfectly to the driver's braking input, almost half the road users involved in pertinent accidents do not use the brakes significantly (i.e. enough to be traced by the accident investigator). In application, this would mean that half the users that would need the system's intervention to avoid the collision or minimise its consequences, would not get it because they virtually do no have a brake input at all. On the other hand, braking is by far the most common driver/rider reaction, when there is any, both in "failure to stop" and in "sudden braking" cases (>90\% of reactions in both cases). This trend is in accordance to the results from an experimental
study testing driver reactions to imminent collisions (Muttart, 2005), however the extent of this trend is much wider in the present accident study.

The results on tables 17-18 additionally support the development of a valid design for the controlled road/ emergency test study that follows in chapter 6. As happened in the accident cases, it is expected that almost half the drivers will not brake significantly during the release of the trailer from the confederate vehicle on the closed track. The design of the empirical study will be influenced by the prevalence of rear-end collisions found in both "failure to stop" (65.3\%) and "sudden braking" cases (62.5\%; table 10). This is the type of collision risk the empirical study will attempt to replicate on the test track and is also the most typical collision associated to longitudinal control failures according to the accident data.

The second most common type of collision in "failure to stop" cases is collisions during crossing (table 6). This result points towards a brake system that should be particularly effective at junctions. It also supports the engagement of a braking system at traffic junctions, when the intention is to stop; any suggested technological solution should account for that. It will be interesting to see how future solutions will deal with this situation.

There is however a variety of collision types associated with sudden braking that cannot be directly accounted for by a brake system (table 10). Although still less common than in other types of accidents, overtaking, loss of control, and head-on collisions do happen as a result of sudden braking. Mitigation of such diverse type of accidents calls for the integration of longitudinal and lateral control safety systems.

The prevalence of car drivers as the road users involved in road accidents initiated by a longitudinal control failure (tables 8-9) influences the choice to use a car as the test vehicle for the road studies that follow. About $80 \%$ of road users involved in such accidents are car occupants. On the other hand, more than 15\% of road users involved in "sudden braking" cases are LGV and HGV occupants. There might be a need for follow-up studies of braking in commercial vehicles specifically. Another notable result of the road-user type analysis, is the limited involvement of pedestrians and cyclists (less than 3\% in aggregate), while manufacturers promote brake assist systems as particularly helpful targeting pedestrian accidents and contributing to the safety of sensitive road users (Breuer et al., 2007; Page, Foret-Bruno, \& Cuny, 2005). Sudden braking cases in particular have no involvement by pedestrians at all and the cyclists have same representation as bus occupants (2.6\%).

Special note should be made about the $5.9 \%$ of motorcyclists involved in "sudden braking" cases. The frequency is not unexpected per se, however careful examination of the cases indicated that all of them involved loss of control during heavy braking and had fatal results. They were also the only single-vehicle cases in both datasets.

The OTS causation system revealed a much more "psychological" profile for these accidents. The commonly quoted contribution of driver inattention and distraction (Harbluk, Noy, Trbovich, \& Eizenman, 2007/3; J. D. Lee, 2006) on compromised longitudinal vehicle control is here supported by accident data. Aggregating all three levels of confidence, $73.3 \%$ of road user interactions in "failure to stop" cases were influenced by inattention (table 12).

Also, other cognitive factors like failure to judge other paths and failure to look appears to have contribution over 25\% each (table 12). Cognitive factors have also strong impact on "sudden braking" cases (table 15). These are factors that cannot be associated directly or dealt with by a brake system. However, cognitive support is a promising area of driver support for the future.


Figure 25: Main characteristics of longitudinal control failures and conceptual remedies

The same applies to psycho-emotional factors that contribute to such accidents as indicated by tables 13-14. In "failure to stop", aggressive driving, urgency to get to the destination and recklessness in aggregate contribute to nearly $80 \%$ of road user interactions. In "sudden braking", recklessness, panic behaviour, aggressiveness and nervousness have aggregated contribution of over $80 \%$. All the above are strong contributory factors that cannot be directly addressed by the proposed adaptive braking system. On the contrary, a holistic approach is necessary (figure 25).

A successfully-specified brake assist system in conjunction with successfully specified ACC systems aims at the rear-end type of collision and the strong contribution of close-following behaviour conceptually. In addition, in the system simulation chapter (chapter 7), it will be examined whether an adaptive version of such system can identify the intention to stop before junctions and queued traffic. This trend of the system could mitigate longitudinal failures when crossing junctions (a common collision type, see table 6). However, even if the maximum potential of these systems is achieved, the psychological and cognitive factors cannot be addressed by the proposed system in chapter 6 or any other brake system engineered so far. Separate technologies and policies are needed.

The introduction of a "psycho-meter", a technology that would not allow upset, nervous, "day-dreaming" drivers to get a car moving and supplement a legislative policy on the matter. Of course, such technology does not exist, however there is a wealth of research in psychoneurology/neurobiology (e.g. Schneider, Burgess, Horton, \& Levine, 2009; Siever, 2008; S. N. Young, 2008) that can support the biochemical basis for the development of such technology. There is also a group of ergonomists with a special focus on neurobiology and technology (PIE.), with active research portfolio in the area.

The final major block of the driver support necessary, corresponds to cognitive support. The OTS accident data clearly suggested the importance of cognitive failures in the cases examined. It is therefore rational to argue for cognitive support technologies and policies. Specifically, drivers need enhancements that facilitate conspicuity, traceability of other road users, judgement of relative paths, and finally decision making. The significance of
cognitive support has been identified in previous studies, especially in accidents with senior driver involvement (Ball, 1997; McGwin Jr., Owsley, \& Ball, 1998; McGwin \& Brown, 1999). The significance is further increased by the growing population of senior-aged drivers in Europe, USA and Japan (L. Evans, 2004; G. D. Jacobs \& Aeron-Thomas, 2000). This is a promising area for the development of driver support technologies.

Overall, this chapter provided real-world data from accidents pertinent to the proposed adaptive brake system. Evidence was provided to support the design of the empirical studies that follow, but at the same time, the limitations in mitigating accidents through engineering braking systems in isolation were revealed. A more holistic approach, as described above, is necessary in order to target the multiple parameters in this type of accidents. On the other hand and although its limitations, systems like an effective EBA and systems like ACC target some of the major factors in longitudinal control failures and accidents. It is therefore worth developing them further and harmonising their functions according to human user's characteristics - as will be attempted throughout this Thesis.

## Summary

Chapter 4 presented the in-depth accident study of longitudinal control failures - accident cases pertinent to incorrect driver braking control. The accident-study provided the real-world reference for the empirical studies to follow. The road-user-interaction files from 3024 accident cases in Thames Valley and South Nottinghamshire regions of the UK, as covered by the OTS
study, were employed. The cases where "failure to stop" or "sudden braking" reaction was deemed as the precipitating factor of the accident were identified. First, the relevant contributory factors from the National Statistics (STATS19) data were examined. Results indicated a strong contribution of emotional and cognitive factors as well as the established perception that close-following behaviour contributes to longitudinal control failures. Then, the same analysis was repeated using the OTS causation form from the same accident cases. Contribution of cognitive failures and distraction was even more prominent in the OTS causation data. In addition, examination of driverreaction data indicated that about 50\% of the drivers do not engage significant braking during the course of an accident. Overall, results indicated the potential of headway-control and effective augmented braking technologies to address some of the contributory factors; however, significant part of the causation behind longitudinal failures requires alternative methods and technologies.

## Chapter 5: "Naturalistic braking" study ${ }^{3}$

As described in the methods chapter, the plan included a naturalistic study to provide a comparison for the quantitative data from the empirical studies and to confirm the validity of the methodology as a whole.

Furthermore, as established in the chapter on braking studies, it is obvious that no matter how much information is obtained on driver braking in specific instants regarding specific accident mitigation (Perron et al., 2001; Schmitt \& Färber, 2005), too little is known about how (qualitative) and how much (quantitative) people use braking systems while driving. To put it plainly, it looks like we know more about the ergonomics of "intelligent" brakes than we know about the ergonomics of brakes as they have been for almost a century. As Eaton and Dittmeier (1970) suggested that "the wealth of reported data on human efforts on foot and hand controls" may explain the limited number of study on the ergonomics of braking and steering controls, we could say that today the amount of interest in "intelligent", "future", "active", "autonomous" longitudinal control is to be partially blamed for the limited interest in basic ergonomic aspects of the controls as they stand. Studies like Perron et al. (2001) and Schmitt \& Färber (2005) provided a lot of information about how drivers operate the pedals to avoid an obstacle during an emergency event, however little can be inferred about how drivers typically interact with the pedals during their daily trips. In such studies, the "normal" trend is inferred

[^3]from the participants' braking in a closed road-section right before the emergency event. A similar approach was used in the empirical study described in the next chapter. The assumption that such an approach covers the whole spectrum of driver braking within such limited time and space is arguable. Therefore, data is needed which can be directly associated to drivers' routine braking.

Closest to "natural" is "naturalistic". Although collecting real-time data from drivers while driving their own cars to their own destinations (natural) was beyond the resources of the current research, using an instrumented vehicle that is given out to drivers and driven for a limited period was possible. As quoted in the "methods" chapter, evolution of data collection technology has made it possible for such methodologies to be used in driver safety research. With a few limitations, it is now possible for such a study to be carried out within the frame of a PhD course, if the right amount of resources to plan, prepare, build/install, and commence is available. The study that follows testifies this.

Thirty fully-licensed drivers drove an instrumented car for a day. The types of trip analysed included commuting to work, shopping, and picking up children from school. Measures taken included throttle-pedal angle, brakepedal pressure, and clutch pedal pressure. The foot well was constantly video recorded during each trip. This chapter presents the naturalistic braking study in detail.

## Aims

The main aim of the study was to provide evidence in regards to the nature of "normal" driver braking input and tackle the respective research question of the thesis. In parallel, the study is expected to provide evidence with regards to the validity of other more limited on-road studies of braking. Thus, further studies will be able to examine in-depth more variables within a controlled environment and still have a point of reference regarding their ecological/external validity. In line with this, as described in the Methods chapter, a naturalistic study is included in the research-plan for the ecological/external validity of the research presented in the Thesis as a whole.

## Design

## The variables of interest

The dependent variables of interest were the sequence of quantitative parameters of driver's input to the brake-pedal, starting from the speed by which the throttle-pedal is released (expressed in degrees/sec), to the time it takes for the foot to move between throttle and brake-pedal and finally the input to the brake pedal itself. The latter measured both in terms of the speed by which the pedal moves at the beginning of its movement and the force which is applied on the surface of the pedal itself.

## Apparatus

Any study of drivers in a "naturalistic" environment, requires the employment of at least one instrumented vehicle. This is a vehicle fitted with sensors that monitor the driving variables of interest. The same vehicle and similar equipment as for the "Controlled Road Study" (chapter 6) were employed. The equipment in detail:

- A video camera (Microsoft® Litecam VX-1000) was fixed in the footwell to record feet/pedal movements (figure 26).


Figure 26: The position of the VX-1000 in the nearside of driver's footwell.

- A potentiometer was fixed at the centre of the throttle-axis rotation (figure 27) to record throttle depression/release. Speed of throttle release or "throttle-off" was recorded in terms of the change in angle at 0.02 sec intervals. This measurement provided the rate by which the angle changed over a period time (e.g. during release).


Figure 27: The potentiometer at the centre of rotation (throttle pedal)

- Two Tekscan Flexiforce ${ }^{\circledR}$ pressure/force sensors were attached on the surface of the brake pedal and concealed by the rubber cover (figure 28). As the cost for a customised pressure sensor was beyond the financial resource of the study, Two smaller sensors were employed, one at the top-half of the surface and one at the bottom-half. Thus, the total force/pressure on the surface could be extrapolated by the data from those two sensors.
- An additional pressure/force pad was attached on the surface of the clutch pedal and concealed by its rubber cover. Flexiforce ${ }^{\circledR}$ sensors were calibrated and conditioned according to Tekscan guidelines (Tekscan, 2008). Clutch-pedal inputs were measured
as per previous pedal operation studies (Kassaagi, 2001;
Bouslimi, 2005).


Figure 28: The layout of the force sensors on the brake pedal

A U12 Labjack® Data Acquisition card in conjunction with a Toshiba Tecra 3 laptop using the Data Acquisition Factory Express® software were used for data logging (figure 29). The laptop was hidden underneath the passenger's seat. The instrumentation had no visible or tangible alterations to the foot-well.


Figure 29: Parts of the vehicle instrumentation

## The sample

30 drivers were recruited through adverts in the local press and posters around the Loughborough University Campus. The advertising media invited volunteers to contact the experimenter for the opportunity to "own a car with free fuel for a day". Participants had to be at least 21 years of age and have less than 6 penalty-points on their driving license to be eligible to drive a University-vehicle, able-bodied and have no history of serious illness (stroke, heart-disease etc). Seventeen of them were male and twelve were female drivers, while one of them preferred not to declare their gender. Age ranged between 24 and 60 years (figure 30 ) and driving experience between 4 and

41 years (figure 31). Their annual mileage ranged from 1000 to 30000 miles (mean=8 178.6 miles) and two of them had 3 points on their driving license (mean=0.21). Two drivers did not report age. Overall, the sampling strategy did not intend to favour any driver group within the vicinity of Loughborough in particular. In practice however, participation was more convenient to drivers based near the University Campus or somehow associated with it (in order to hear about the study). National data available for comparison are limited to drivers' age (DVLA, 2007). In comparison to the sample, the national fullylicensed driver population exhibits similar mean age (41 against 39 years), but wider spread (SD is 14 years against 10 years in the sample). The latter is not surprising, as the general population includes many drivers over 60 years and below 21 years of age.


Figure 30: The age distribution of the sample


Figure 31: The driving experience distribution of the sample (in years)

Drivers' size is one of the variables reported to affect posture and the way in which they interact with the vehicle environment and controls (Porter \& Gyi, 1998). Stature ranged between 158 cm and 195 cm (figure 32 ) and weight ranged between 58 kg and 93 kg (figure 33). Distributions were "normal-like" and the range matches the $5^{\text {th }}$ female to $95^{\text {th }}$ male percentile stature and weight range (with some corrections for secular growth) quoted by Pheasant (1996).


Figure 32: Height distribution among participants

The sample benefited from the multi-cultural nature of the local
community and consisted of 5 different nationalities. 17 participants declared English nationality, and 7 other identified themselves as non-English British. 2 participants were Turkish, 1 Chinese and 1 Greek. 2 participants choose not to report nationality.


Figure 33: Weight distribution among participants (kg)

## The protocol

The insurance for the study would only cover drivers with less than 6 penalty points on their driving license. This effectively restricted the eligible drivers to those who had up to 3 points on their license. Those eligible were required to provide a copy of the paper counterpart of their license and complete the insurer's form before the study commenced. Additional paperwork included the demographics form, the information sheet and the consent form that had to be completed in advance. A date was then arranged during which the participant would effectively "own" the vehicle. On the day, the vehicle would be delivered early in the morning to the address of the
participant. The participant would use the vehicle as preferred during the day. A confederate to the study would collect the vehicle during the evening.

Participants had almost absolute freedom in terms of the journeys they made and the routes they chose to follow. However, the location of their home and its relationship to Loughborough provided an estimate of the main area within which the trips would likely take place (figure 34). The area includes A-roads, B-roads, motorways and urban road sections.


Figure 34: The main area of driving according to home and work locations

## Data analysis

Throughout each day, pedal operation in terms of throttle pedal movement, brake-pedal force, clutch-pedal force through the sensors and feet
movements through the video were recorded. All data was saved in the laptop's hard disk and was then analysed using Statistics Package for Social Sciences (SPSS®) version 15, and Microsoft® Excel. Descriptive statistics, gender differences, intra-personal differences and correlations of braking parameters were examined. For the video analysis, 11 randomly selected braking sequences per participant were examined. The scenes examined were randomly selected to satisfy typical sampling criteria (Coolican, 2009). In addition, it was expected that video analysis would offer the ability to identify qualitative characteristics of braking, otherwise untraceable.

The rationale behind this selection is in accordance to previous braking studies (Bouslimi et al., 2005; Eaton \& Dittmeier, 1970; Kassaagi, 2001; Schmitt \& Färber, 2005), which saw the variables of pedal movement and force as the predominant descriptors of driver braking operation. Compared to those studies, the additional element of video recording could provide secondary information on parameters that could not be measured through the other sensors. All these variables can provide the basic characteristics of "normal" braking, as requested by the first research question.

To explore general properties and quantitative characteristics of naturalistic driver braking, descriptive statistics will be used. Such statistics indicate the concentration, the spread and the shape of the distribution of each variable examined. Those parameters may yield a statistical definition of "normal" driver braking. In addition, correlation-analysis will be employed to examine interactions between variables. Thus, the quantitative interactions between variables will be revealed.

## Results

Table 19: Summary of main results

|  | Typicar ${ }^{\text {? }}$ <br> force on <br> lower brake <br> sensor ( $N$ ) | Typical force on upper brake sensor (N) | Typical <br> force on <br> clutch <br> sensor ( $N$ ) | Typical angle change, <br> throttle pedal <br> (deg/0.02sec) | Estimated <br> force on <br> brake <br> pedal ( $N$ ) |
| :---: | :---: | :---: | :---: | :---: | :---: |
| N | 28 | 21 | 28 | 28 | 29 |
| Mean | 6.5317 | 8.2359 | 58.3797 | . 5402 | 140.774 |
| Median | 4.2881 | 4.7429 | 24.6723 | . 5394 | 85.558 |
| Std. Deviation | 5.92062 | 8.13111 | 62.01004 | . 01255 | 124.7026 |
| Percentiles 1 | 2.1522 | 2.2000 | 2.4960 | . 4984 | 43.044 |
| 5 | 2.2584 | 2.2000 | 2.6765 | . 5124 | 45.37 |
| 95 | 25.2519 | 31.1325 | 181.5245 | . 5662 | 508.948 |
| 99 | 29.8536 | 32.2529 | 193.6403 | . 5730 | 621.066 |

Table 19 summarises the main results of the study. 28 participants had an input on the lower brake pedal sensor, while 2 participants did not use this area of the brake pedal at all. Mean force input was 6.53 newtons, median was 4.28 and the standard deviation was 5.92 newtons. Estimated first, fifth, ninety-fifth and ninety-ninth percentile was $2.15,2.25,25.25$ and 29.85 newtons respectively. Fewer people used the upper area of the brake pedal (21 persons). Nine drivers had no input to the upper brake pedal sensor. The average input though was stronger than on the lower sensor ( 8.23 newtons). The standard deviation was 8.13 and the median value was 4.74 , relatively close to the lower-sensor median. Due to a disconnected wire, data from the clutch-pedal sensor was not collected in two cases. In the 28 cases

[^4]remaining, average typical input on the clutch-pedal sensor was 58.38 newtons, the median was 24.67 newtons and the standard deviation was 62.01. The estimated $1^{\text {st }}$ percentile was 2.5 newtons, the $5^{\text {th }}$ percentile was 2.68 newtons, the $95^{\text {th }}$ percentile was 181.52 newtons and the $99^{\text {th }}$ percentile was 193.64 newtons. A similar problem with the wiring influenced throttlepedal data acquisition in the first two days. Therefore, reliable data from 28 participants were collected. Average throttle-off angle change at 50 Hz sampling rate was just over half a degree (0.54). The median was quite close to that -0.54 - and the standard deviation quite smaller at 0.01 degrees. The estimated percentiles were $0.5,0.51,0.57$ and 0.57 for $1^{\text {st }}, 5^{\text {th }}, 95^{\text {th }}$ and $99^{\text {th }}$ percentile respectively. Regarding the estimated force applied on the full brake-pedal surface, there was an interesting result with one driver, who almost didn't use the brake pedal at all or at least below the 2 newton/sensor criterion during sensor-noise cleaning. The average for the other 29 drivers was 140.77 newtons, the median value was 85.56 newtons and the standard deviation was 124.7 newtons. The estimated first percentile value was 43.04 newtons, the fifth percentile was 45.37 , the ninety-fifth percentile was 508.95 newtons and the ninety-ninth percentile was 621.07 newtons.


Figure 35: The distribution of typical force inputs on the lower brake-pedal sensor (newtons)

The distribution of typical inputs to the lower pedal-sensor as can be seen on figure 35 looks rather skewed towards its lower bound. Thus a Kolmogorov -Smirnov test was employed to test for normality (table 20). Additionally, as its shape suggested an exponential distribution, an additional K-S test commenced (table 21). The results showed asymptotic significance above a typical 0.05 criterion ( $p=0.12$ ) for normality, thus it cannot be assumed that the distribution is not normal, while the asymptotic significance for an exponential distribution was below the 0.05 criterion ( $p=0.03$ ). This result allows for assumption that the distribution is not exponential.


Figure 36: Distribution of typical force inputs on the upper brake sensor (newtons)

The distribution of typical inputs to the upper pedal-sensor, as can be seen on figure 36, looks skewed towards its lower bound. A Kolmogorov-Smirnov test was employed to test for normality (table 20). Additionally, as its shape looks much like an exponential distribution, an additional K-S test commenced (table 21). The results showed asymptotic significance above a typical 0.05 criterion ( $p=0.06$ ) for normality, thus it cannot be assumed that the distribution is not normal. Regarding comparison to an exponential distribution, results showed an asymptotic significance above the 0.05 criterion ( $p=0.22$ ), thus it cannot be assumed that the distribution is not exponential either.


Figure 37: The distribution of typical force inputs on the clutch pedal sensor (newtons)

The distribution of typical inputs to the clutch pedal-sensor as can be seen on figure 37 looks rather skewed towards its lower bound. Thus a Kolmogorov -Smirnov test was employed to test for normality (table 20). Additionally, as its shape looks very much like an exponential distribution an additional K-S test commenced (table 21). The results showed asymptotic significance below a typical 0.05 criterion $(p=0.02)$ for normality, thus it can be assumed that the distribution is not normal. The asymptotic significance for an exponential distribution was above the 0.05 criterion $(p=0.17)$, thus it cannot be assumed that the distribution is not exponential.


Figure 38: The distribution of typical throttle-off rate (deg/0.02sec)

The distribution of typical throttle-off rate as can be seen on figure 38 looks normal with a few gaps in data near its bounds. A Kolmogorov-Smirnov test was employed to test for normality (table 20). Additionally, although its shape does not look very much like an exponential distribution, it was included in the additional K-S test (table 21). The results showed asymptotic significance above a typical 0.05 criterion ( $p=0.33$ ) for normality, thus it cannot be assumed that the distribution is not normal. The asymptotic significance for an exponential distribution was below the alpha criterion ( $p=0.0001$ ), suggesting very low probability that the distribution could correspond to an exponential one.


Figure 39: Distribution of average force inputs between both brake pedal sensors (newtons)

The distribution of combined typical forced inputs on both brake-pedal sensors as can be seen on figure 39 looks rather skewed towards its lower bounds. Thus a Kolmogorov -Smirnov test was employed to test for normality (table 20). Additionally, as its shape looks like an exponential distribution an additional K-S test commenced (table 21). The results showed asymptotic significance above a typical 0.05 criterion ( $p=0.15$ ) for normality, thus it cannot be assumed that the distribution is not normal. The asymptotic significance for an exponential distribution was on the alpha criterion $(p=0.05)$, thus it can be assumed that the distribution is not exponential.

Table 20: One-Sample Kolmogorov-Smirnov Test (normal)

|  | Average force input to lower brake sensor | Average force input to upper brake sensor | Average force input to clutch sensor | Average angle change rate | Mean force between sensors |
| :---: | :---: | :---: | :---: | :---: | :---: |
| N | 28 | 22 | 28 | 28 | 29 |
| Normal Mean | 6.67 | 8.70 | 58.38 | . 54 | 7.38 |
| Parameters(a,b) Std |  | 8.70 | 58.38 | . 54 | 7.38 |
| Std. <br> Deviation | 5.96 | 8.23 | 62.01 | . 013 | 6.36 |
| Most Extreme Absolute | . 225 | . 280 | . 286 | . 180 | . 213 |
| Positive | . 210 | . 280 | . 286 | . 180 | . 213 |
| Negative | -. 225 | -. 215 | -. 184 | -. 176 | -. 206 |
| Kolmogorov-Smirnov Z | 1.19 | 1.31 | 1.52 | . 950 | 1.15 |
| Asymp. Sig. (2-tailed) | . 119 | . 064 | . 020 | . 327 | . 145 |

a Test distribution is Normal.
b Calculated from data.

Table 21: One-Sample Kolmogorov-Smirnov Test (exponential)

|  | Average force input to lower brake sensor | Average force input to upper brake sensor | Average force input to clutch sensor | Average angle change rate | Mean force between sensors |
| :---: | :---: | :---: | :---: | :---: | :---: |
| N | 28 | 22 | 28 | 28 | 29 |
| Exponential Mean parameter. $(\mathrm{a}, \mathrm{b})$ | 6.67 | 8.70 | 58.38 | . 540 | 7.38 |
| Most Extreme Absolute | . 276 | . 223 | . 210 | . 603 | . 253 |
| Positive | . 125 | . 157 | . 210 | . 346 | . 077 |
| Negative | -. 276 | -. 223 | -. 170 | -. 603 | -. 253 |
| Kolmogorov-Smirnov Z | 1.46 | 1.05 | 1.11 | 3.19 | 1.36 |
| Asymp. Sig. (2-tailed) | . 028 | . 222 | . 168 | . 000 | . 049 |

a Test Distribution is Exponential.
b Calculated from data.

## Gender differences

Table 22 presents the gender group statistics of the main variables plus two variables for intra-personal variance (SD of brake pedal force and SD as percentage of brake pedal force). Average force input to the lower brakepedal sensor was 7 newtons and the standard deviation was 7.36 newtons for male drivers. For female drivers, the mean was 6.16 newtons and the
standard deviation was 3 newtons. Average force input to the upper brakepedal sensor was 11.26 newtons for males and 6 newtons for female drivers. The respective standard deviations were 10.2 and 3.42 newtons. On the clutch-pedal sensor, average inputs were 57.35 newtons for male and 59.75 newtons for female drivers. The relevant standard deviations were 61.09 newtons for the male and 65.93 newtons for the female group. Regarding throttle-off, average release-rate for both gender groups was 0.54 degrees $/ 0.02 \mathrm{sec}$, while standard deviations were 0.02 for male and 0.01 degress/0.02sec for female drivers. Combining input from both sensors on the brake pedal, the mean for male drivers was 8.06 newtons and the standard deviation was 7.95 newtons. For female drivers the mean was 6.4 newtons and the standard deviation was 3.05 newtons.

Table 22: Group statistics for gender
$\left.\begin{array}{l|lrrrr}\hline & \text { gender } & N & & \text { Mean } & \text { Std. Deviation }\end{array} \begin{array}{c}\text { Std. Error } \\ \text { Mean }\end{array}\right]$

Looking at intra-personal differences, "SD of brake pedal force" is the standard deviation of the force inputs on the brake pedal sensors during each driver's day. This provides an indication of the variation in each driver's
braking. The "SD as a percentage of brake pedal force" variable is the proportionate comparison between the "SD of brake pedal force" and the mean for each driver's day. For male drivers, the mean SD for brake-pedal force was 8.2 newtons, and the standard deviation of this measure was15.03 newtons. For the female group, mean SD for brake-pedal force was 4.12 newtons and the standard deviation of this, 3.03 newtons. The SD as percentage to the average brake pedal force was $58.64 \%$ for male drivers ( $\mathrm{SD}=55.57 \%$ ) and $58.9 \%$ for female drivers ( $\mathrm{SD}=29.83 \%$ ). Intra-personal differences are further examined in the next section of the results.

Table 23: Independent samples T-test for gender groups

|  | Levene's Test for Equality of Variances |  | t-test for Equality of Means |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | F | Sig. | t | df | Sig. (2-tailed) |
| Average |  |  |  |  |  |
| force input to | 2.18 | . 152 | . 355 | 26 | . 725 |
| lower brake sensor |  |  |  |  |  |
| Average |  |  |  |  |  |
| force input to | 19.59 | . 000 | 1.677 | 14.11 | . 116 |
| upper brake sensor |  | . 00 |  | 14.1 | .16 |
| Average |  |  |  |  |  |
| force input to | . 052 | . 821 | -. 099 | 26 | . 922 |
| clutch sensor |  |  |  |  |  |
| Average |  |  |  |  |  |
| throttle angle change rate | 538 | 470 | -. 575 | 26 | . 570 |
| change rate Mean force |  |  |  |  |  |
| between | 5.96 | . 022 | . 782 | 21.99 | 442 |
| sensors |  |  |  |  |  |
|  |  |  |  |  |  |
| pedal force | 4.11 | . 052 | . 923 | 27 | . 364 |
| SD as |  |  |  |  |  |
| percentage |  |  |  |  |  |
| of mean | 2.57 | . 120 | -. 015 | 27 | . 989 |
| brake pedal |  |  |  |  |  |
| force |  |  |  |  |  |

Table 23 presents the results of independent samples T-test for differences between the two gender groups. Regarding average force input to
the lower brake sensor, Levene's test indicated that equal variances between the two groups can be assumed. Thus, for 26 degrees of freedom (df), the resulted $t$-value of 0.35 has statistical significance $p=0.73$ (>alpha=0.05). For inputs to the upper brake-pedal sensor, Levene's test indicated that equal variances cannot be assumed. According to Levene's test, df were corrected to 14.11 in order to account for that. With this amount of df the $t$-value of 1.68 had statistical significance $p=0.12$ (>alpha=0.05). Regarding inputs to the clutch-pedal sensor, Levene's test indicated equal variances between groups and the full df were used. For $\mathrm{df}=26$ the t -value of 0.09 has a significance of $92.2 \%$ (>alpha=0.05). Comparison of throttle-off rate between genders provided a t-value of 0.58 , which for 26 (full) df had significance $p=0.57$. Regarding combined inputs from both brake-pedal sensors, Levene's test indicated inequality of variance between groups, thus df were corrected to 22 . For these df, the $t$-value of 0.78 had significance $p=0.44$. Levene's test for equality of variance between groups indicated that for SD of brake pedal force and SD as percentage of mean brake-pedal force exhibited equal variance between the two gender groups. For $\mathrm{df}=27$, SD of brake pedal force had $t=0.92, p=0.36$ and $S D$ as percentage of mean brake-pedal force had $t=(-$ $) 0.02$ and $p=0.99$. Overall comparative analysis did not provide statistically significant values low enough to satisfy the typical alpha=0.05 criterion.

## Intra-personal differences

Table 24 presents statistics regarding the intra-personal variation in the pedal-operation parameters measured. The standard deviation against the mean value for the brake-pedal inputs of each individual driver ranged
between $4 \%$ and 199\%. The mean percentage was $58.75 \%$. For the lower section of the brake pedal, the range was between $4 \%$ and $201 \%$, with a mean of $57.96 \%$. For the upper brake pedal section, the standard deviation of the force applied to the sensor ranged between 0\% and 198\% of the mean value per driver. The mean percentage was $52.55 \%$. Regarding throttle-off rate, SD as proportion of mean throttle-off rate per driver ranged between 0 and $21 \%$. The mean percentage was $9.63 \%$. As for force on the clutch pedal sensor, SD ranged between $1 \%$ and $1880 \%$ of the mean clutch pedal input per driver. Overall, with the exception of throttle-off, these results suggest intra-personal variations and differences.

Table 24: Descriptive statistics of intra-personal differences

|  | $N$ | Range | Minimum | Maximum | Mean |
| :--- | :---: | :---: | :---: | :---: | :---: |
| SD as proportion of <br> mean brake pedal force | 29 | 1.95 | .04 | 1.99 | .5875 |
| SD as proportion of <br> mean brake pedal force <br> at lower section | 27 | 1.97 | .04 | 2.01 | .5796 |
| SD as proportion of <br> mean brake pedal force <br> at upper section | 19 | 1.98 | .00 | 1.98 | .5255 |
| SD as proportion of <br> mean throttle-off rate | 28 | .20 | .00 | .21 | .0963 |
| SD as proportion of <br> mean clutch pedal force <br> Valid $N$ (listwise) | 28 | 18.80 | .01 | 18.80 | 1.6391 |

Correlations

Table 25: Correlation parameters between demographic data

\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline \& \& age \& $$
\begin{gathered}
\text { experienc } \\
e
\end{gathered}
$$ \& Annual mileage \& Licence points \& height \& weight <br>
\hline age \& Pearson Correlation Sig. (2tailed) N \& 1
28 \& $$
\begin{array}{r}
.920(\star \star) \\
.000 \\
28
\end{array}
$$ \& $$
\begin{array}{r}
-.147 \\
.455 \\
28
\end{array}
$$ \& $$
\begin{array}{r}
-.059 \\
.767 \\
\\
28
\end{array}
$$ \& $$
\begin{array}{r}
-.333 \\
.084 \\
28
\end{array}
$$ \& $$
\begin{array}{r}
-.010 \\
.962 \\
28
\end{array}
$$ <br>
\hline experience \& Pearson Correlation Sig. (2tailed) N \& $$
\begin{array}{r}
\hline .920(\star \star) \\
.000 \\
28
\end{array}
$$ \& 1
28 \& $$
\begin{array}{r}
\hline .109 \\
.580 \\
28
\end{array}
$$ \& $$
\begin{array}{r}
.004 \\
.984 \\
28
\end{array}
$$ \& $$
\begin{array}{r}
-.158 \\
.421 \\
28
\end{array}
$$ \& .097
.625
28 <br>
\hline Annual mileage \& Pearson Correlation Sig. (2tailed) N \& $$
\begin{array}{r}
-.147 \\
.455 \\
28
\end{array}
$$ \& $$
\begin{array}{r}
-.109 \\
.580 \\
28
\end{array}
$$ \& 28 \& -.126
.523
28 \& $$
\begin{array}{r}
\hline .468\left(^{*}\right) \\
.012 \\
28
\end{array}
$$ \& .218
.264
28 <br>
\hline Licence points \& Pearson Correlation Sig. (2tailed) N \& $$
\begin{array}{r}
\hline .059 \\
.767 \\
28
\end{array}
$$ \& $$
\begin{array}{r}
.004 \\
.984 \\
28
\end{array}
$$ \& $$
\begin{array}{r}
\hline .126 \\
.523 \\
28
\end{array}
$$ \& 1
28 \& $$
\begin{array}{r}
-.100 \\
.611 \\
28
\end{array}
$$ \& -.241
.217
28 <br>
\hline height \& Pearson Correlation Sig. (2tailed) N \& $$
\begin{array}{r}
-.333 \\
.084 \\
28
\end{array}
$$ \& $$
\begin{array}{r}
\hline .158 \\
.421 \\
28
\end{array}
$$ \& $$
\begin{array}{r}
\hline .468\left(^{*}\right) \\
.012 \\
28
\end{array}
$$ \& $$
\begin{array}{r}
-.100 \\
.611 \\
28
\end{array}
$$ \& 1
28 \& $$
\begin{array}{r}
.651(\star \star) \\
.000 \\
28
\end{array}
$$ <br>
\hline weight \& Pearson Correlation Sig. (2tailed) N \& -.010
.962
28 \& .097
.625

28 \& .218
.264
28 \& -.241
.217

28 \& $$
\begin{array}{r}
\hline .651\left({ }^{\star \star}\right) \\
.000 \\
28
\end{array}
$$ \& 1

28 <br>
\hline
\end{tabular}

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Exploration of correlations (Pearson's R) between variables showed some predictable relationships. Table 25 shows the correlation parameters between demographic data. Age and driving experience shared a correlation of $92 \%$, which for $\mathrm{N}=28$, has statistical significance $\mathrm{p}<0.0001$. Correlations between age and the rest of the other variables (mileage, license points, height and weight) did not satisfy the typical alpha= 0.05 criterion of statistic significance. The same applied between driving experience and the other variables. Annual mileage exhibited a $46.8 \%$ correlation with driver's stature. The correlation
had $p=0.01$ statistic significance, which is below the critical alpha 0.05 level.
Other than this, annual mileage did not exhibit any correlation with other variables that satisfies the statistic significance criterion. Similarly, license points had no correlation with other variables that could satisfy this criterion.

Apart from the aforementioned correlation between annual mileage and driver's height, height had another correlation that satisfied the $5 \%$ criterion for statistical significance. Correlation with weight was $65.1 \%$, which has 0.0001 statistic significance for $\mathrm{N}=28$. Neither driver's height nor weight had any other correlation that satisfied the criterion for statistical significance with another demographic variable.

Table 26: Correlations between demographic and main pedal operation variables

|  |  | Average force input to lower brake sensor | Average force input to upper brake sensor | Average force input to clutch sensor | Average angle change rate | Mean force between sensors | SD of brake pedal force | SD as percent age of brake pedal force |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| age | Pearson Correlatio n | -. 247 | -. 371 | . 196 | -. 058 | -. 278 | -. 282 | -. 123 |
|  | Sig. (2tailed) | . 215 | . 108 | . 327 | . 778 | . 152 | . 146 | . 534 |
|  | N | 27 | 20 | 27 | 26 | 28 | 28 | 28 |
| experience | Pearson Correlatio n | -. 228 | -. 319 | . 222 | -. 020 | -. 254 | -. 263 | -. 158 |
|  | Sig. (2tailed) | . 252 | . 171 | . 265 | . 921 | . 192 | . 176 | . 421 |
|  | N | 27 | 20 | 27 | 26 | 28 | 28 | 28 |
| Annual mileage | Pearson Correlatio n | -. 340 | . 061 | -. 041 | -. 099 | -. 142 | -. 194 | -. 267 |
|  | Sig. (2tailed) | . 083 | . 799 | . 840 | . 631 | . 471 | . 323 | . 169 |
|  | N | 27 | 20 | 27 | 26 | 28 | 28 | 28 |
| Licence points | Pearson Correlatio n | -. 127 | -. 012 | -. 211 | . 238 | -. 110 | -. 091 | -. 034 |
|  | Sig. (2tailed) | . 528 | . 959 | . 292 | . 242 | . 578 | . 645 | . 865 |
|  | N | 27 | 20 | 27 | 26 | 28 | 28 | 28 |
| height | Pearson Correlatio n | -. 085 | . 147 | . 030 | -. 225 | . 008 | . 053 | -. 039 |
|  | Sig. (2tailed) | . 673 | . 536 | . 884 | . 270 | . 969 | . 790 | . 842 |


|  | $N$ | 27 | 20 | 27 | 26 | 28 | 28 | 28 |
| :--- | :--- | ---: | ---: | ---: | ---: | ---: | ---: | ---: |
| weight | Pearson <br> Correlatio | -.013 | .196 | -.008 | $-.433\left(^{*}\right)$ | .039 | .062 | .098 |
|  | n |  |  |  |  |  |  |  |
|  | Sig. (2~ <br> tailed) | .950 | .407 | .969 | .027 | .845 | .754 | .619 |
|  | N | 27 | 20 | 27 | 26 | 28 | 28 | 28 |

* Correlation is significant at the 0.05 level (2-tailed).

Correlation-analysis between main pedal-operation variables and demographics showed only one interaction that satisfied the criterion for statistic significance (table 26). A negative correlation of $43.3 \%$ between weight and average throttle-off rate was found. The associated statistical significance was $p=0.03$. Other demographics did not exhibit any correlation with variables of pedal operation that satisfied the alpha $=0.05$ criterion for statistical significance.

Correlation analysis between the main variables of pedal operation revealed multiple correlations that satisfy the criterion for statistical significance (table 27). Average force inputs to lower and upper brake-pedal sensors had an R correlation of $84 \%$, statistically significant below the $p=0.0001$ level. Average force input to the lower brake-pedal sensor shared $54.8 \%$ correlation with the average throttle-off rate, $95.2 \%$ correlation with the mean force between both brake-pedal sensors, $95 \%$ correlation with the SD of brake pedal force and $80.5 \%$ of the SD as percentage of the mean brake pedal force. All these correlations satisfy a 0.01 criterion for statistical significance. Similarly, force input to the lower brake-pedal sensor had 75.9\% correlation with throttle-off rate, $96.8 \%$ correlation with mean force between both brake-pedal sensors, $83.8 \%$ correlation with SD of brake pedal force and $75.5 \%$ correlation with SD as percentage of mean brake pedal force. All these correlations were statistically significant at least at $p=0.001$ level. Average
input to the clutch-pedal sensor did not show any strong correlations with the rest of the variables. Throttle-off rate though, showed additional correlations that satisfy criteria of 0.05 and 0.01 for statistical significance. Correlation with mean force between the two brake-pedal sensors was $63.8 \%$, statistically significant at $p=0.0001$ level. Correlation with SD of brake-pedal force was $49.3 \%$, significant at $p=0.009$ level. Correlation with SD as percentage of typical brake pedal force was $46.5 \%$, statistically significant below 0.05 $(p=0.015)$. Mean force between the two brake-pedal sensors exhibited additional correlations with SD of brake-pedal force and SD as percentage of brake pedal force $-92.4 \%$ and $77.1 \%$ respectively. Both correlations satisfy the 0.01 criterion for statistical significance. Unsurprisingly, the correlation between the two indicators of intra-personal differences (SD of brake-pedal force and SD as percentage of that force) shared a correlation of $85.1 \%$, statistically significant below 0.001 .

Table 27: Correlations between main variables of pedal operation

\begin{tabular}{|c|c|c|c|c|c|c|c|c|}
\hline \& \& Average force input to lower brake sensor \& Average force input to upper brake sensor \& Average force input to clutch sensor \& Average angle change rate \& Mean force between sensors \& SD of brake pedal force \& SD as percent age of brake pedal force <br>
\hline \multirow[t]{2}{*}{Average force input to lower brake sensor} \& Pearson Correlatio n \& 1 \& .840(**) \& -. 002 \& .548(*) \& .952(**) \& .950(**) \& .805(**) <br>
\hline \& Sig. (2tailed) N \& 28 \& .000

20 \& .993

27 \& .004
26 \& .000

28 \& .000
28 \& .000
28 <br>
\hline \multirow[t]{2}{*}{Average force input to upper brake sensor} \& Pearson Correlatio n \& .840(**) \& 1 \& -. 031 \& .759(*) \& .968(**) \& .838(**) \& .755(**) <br>
\hline \& Sig. (2tailed) N \& .000
20 \& 21 \& .894
21 \& .000
21 \& .000
21 \& .000
21 \& .000
21 <br>
\hline \multirow[t]{2}{*}{Average force input to clutch sensor} \& Pearson Correlatio n \& -. 002 \& -. 031 \& 1 \& -. 082 \& -. 034 \& . 036 \& -. 176 <br>
\hline \& Sig. (2tailed) N \& .993
27 \& .894
21 \& 28 \& .686
27 \& .862
28 \& .855

28 \& .371
28 <br>
\hline \multirow[t]{2}{*}{Average angle change rate} \& Pearson Correlatio n \& .548(**) \& .759(**) \& -. 082 \& 1 \& .633(**) \& .493(**) \& .465(*) <br>
\hline \& Sig. (2tailed) N \& .004
26 \& .000
21 \& .686
27 \& 28 \& .000
27 \& .009
27 \& .015

27 <br>
\hline \multirow[t]{2}{*}{Mean force between sensors} \& Pearson Correlatio n \& .952(**) \& .968(**) \& -. 034 \& .633(**) \& 1 \& .924(**) \& .771(**) <br>
\hline \& Sig. (2tailed) N \& .000
28 \& .000
21 \& .862
28 \& .000
27 \& 29 \& .000

29 \& .000
29 <br>
\hline \multirow[t]{2}{*}{SD of brake pedal force} \& Pearson Correlatio n \& .950(**) \& .838(**) \& . 036 \& .493(**) \& .924(**) \& 1 \& .851(**) <br>
\hline \& Sig. (2tailed) N \& .000

28 \& .000
21 \& .855

28 \& .009
27 \& .000

29 \& 29 \& .000

29 <br>

\hline \multirow[t]{2}{*}{$$
\begin{aligned}
& \text { SD as } \\
& \text { percent } \\
& \text { age of } \\
& \text { brake } \\
& \text { pedal } \\
& \text { force }
\end{aligned}
$$} \& Pearson Correlatio n \& .805(**) \& .755(**) \& -. 176 \& .465(*) \& .771(**) \& .851(**) \& 1 <br>

\hline \& Sig. (2tailed) N \& .000
28 \& .000
21 \& .371
28 \& .015
27 \& .000

29 \& .000

29 \& 29 <br>
\hline
\end{tabular}

[^5]* Correlation is significant at the 0.05 level (2-tailed).


## Video data

Video analysis provided additional data about foot and pedal operation that could not be collected via the other sensors. Table 28 displays the descriptive statistics for the two quantified variables of the video analysis. Eleven random braking sequences were included from each of the 20 drivers that video quality allowed for such an analysis. The time for the foot to move from throttle to brake pedal was measured in frames (30fr/sec). This is the difference between the first frame the foot looses contact with the throttlepedal and the frame the foot is in contact with the brake-pedal. Initial brake pedal displacement was measured in the number of pixels on the camera lens image the brake pedal moved within 0.08 sec . Again, descriptive statistics, comparisons and correlations were examined.

Table 28: Aggregate descriptive statistics for throttle-to-brake-pedal displacement time and brake-pedal initial displacement

|  | $N$ | Minimum |  |  |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: | ---: |
|  | Maximum | Mean | Std. Deviation |  |  |  |
| Foot displacement time <br> during public road driving <br> (frames) | 220 | 4.00 | 138.00 | 12.6065 | 14.06886 |  |
| Brake pedal displacement <br> at 80ms during public road <br> driving (pixels on camera <br> lens) | 220 | 1.00 | 166.00 | 17.3972 | 30.64849 |  |
| Valid $N$ (listwise) | 220 |  |  |  |  |  |

Out of 220 braking sequences examined, the mean foot displacement time was 12.6 frames, with a minimum of 4 , a maximum of 138 frames and a standard deviation of 14.07 frames. For initial brake pedal displacement, the average was 17.4 pixels and the standard deviation 20.65. Minimum value was 1 pixel and maximum value was 166 pixels.

Table 29: Correlations between the two quantified video variables

|  |  | Foot displacement time during public road driving (frames) | Brake pedal displacement at 80 ms during public road driving (pixels on camera lens) |
| :---: | :---: | :---: | :---: |
| Foot displacement time during public road driving (frames) | Pearson Correlation | 1 | . 042 |
|  | Sig. (2-tailed) |  | . 543 |
|  | N | 220 | 220 |
| Brake pedal displacement at 80 ms during public road driving (pixels on camera lens) | Pearson Correlation | . 042 | 1 |
|  | Sig. (2-tailed) | . 543 |  |
|  | $N$ | 220 | 220 |

Then, the relationship between the two variables was examined (table 29).
Pearson R correlation was just $4.2 \%$ and the statistical significance at $p=0.54$, nowhere near the typical criterion for significance.


Figure 40: Distribution of typical foot displacement time per driver (number of video frames)

Looking at the data as typical values per driver (table 30), the typical foot displacement time ranged between 5.6 and 44.2 frames (see also figure 40).

The mean was 12.44 frames and the standard deviation 8.7 frames. For initial brake-pedal displacement (figure 42), typical values per driver ranged between 5.5 and 22.6 pixels. The average was at 11.2 pixels and the standard deviation was 4.9 pixels.

Table 30: Descriptive statistics for typical ${ }^{5}$ values per driver (video data)

|  | Ninimum | Maximum | Mean <br> Deviation |  |  |
| :--- | ---: | ---: | ---: | ---: | ---: |
| Typical foot <br> displacement time | 20 | 5.60 | 44.20 | 12.44 | 8.72 |
| Typical brake pedal <br> displacement at 80 ms <br> Valid N (listwise) | 20 | 5.50 | 22.60 | 11.20 | 4.87 |

[^6]

Figure 41: Distribution of typical initial brake pedal displacement per driver

As both distributions on figure 40 and figure 41 do not seem to be normally distributed, a Kolmogorov-Smirnov test for normality was employed to investigate the issue. Distributions were tested against a calculated normal (table 31) and an exponential distribution (table 32).

Table 31: One-sample Kolmogorov-Smirnov test for normality

|  |  | Typical foot <br> displacement <br> time | Typical brake <br> pedal <br> displacement <br> at 80 ms |
| :--- | :--- | ---: | ---: |
| N | Mean | 20 | 20 |
| Normal Parameters(a,b) | Std. Deviation | 12.4437 | 11.2030 |
| Most Extreme | Absolute | 8.71958 | 4.86996 |
| Differences | Positive | .316 | .162 |
|  | Negative | .316 | .162 |
| Kolmogorov-Smirnov Z |  | -.216 | -.121 |
| Asymp. Sig. (2-tailed) |  | 1.412 | .725 |

a Test distribution is Normal.
b Calculated from data.

The test showed a 1.41 z -value for typical foot displacement time and a 0.73 z-value for typical initial brake pedal displacement. The former was statistically significant below a typical alpha $=0.05$ criterion while the second was not. Thus, the distribution of typical foot displacement time could be assumed non-normal, while the distribution of initial brake pedal displacement could not.

Table 32: One-sample Kolmogorov-Smirnov test against an exponential distribution

|  |  | Typical foot <br> displacement <br> time | Typical brake <br> pedal <br> displacement <br> at 80ms |
| :--- | :--- | ---: | ---: |
| N | Mean | 20 | 20 |
| Exponential <br> parameter.(a,b) <br> Most Extreme Differences | Absolute | 12.4437 | 11.2030 |
|  | Positive |  |  |
|  | Negative | .362 | .388 |
|  |  | .178 | .133 |
| Kolmogorov-Smirnov Z |  | -.362 | -.388 |
| Asymp. Sig. (2-tailed) |  | 1.621 | 1.735 |
|  | a Test Distribution is Exponential. |  |  |
| b Calculated from data. |  |  |  |

Compared against an exponential distribution, both variables exhibited zvalues above 1.6 (table 32). For foot displacement time the $z$-value of 1.62 had asymptotic significance 0.01 . The $z$-value for initial brake-pedal displacement was 1.73 , which has asymptotic significance 0.005 . These results allow the assumption that the distributions are not exponential.

Table 33 presents the correlations between the two video variables and the demographics. Neither foot displacement time nor initial brake-pedal displacement showed any correlations with age, experience, height, or weight that yielded statistical significance indicators close to the 0.05 criterion.

Table 33: Correlations between the video-variables and the demographics

|  |  | Typical foot displacement time | Typical brake pedal displacement at 80 ms |
| :---: | :---: | :---: | :---: |
| Age | Pearson Correlation | -. 145 | -. 001 |
|  | Sig. (2-tailed) | . 554 | . 997 |
|  | N | 19 | 19 |
| Experience | Pearson Correlation | -. 167 | -. 031 |
|  | Sig. (2-tailed) | . 494 | . 901 |
|  | N | 19 | 19 |
| Annual_mileage | Pearson Correlation | . 114 | -. 384 |
|  | Sig. (2-tailed) | . 643 | . 104 |
|  | N | 19 | 19 |
| Licence_points | Pearson Correlation | -. 219 | . 413 |
|  | Sig. (2-tailed) | . 368 | . 079 |
|  | N | 19 | 19 |
| Height | Pearson Correlation | -. 066 | -. 166 |
|  | Sig. (2-tailed) | . 789 | . 496 |
|  | N | 19 | 19 |
| Weight | Pearson Correlation | . 261 | -. 145 |
|  | Sig. (2-tailed) | . 281 | . 555 |
|  | N | 19 | 19 |
| Typical foot displacement time | Pearson Correlation | 1 | -. 329 |
|  | Sig. (2-tailed) |  | . 157 |
|  | N | 20 | 20 |
| Typical brake pedal displacement at 80 ms | Pearson Correlation | -. 329 | 1 |
|  | Sig. (2-tailed) | . 157 |  |
|  | N | 20 | 20 |

In contrast, both foot displacement time and initial brake pedal displacement showed significant relationships with the main pedal-operation variables (table 34). Force input to the lower brake-pedal sensor shared a $56.6 \%$ correlation with initial brake-pedal displacement. This had statistical significance below 0.01 level. Similarly high was the correlation between initial brake-pedal displacement and force input to the upper brake-pedal sensor (60.7\%). This correlation was significant below $5 \%$ level. Additional significant correlations were found between initial brake-pedal displacement and the
other brake-pedal related variables. Correlation with combined input from both brake-pedal sensors was $61.6 \%$, significant below 0.01 level. Correlation with the SD of brake pedal force was $49.4 \%$, which was significant below 0.05 level, and correlation with SD as percentage of mean brake force was $55.7 \%$, which is significant at 0.01 level. Foot displacement time had one strong correlation with throttle-off rate (70.2\%). This correlation had statistical significance of 0.001 . Foot displacement had no other correlations that satisfy a typical alpha=0.05 criterion for statistic significance. Force on clutch-pedal sensor did not exhibit any significant correlations either.

Table 34: Correlations between the video-variables and the main pedal-operation variables

|  |  | Typical foot displacement time | Typical brake pedal displacement at 80 ms |
| :---: | :---: | :---: | :---: |
| Average force input to lower brake sensor | Pearson Correlation | -. 219 | .566(**) |
|  | Sig. (2-tailed) | . 355 | . 009 |
|  | N | 20 | 20 |
| Average force input to upper brake sensor | Pearson Correlation | -. 168 | .607(*) |
|  | Sig. (2-tailed) | . 583 | . 028 |
|  | N | 13 | 13 |
| Average force input to clutch sensor | Pearson Correlation | . 014 | -. 411 |
|  | Sig. (2-tailed) | . 955 | . 080 |
|  | N | 19 | 19 |
| Average angle change rate | Pearson Correlation | -.702(**) | .395 |
|  | Sig. (2-tailed) | . 001 | . 105 |
|  | $N$ | 18 | 18 |
| Mean force between sensors | Pearson Correlation | -. 236 | .616(**) |
|  | Sig. (2-tailed) | . 316 | . 004 |
|  | N | 20 | 20 |
| SD of brake pedal force | Pearson Correlation | -. 091 | .494(*) |
|  | Sig. (2-tailed) | . 704 | . 027 |
|  | N | 20 | 20 |
| SD as percentage of mean brake pedal force | Pearson Correlation | -. 102 | .557(*) |
|  | Sig. (2-tailed) | . 669 | . 011 |
|  | N | 20 | 20 |

Regarding qualitative characteristics of driver braking, two trends were transparent: first, a hesitant movement of the foot from the throttle to the brake pedal and then briefly back to the throttle pedal was not uncommon before an input to the brake pedal. In fact, this hesitation was apparent before more than $10 \%$ of all braking sequences examined ( 25 out of 220 sequences examined). Second, the clutch was engaged in tandem with the brake pedal in about $60 \%$ of sequences (124 out of 220), but predominantly after the initial brake input (117 sequences).

## Discussion

## In general

The naturalistic study was undertaken to support two main purposes within the scope of this PhD thesis. The establishment of what constitutes "normal" braking was the first purpose. The study provided a statistical/quantitative definition based on the main empirical results. As discussed below, although the visualisation of the distributions for some variables did not imply they were normal (figures 32-36), statistical testing for normality suggested that the distributions cannot be seen as non-normal - with the exception of clutchpedal force (tables 20-21). Since tests for normality, allow for the rest of the variables to be treated as normally distributed, it can be assumed that the mean is the most common and representative value of the distribution (Field, 2005). By definition, this is the most "normal" value. These values can be found on table 4. The most meaningful values are the estimated typical force
on the brake pedal surface (140.8N) and the typical throttle-off rate (0.54 deg $/ 0.02 \mathrm{~s}=27 \mathrm{deg} / \mathrm{sec}$ ) . Normal braking is limited to those values universally; however for the population examined and the vehicle used, according to the data it can be assumed that statistically any values within two standard deviations from the annotated means are "normal".

The second purpose of the naturalistic study was to provide a point of reference for more confined, more controlled on-road studies of driver braking. Within this framework, the results and distributions encountered here will be compared to the respective results of the "controlled study", in the following chapter (chapter 6) The average of both brake pedal force (approx. 140 N , figure 54 ) and throttle-off rate ( $25.8 \mathrm{deg} / \mathrm{sec}$, figure 53 ) in that study are within one standard deviation from the respective means in the current naturalistic study. There is more discussion of this issue in the chapter that follows.

## Design

Regarding the apparatus of this study, the use of only one vehicle for all participants is a limiting factor: participants did not drive their own vehicle, even though they selected their own routes. As discussed in the Methods chapter, it is desirable to have participants being monitored in their regular vehicles, or at least accounting for vehicle effects through the use of various vehicles within the framework of naturalistic-driving studies. Nevertheless, within budget limitations, the vehicle used was one of the most common vehicles on the road (Colorado Springs Gas Prices, 2009), and thus among the best options as a single instrumented vehicle.

The use of two sensors on the brake-pedal surface provided the ability to localise the area of the pedal to which force was applied, however it did not allow for direct collection of force data for the whole pedal surface. Total force applied on the pedal surface had to be estimated instead based on the assumption that the same amount of force placed on each sensor is also placed on its neighbouring areas. Of course, the use of multiple sensors compensated for that partly, however ideally a sensor exactly at the size of the pedal should be employed. At the time these lines are written, the cost for such a customised sensor is far outside the financial boundaries of this project. It remains as a possibility for future research studies.

Regarding the sample used in the study, size was sufficient for the type of statistical analysis undertaken - with the exception of estimating percentiles for gender groups. For such a purpose sample size should increase significantly to minimise uncertainty. This can be achieved through an extended future study. In terms of quality, demographic data indicated a desirable spread in mileage, stature and weight of drivers. The distribution of the last two variables had very similar properties to UK adult anthropometric data (with correction for secular growth, (Pheasant, 1987). The age distribution had two peaks at 30 and 50 years (figure 27). This is coherent with UK (DVLA, 2007) and US data (Idaho Office of Highway Operations and Safety, 2006) on licensed driver statistics. This phenomenon can partly be attributed to the "baby-boomers" population. Ethnically, the sample drew participants from a variety of backgrounds. The wealth of ethnic backgrounds in the area where this study commenced (Leicestershire) should have a contribution to this (Leicester: Ethnicity profile.).

On the negative side, insurance terms did not allow for drivers with probable history of risk-taking to be included in the sample. Effectively, only drivers with up to three points on their license were included in the study. Therefore the sample was missing an important part of the driver population arguably the one that needs driver assistive technology more. Also, the benefit from the multi-ethnic background of the drivers was not supplemented by a multi-national road environment. Although there was no mileage restriction during the day they "owned" the car, participants drove on UK roads only.

## Results

According to the results summary on table 19, more people used the lower part of the brake pedal than the upper when braking. This qualitative tendency to use the lower part of the pedal was balanced quantitatively however, as inputs to the upper brake pedal area were more powerful. This finding might be explained by the orientation of the pedal controls; as they are positioned in an angle against the floor, it is the lower part that is closer to the driver seat. Thus, this was the first area of the pedal a foot would touch aiming at pedal depression. However, it should be noted though that the correlation-analysis with driver-stature did not show evidence that smaller people had stronger inputs to the lower sensor and weaker to the upper one. An alternative analysis or even a new study-design is necessary to examine this further.

As per the following "controlled" study (chapter 6), throttle-off showed the least within-groups variance. Its standard deviation was very small compared to its mean and the strong concentration of values around the mean suggest
the latter is a very good representative number for the whole distribution. The major difference with the studies in chapter 6 is that in this chapter the variable also showed the most normal spread as a distribution (figure 34). This result enhanced the reliability of the parametric statistics for the variable that followed in the results section.

Table 35: Comparison of current results against previous driver braking studies

|  |  <br> Dittmeier <br> (1970) | Humanscale <br> (Diffrient, Tilley, <br> \& Harman, <br> 1993) | (Curry et al., <br> 2003) | (Kassaagi, <br> 2001) | Present <br> study |
| :--- | :--- | :--- | :--- | :--- | :--- |
| Max force/ <br> 99 th <br> percentile <br> Optimum <br> force/50th <br> percentile <br> Minimum <br> force/ 1st <br> percentile | 620 N | 266.9 N | $\approx 500 \mathrm{~N}$ | 1261 N | 621 N |

Results regarding the distribution of driver brake-force are not directly comparable to results from previous studies (table 35), primarily because all those data came from different experiments serving different purposes. To the author's awareness, this is the first study on driver-braking force in a naturalistic setting. Note that the values on table 35 are not directly comparable, as apart from the fact that data was collected in different settings; data was also collected from different areas of the braking mechanism. Despite the differences, it is still constructive for the results of the studies to be discussed in parallel. The early study by Eaton \& Dittmeier (1970) was designed to discover the maximum effort capabilities of female drivers. Thus, only results on maximum effort were provided. The result of 620 newtons is very close to the $99^{\text {th }}$ percentile value for brake-pedal force in the
present study (621 N). Humanscale's recommendations (Diffrient, 1993) refer to what the acceptable limits of force for the operation of the brake pedal are. The maximum force of 266.9 newtons is far from the maximum observed in the other studies or the $99^{\text {th }}$ percentile in the current study; however it is recommendation rather than an absolute maximum and as such is close to one standard deviation from the mean in the current study. The optimum range according to Humanscale is between 18-133 newtons, and the upper bound is close to the mean reported in the present study. The minimum recommended force is 17.8 newtons which is less than the $1^{\text {st }}$ percentile for the current study.

The differences can be further explained by the particular purpose of the Humanscale; it is a tool to help designers and engineers design for human use. Its recommendations are for the resistance of the brake pedal during application. It recommends an $18 \mathrm{~N}-133 \mathrm{~N}$ requirement for the pedal to be operated, so that the pedal can be operated by the driver without being "too soft" and result in random engagement of the brake mechanism. The relevant value in the distribution observed in this chapter's study is not the mean; it is the $1^{\text {st }}$ percentile. This is the value that would be recommended as the absolute maximum resistance of a brake pedal mechanism for use by the population of drivers that this study's sample came from. This value is actually within the recommendation by Humanscale.

The studies by Curry et al (2003) aimed at exploring drivers' reaction and perception of primary brake systems failure. So the only related result provided was the maximum brake pedal force during the system failure, as measured through the car's ECU. The maximum value reported was about

500 N , which is actually quite close to the $95^{\text {th }}$ percentile brake pedal force value for the current study (table 19). Again though, the settings upon which data were collected are quite different; in Curry et al (2003) pedal-force data were collected during circumstances (brake circuit/servo failure) that are extremely rare in the natural road environment (Sabey \& Staughton, 1975; Treat et al., 1977).

Reported maximum, average and minimum values for brake force were far greater in Kassaagi's (2001) study than in any of the other studies. This can partly be attributed to the fact that his thesis was about emergency braking and his studies examined mainly collision-imminent situations in a simulator as well as on a test track. Force values were estimated through the measured pressure in the brake circuit cylinder, which is different to the methods the other studies used to collect brake force data. For all those reasons, it is not surprising that, with the exception of the minimum value observed, both average and maximum values were more than twice the amounts in all the other reported studies.

## Detailed results

Looking back to the present study's results and the qualitative characteristics in particular, normality testing (table 20) suggested that lowerbrake force, throttle-off rate, and combined force from both brake-pedal sensors can be assumed as normally distributed. On the other hand, clutchpedal force can be assumed exponentially distributed (table 21), while upper brake-pedal force can be assumed as neither a normal nor an exponential distribution. These characteristics did not affect the analysis much, as there
was no other indication that data does not fulfil the prerequisites for parametric statistical testing (Field, 2005).

## Gender comparisons

Comparative analysis between genders across the range of variables did not reveal any statistically significant differences. The sample size might have played a role, as splitting it into gender groups resulted in groups with size between 17 and 12 participants. Thus, although the total sample was sufficient for most other analyses, it is probably necessary to have greater numbers for a reliable comparison between genders. Nevertheless, it is worth reporting the average estimated brake-pedal force values of 161.3 N for male and 128 N for female participants. Variance was significant within groups (this partly explains the absence of meaningful statistical differences) as well as within individuals; standard deviations of brake pedal force averaged above $50 \%$ of the means for both male and female drivers (table 22).

## Intra-personal differences

This amount of variance was noticed for the total sample as well. With the exception of throttle-off rate, all other variables exhibited standard deviations up to $1880 \%$ of their respective means with all average standard deviations above $50 \%$ of the means (table 26). These results suggest that braking varies not only from driver to driver; it also varies from braking sequence to braking sequence for the same driver. It is not only that participant $X$ 's braking is different to participant $Y$ 's, but also participant $X$ 's braking is different at time $Z$
to time W. And these differences are quantitative; they can be observed in braking parameters like the ones measured and reported in this study.

## Correlation-analysis

The exploration of relationships between the variables provided some interesting results. Apart from the more-or-less expected relationship between age and experience, a 47\% correlation between driver stature and annual mileage suggested that the taller drivers in the sample also drove more during the year. As general driver-population data on the matter is not available, it would be risky to expand this result to the general population, just on the grounds of this result. The relationship though, could be partly explained if male drivers have longer mileage.

Another demographics-related correlation was that found between driver weight and throttle-off rate. The correlation was $43.3 \%$ and the heavier the drivers were, the slower the release of the throttle-pedal. Although theoretically a correlation does not show effect, as it is bidirectional, in this case it could be assumed that weight somewhat slows throttle-off responses down, rather than throttle-off affects drivers' weight. In addition, although the above correlations fulfil the criterion for statistical significance, they both exhibit values below 50\%. Such values imply low (below 25\%) interactions between variables. Furthermore, considering the size of the sample $(\leq 30)$, the extensive correlation-analysis (twenty-seven correlations in total) which took place could facilitate Type I errors. Type I errors occur, when the experimenter accepts the alternative hypothesis as true, although the nil hypothesis is true. Within the present study, this argument implies that
relationships such as those reported above, could be random rather than represent a true phenomenon. Therefore, the two aforementioned correlations should be interpreted with caution.

Outside those two correlations, all the brake-pedal force measures were closely related. Their correlations ranged between $84 \%$ and $96.8 \%$. Between the three variables, there could be a common underlying mechanism. Their high correlations to the intra-personal indicators (SD of brake pedal force \& SD as percentage of brake pedal force) also indicated that the higher the typical pedal force values for a participant, the greater the intra-personal variance.

Throttle-off rate had a similar relationship to the indicators of intra-personal variance. Its correlation to SD of brake pedal force was $49.3 \%$ and $46.5 \%$ to the SD as percentage of brake pedal force. Quicker throttle-off rates were associated with more intra-personal variation. Throttle-off rate was also directly associated to brake-pedal force; they shared a correlation of $63.3 \%$. The results are in line with an argument that throttle-pedal release is part of the braking task itself and thus should be included in a study of braking. Clutch-pedal force on the other hand, did not show noteworthy relationships with any other braking variable, raising questions regarding how much it really fits into the braking task.

The two indicators of intra-personal differences have, as expected, very high correlation. It should be noted that, although the second (SD as percentage...) derives from the first (SD of brake-pedal force), they are not identical; their correlation is meaningful and implies that the greater the personal SD, the greater its proportion to the mean of the individual braking
force distribution. In other words, as the SD increases from person to person, the mean does not increase equally.

## Video

Video analysis was neither easy, nor problem-free. Practically, it was outside human limitations to analyse in-depth every single braking sequence in the videos. If a minute of action requires one hour to be analysed in-depth, there were enough hours of video-recorded material to occupy more than half of the time available for the whole PhD programme. Thus, braking sequences had to be sampled to be analysed by frame. Eleven braking sequences per participant were randomly selected for that purpose. This number, multiplied by the number of participants, is substantial; however the sample of braking sequences examined is only a fraction of the thousands of sequences performed during those 30 days the participants drove the vehicle. Further limitations came from the tendency of a couple of drivers to cover the lens with their left foot/shoe/boot, the video quality and the sensitivity of the camera during really dark days/evenings. All the problems together resulted in useful data from 20 participants in the end.

However, there were some useful and valid results. The correlation between the two video-variables was very low (4\%). The initial travel of the brake pedal seems to be irrelevant of the speed in which the foot moves from throttle to brake pedal. Also, it was interesting to see slight differences between the statistics of aggregate braking sequences (table 28) and those of descriptives per driver (table 30). The K-S tests (tables 31, 32) suggested that the distribution of foot-displacement time might be neither normal nor
exponential. Initial pedal-displacement did not show similar results.
Exploration of relationships with other variables (tables 33-34) revealed no significant relationship with the demographics; however both variables shared significant correlations to other brake-related variables. Foot-displacement time shared a 70.2\% correlation with the throttle-off rate. At the same time, initial-pedal displacement time shared a $56.6 \%$ correlation with the lower brake-pedal sensor force, a 60.7\% correlation with the upper brake-pedal sensor force, a 61.6\% correlation with the combined brake-pedal sensor input, $49.4 \%$ correlation with the SD of brake pedal force and $55.7 \%$ with the SD as percentage of mean brake pedal force. All these correlations suggest that the time to move the foot between throttle and brake pedal is associated more to the throttle-related part of the braking sequence. The initial speed of brake pedal application on the other hand is associated with the rest of the brakepedal variables, basically creating a two-stage basis of driver braking. The issue is discussed further in the final chapter of this Thesis.

The two qualitative results of the video analysis can be quite important for the specification of braking systems and the "hesitation phenomenon" partly explains some of the irregularities in the foot-displacement time measure. This is, because the appearance of a hesitant movement, where the foot is not determined to depress the brake pedal, results in disproportionately long footdisplacement times. The foot spends time touching neither the throttle nor the brake pedal, and thus, when decided to brake, the starting point of the movement is not the throttle pedal. No contemporary sensor-technology can account for this and the incorporation of foot-displacement time to intelligent brake systems might be challenged by this trend. Equivalently problematic
might be the employment of clutch-related variables; first, not all vehicles have a clutch pedal. Automatic/semi-automatic transmission is becoming increasingly common. Second, although the application of clutch pedal in tandem with the brake pedal was noticeable in the video analysis, it was very rare that the clutch-pedal application would precede the brake-pedal depression. Therefore, incorporation of clutch input to future brake systems has the potential to delay the response of the system.

## The lessons derived through the naturalistic study

The examination of driver braking in a naturalistic setting provided a series of findings with regards to the nature of driver braking input. First, evidence for a statistical definition of normal driver braking was provided. Inputs within two SD of the mean force-input to the brake-pedal, are considered statistically "normal", whereas values outside those bounds are considered "extreme". Therefore, braking inputs between 40 N and 390 N of force can be assumed as "normal" according to the statistical evidence provided by the study.

Second, the underlying intra-personal variability of driver braking was revealed. The standard deviations in brake-pedal force input for each participant ranged between $50 \%$ and $1880 \%$ of their respective mean input. This range implies that, during the same day, the same driver may perform braking inputs as much as eighteen times stronger than their average input. Such size of intra-personal variability is huge and indicates how demanding a task it is to design braking systems that account for it.

Third, relevant results were coherent with results from previous test-track studies regarding minimum, average and maximum brake-pedal force applied by drivers under braking. The ecological validity of those test-track studies (Eaton \& Dittmeier, 1970; Curry et al., 2003) is supported by the findings of the current study. However, there were other studies, whose scope was such that direct comparison with the current results is problematic.

Finally, correlation-analysis between pedal-operation parameters indicated that clutch-pedal operation is probably irrelevant to the operation of the brake-pedal during braking. Although clutch-pedal operation is often included in the measures of driver braking (e.g. Kassagi, 2001), in this instance it showed no relationship to the other variables. On the contrary, brake-pedal force, throttle-off and initial displacement of the exhibit considerable interaction among them.

## Summary

Chapter 5 presented a naturalistic braking study. 30 fully-licensed drivers "owned" an instrumented vehicle for a day. Operation of the pedals was monitored through force, positions sensors and a camera in the foot-well. Each day, the vehicle was delivered to the participant's home address early in the morning and collected from the same location in the evening. Typical trips during the day included commuting to work, getting the children to school, going shopping etc. Some participants reported extra-urban use such as for trips in the countryside.

Results indicated strong individual differences as well as intra-personal variation in terms of the force applied and the speed of operation of the brake pedal. Comparison with previous results from studies examining braking indicated a slight incoherence, which can be attributed to the difference in the scope and the consequent design of each study.

## Chapter 6: Controlled Road Study ${ }^{6}$

In the previous chapter, driver braking was examined within a naturalistic setting. That investigation produced a realistic image of the quantitative characteristics of driver braking. Within this framework, a statistical definition of normal driver braking was developed. However, the limited control provided by the design of the study did not allow for the examination of extreme braking inputs, such as emergency braking. The present chapter describes an extensive driver braking study on a pre-determined public road route and on a closed road track. The public road section was employed for data collection in a realistic setting and the closed road track was used for the execution of an emergency braking experiment in a setting where risk can be controlled. 48 drivers (24 male - 24 female) drove an instrumented vehicle on a 6.7 mile/10km public road section before they arrived at the test track where they were instructed to follow, at their preferred distance, another vehicle towing a trailer. They were told the aim was to measure their preferred carfollowing distance. They were naïve of the fact that 0.2 miles down the track the trailer would be released. Throughout both sessions (public and closed road) pedal-operation data was collected through position and force sensors as well as video cameras in the foot-well. Data from each session were explored before they were compared between sessions, and finally, relationship models between parameters were tested. Comparison aimed at

[^7]exploring the previously established difference between normal and emergency braking (Perron et al., 2001), while relationship models between parameters were tested to provide evidence regarding the third research question, regarding the relationship between normal and emergency braking parameters.

## Aims

The controlled road-study commenced with four objectives in mind:

1. The overarching aim was to examine both normal and emergency driver braking microscopically in a highly realistic environment.
2. Within the above aim, the study attempted to challenge results from previous studies supporting quantifiable differences between normal and emergency driver braking (Kassaagi, 2001).
3. Furthermore, it aimed to test the hypothesis that there are additional intra-personal relationships among braking parameters and between normal and emergency braking.
4. Depending on the result of the investigation above, the final objective of the study was to examine the relative merits of the dominant relationships as the basis for future braking-assist systems.

## Design

## The variables of interest

The main dependent variables were the sequence of quantitative parameters of driver's input to the brake-pedal, starting from the speed by which the throttle-pedal is released (expressed in degrees/sec), to the time it takes for the foot to move between throttle and brake-pedal and finally the input to the brake pedal itself. The latter measured both in terms of the speed by which the pedal moves at the beginning of its movement and the force which is applied on the surface of the pedal itself.

The above variables were examined comparatively in two conditions: first on an open road section and then on a closed test-track, where an emergency braking test took place.

## Sample

48 (24 male - 24 female) local drivers were recruited through adverts in local press (newspapers and magazines within Leicestershire and Nottinghamshire). In order to satisfy the insurance requirements, drivers had to be at least 21 years old and hold a UK or equivalent full driving license with no more than 5 penalty-points charged. There were no other exclusion criteria and virtually anybody within the local area could take part. The local population is also highly diverse in terms of the ethnic background of its residents, and thus the participants came from 18 different ethnicities. Of course, English and other British ethnicities comprised half of the sample (49\%), however drivers with Afghan, Australian, Brazilian, Cypriot, German,

Greek, Indian, Persian, Irish, Italian, Korean, Malaysian, Pakistani, Spanish, St Helen, and Turkish background made for the other half (51\%). Table 36 presents the driving demographics information of the participants' sample recruited.

Table 36: Descriptive demographics of driver sample

|  | $N$ |  | Minimum | Maximum | Mean |
| :--- | ---: | ---: | ---: | ---: | ---: |
| Age | Std. Deviation |  |  |  |  |
| Experience | 48 | 21.00 | 84.00 | 31.33 | 13.47 |
| (years) | 48 | 1.00 | 48.00 | 11.9184 | 11.55 |
| Annual mileage |  |  |  |  |  |
| Licence points | 48 | 1000.00 | 30000.00 | 9653.06 | 6619.26 |
| Height (cm) | 48 | .00 | 3.00 | .3673 | .993 |
| Weight (kg) | 48 | 152.00 | 193.00 | 171.29 | 10.08 |
| Valid N (listwise) | 48 | 50.00 | 115.00 | 73.85 | 15.90 |

The sample included a wide range of ages in line with the general UK driver age-data (DVLA, 2007). The youngest participant was 21 year old and the oldest was 84 years of age. The standard deviation was very similar to the standard deviation of the national driver population (about 14 years); however the mean of the sample was 31.33 years against 42 years for the general population. The most experienced driver participating held a full driving license for 48 years and the novice had just one year of driving with a full license. Mean experience was 11.92 years and the SD was 11.55. Annual mileage ranged between just 1000 miles/year to some 30000 miles/year. The respective mean was 9653 miles and the SD was 6619 miles. 6 participants had 3 points charged on their license, while most participants had no points at all. In terms of size, stature (figure 42) ranged between 152 cm
and 193 cm , with an average of 171.3 cm and a SD of 10 cm . Weight (figure 43 ) ranged between 50 and 115 kilograms, with a mean of 73.8 kg and a standard deviation of 15.9 kg .

All participants were paid $£ 10$ in compensation for their time.


Figure 42: Participants' distribution of stature (cm)


Figure 43: Participants' distribution of weight (kg)

## Apparatus

A Ford Fiesta ('O0 model year) was fitted with sensors on the pedals, two video cameras, a data acquisition module and a laptop to log all data. A potentiometer was fitted at the centre of throttle pedal axis rotation (figure 28). Its purpose was to provide information on the position of the pedal and the resultant changes in angle during operation. The release of this pedal before depression of the brake pedal is commonly considered as part of the braking reaction (Perron et al., 2001) and on its own results in vehicle deceleration. It therefore contributes to successful longitudinal control (see also discussion in the previous chapter).

Two Tekscan Flexiforce® sensors were fixed on the brake pedal surface. One provided data from the higher part of the surface and one from the lower (figure 29). One sensor was placed 25 mm from the top edge of the pedal and 25 mm from each side edge and another 20 mm from the lower edge of the pedal and 20 mm from each side (pedal was not square). Another Flexiforce ${ }^{\circledR}$ sensor was fitted on the clutch-pedal surface. Sensors were calibrated according to Tekscan's guidelines (Tekscan, 2008).

Two cameras were installed in the vehicle cabin. A Microsoft® LifeCam VX-1000 was installed on the inside of the footwell, approximately parallel to the pedal rods (figure 27). This provided a constant view of the pedals during trials. A Sony DCR-HC22E camcorder was mounted on the dashboard, facing the windscreen, to record the road environment.

A Labjack® U12 data acquisition module was connected to a Toshiba $®$ Tecra 3 laptop using Azeotech® DAQFactory® Express software for data logging. Power was provided through the vehicle's battery when the engine was on and through the laptop's battery when it was off. All quantitative and qualitative data was stored on the laptop's hard drive, except the video from the on-board camera which was stored on digital tapes.

A lightweight ( $\mathrm{m}<30 \mathrm{~kg}$ ) trailer was built for the purpose of replicating a lead vehicle's sudden braking ( $\mathrm{a}<-5 \mathrm{~m} / \mathrm{s}^{2}$ ) on the test track. The trailer's stopping properties were representative of average emergency decelerations of real vehicles in experimental (Vangi \& Virga, 2007) and field studies (van der Horst, 1990). The trailer (figure 44, see appendix A for more detail) was threewheeled for extra straight-line stability; with dimensions of 2.2 m length, 1.25 m rear width, 0.3 m front width, and 0.4 m height at the back. Wheels were 20 inch
standard road bicycle wheels. It was basically a sheet of waterproof wood reinforced with an aluminium skeleton. Two $0.75 \times 0.5 \times 0.5$ cardboard boxes were filled with closed empty plastic bottles and wrapped with white plastic bags before they were attached at the rear of the trailer to create a "bulkiness" illusion (figure 45). Standard bicycle "V-brakes" were installed and were activated by the rotation of a lever which was activated by two springs upon release from the car (figure 46). During testing, average acceleration of the trailer after release was $-6.81 \mathrm{~m} / \mathrm{s}^{2}$ with an instantaneous minimum of -
$17.24 \mathrm{~m} / \mathrm{s}^{2}$ achieved.


Figure 44: The trailer, close to its completion phase


Figure 45: Driver's view during the test


Figure 46: The simple but effective "auto-brake" mechanism

A Mercedes Benz G-class equipped with a tow bar was used as the confederate vehicle. A track about 1 mile long, which had a crest at its
midpoint, was used for the emergency test described in the next section. A map of the track can be accessed using the following link:
http://maps.google.co.uk/maps?f=d\&source=s d\&saddr=Unknown+road\&dad $\mathrm{dr}=52.790202,-$
1.132364\&geocode=FYiSJQMd8lbu w\%3B\&hl=en\&gl=uk\&mra=mi\&mrsp=1,0
\& $\mathrm{sz}=14 \& \mathrm{~s} \|=52.793784,-$
1.129446\&sspn $=0.037628,0.076904 \& i e=U T F 8 \& \|=52.793316,-$
$1.137192 \& \mathrm{spn}=0.009407,0.02738 \& \mathrm{t}=\mathrm{h} \& \mathrm{z}=16$
Also, a simple stress index where participants could rate their subjective stress level from 1 to 7 was administered before and right after completion of the study.

## Protocol

The study had two parts: first, participants drove the test vehicle on a public road route, across Loughborough, via the town centre (urban section). Then, via a combination of road types (rural section), they drove to the test track, where the second part would take place: the emergency test (figure 47).


Figure 47: The route followed during the study

## Public Road section

Participants provided the necessary demographic information as well as completed a health-screen questionnaire and the Loughborough University's General Driver Application Form (see Appendix B), in order to be eligible to drive University vehicles. They met the experimenter at the Holywell car park and provided a subjective measurement of their level of stress on a scale from 1 to 7 . They were asked to make themselves comfortable in the driver's seat, adjusting seat, mirrors and ventilation. They read the participant's information sheet and signed the relevant consent form. The experimenter initiated data logging and placed the laptop below the carpet on the passenger/co-driver's side. Then, the participant drove the car out of the car park, on to the A512 towards Loughborough town centre. At the end of the A512, they would join the A6 southbound briefly, before turning towards the A60. This road turns
rural after the railway bridge and runs through the village of Cotes.
Participants would leave the A60 by turning right at the entrance of Hoton village to find the entrance of Wymeswold Airfield that served as the test track for the study.

## Closed Test Track



Figure 48: The design of the emergency-brake test

Upon arrival at the test track, the driver was asked to pull over in a lay-by at the site entrance. The experimenter checked with the marshals on site that everything was ready for the test. The track used for the experiment can be viewed through the internet link on page 182. The long strip of tarmac was separated into two lanes using road-cones. The left-hand lane was used for the experiment. The participants were informed that the purpose of the study was to identify their preferred driving distance from other vehicles and for this
purpose they would follow an instrumented trailer that would record their headway distance. Accordingly, they were prompted to enter the track and adjust their headway to the leading vehicle according to their preference.

They were naïve of the fact that the trailer would be released after 0.2 miles
$(321.86 \mathrm{~m})$ in the straight (figure 48-49). The lead vehicle accelerated to 30 mph (speed measured using GPS) and kept to this speed until the release of the trailer.


Figure 49: Driver's view sequence of the emergency test on the test track

## Data analysis

Throughout each session pedal operation was recorded in terms of throttle movement, brake-pedal force, clutch-pedal force through the sensors and feet movements though the video. Also, trailer size on the on-board camera lens (pixel size) was calibrated and the instantaneous time-headway during the
emergency test was calculated. Then, data were analysed using Statistics Package for Social Sciences (SPSS®) version 15, and Microsoft® Excel. Both sessions - on public and closed road - were analysed separately and in comparison.

To explore the general quantitative characteristics of driver braking under each condition, the descriptive statistics will be presented for each variable examined. Those include indicators of central tendency, spread and shape for each distribution. To challenge the hypothesis that normal and emergency braking inputs are quantitatively different, a t-test will be employed for pairwise comparisons of driver braking between the open-road and the test-track/emergency-test section. To test the hypothesis that relationships exist between each driver's normal and emergency braking inputs, linear and nonlinear regression analysis will be employed. Then, the respective equations will be developed to describe the relationship between normal and emergency braking input.

## Results

## Public Road Section

Table 37: Descriptive statistics of the main variables recorded on the public road section

|  | $N$ |  | Minimum | Maximum | Mean | Std. Deviation |
| :--- | :---: | :---: | :---: | :---: | :---: | ---: |
| Force input on lower |  | 46 | .00 | 17.17 | 5.23 | 2.97 |
| part of the brake pedal |  |  |  |  |  |  |
| (newtons) |  |  |  |  |  |  |
| Force input on upper <br> part of the brake pedal |  |  |  | 20 | 21.54 | 6.17 |


| (newtons) | 48 | 9.32 | 208.72 | 111.93 | 56.15 |
| :--- | :---: | :---: | :---: | :---: | :---: |
| Force input on clutch |  |  |  |  |  |
| pedal (newtons) <br> Throttle-off rate, public | 48 | 9 | 27 | 25.18 | 3.70 |
| road driving |  |  |  |  |  |
| (degrees/sec) |  |  |  |  |  |
| Average force on brake <br> pedal sensors, public <br> road driving (newtons) | 47 | 1.10 | 16.93 | 5.68 | 3.39 |

Table 37 presents the descriptive statistics of the main variables recorded during driving on the public road section (figure 47). Force input on the sensor fixed on the lower part of the brake pedal ranged between 0 and 17.17 newtons. Mean input was 5.23 newtons and the standard deviation 2.97 (figure 50 ). 2 drivers out of the 48 did not use the lower section of the pedal surface and had no input to the sensor during the public road trial.


Figure 50: Distribution of typical force inputs to the lower part of the brake pedal during the public road trial (newtons)

Force input on the sensor fixed on the upper part of the brake pedal ranged between 0 and 21.54 newtons. Mean input was 6.17 newtons and the standard deviation 5.17 (figure 51). 2 drivers out of the 48 did not use the lower section of the pedal surface and had no input to the sensor during the public road trial.


Figure 51: Distribution of force inputs on the upper brake pedal sensor during public road driving (newtons)

Nominal values of force on the clutch pedal were significantly higher than on the brake pedal. Force input on the sensor fixed on the centre of the clutch pedal ranged between 9.32 and 208.72 newtons. Mean input was 111.93 newtons and the standard deviation 56.14 (figure 52). All 48 drivers had inputs on this sensor.


Figure 52: Distribution of typical clutch pedal inputs during the public road trial (newtons)

Throttle release was measured as rate of change of throttle pedal of angle.
Typical values per participant ranged between 9 and 27 degrees per second.
Mean was $25.18 \mathrm{deg} / \mathrm{sec}$ and the standard deviation was $3.7 \mathrm{deg} / \mathrm{sec}$.
Compared to the previous pedal force inputs, "throttle-off" values were a lot less dispersed and concentrated around 25 and $18 \mathrm{deg} / \mathrm{sec}$ (figure 53)


Figure 53: Distribution of typical throttle release rates during the public road section

$$
\left(\operatorname{deg} / 2^{\star} 10^{-2} \mathrm{sec}\right)
$$

Finally, combined inputs from both sensors on the brake-pedal surface were similarly dispersed as the other force inputs (figure 54). The average force between the two brake pedal sensors ranged between 1.1 and 16.93 newtons. The mean for the whole sample was 5.68 newtons and the standard deviation was 3.39.


Figure 54: Distribution of average input between the two brake pedal force sensors (newtons)

## Controlled Test-Track Section

Table 38 presents the descriptive statistics of the main variables recorded during the emergency brake test on the closed road track. Force input on the sensor fixed on the lower part of the brake pedal ranged between 0 and 98.2 newtons. Mean input was 14.14 newtons and the standard deviation 19.27 (figure 55). 2 drivers out of the 48 in total did not use the lower section of the pedal surface and had no input to the sensor during the test on the closed track. Another 25 participants had inputs lower than 10 newtons. The resulting distribution was quite skewed towards its lower bounds.

Table 38: Descriptive statistics of main variables during the closed track emergency-
event session

|  | $N$ | Minimum | Maximum | Mean | Std. Deviation |
| :--- | :---: | :---: | :---: | :---: | :---: |
| Force input on lower part of | 46 | .00 | 98.20 | 14.14 | 19.27 |
| the brake pedal (newtons) |  |  |  |  |  |
| Force input on upper part of | 46 | .00 | 123.90 | 19.02 | 27.09 |
| the brake pedal (newtons) |  |  |  |  |  |
| Force input on clutch pedal | 47 | .00 | 285.50 | 208.49 | 97.41 |
| (newtons) |  |  |  |  |  |
| Throttle-off rate, emergency | 48 | 26 | 61.5 | 33.75 | 6.53 |
| test (degrees/sec) | 46 | .00 | 74.30 | 16.81 | 19.13 |
| Average force on brake |  |  |  |  |  |
| pedal sensors, emergency | 48 | 1.53 | 2.73 | 2.60 |  |
| test (newtons) |  |  |  |  |  |
| time_headway_at_30mph |  |  |  |  |  |



Figure 55: Distribution of force inputs on the lower brake pedal sensor during the emergency test

Force input on the sensor fixed on the upper part of the brake pedal ranged between 0 and 123.9 newtons. Mean input was 19.02 newtons and the standard deviation 27.09 (figure 56). 2 drivers out of the 48 in total did not use the lower section of the pedal surface and had no input to the sensor during the test on the closed track. Another 25 participants had inputs lower than 10 newtons. The resulting distribution was quite skewed towards its lower bounds, but demonstrated higher nominal values than brake inputs on the public road section.


Figure 56: Distribution of force inputs on the upper brake pedal sensor during the emergency test

Again, nominal values of force on the clutch pedal were significantly higher than on the brake pedal. Force input on the sensor fixed on the centre of the clutch pedal ranged between 0 and 285.5 newtons. Mean input was 208.4849 newtons and the standard deviation 97.4 (figure 57). Only one driver had no input on this sensor during the test $(\mathrm{F}=0)$. Compared to the public road section, this distribution exhibits a strong skew towards its higher bound.


Figure 57: Distribution of force inputs on the clutch pedal sensor during the emergency test

Throttle-off in the emergency test was measured in degrees of change against time. Peak values per participant ranged between 26 and 61 degrees per second. Mean was $33.75 \mathrm{deg} / \mathrm{sec}$ and the standard deviation was 6.53 deg/sec. Compared to the previous pedal force inputs, "throttle-off" values were a lot less dispersed and concentrated around 25 and 35 deg/sec (figure 58).


Figure 58: Distribution of peak throttle release rate during the emergency test

$$
\left(\operatorname{deg} / 2^{\star} 10^{-2} \mathrm{sec}\right)
$$

Combined input from both sensors on brake pedal surface was dispersed as its source (upper and lower-sensor) force inputs (figure 59). The average force between the two brake pedal sensors ranged between 0 and 74.30 newtons. The mean for the whole sample was 16.81 newtons and the standard deviation was 19.13. Twenty drivers had a lower input than 5 newtons and another 5 participants had inputs below 10 newtons.


Figure 59: Distribution of average input between the two brake pedal force sensors during the emergency test

Time headway at the instant of trailer release ranged between 1.53 and 2.73 sec . The mean was 2.6 sec and standard deviation 0.19 . The resultant distribution (figure 60) was quite skewed towards the upper bound.


Figure 60: Distribution of estimated time-headway at the instant of the trailer release

## Comparative analysis

The measured braking parameters in both sections were compared using parametric and non-parametric analysis. To focus on the meaningful part of the data, participants who had an average brake input below 5 newtons during the emergency test were not included in this analysis (in essence, they did not brake). A similar comparative analysis was made between self-rated stress level at the start of the session and on completion of the session.

Table 39: Paired sample statistics of pedal operation between the public road and the test track sections

|  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Mean | $N$ | Std. Deviation | Std. Error <br> Mean |
| Pair 1 | Typical force input on | 5.04 | 25 | 1.93 | . 38 |
|  | lower part of the brake |  |  |  |  |
|  | pedal (public road) |  |  |  |  |
|  | Force input on lower | 16.14 | 25 | 14.48 | 2.89 |
|  | part of the brake pedal |  |  |  |  |
|  | (test track) |  |  |  |  |
| Pair 2 | Typical force input on | 8.48 | 24 | 5.03 | 1.03 |
|  | upper part of the brake pedal (public road) |  |  |  |  |
|  | Force input on upper | 25.85 | 24 | 20.97 | 4.28 |
|  | part of the brake pedal |  |  |  |  |
|  | (test track) |  |  |  |  |
| Pair 3 | Typical force input on | 127.94 | 25 | 56.64 | 11.34 |
|  | clutch pedal (public road) |  |  |  |  |
|  | Force input on clutch | 226.26 | 25 | 84.31 | 16.86 |
|  | pedal (test track) |  |  |  |  |
| Pair 4 | Throttle-off rate, public | . 50 | 25 | . 09 | . 017 |
|  | road driving |  |  |  |  |
|  | Throttle-off rate, | . 66 | 25 | . 15 | . 03 |
|  | emergency event |  |  |  |  |
| Pair 5 | Typical force on brake- | 6.69 | 25 | 3.12 | . 62 |
|  | pedal sensors, public |  |  |  |  |
|  | road driving |  |  |  |  |
|  | Force on brake-pedal | 20.94 | 25 | 12.59 | 2.52 |
|  | sensors, emergency |  |  |  |  |
|  | event |  |  |  |  |

Table 39 presents the paired statistics of the comparative analysis. Mean (typical) input on the lower brake pedal sensor during public-road braking was 5.04 newtons and the standard deviation of this variable was 1.93 newtons. The respective values on the emergency test on the closed track were 16.14 and 14.49 newtons. Typical force input on the upper brake-pedal sensor during the public road session was 8.48 newtons and the standard deviation was 1.03 newtons. On the test track, average force on the upper brake-pedal sensor was 25.85 newtons and the standard deviation was 20.97 newtons. Regarding clutch pedal operation, typical force on the sensor on the public road was 127.94 newtons and the standard deviation was 56.64 newtons. On the closed track, mean force on the clutch-pedal sensor was 226.25 newtons and the standard deviation 84.31 newtons. Average throttle-off rate on the public road was 0.50 degrees $/ 2 \mathrm{sec}^{*} 10^{-2}$ and the standard deviation 0.09 . On the closed track, mean throttle-off rate was $0.66 \mathrm{deg} / 2 \mathrm{sec}^{*} 10^{-2}$ and the standard deviation 0.14. Taking into account both brake-pedal sensors, average input between them was 6.69 newtons on the public road section and 20.94 newtons on the test track. The respective standard deviations were 3.12 and 12.52 newtons.

Table 40: Paired correlations of pedal operation parameters

|  | $N$ | Correlation | Sig. |
| :--- | :---: | :---: | :---: |
| Pair 1 | 25 | .511 | .009 |
|  |  |  |  |
| Pair 2 | 24 | .386 | .062 |
|  |  |  |  |
| Pair 3 | 25 | .281 | .173 |
|  |  |  |  |


| Pair 4 | 25 | -.029 | .892 |
| :--- | :---: | :---: | :---: |
|  |  |  |  |
| Pair 5 | 25 | .454 | .023 |
|  |  |  |  |

The correlation (table 40, pair 1) of force input to the lower brake-pedal sensor between the two road sections was $51.1 \%$, statistically significant below $0.01(p=0.009)$. The correlation of force input to the upper brake-pedal sensor between the two sections (pair 2) was lower (38.6\%) and the statistical significance over a typical alpha= 0.05 criterion. The combined inputs of both brake-pedal sensors between the two sections (pair 5) demonstrated a correlation of $45.4 \%$, statistically significant below $0.05(p=0.023)$. The other pairs demonstrated very low correlations.

Table 41: Paired Student's T-test of pedal operation between the two sections

|  | Mean | Std. Deviation | $t$ |  | Sig. <br> (2tailed) |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Pair 1 | -11.10 | 13.60 | -4.08 | 24 | . 000 |
| Pair 2 | -17.37 | 19.59 | -4.34 | 23 | . 000 |
| Pair 3 | -98.32 | 87.33 | -5.62 | 24 | . 000 |
| Pair 4 | -. 16 | . 17 | -4.79 | 24 | . 000 |
| Pair 5 | -14.24 | 11.51 | -6.19 | 24 | . 000 |

Table 41 presents the results of T-test comparison between each pair. The mean difference of force inputs to the lower brake-pedal sensor between the
two road sections (pair 1) was 11.1 newtons and the standard deviation of this difference was 13.6 newtons. The mean standard error was 2.72 and the $95 \%$ confidence interval of the difference was between 16.72 and 5.49 newtons. The respective t-value was 4.081, which for 24 degrees of freedom (df) is highly statistically significant ( $p<0.0001$ ). The mean difference between the second pair (upper brake sensor) was 17.37 newtons, with a standard deviation of 19.59 newtons. The standard error mean was 4 newtons and the estimated 95\% confidence was between 25.64 and 9.09 newtons. The resultant t -value was 4.34 , which for $\mathrm{df}=23$ is statistically significant below 0.0001 level. The mean difference between the third pair (clutch force sensor) was 98.32 newtons and its standard deviation 87.34 newtons. The mean standard error was 17.47 and the $95 \%$ confidence interval between 134.37 and 62.26 newtons. The resultant $t$-value was 5.63 , highly significant below 0.0001 level for $\mathrm{df}=24$. The mean difference between the fourth pair (throttleoff rate) was 0.16 and the standard deviation 0.17 . Mean standard error was 0.03 and the boundaries of the $95 \%$ confidence interval of the difference were 0.23 and 0.09 . The resulted $t$-value of 4.79 was statistically significant below 0.0001 level for $\mathrm{df}=24$. However, because the distributions of throttle-off rates both on public roads (figure 53) and on track (figure 58) were clearly lacking both homogeneity and normality, this pair's difference was also analysed using a non-parametric test. Table 42 displays the comparison employing Wilcoxon's non-parametric test. In 6 cases throttle-release rate on public road was greater than on the closed track. The resultant mean rank was 3.83 and the sum of ranks was 23 . In 18 cases the throttle-off rate was greater on the test track and the mean rank was 15.39 . The sum of ranks was 277 . There
was also one case where throttle-off was tied between the two sessions. The resultant Z-value of 3.629 has an asymptotic significance below 0.0001 (table 43).

Table 42: Wilcoxon's signed ranks for throttle-off on the public road and on the test track

|  |  | N |  | Mean Rank |
| :--- | :--- | ---: | ---: | ---: | Sum of Ranks (

a Throttle-off rate, emergency event < Throttle-off rate, public road driving
b Throttle-off rate, emergency event > Throttle-off rate, public road driving
c Throttle-off rate, emergency event = Throttle-off rate, public road driving

Table 43: Wilcoxon signed ranks test statistics

a Based on negative ranks.

Combined input on the brake pedal sensors (pair 5, table 41) displayed a mean difference of 14.24 newtons between public road and test track. The standard deviation was 11.51 and the mean standard error 2.3. The $95 \%$ confidence interval of the difference was between 19.00 and 9.49. The resulted $t$-value of 6.189 was significant $(p<0.0001)$ for 24 degrees of freedom.

## Relationships

The relationships between the braking parameters of interest were examined. All the measurable variables of pedal operation were included, including throttle, brake and clutch pedal inputs. These are the variables included in the previous relevant studies (e.g. Kassaagi, 2001) and also as this is the first time the relationships are examined in this way, it was considered reasonable to be exploratory and include all the variables of pedal operation measured during the road and track-trials. Linear and non-linear regression models were tested - predominantly linear, logarithmic, inverse, quadratic, cubic, compound, power, S , growth, exponential and logistic regression models. Again, the focus was on variables possibly exploitable by a system identifying emergency braking.

## Brake force

Figure 61 is the graphical representation of the regression analysis for the lower brake sensor data. The typical values for each driver during the public road section are plotted on the X -axis, while the Y -axis displays the corresponding values during the emergency test on the closed road track. Table 44 presents the analysis of variance for each model tested. Compound, power, S, growth, exponential and logistic regression cannot be calculated because the data set contains zeros (see also the graph on figure 61). Linear exhibited an F-value of 8.14 , which is significant below 0.01 ( $p=0.009$ ), and explained $26.1 \%$ of the variance $\left(R^{2}=0.261\right)$. There are two columns for degrees of freedom, as they are affected by the number of parameters in the equation of each regression model. First column is based on the degrees of
freedom for the regression and the second column is the degrees of freedom for the residuals. The "parameter estimates" section on table 44 presents the parameters of the equation upon which the emergency-test input on the lower sensor can be calculated if the typical public-road value is known. Logarithmic regression explained $19.6 \%$ of the variance and exhibited an F-value of 5.62, which has statistical significance below $0.05(p=0.027)$. Inverse regression provided an $R^{2}=14.6 \%$ and an $F=3.93$, resulting in statistical significance above $0.05(p=0.06)$. Quadratic regression yielded $R^{2}=41.9 \%$ and $F=7.93$, which is statistically significant below $0.01(\mathrm{p}=0.003)$. Cubic regression yielded $R^{2}=59.2 \%$ and $F=10.17$, which resulted in the highest statistical significance ( $p<0.001$ ).


Figure 61: Application of various regression models to explain the relationship between emergency and non-emergency braking using the lower part of the brake pedal

Table 44: Summary of regression models and analysis of variance for lower brake force data in the two sessions

| Equation | Model Summary |  |  |  |  | Parameter Estimates |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | R Square | F | $\begin{gathered} \mathrm{df} \\ 1 \\ \hline \end{gathered}$ | df2 | Sig. | Constant | b1 | b2 | b3 |
| Linear | . 261 | 8.140 | 1 | 23 | . 009 | -3.186 | 3.835 |  |  |
| Logarithmic | . 196 | 5.620 | 1 | 23 | . 027 | -8.816 | 16.161 |  |  |
| Inverse | . 146 | 3.934 | 1 | 23 | . 059 | 29.648 | -58.603 |  |  |
| Quadratic | . 419 | 7.934 | 2 | 22 | . 003 | 35.552 | -12.380 | 1.483 |  |
| Cubic | . 592 | 10.172 | 3 | 21 | . 000 | -82.128 | 64.843 | -13.727 | . 914 |
| Compound(a) | . | . | . | . |  | . 000 | . 000 |  |  |
| Power(a) | . | . | . | . | . | . 000 | . 000 |  |  |
| S(a) | . | . | . | . | . | . 000 | . 000 |  |  |
| Growth(a) | . | . | . | . | . | . 000 | . 000 |  |  |
| Exponential(a) | . | . | . | . | . | . 000 | . 000 |  |  |
| Logistic(a) | . | . | . | . | . | . 000 | . 000 |  |  |

[^8]

Figure 62: Application of various regression models to explain the relationship between emergency and non-emergency braking using the upper part of the brake pedal

Figure 62 is the graphical representation of the regression analysis for the upper brake sensor data. The typical values for each driver during the public road section are plotted on the X -axis, while the Y -axis displays the corresponding values during the emergency test on the closed road track.

Table 45 presents the analysis of variance for each model tested. Compound, power, S, growth, exponential and logistic regression cannot be calculated because the data set contains zeros (see also the graph on figure 62). Linear regression exhibited an F-value of 3.86 , which is not significant below 0.05
$(p=0.06)$, and explained $14.9 \%$ of the variance $\left(R^{2}=0.149\right)$. There are two columns for degrees of freedom, as in the previous table. The "parameter estimates" section, as in table 44, presents the parameters of the equation upon which the emergency-test input on the lower sensor can be calculated if the typical public-road value is known. Logarithmic regression explained $14.6 \%$ of the variance and exhibited an F-value of 3.86 , which does not have statistical significance below $0.05(p=0.06)$. Inverse regression provided an $R^{2}=13.4 \%$ and an $F=3.41$, resulting in statistical significance above 0.05 ( $p=0.08$ ). Quadratic regression yielded $R^{2}=15.3 \%$ and $F=1.9$, which is not statistically significant below $0.05(p=0.17)$. Cubic regression yielded $R^{2}=15.7 \%$ and $F=1.24$, which resulted in the minimum statistical significance ( $p=0.32$ ).

Table 45: Summary of regression models and analysis of variance for upper brake force data in the two sessions

| Equation | Model Summary |  |  |  |  | Parameter Estimates |  |  |  |
| :--- | ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: |
|  | R <br> Square | F | df1 | df2 | Sig. | Constant | b 1 | b2 | b3 |
| Linear | .149 | 3.859 | 1 | 22 | .062 | 12.184 | 1.611 |  |  |
| Logarithmic | .149 | 3.859 | 1 | 22 | .062 | -.068 | 13.194 |  |  |
| Inverse | .134 | 3.408 | 1 | 22 | .078 | 38.685 | -76.755 |  |  |
| Quadratic | .153 | 1.901 | 2 | 21 | .174 | 8.380 | 2.583 | - |  |
| Cubic | .157 | 1.243 | 3 | 20 | .321 | 16.526 | -.640 | .283 | -.009 |
| Compound(a) |  | . | . | . | . | . | .000 | .000 |  |
| Power(a) |  | . | . | . | . | . | .000 | .000 |  |
| S(a) |  | . | . | . | . | .000 | .000 |  |  |
| Growth(a) |  | . | . | . | . | . | .000 | .000 |  |
| Exponential(a) |  | . | . | . | . | .000 | .000 |  |  |
| Logistic(a) |  | . | . | . | . | .000 | .000 |  |  |

Dependent Variable: test_brake_force_upper
The independent variable is pub_road_brake_force_upper_avg.
a The dependent variable (test_brake_force_upper) contains non-positive values. The minimum value is .00. Log transform cannot be applied. The Compound, Power, S, Growth, Exponential, and Logistic models cannot be calculated for this variable.


Figure 63: Application of various regression models to explain the relationship between emergency and non-emergency braking pedal force

Figure 63 is the graphical representation of the regression analysis for the combined brake sensor data. The typical values for each driver during the public road section are plotted on the X -axis, while the Y -axis displays the corresponding values during the emergency test on the closed road track. Table 46 presents the analysis of variance for each model tested. Linear regression exhibited an F-value of 5.98 , which is not significant below 0.05 ( $p=0.023$ ), and explained $20.6 \%$ of the variance $\left(R^{2}=0.206\right)$. The "parameter estimates" section, as on table 46, presents the parameters of the equation upon which the emergency-test input on the lower sensor can be calculated if the typical public-road value is known. Logarithmic regression explained $15.2 \%$ of the variance and exhibited an F -value of 4.11 , which has statistical
significance $p=0.05$. Inverse regression model provided an $R^{2}=9.8 \%$ and an $F=2.5$, resulting in statistical significance above 0.05 ( $p=0.13$ ). Quadratic regression yielded $R^{2}=25.9 \%$ and $F=3.84$, which is statistically significant below $0.05(p=0.04)$. Cubic regression yielded $R^{2}=26 \%$ and $F=2.46$, which resulted in statistical significance above the typical 0.05 criterion ( $p=0.09$ ).

Table 46: Summary of regression models and analysis of variance for combined brake force data in the two sessions

| Equation | Model Summary |  |  |  |  | Parameter Estimates |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | R Square | F | df1 | df2 | Sig. | Constant | b1 | b2 | b3 |
| Linear | . 206 | 5.976 | 1 | 23 | . 023 | 8.674 | 1.832 |  |  |
| Logarithmic | . 152 | 4.114 | 1 | 23 | . 054 | 1.44 | 10.819 |  |  |
| Inverse | . 098 | 2.496 | 1 | 23 | . 128 | 29.96 | -49.735 |  |  |
| Quadratic | . 259 | 3.837 | 2 | 22 | . 037 | 22.900 | -2.434 | . 265 |  |
| Cubic | . 26 | 2.464 | 3 | 21 | . 091 | 30.125 | -5.767 | . 711 | -. 018 |
| Compound | . 129 | 3.418 | 1 | 23 | . 077 | 10.96 | 1.073 |  |  |
| Power | 0.79 | 1.984 | 1 | 23 | . 172 | 8.845 | . 382 |  |  |
| S | . 038 | . 906 | 1 | 23 | . 351 | 3.142 | -1.511 |  |  |
| Growth | . 129 | 3.418 | 1 | 23 | . 077 | 2.394 | . 071 |  |  |
| Exponential | . 129 | 3.418 | 1 | 23 | . 077 | 10.960 | . 071 |  |  |
| Logistic | . 129 | 3.418 | 1 | 23 | . 077 | . 091 | . 932 |  |  |



Figure 64: Application of various regression models to explain the relationship between emergency and non-emergency throttle release

Figure 64 is the visual representation of the regression analysis for the throttle-release data. The typical values for each driver during the public road section are plotted on the X -axis, while the Y -axis displays the corresponding values during the emergency test on the closed road track. Table 47 presents the analysis of variance for each model tested. As can be clearly seen in figures 53 and 58, the data lacks normality and is concentrated on particular coordinates. It is no surprise that the regression models tested, fail to provide statistical evidence anywhere near the typical criterion $\mathrm{a}=0.05$. Linear regression exhibited an F-value of 0.2 , which has p-value 0.89 , and explains just $0.1 \%$ of the variance $\left(R^{2}=0.001\right)$. Logarithmic regression explained $0.2 \%$ of the variance and exhibited an F-value of .04 , which has a $p=0.85$. Inverse
regression provided an $R^{2}=0.2 \%$, an $F=0.06$, and $p=0.81$. Quadratic regression yielded $R^{2}=0.7 \%, F=0.77$, and $p=0.93$. Cubic regression yielded $R^{2}=0.7 \%, F=0.081$, and $p=0.92$. One of the cubic parameters is excluded, because the best fit happens when it functions as a quadratic model instead (with $2+1$ constant parameters, where one parameter is raised to the cube). A compound regression model explained $0.4 \%$ of variance and analysis of variance provided $\mathrm{F}=0.083$ and $\mathrm{p}=0.77$. The power regression yielded $R^{2}=0.005, F=0.119$ and $p=0.77$. The respective values for the S-model were $R^{2}=0.007, F=0.155$ and $p=0.698$. Growth regression explained $0.4 \%$ of variance and had $\mathrm{F}=0.08$ and $\mathrm{p}=0.77$. The results for exponential regression and for logistic regression were $\mathrm{R}^{2}=0.004$. $\mathrm{F}=0.08$ and $\mathrm{p}=0.77$.

Table 47: Summary of regression models and analysis of variance for throttle-off data in the two sessions

| Equation | Model Summary |  |  |  |  | Parameter Estimates |  |  |  |
| :--- | ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: | ---: |
|  | R Square | F | df1 | df2 | Sig. | Constant | b1 | b2 | b3 |
| Linear | .001 | .019 | 1 | 23 | .892 | .688 | -.048 |  |  |
| Logarithmic | .002 | .036 | 1 | 23 | .850 | .646 | -.024 |  |  |
| Inverse | .002 | .058 | 1 | 23 | .813 | .644 | .009 |  |  |
| Quadratic | .007 | .077 | 2 | 22 | .926 | .869 | -1.102 | 1.346 |  |
| Cubic | .007 | .081 | 3 | 21 | .922 | .829 | -.675 | (a) | 1.283 |
| Compound | .004 | .083 | 1 | 23 | .775 | .696 | .875 |  |  |
| Power | .005 | .119 | 1 | 23 | .733 | .625 | -.057 |  |  |
| S | .007 | .155 | 1 | 23 | .698 | -.472 | .020 |  |  |
| Growth | .004 | .083 | 1 | 23 | .775 | -.363 | -.133 |  |  |
| Exponential | .004 | .083 | 1 | 23 | .775 | .696 | -.133 |  |  |
| Logistic | .004 | .083 | 1 | 23 | .775 | 1.437 | 1.142 |  |  |

a The tolerance limit for entering variables is reached.

## Clutch force



Figure 65: Application of various regression models to explain the relationship between emergency and non-emergency clutch-pedal use

Figure 65 is the graphical representation of the regression analysis for the clutch-force sensor data. The typical values for each driver during the public road section are plotted on the X -axis, while the Y -axis displays the corresponding values during the emergency test on the closed road track. Table 48 presents the analysis of variance for each model tested. Linear regression exhibited an F-value of 1.98 , which has a p-value 0.17 , and explains just $7.9 \%$ of the variance $\left(R^{2}=0.079\right)$. Logarithmic regression explained $18 \%$ of the variance and exhibited an F-value of 5.04 , which has a $\mathrm{p}=0.04$. Inverse regression provided an $\mathrm{R}^{2}=26.7 \%$, an $\mathrm{F}=8.36$, and $\mathrm{p}=0.01$. Quadratic regression yielded $R^{2}=15.6 \%, F=2.04$, and $p=0.15$. Cubic regression yielded $R^{2}=21.3 \%, F=1.89$, and $p=0.162$. A compound regression
model explained $6.6 \%$ of variance and analysis of variance provided $F=1.623$ and $p=0.215$. The power regression yielded $R^{2}=0.22, F=6.584$ and $p=0.017$. The respective values for the $S$-model were $R^{2}=0.387, F=14.536$ and $p=0.001$. Growth regression explained $6.6 \%$ of variance and had $F=1.62$ and $p=0.21$. The results for exponential regression and for logistic regression were $R^{2}=0.07, F=1.62$ and $p=0.21$.

Table 48: Summary of regression models and analysis of variance for clutch-pedal force data in the two sessions

| Equation | Model Summary |  |  |  |  | Parameter Estimates |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | R Square | F | $\begin{gathered} d f \\ 1 \\ \hline \end{gathered}$ | df2 | Sig. | Constant | b1 | b2 | b3 |
| Linear | . 079 | 1.979 | 1 | 23 | . 173 | 172.655 | . 419 |  |  |
| Logarithmic | . 18 | 5.037 | 1 | 23 | . 035 | -20.727 | 52.566 |  |  |
| Inverse | . 267 | 8.362 | 1 | 23 | . 008 | 254.433 | -2150.934 |  |  |
| Quadratic | . 156 | 2.038 | 2 | 22 | . 154 | 84.965 | 2.222 | -. 007 |  |
| Cubic | . 213 | 1.891 | 3 | 21 | . 162 | 4.291 | 6.168 | -. 051 | . 000 |
| Compound | . 066 | 1.623 | 1 | 23 | . 215 | 107.62 | 1.004 |  |  |
| Power | . 223 | 6.584 | 1 | 23 | . 017 | 9.283 | . 634 |  |  |
| S | . 387 | 14.536 | 1 | 23 | . 001 | 5.577 | -28.108 |  |  |
| Growth | . 066 | 1.623 | 1 | 23 | . 215 | 4.679 | . 004 |  |  |
| Exponential | . 066 | 1.623 | 1 | 23 | . 215 | 107.62 | . 004 |  |  |
| Logistic | . 066 | 1.623 | 1 | 23 | . 215 | . 009 | . 996 |  |  |

## Video data

Video recording of the vehicle's footwell provided both qualitative and quantitative data for foot and pedal movements. The quantitative measures were time for foot displacement (between throttle and brake pedal) and brake pedal displacement at 80 ms (after initial contact with the pedal). Time was measured as the number of video-frames it took the foot to touch the brake-
pedal after losing touch with the throttle-pedal. Pedal-displacement was measured by the number of pixels one end of the pedal travelled on the camera lens. The frame at 80 ms was the nearest to the 100 ms time stamp used previously by Kasaagi (2005). Again, data from the emergency test was compared against the data from the public road section. Due to the nature of manual video-analysis, ten random brake instances in the public road section per individual were used for the analysis (250 in total). The number of braking scenes examined was limited by the number of drivers (25) who had significant input ( $>5 \mathrm{~N}$ on the sensor) to the brake pedal during the emergency test and the plausible number of frame-by-frame analyses of braking sequences (10 per driver).


Figure 66: Public-road brake pedal displacement at 80 ms against the same variable in the emergency test (in pixels through the camera lens)

Figure 66 presents a plot of participants' braking in terms of initial ( 80 ms ) brake pedal displacement and figure 67 presents braking in terms of footdisplacement time (from throttle to brake pedal) during "normal" driving on the public road route and emergency braking on the closed track. Table 49 presents the paired statistics of the comparative analysis between the two sections. Mean (typical) pedal displacement during the public road section was 19.04 pixels (on the lens) and the standard deviation of this variable was 7.87 pixels. The respective values on the emergency test in the closed track were 45.4 and 24.48 pixels. Typical foot displacement time during the public road session was 8.13 frames and the standard deviation was 2.32 frames.

On the test track, average foot displacement time was 4.8 frames and the standard deviation was 1.6 frames.

Table 49: Paired sample statistics for foot displacement time and brake pedal displacement at 80 ms between public road and emergency test braking

|  |  | Mean | $N$ | Std. Deviation | Std. Error Mean |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Pair 1 | Typical foot displacement time Emergency foot displacement time | $\begin{aligned} & \hline 8.13 \\ & 4.80 \end{aligned}$ | $25$ $25$ | $2.33$ $1.61$ | $.47$ $.32$ |
| Pair 2 | Typical brake pedal displacement at 80 ms Emergency brake pedal displacement at 80 ms | $\begin{aligned} & 19.05 \\ & 45.40 \end{aligned}$ | 25 <br> 25 | $\begin{array}{r} 7.87 \\ 24.48 \end{array}$ | $1.57$ $4.90$ |



Figure 67: Foot displacement time (in video frames) between throttle and brake pedal during public-road driving and during the emergency test

Table 50 presents the results of the T-test employed to test the difference of foot-displacement time and initial brake-pedal displacement between normal driving and the emergency test. The mean difference in footdisplacement time was 3.33 frames and the standard deviation of the difference was 2.54 frames. For 24 degrees of freedom, the resultant T-value 6.54 is statistically significant below 0.001 ( $p<0.0001$ ). The mean difference of initial brake-pedal displacement was 26.35 pixels and the standard deviation was 23.39 pixels. The resultant T-value of (-) 5.63 is statistically significant below $0.001(\mathrm{p}<0.0001)$ for $\mathrm{df}=24$.

Table 50: Paired samples T-test comparison between public road driving and emergency test


Relationships


Figure 68: Application of various regression models to explain the relationship between emergency and non-emergency initial brake-pedal displacement

Figure 68 is the graphical representation of the regression analysis for initial ( 80 ms ) brake-pedal displacement data. The typical values for each driver during the public road section are plotted on the X -axis, while the Y -axis displays the corresponding values during the emergency test on the closed road track. Table 51 presents the analysis of variance for each model tested. Linear regression exhibited an F-value of 2.20, which is not statistically significant below $0.05(\mathrm{p}=0.15)$, and explained $8.8 \%$ of the variance $\left(R^{2}=0.088\right)$. Logarithmic regression explained $13.7 \%$ of the variance and exhibited an F-value of 3.662 , which has statistical significance above 0.05 $(p=0.07)$. Inverse regression provided an $R^{2}=17.8 \%$ and an $F=4.99$, resulting in statistical significance below $0.05(p=0.04)$. Quadratic regression yielded
$R^{2}=31.1 \%$ and $F=4.96$, which is statistically significant below $0.05(p=0.02)$. Cubic regression yielded $R^{2}=31.2 \%$ and $F=3.18$, which resulted in statistical significance below 0.05 ( $p=0.045$ ). Compound model explained $13.8 \%$ of the interaction between the two variables, while analysis of variance provided an $F=3.67$, which is significant above 0.05 level $(p=0.07)$. Power regression exhibited $R^{2}=17.5 \%, F=4.88$ and $p=0.04$ (below the 0.05 criterion). The $S$ regression model explained $19.3 \%$ of the variation and analysis of variance gave an $F=5.5$, which is statistically significant below $0.05(p=0.03)$. Growth and exponential models had identical results; $R^{2}=13.8 \%, F=3.67$ and $p=0.07$.

Table 51: Regression model summary and parameter estimates for brake pedal displacement between public road and emergency test sessions

| Equation | Model Summary |  |  |  |  | Parameter Estimates |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | R Square | F | df1 | df2 | Sig. | Constan t | b1 | b2 | b3 |
| Linear | . 088 | 2.207 | 1 | 23 | . 151 | 27.861 | . 921 |  |  |
| Logarithmic | . 137 | 3.662 | 1 | 23 | . 068 | -17.131 | 21.828 |  |  |
| Inverse | . 178 | 4.989 | 1 | 23 | . 036 | 70.869 | -412.022 |  |  |
| Quadratic | . 311 | 4.962 | 2 | 22 | . 017 | -51.621 | 9.713 | -. 208 |  |
| Cubic | . 312 | 3.178 | 3 | 21 | . 045 | -67.665 | 12.348 | -. 339 | . 002 |
| Compound | . 138 | 3.673 | 1 | 23 | . 068 | 19.702 | 1.035 |  |  |
| Power | . 175 | 4.882 | 1 | 23 | . 037 | 4.703 | . 726 |  |  |
| S | . 193 | 5.499 | 1 | 23 | . 028 | 4.410 | -12.636 |  |  |
| Growth | . 138 | 3.673 | 1 | 23 | . 068 | 2.981 | . 034 |  |  |
| Exponential | . 138 | 3.673 | 1 | 23 | . 068 | 19.702 | . 034 |  |  |

Dependent Variable: Emergency brake pedal displacement at 80 ms
The independent variable is Typical brake pedal displacement at 80 ms .

Figure 69 is the graphical representation of the regression analysis for foot displacement data (throttle to brake pedal). The typical values for each driver during the public road section are plotted on the X -axis, while the Y -axis displays the corresponding values during the emergency test on the closed road track. Table 52 presents the analysis of variance for each model tested.

Linear regression exhibited an F-value of 1, which is not statistically significant below $0.05(p=0.33)$, and explained $4.2 \%$ of the variance $\left(R^{2}=0.042\right)$.

Logarithmic regression explained $5.7 \%$ of the variance and exhibited an Fvalue of 1.4 , which has statistical significance above $0.05(p=0.25)$. Inverse regression provided an $R^{2}=6.7 \%$ and an $F=1.6$, resulting in statistical significance above $0.05(p=0.21)$. Quadratic regression yielded $R^{2}=10.1 \%$ and $F=1.23$, which is statistically significant above $0.05(p=0.31)$. Cubic regression yielded $R^{2}=12.7 \%$ and $F=1.01$, which resulted in statistical significance above $0.05(p=0.4)$. Compound model explained $4.5 \%$ of the interaction between the two variables, while analysis of variance provided an $\mathrm{F}=1.08$, which is significant above 0.05 level ( $p=0.30$ ). Power regression exhibited $R^{2}=5.9 \%$, $F=1.45$ and $p=0.24$ (above the 0.05 criterion). The $S$ regression model explained $6.7 \%$ of the variation and analysis of variance gave an $F=1.65$, which is statistically significant above $0.05(p=0.21)$. Growth and exponential models had identical results; $R^{2}=4.5 \%, F=1.09$ and $p=0.31$.

Table 52: Regression model summary and parameter estimates for foot displacement time between public road and emergency test sessions

| Equation | Model Summary |  |  |  |  | Parameter Estimates |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | $\begin{gathered} \mathrm{R} \\ \text { Square } \\ \hline \end{gathered}$ | F | df1 | df2 | Sig. | Constant | b1 | b2 | b3 |
| Linear | . 042 | 1.001 | 1 | 23 | . 328 | 3.654 | . 141 |  |  |
| Logarithmic | . 057 | 1.397 | 1 | 23 | . 249 | 1.694 | 1.506 |  |  |
| Inverse | . 067 | 1.640 | 1 | 23 | . 213 | 6.549 | -13.351 |  |  |
| Quadratic | . 101 | 1.235 | 2 | 22 | . 310 | -. 801 | 1.121 | -. 049 |  |
| Cubic | . 127 | 1.017 | 3 | 21 | . 405 | 9.730 | -2.503 | . 342 | -. 013 |
| Compound | . 045 | 1.086 | 1 | 23 | . 308 | 3.629 | 1.029 |  |  |
| Power | . 059 | 1.454 | 1 | 23 | . 240 | 2.473 | . 298 |  |  |
| S | . 067 | 1.647 | 1 | 23 | . 212 | 1.861 | -2.599 |  |  |
| Growth | . 045 | 1.086 | 1 | 23 | . 308 | 1.289 | . 028 |  |  |
| Exponential | . 045 | 1.086 | 1 | 23 | . 308 | 3.629 | . 028 |  |  |

[^9]

Figure 69: Application of various regression models to explain the relationship between emergency and non-emergency foot displacement time (from throttle to brake pedal)

## Discussion

Overall, the study employed methods to provide evidence regarding the second and third research questions as those were quoted in chapter 2. In summary, the results supported a quantitative distinction between normal and emergency brake application and confirmed the results from Perron et al (2001), Kassaagi (2001), Bouslimi (2005) and Schmitt \& Färber (2005). The findings also went one step further, providing evidence of relationships between emergency and non-emergency braking inputs per driver. The
potential of employing this relationship for the specification of adaptive brake systems is examined in the penultimate main study of this Thesis ("System Simulation"). In this section, a closer look is taken and discussion of the study as a whole and is made.

## Sampling

The sample used in the current study compares favourably with those reported in the previous driver-braking studies quoted in the "Literature review" chapter (Bouslimi et al., 2005; Perron et al., 2001; Schmitt \& Färber, 2005). Participants were neither recruited from a "customer" participant database, as in (Kassaagi, 2001), nor were specialist test drivers; they were recruited through adverts in local press and contributed to a realistic variability within the sample. The range of ethnic backgrounds represented in the sample could both represent the local population (Leicester: Ethnicity profile.), as well as facilitate future application of results outside the UK. This inclusive trend is repeated in age, driving experience, size and weight. Size is particularly important as the angle through which a force is applied on a pedal effects its resultant movement (Diffrient et al., 1993; Pheasant, 1987). This is affected by driving posture and in turn this is affected by size (Porter \& Gyi, 1998). Those characteristics of the sample displayed normal or "normal-like" distributions (figures 42, 43). The weight distribution lacks another column below 50 kg to compensate for the extreme values found at the other end of the range, however, this can also be seen as representative of the commonly quoted obesity in the modern society (Department of Health - Freedom of Information). The main limitation of the sampling method was imposed by the
insurance company; nobody with more than five points on their driving license could take part. This requirement, ruled out any opportunity to collect data from drivers who objectively take more risks according to society's legislative and enforcing system.

## Apparatus

The instrumented vehicle used in the study is among the most common road vehicles in Europe (Colorado Springs Gas Prices, 2009). This is an advantage of independent (from manufacturers' involvement) research, as vehicle selection for the study was not restricted to a particular manufacturer's fleet. Thus, one of the most common vehicles could be selected and compensate for having to use a single vehicle for the study. However, this is one side of the coin; the other side is the fact that independent research comes with limited budget and thus only one vehicle could be instrumented. Funds could cover the cost of the vehicle and its instrumentation but could not go further into supporting the employment of an additional vehicle.

Accordingly, although the results should be representative of a significant part of the vehicle fleet, they will reflect the vehicle's particular design and specification of controls. The discussion of results regarding the throttle-pedal operation that follows provides an example of what this might involve. An insight can be provided by the early study from Eaton (1970), where drivers were tested in two types of vehicle (medium-large). Results from that study indicated that there is a very small effect for vehicle size; the large vehicle was associated with heavier braking, although nominal values remained proportionate to the same values in the other car. Thus, as the focus of this
study is on proportions, trends and relationships rather than the exact values, the vehicle factor has probably little effect on the results.

Taking into account the cost for each part of the equipment used, the throttle-pedal potentiometer proved reliable throughout its 3-month use for the study. Against initial intention, another potentiometer was not installed on the brake pedal axis, as the design of the latter made it impossible to fit the former there. Thus brake pedal movement was recorded through the video camera. This solution had two consequences; first, data logging rate fell from 50 Hz to $30 \mathrm{~Hz}(60 \mathrm{~Hz}$ interpolated), and second, data would be affected by the lens properties and limitations (resolution, light, occasional cover of the object of interest). Again though, that was not too big a problem, as the focus is on trends and relationships, not precise numbers.

The force sensors used to measure brake pedal activation provided high precision and proved very reliable. This precision was enhanced by the conditioning of the sensor (Tekscan, 2008) performed before each trial. In addition, the use of two sensors on the brake pedal surface provided information on the localisation of pedal inputs (upper/lower part). However, the limited size of the sensors compared to the total pedal surface, necessitated extrapolation for the actual forces applied on the pedal to be estimated.

The second camera, mounted on the dashboard, apart from recording information of the road environment, allowed (after calibration) estimation of time headway through measuring the size of the image of the trailer. Again, such process could be open for argument regarding its precision; however the results (figure 60) exhibit the expected resolution in accordance with previous
studies regarding time-headway in relation to human-eye properties (Olson, 1996).

Of course, the most impressive element of the equipment used in this study was the custom-made trailer. And it is so, not because it stopped equally quickly as road vehicle (Vangi \& Virga, 2007), or because it proved extremely safe. It was impressive because it achieved both, without compromising on either. Finally, the test site necessitated a strict schedule for the sessions, as access was restricted to specific days and times, however taking into account the fact it was offered for free, this was a limitation the project could easily manage with. The alternative option, hiring a venue, would impose unbearable costs to the project and it is doubtful the above access limitations would not apply in that case too. Last but not least, the location of the test site was ideal; the 10 km route to there provided a wealth of realistic "normal" data including both urban and rural road sections.

## Execution

A key advantage of this study over previous driver braking studies (Bouslimi, 2006; Curry et al., 2003; Eaton \& Dittmeier, 1970; Kassaagi, 2001; Perron et al., 2001; Schmitt \& Färber, 2005; Tijtgat, Mazyn, De Laey, \& Lenoir, 2008; W. van Winsum \& Brouwer, 1997) is the collection of "normal braking" data on a public road with uncontrolled traffic. Accordingly, the results obtained from this part of the study exhibit a high degree of ecological validity. Although this fact does not guarantee that the data collected is "normal", it approximates "normal" more than any previous study.

Continuing on the issue of ecological validity, safety-related, ethical and practical reasons demanded an experimenter to be in the car with the participant at all times. Although it is not certain that this could influence the results, it is equally uncertain that it did not. Some insight is provided through comparison of the results from the public road section in this study against results from the naturalistic study described in the previous chapter. Under contemporary regulations, technologies available and research ethics it is doubtful that any further step can be taken without compromising the safety of participants. In addition, the sample exhibited similar inputs to the brake-pedal during the road section of the present study (figure 55) and the naturalistic study in the previous chapter (figure 40). A t-test comparison between the two distributions results in a p-value of 0.22 , far above the typical statistical criterion for significance.

Regarding the emergency test, the design of the study matched the definition of driver emergency braking on page 62. The two key elements, causal to the reactive operation of vehicle pedals, were: the element of surprise (sudden) and the introduction of an obstacle with which the vehicle would collide unless the reactive pedal operation takes place. Although some participants had more complex reactions, involving steering, gearing down and minimising brake pedal use, the use of the released trailer and the cones separating the two lanes (figure 48) satisfies the definition without putting the participants at serious risk.

The restriction of vehicle speed to $30 \mathrm{mph} / 48 \mathrm{kmh}$ was imposed by the safety management of the study. Therefore, any results from this study might not be applicable to higher speeds. In reality however, this is the most
pertinent speed level, as at present most rear-shunts happen at low speed (L. Evans, 2004) and future integrations with ACC systems should take into account the tendency for drivers to disengage ACC at speeds below 50kmh (Pauwelussen \& Minderhoud, 2008).

## Results

The descriptive statistics of the main variables during both the public road section (table 37) showed more inter-personal variation in some and more concentrated values around the mean for other variables. As mentioned above in the discussion of the apparatus, the nominal values from the force sensors cannot be used per se for a vehicular application. However, the individual differences regarding pedal force are directly indicated by the large standard deviations (compared to the means). This diversity is in line with previous results regarding brake-pedal force and speed of operation reported by Perron et al. (2001). In more detail, force on different areas of the brake pedal was almost identical overall; however some drivers used one area more than the other (upper-lower sensor data). Thus in practical terms it seems reasonable to use the total pedal force when designing/specifying the pedal controls. All distributions of force-related measures (figures 50-52,54) were "normal" or "normal-like", taking into account that in practice there cannot be values below " 0 ".

Throttle-off showed a much more typical behaviour; values were very much concentrated indicating much more constant throttle-release operation (figure 53). Looking at figure 53, it is possible to distinguish two groups of typical throttle-off, one around 0.37 degrees and another around 0.53 degrees per 0.02 sec . Furthermore, this distribution is obviously non-normal and
homogeneous, thus non-parametric tests were employed in the comparative analysis that followed.

Similar trends were noted in the closed track (table 38). Force-related measures showed more variation and inter-personal differences. There was one difference though; since some drivers' reaction was not restricted to pedal operation to avoid collision with the obstacle, a substantial amount of nearzero values made their appearance. This applies mainly to the brake-related variables (figures $55,56,59$ ) and less to the clutch variable, which showed a heavily skewed distribution, even by ruling the near-zeros out (figure 57).

As on the public road, throttle-off in emergency showed responses concentrated around two values. There was a shift though, as in this case the values were 0.50 and 0.70 degrees $/ 0.002 \mathrm{sec}$ (figure 58). Again, the distribution is unlikely to be seen as normal, and thus the non-parametric test in the comparative analysis.

The closed track session included a variable that could not be calculated in the public road section; time-headway at the instant the trailer was released. The instant the trailer was released was considered a key moment for headway measurement, as it was the headway temporarily closest to the braking input that follows. It was also expected that following the given instructions, drivers would have adopted their preferred headway by then. The distribution is very much skewed towards the top end, and seems to map very well on the visual properties of humans when judging distances (Olson, 1996). The size of objects on our retina follows an exponential curve, much like the one that could fit on the distribution on figure 60. This result follows previous findings supporting the use of rate of object-size change by drivers to estimate
their headway and control this headway through braking (Li \& Milgram, 2005; Olson, Cleveland, Fancher, Kostyniuk, \& Schneider, 1984).

Previously, in the "apparatus" section, it was noted that although the method and apparatus used is close to the limit of what is possible in terms of ecological validity, still it is far from ideal. The availability of a single vehicle, instead of multiple vehicles that would allow for vehicle effects control, could be a shaping factor of the nominal values of the results and possibly influence slightly some trends. Although previous study of vehicle-type effects on braking showed only a slight shift towards heavier braking when moving from a smaller to a larger vehicle (Eaton \& Dittmeier, 1970), there is no evidence regarding effects on other variables. Notably, throttle-off in this study was limited by the maximum angle of movement of the throttle pedal in the Ford Fiesta (<50deg in this model). A similar effect of the vehicle specification of controls to the nominal values of force during brake and clutch pedal operation could be behind their differences. Greater resistance of the clutch pedal during depression could explain the higher forces compared to the brake pedal, although these values could be influenced by other factors like the leg in use (left for clutch, right for brake pedal and for most people the right leg is more controlled and thus "gentle" when used). On the other hand, modern vehicle engineering has been very much standardised at its basics, and it is arguable that the fine differences can have significant impact on variables such as those measured here.

## Comparative and relational analysis

Comparative analysis between normal braking as measured on the public road section and the emergency brake response as measured on the emergency test on the closed track indicated that there are differences between the two types of braking. Parametric and non-parametric statistics tests indicated very low probabilities that the differences in all five braking variables are random (tables 41, 43, all probabilities $p<0.001$ ). These results provide further evidence in line with previous studies (Kassaagi, 2001; Perron et al., 2001; Schmitt \& Färber, 2005) in support of the argument that there are quantifiable differences between normal and emergency driver braking.

Regression analysis for the examination of the relationships of braking variables between conditions (emergency-normal) provided arguably the most important result of this study. Meaningful regression models can be applied for the force applied to the lower part of the brake pedal, the total pedal force and the clutch-pedal force between the two conditions. The properties of the throttle-off variable - mainly the concentration of values around specific points - did not allow for meaningful models to be established.

Clutch pedal force is a variable which was not included in the results reported either in Perron et al. (2001), Bouslimi (2005), or Schmitt \& Färber (2005). Results in the current study indicated that not only is clutch-pedal force different between normal and emergency conditions (table 41), but there is also a relationship that can be expressed through a logarithmic, inverse, power or $S$ regression model (table 48). The $S$ model in particular is both the most representative of the relationship (only 0.001 probability for the relationship to be result of chance) and the best predictor, explaining $38.7 \%$ of the interaction between normal and emergency clutch-pedal force. The main
drawback of using this variable for intelligent brake applications is the fact that clutch is not always used while braking and is also commonly used after the brake pedal depression.

The distinction between brake pedal areas and the separate analysis of each were not included in the methodology or the results reported either in Perron et al. (2001), Bouslimi (2005), or Schmitt \& Färber (2005). Results in the current study indicated that not only there are two areas (upper-lower) subject to different amounts of force between normal and emergency conditions (table 41), but also, in the case of the lower brake pedal area, there is a relationship that can be expressed through a linear, logarithmic, quadratic or cubic regression model (table 44). The cubic model in particular is both the most representative of the relationship (only 0.001 probability for the relationship to be result of chance) and the best predictor, explaining $59.2 \%$ of the interaction between normal and emergency clutch-pedal force. The quadratic model is also relevant; statistical significance $p=0.003$ and $R^{2}=41.9 \%$. The main weakness of incorporating this relationship in an intelligent braking system is the fact that some drivers rarely use this area of the pedal, as noticed both on the public road section and during the emergency test.

The use of the whole pedal surface as the area of force application during driver braking overcomes this problem, as it accounts for drivers who do not use one part of the pedal. This is not a significant compromise as the combined force on both areas of the pedal exhibits a relationship between normal and emergency instances (table 46). The linear and quadratic regression models satisfy the 0.05 statistical significance criterion. Between
them, it is the quadratic model that explains greater part of the interaction $25.9 \%$ for the quadratic against $20.6 \%$ for the linear regression model. It should be noted that the cubic model has the highest R-square (26\%), however the analysis of variance did not satisfy the typical criterion of 0.05 for statistical significance ( 0.09 in this case). According to statistical criteria, only the linear and quadratic models are valid though.

## Video data

Results of the quantitative parameters measured through the footwell camera supported both the differentiation between normal and emergency braking and the relationship of another two braking parameters between the two conditions. The T-test comparison on table 50 indicated that both foot displacement time (from throttle to brake pedal) and initial (at 80ms) brake pedal displacement differentiated significantly between normal and emergency conditions. In both cases T-values have probabilities below 0.001 of being the result of chance. This result provides extra evidence in support of the argument that normal and emergency braking are quantitatively different.

Analysis of variance to examine the validity of using various regression models to describe the relationship between normal and emergency braking showed the potential of initial brake pedal displacement (table 51). Inverse, quadratic, cubic, power, and $S$ regression models satisfied the typical 0.05 criterion of statistical significance. Among them, cubic and quadratic models explain more of the variance in the variable between the two conditions (31.2\% and $31.1 \%$ respectively). Such meaningful regression models could not be applied to the foot-displacement time variable. However, the results of
the application and analysis of variance of the regression models for brake pedal displacement in normal and emergency conditions is another result in support of the argument that relationships do exist between normal and emergency braking parameters.

The presence of relationships of variables between normal and emergency conditions is important because the relationships can be used by an intelligent brake system that adjusts its full-brake-activation trigger according to the typical normal braking values for each driver. An example of how this can be implemented is given in the "System Simulation Study" chapter.

Acording to the statistical criteria and analysis presented, the study provided good quality evidence in support of arguments that answer the $2^{\text {nd }}$ and $3^{\text {rd }}$ research questions of this Thesis; whether normal and emergency braking inputs are quantitatively different and whether a relationship exists between each driver's normal and emergency braking inputs. The evidence provided showed that there are quantitative differences between normal and emergency braking. In addition, evidence of relationships of variables between conditions was found. These relationships can potentially be incorporated in the specification of intelligent brake systems that adapt to different driving (braking) styles. Chapter 7 provides more details on this.

## Lessons from the controlled on-road study

The present chapter yielded basic evidence regarding driver braking inputs under normal and emergency conditions. First, evidence was provided of quantifiable differences between normal and emergency driver braking input. Among the dependant variables, throttle-off was found to be the best
variable in distinguishing between the two conditions (normal - emergency). Additional variables that exhibited statistically significant differences under the two conditions included brake-pedal force, initial displacement of brake-pedal (at 80 ms after initial contact with the pedal), and foot-displacement time (between throttle and brake-pedal). Therefore, it is reasonable to adopt the hypothesis that measurable differences exist between normal and emergency braking inputs.

Second, evidence of interactions and relationships between variables under both conditions was provided. The result suggested that for each driver, the braking inputs under an emergency are not random; they rather are related to the previous history of braking inputs and the representative mean of the respective distribution. Therefore, the hypothesis that relationships exist between normal and emergency braking inputs can be assumed.

Third, some of the various models employed to examine and explain the relationship between normal and emergency braking inputs were more successful than others. Among them, brake-pedal force and initial brake-pedal displacement (at 80 ms ) exhibited the strongest statistical properties. Between them, seven models in total satisfied the criterion for statistical significance (table 53). The quadratic and cubic models of the initial brake-pedal displacement between the two conditions explained more variance that the rest; however, the raw data upon which they were developed came from recorded video. Therefore, compared to data recorded through the force sensors, video data were inferior in terms of the rate and accuracy by which they were recorded. The quadratic model for the brake-pedal force somewhat lacks the statistical rigour of the two aforementioned models; however, it is
based on a wealth of accurate data, while it still retains strong statistical properties relatively to the rest of the models.

Table 53: Relative merits of the most pertinent variables and models for modelling the relationship between normal and emergency braking inputs

| Model - Variable | Total variance explained |  |
| :---: | :---: | :---: |
| $\begin{aligned} & \hline \text { Quadratic - Initial brake- } \\ & \text { pedal displacement (at } 80 \mathrm{~ms} \text { ) } \end{aligned}$ | 31\% | Based on video data |
| Cubic - Initial brake-pedal displacement (at 80 ms ) | 31\% | Based on video data |
| Quadratic - Brake-pedal force | 26\% | There are statistically stronger models |
| Linear - Brake-pedal force | 20\% | Explains only 20\% of variance |
| S - Initial brake-pedal <br> displacement (at 80 ms ) | 19\% | Explains only 19\%; based on video data |
| Inverse - Initial brake-pedal displacement (at 80 ms ) | 18\% | Explains only 18\%; based on video data |
| Power - Initial brake-pedal displacement (at 80 ms ) | 17\% | Explains only 17\%; based on video data |

The research question regarding the exploitability of the relationships between braking-input parameters under normal and emergency braking is predominantly tackled in the following chapter, where a basic adaptive brake
assist concept is presented and virtually tested based on on-road and ontrack data from 25 drivers. Nevertheless, the results of the studies in the present chapter qualified two braking parameters as the basis for the development of a method to continuously adapt the triggering value which engages the brake assist (figure 70). For this purpose, the instantaneous average/typical value of all the previous braking inputs can be employed. For example, the instantaneous mean of the initial displacement of the brake pedal can be used to estimate the "ideal" initial displacement, over which additional braking torque should be engaged by the braking system. An extensive example of this opportunity is provided in the following chapter.


Figure 70: The appropriate braking-input parameters for the successful specification of conventional and adaptive brake assist systems, as suggested by the results of the present study.

## Summary

Chapter 6 described an extensive study of driver braking on an open and a closed road section. 48 drivers drove an instrumented vehicle on a public road section before arriving at a test track, where they were instructed to follow at their preferred distance another vehicle towing a trailer. They were told the aim was to measure their preferred car-following distance. They were naïve to the fact that 0.2 miles down the track the trailer would be released and rapidly decelerate to a stop. The main variables analysed included "throttle-off" rate, brake pedal pressure/force, and clutch pedal pressure/operation. The results indicate a series of relationships exploitable by an intelligent brake assist system. An intelligent brake assist system could take advantage of those characteristics and adapt its performance to individuals' braking style.

Limitations of the study include resource constraints (use of a single instrumented vehicle, time-limited access to the test track) and the contrived nature of the emergency braking scenario (need for surprise element, practically a one-off study, limitation of speed to $30 \mathrm{mph} / 48 \mathrm{kmph}$ ). The study provides evidence of a background for a customisable brake assist system that learns from the driver and adjusts its trigger for maximum braking torque accordingly.

## Chapter 7: System simulation study ${ }^{7}$

## Introduction

Results from chapter 6 (controlled road study) indicated relationships between driver braking parameters in normal and emergency conditions. Further regression analysis provided some meaningful models to simulate the relationship between some variables. Analysis of variance supported the validity of regression models for two driver braking parameters: pedal-force to the brake pedal and initial displacement of the brake-pedal (at 80 ms after contact).

Such models can be exploited by a brake system that constantly adapts the full-brake trigger according to the braking history of the driver/vehicle. Previous approaches by Schmitt \& Färber (2005) and Bouslimi (2005) suggested fusion of multiple variables in order to predict emergency braking. However, in both approaches it is not the trigger that changes; it is the relative contribution of the component/agents of the respective predictive systems. To express it in plain language, although these two models are different, they are based on the notion that "if $X$ is such and $Y$ is such or $A$ is such, then apply full-brakes". Either a single or a combination of values of parameters (e.g. throttle-off rate) consist the trigger which is the same for all drivers on all occasions.

Bouslimi et al. (2005) aimed at "modelling driver behaviour in a straightline emergency situation". They employed the behavioural dataset provided

[^10]by the earlier studies at LAB (Perron et al., 2001) with neural networks and a genetic algorithm. A Multi Layer Perception (MLP) architecture was adopted for the neural networks, based on its merit in modelling functions of high complexity (Rumelhart, Hinton, \& Williams, 1985). Then the genetic algorithm was developed to optimise the structure of the neural networks. The results supported the improved performance of the hybrid (neural networks + genetic algorithm) against the neural-network model in predicting an emergency situation. Nevertheless, the model exhibited two basic weaknesses: first, the results of its validation were incongruent regarding some basic variables (e.g. throttle-off). Data from earlier on-track and driving simulator studies indicated inconsistencies in the accuracy of some variables. Second, some of the variables in the model, refer to the result of the emergency manoeuvre; in practice, such variables are inapplicable, as their value cannot be knownbefore the end result of the manoeuvre (crash - evasion) is confirmed.

Schmitt and Färber (2005) utilised Fuzzy-Logic (Klir \& Yuan, 1995) to create a model that could distinguish successfully between normal and emergency braking. The model was based on three parameters of throttlepedal operation: change of radius, jerk, and foot-displacement time (from throttle to brake pedal). Data for this study was collected through the CAN bus of the vehicle 54 participants drove in a test-track study. The authors claimed that their model predicts correctly $85 \%$ of emergency braking and $97 \%$ of braking before a corner, against 77\% emergency braking and 99\% braking before a bend correctly predicted by a system with a fixed trigger-level.

Although, both models resulted in high theoretical predictability of the emergency situation, they failed from their conceptual phase to account for
the fact that driver braking is variable, as indicated by the results of the naturalistic braking study in chapter 5 . The issue is discussed further at the end of this chapter.

Coming back to the results of the study in chapter 6, each of the variables with meaningful results has its own merit as an adaptive function for brake assist systems. Force input to the lower part of the brake pedal proved to be highly representative of the data as well as important in accounting for variance. The problem with incorporating these models in a brake system is the fact that some drivers do not use this part of the brake pedal at all. If this model were to be used, then some drivers would be designed out by the system specification. Clutch-pedal force also generated a similarly representative model. In application though, the implementation of this model suffers by the fact that not all vehicles have a clutch pedal - there is also automatic transmission available. Furthermore, video data from the studies in chapter 5 showed the clutch is not always used when braking and, even when it is used, it is after the initial brake-pedal displacement. Total brake-pedal force, on the other hand, explains slightly less variance compared to the aforementioned models. However, in practice it accounts for both sections of the brake pedal and thus does not exclude any driver (other than those who do not apply brakes at all). In addition, it is more compatible with current trends in brake assist system specifications (The Society of Motor Manufacturers and Traders Ltd, 2008). Initial brake-pedal displacement, as measured through the video analysis, had very high amounts of variance explained by its models and satisfied the statistical criteria for quality of evidence. However the limitations imposed by the method this datum was
collected (video data, sampling necessary, limited precision compared to the continuous flow of numerical data from the force and position sensors), make this variable less favourable at the current stage.

Therefore, among the measurements with continuous and high-frequency sampling, total brake-pedal force was selected to be incorporated into a virtual adaptive brake assist system, as the best compromise between the strength of the conceptual models and the characteristics of driver braking. Furthermore, for this variable there were two models (linear, quadratic) that analysis of variance indicated as representative of the relationship between normal and emergency braking and another model (cubic) that explained more variance that these two. The latter can be dismissed as it does not satisfy the statistical requirement set at the beginning of the analysis $(a=0.05)$. Between the two that remain, the linear one is theoretically more powerful, as it exhibited lower probability of randomness ( $p=2 \%$ ), however it explains less variance ( $21 \%$ ) compared to the quadratic model ( $26 \%$ ). Thus, it is reasonable to incorporate the quadratic model into an adaptive brake assist system.

The following section does exactly this; the algorithm of the model is incorporated into a virtual adaptive brake assist system and the system's behaviour is simulated using braking data from twenty-five participants that drove the instrumented vehicle on the public road and the test-track route described in chapter 6. These participants are the ones that had an input of at least 5 Newtons to the brake-pedal sensors during the emergency test on the test track.

## The system



Figure 71: The basic layout of the adaptive function of the system

The system starts with a universal trigger (much as current EBA specifications do). This is the value of the variable (force in this case) that activates full-brakes (effectively the Antilock Brake System too). The first time the driver applies brakes, the force applied is averaged with the "global average" and a new "average braking force" emerges (figure 71). Then, this becomes input in the equation to calculate the emergency brake trigger (using the selected algorithm - quadratic function in this case). This circle takes place whenever the driver makes use of the brake pedal. Thus, the trigger moves along the quadratic-model line on figure 63.

To simulate the behaviour of the system, MatLab $®$ r2008a was employed.
The MatLab code employed as a base for the system can be found in Appendix C. A program reflecting the system function described in figure 71
was developed and the system's behaviour was examined using the actual driving/braking data from 25 participants from the controlled road study (chapter 6). These subjects were the drivers that had a minimum brake pedal input of 5 Newtons during the emergency test on the closed track. The steps of the algorithm for adapting the threshold for a maximum braking torque request are:

1. When the engine is switched on, the system has a triggering-force value, as per a conventional Brake Assist System.
2. Whenever the driver applies an average force above 5 N between the two sensors on the brake-pedal, the system employs these data to calculate the mean force applied by the driver on the brakepedal.
3. Then, the quadratic equation described previously employs the instantaneous mean brake-pedal force to estimate a new triggeringforce value.
4. The above cycle is continuously repeated and the threshold adapted whenever the driver employs the brake-pedal. Concurrently, when a braking input exceeds the adapted threshold, the system communicates a maximum braking torque on the wheels.

Simulation


Figure 72: $1^{\text {st }}$ participant's journey and system behaviour
Participant 1's journey would have had the system engaged in four instances. Examination of the respective instances in the journey video showed that the first instance was just before a red-light situation at a signalised traffic junction. The second instance was in a similar situation when queuing before a signalised intersection and while the vehicle was almost still. The third instance was when queuing in traffic in almost identical situation as the second instance. Finally, the fourth instance was at the release of the trailer in the test track. Overall, the system "engaged" only when the driver intended to stop during the emergency test to prevent an imminent collision. It was never engaged when the pedal was used to decelerate the vehicle.


Figure 73: $\mathbf{2}^{\text {nd }}$ participant's journey and system behaviour

The second participant used the brake pedal on multiple occasions (figure 73). This frequent use gave the system the opportunity to adapt quite quickly; the trigger went up by $25 \%$ within a few minutes. Thus, repetitive engagement of the system during the first part of the journey was avoided. In fact, the system was engaged only at the end of the journey after the trailer was released in the test track. Again, the system identified successfully the emergency in the test on the closed track without engaging when there was no intention to stop the vehicle.


Figure 74: 3rd participant's journey and system behaviour
The very first input of the third participant took place even before the vehicle started moving and was strong enough to activate the system (figure 74). However, in practice it made no difference as the vehicle was still stationary with the engine running. The input had an effect on the system though, as it changed the triggering level (upwards). After a few further inputs the triggering level decreased and another engagement of the system took place during a yellow-light phase at a signalised traffic junction. The abrupt input resulted in a complete stop before the pedestrian crossing. The final system engagement took place right after the release of the trailer during the emergency test in the test-track. Overall, the system was successful in identifying the emergency on the test track, as well as identifying a critical situation on the public road section without compromising with any unintended full-brake application.


Figure 75: 4th participant's journey and system behaviour

The behaviour of the system during the fourth driver's journey was almost ideal (figure 75). As the driver was gentle on the pedals the system adjusted the trigger accordingly within two minutes. Furthermore, it did not engage in any of braking inputs until the release of the trailer in the emergency test on the test track.


Figure 76: 5th participant's journey and system behaviour

The simulation with data from the $5^{\text {th }}$ participant showed the system's inability to adapt in time to trigger full-brake application during the emergency test on the track. An initial strong input before the car started moving altered the triggering level significantly. Thus, the system avoided being activated during the early stage of journey; however it did not lower the trigger in time to match the final input upon the trailer release on the test track. It should be noted however, that the execution of the trailer release was not perfect and the trailer steered to the right upon braking. Thus, even though the final input on the sensors was above 10 N , it was combined with a strong steering input to the left that resulted in the avoidance of the trailer (figure 76).


Figure 77: 6th participant's journey and system behaviour

Participant 6 was among the gentle "pedipulators" (figure 77). She made multiple inputs of just over 5 N to the brake-pedal sensors and few over 10 N before the final $15+\mathrm{N}$ input on the test track. During the test, the trailer had a slight right-departure that allowed the driver to use both steering (to the left) and braking to avoid it. Although under the current specification the brake assist system was not triggered, the threshold was within 2 N of the brake input of the participant at that moment. The system behaved well initially by quickly lowering the triggering-level; however, no matter how close it got to it, it did not match the pedal input on the test track.


Figure 78: 7th participant's journey and system behaviour

At the start of $7^{\text {th }}$ participant's journey the system raised the triggeringlevel and then compensated after a few inputs. The first time it was activated was during queuing in traffic when the vehicle was close to a stop. The inputs that followed were not strong enough to activate full braking until the trailerrelease phase on the test track. There, the input by the driver was both strong and persistent. Overall, the system behaved quite well, as it identified the emergency input in the emergency test and avoided being triggered in circumstances other than in the slow-moving queuing traffic scenario.


Figure 79: 8th participant's journey and system behaviour

The $8^{\text {th }}$ driver would probably be happy to have a real implementation of the virtual system during his journey. His initial input during driving out of the parking bay increased the trigger-level dramatically; however a few inputs later the level was almost identical to the final input on the test track (figure 79). As the session took place on a wet day, the immediate augmentation of his braking and the direct engagement of ABS would probably be of benefit to him. Again, the system adaptation worked very well avoiding engagement throughout the journey up to the emergency test with the release of the trailer.


Figure 80: 9th participant's journey and system behaviour

The $9^{\text {th }}$ driver was quite smooth on the pedals and used the brake pedal scarcely throughout his journey (figure 80). Apart from the final input on the test track, there were only two other inputs stronger than 5 N . Since this was the lower bound of the inputs the algorithm accounts for, two inputs were not enough for the system to adapt in time to accommodate for the final input during the emergency test. In this case the system avoided being activated on the way to the test track, however it failed to identify the emergency input as such. However, the driver barely used the brakes at all during the journey and there was limited opportunity for the system to adapt.


Figure 81: 10th participant's journey and system behaviour

Driver number 10 was another gentle "pedipulator". He used the pedal multiple times through the journey, and one of them exceeded the systemactivation threshold. This was during a yellow-light phase before a traffic junction (see picture on figure 81). However, the driver's brake input after the release of the trailer on the closed track was less powerful and did not trigger the system. Overall, the system was successful in identifying a critical situation on the road; however it failed to replicate this success on the test track.


Figure 82: 11th driver's journey and system behaviour

The eleventh driver was among the regular users of the brake pedal (figure 82). She used the pedal about three times per minute during the journey to the test track. Thus the system adapted quickly to the "ideal" level for the trigger and was not activated until the very last input on the test track. In that case the threshold perfectly matches the brake input to the sensors during the emergency test with the trailer release. Overall, this journey is another "ideal" example of how good the adaptive algorithm can be in avoiding unintended activation and identifying the need for full-brake activation when necessary.


Figure 83: 12th participant's journey and system behaviour

The $12^{\text {th }}$ driver in the simulation was another example of successful function of the system. She used the brake pedal on multiple occasions, however in none of those was the system engaged, apart from the strong input at the end of the journey. In the test track, she had an input over 50\% over the concurrent nominal value of the trigger. A real implementation of the system would have helped her stop further from the trailer (the car stopped a few centimetres from the trailer).


Figure 84: 13th driver's journey and system behaviour

The $13^{\text {th }}$ driver had only three noticeable inputs in the first seven minutes of the journey, but they were enough for the system to lower the triggeringlevel by about $20 \%$. Then, system-engagement happened during the red-light phase at a traffic junction (figure 84). This input at the traffic lights increased the threshold dramatically, but a series of inputs over 5 N that followed brought the trigger back close to the pre emergency-stop phase. Finally, during the emergency test on the closed track, the driver's input was barely over 5 N , just enough to be included in this analysis. However, examination of the video showed that she had adopted the longest time-headway of all participants examined in this study (approx 3 s ). This fact might have allowed her to compensate with less powerful but prolonged input, as she had more time available to deal with the situation than others. Overall, the system was
successful in supporting the driver at the traffic-lights situation; however it was not engaged during the emergency-test on the closed track.


Figure 85: 14th participant's journey and system behaviour

The $14^{\text {th }}$ driver was another particularly gentle "pedipulator". Her inputs were both scarce and weak. She had two significant inputs at the beginning of the journey, but then there were no inputs sensed by the system (remember 5 N criterion) up until the last one in the emergency test. Even this one though was just over 5 N (figure 85). The situation was very similar with the previous driver, as she had a similarly long time-headway (about 3s) at the release of the trailer and, although gentle, the input to the brake pedal was prolonged. Overall, the weakness of the system to adapt quickly with drivers who do not use the brake pedal significantly was obvious.


Figure 86: 15th driver's journey and system behaviour

The $15^{\text {th }}$ case was probably the most problematic for the system (figure 86). There was a gentle input at the start of the journey, however up to the very end on the closed track there was no input over 5 N on the sensors. This means the adaptation circle (figure 71) of the system remains idle and the trigger does not change. This effectively renders the adaptive function of the system redundant. The system cannot operate successfully, unless the drivers use the brake pedal. Again, this weakness of the system dominated the simulation.


Figure 87: 16th participant's journey and system behaviour

The $16^{\text {th }}$ driver did not use the brake pedal significantly until arrival at the town centre about 8 minutes into the journey (figure 87). Then, a few inputs made the system increase its threshold and avoid activation until about halfway through the journey when the system engaged for the first time. Coming over a blind summit (Gran Union Canal Bridge) the driver encountered queued traffic on the other side and her brake input was enough to activate the system. A few minutes later, at the beginning of the rural section, cars ahead queued as the leading car stopped before leaving the main road and taking a right turn into a minor road. The driver's braking reaction was strong enough to activate the brake assist in this session too. After that, there was only one significant input before entrance to the test track and the system was not activated again during the journey. Even on the track, the brake input was not strong enough (or the threshold was not low enough)
to activate the system. Overall, the system identified two critical situations on the public road section; however it failed to be triggered during the emergency test on the track.


Figure 88: $17^{\text {th }}$ participant's journey and system behaviour

Participant 17 was among both the strong and regular "pedipulators". Thus the system quickly adapted the triggering level and avoided activation as the power of the inputs rose. About half-way through the journey, the brake assist was activated (figure 88). It was during the red-light phase at a junction with queued traffic and the vehicle was brought to a stop. Shortly afterwards, the driver encountered queued traffic over the brow of the Grand Union Canal bridge. The braking response was strong enough to activate the brake assist system. The presence of an actual brake assist with an adaptive function would probably be beneficial as (without it) the vehicle stopped very close to
the lead vehicle. After that, the system is not activated during the rural section of the journey thanks to its adaptation to the regular strong inputs. However, this also results in failure to be activated on the test track, where the input to the sensors was lower than the inputs during the rural section.


Figure 89: 18th participant's journey and system behaviour

The $18^{\text {th }}$ driver was both a gentle and infrequent operator of the brake pedal till the emergency test on the test track. The system adapted by lowering the threshold from the very first notable brake input (figure 89). Then, there were very few inputs in the middle section of the journey. A handful of braking inputs took place towards the end of the journey and basically confirmed the triggering-level as it was. The final brake input on the test track triggered the brake assist system. Overall, the system was successful in identifying the emergency-brake input during the test and avoided being engaged when unintended.


Figure 90: 19th participant's journey and system behaviour

The $19^{\text {th }}$ driver made little use of the brake pedal during the first minutes of the journey and then had a strong input about 6 minutes into the journey (figure 90). This input was over the triggering-level and the system was engaged. This happened just before a signalled junction at a roundabout at very low speed and resulted in a stop. After that, the system increases the threshold by $100 \%$ and therefore is not activated during the few brake inputs that followed. The final part of the journey is virtually brake-free and the threshold does not change since the third major input in the urban section. In addition the input during the emergency test is just over 5 N , although from the video the vehicle looks like achieving major (negative) acceleration ( $>5 \mathrm{~m} / \mathrm{s}^{2}$ ). The incoherence between the input to the sensors and the resulting vehicle behaviour allows room for consideration whether something might have interfered with the accuracy of the measurement through the sensors. This is
discussed further later. Overall, the brake assist system was activated when the intention was to stop the vehicle once during the journey, however failed to identify the emergency on the test track. This was particularly important as there was a slight contact as a result of the trailer release.


Figure 91: 20th participant's journey and system behaviour

The $20^{\text {th }}$ driver made some strong inputs at the very beginning of the journey that dramatically changed the triggering-level briefly. Soon though, as more inputs followed the threshold came down again and remained at about 24 N for a few minutes, before a strong input while driving in the town centre increased it by a few newtons again. This input also engaged the brake assist system. Looking at the circumstances under which this input took place, it was while approaching a red traffic on the left lane at a controlled junction with queued traffic on the right (figure 91). Suddenly, a passenger from a vehicle
on the right lane opens the door and enters the left lane. Then, the system is not activated until the end of the journey at the test track. During the emergency test, the driver's input to the sensors was over 5 N and was thus included in the analysis. However, it was too weak an input to engage the brake assist system. Checking the time headway at the instant of trailerrelease, the driver held almost 3 sec headway to the trailer and this allowed her to compensate with a persistent input rather than an abrupt one. She also stopped the vehicle comfortably without making contact with the obstacle. Overall, the system successfully identified a critical situation on the public road section, however failed to be activated during the emergency test.


Figure 92: 21st participant's journey and system behaviour


Figure 93: 22nd participant's journey and system behaviour

The journeys of both the $21^{\text {st }}$ and the $22^{\text {nd }}$ driver were very similar. Both drivers had few inputs over 5 N and those were relatively weak. Thus, the system lowered its triggering-level, however not enough to accommodate their input during the emergency test on the closed track. In addition, both drivers were among those with long time-headway distances and both drove under wet conditions. Overall, the system could not (and probably should not) be activated at such low-force brake inputs.


Figure 94: 23rd participant's journey and system behaviour

With the $23^{\text {rd }}$ driver the system functioned as a conventional constanttrigger brake assist system. As the driver barely used the brake pedal on the way to the test track, when she arrived there, the system had only the initial triggering-level when the emergency test took place. Her input was more than $50 \%$ lower than the threshold for system activation. The system started adapting when this input took place, but this was not enough for the system to be triggered. This case is another example of the system's inability to adapt quickly to drivers who do not use the brake pedal significantly.


Figure 95: 24th participant's journey and system behaviour

The $24^{\text {th }}$ driver was another gentle "pedipulator". His inputs on the brake pedal sensors were both rare and gentle during the journey to the test track. However, a few minutes before arriving at the test track, he suddenly realised that he was about to miss a right turn into a minor road and almost stopped the vehicle in order to take the turn. The input was above the triggering-level and the system was activated (figure 95). As this was the first significant input to the sensors, it also had a profound effect on the triggering-level of the system. However, a couple of inputs later the trigger was balanced again and arriving at the test track, it was about $25 \%$ above its initial value. The input during the emergency test was strong enough to activate the system. The deceleration of the vehicle was just enough to avoid contact with the trailer. Overall, the system behaved surprisingly well, considering the limited brake
inputs, and identified correctly one critical situation on the public road section as well as the emergency brake input on the test track.


Figure 96: 25th participant's journey and system behaviour

The $25^{\text {th }}$ participant's journey had a few significant brake inputs; however the system avoided being activated throughout the public road section. The early gentle inputs lowered the threshold, before a stronger and persistent input raised it again. The second part of the journey did not have any significant inputs and thus the triggering-level remained unchanged. On the test track, the release of the trailer elicited a strong input that engaged the system. The actual presence of the system would probably be beneficial for the driver, as she narrowly missed collision with the trailer. Overall, the system was successful in avoiding unnecessary activation on the public road section and was engaged when needed on the track.

## Discussion

The simulation of an adaptive brake assist system based on the results from the controlled public and closed road study (chapter 6) showed some promising strengths as well as some weaknesses. Matching the on-board video with the pedal-force data showed the ability of the system to detect the emergency inputs both on the public road and the closed track. On the other hand, the most prominent difficulty was encountered in dealing with drivers who neither use the brake pedal regularly nor significantly when they do use it. Of course, data was captured during a single trip from University campus to the test track and the system could adapt more effectively after prolonged use of the vehicle, however within the framework of this study and with the data available, it did not. A case-per-case examination should help clarify this.

The first driver had the virtual system activated on three occasions during the trip: once before the red traffic lights and twice while almost stationary in queued traffic. In all three cases the driver intended to stop the vehicle. In the first occasion the engagement of the system would be beneficial in facilitating vehicle stopping before the junction comfortably. In the other two cases, it would be at least not troublesome; the vehicle was barely moving anyway. In the test track, the system identified the emergency input and would help the driver avoid contact with the obstacle easily. The efficiency of the system becomes more apparent if compared against a conventional EBA with a universal trigger; as the driver was generally strong "pedipulator", the system would be activated multiple times during the trip, even while braking to keep speed to the legal limit. This would be a fearsome scenario. The proposed
adaptive version on the other hand managed to avoid all those unintended activations.

This strength of the system was even more apparent in $2^{\text {nd }}, 3^{\text {rd }}$ and $7^{\text {th }}$ participant's journey. Facilitated by a wealth of information through the frequent use of the pedal, the system adapted quickly, avoided all false activations and matched the input during the emergency test on the track. Again, without the adaptive function, the system would be unintentionally activated multiple times during the journey. During the $3^{\text {rd }}$ journey, the system also correctly recognised the intention to stop promptly during a yellow-to-red phase at a road junction.

The $4^{\text {th }}$ driver's journey was a case where both a conventional and the adaptive system would identify the critical situation on the test track. Driver input was clearly distinctive between the public and the closed road sections. This pattern was also observed with the $8^{\text {th }}, 11^{\text {th }}, 12^{\text {th }}, 18^{\text {th }}, 24^{\text {th }}$ and $25^{\text {th }}$ driver's journey. According to the data, both versions of the system would behave efficiently - i.e. be activated only when intended - in those cases.

Then, there were the cases of mutual "failure" to recognise the criticality of the emergency test. The word "failure" is in quotation marks, because closer examination of the individual characteristics of these tests, indicated that there might not have been so much of an urgency to use the brakes to avoid the obstacle. The relevant cases $\left(6^{\text {th }}, 9^{\text {th }}, 14^{\text {th }}, 15^{\text {th }}, 21^{\text {st }}, 22^{\text {nd }}, 23^{\text {rd }}\right.$ driver's journeys) were characterised by combinations of limited braking on the way to the test track, long time headways on the test track, and or use of steering to avoid contact with the obstacle. Thus the universal version by definition could
not accommodate such gentle inputs and the adaptive version did not have enough data to adapt in time.

In between the total successes and total failures lie many cases where the adaptive system showed promising behaviour on the public road section, but was not activated during the emergency test on the track. In these cases a universal-trigger system would be activated unintentionally or miss critical instances. The relevant journeys that fall in this category are the $5^{\text {th }}, 10^{\text {th }}, 13^{\text {th }}$, $16^{\text {th }}, 17^{\text {th }}, 19^{\text {th }}$, and $20^{\text {th }}$ driver's journeys. In some of them $\left(5^{\text {th }}, 17^{\text {th }}\right.$ in particular), the trigger was very close to the actual input during the emergency and the latter would have probably been accommodated, had there been a few more inputs before the test.

In an attempt to put some numbers down, the success rate of the system can be examined in two ways: first every test-track session can be assumed as an emergency situation, according to the subjective reports of participants after completion of the test. Second, the definition of emergency braking assumed from the beginning of the Thesis as "the driver's reactive operation of vehicle pedals in reponse to the sudden appearance of a perceived obstacle, with which the vehicle will collid unless the reactive pedal operation takes place".

Using the first method, assuming that every test-track session was an instance of emergency, the false-negatives can be identified. These are the cases in which the system should have identified the emergency, and it did not. By definition, there are can be no false-positives, as every case was an emergency. In this context, the adaptive system, although imperfect, shows superior performance to every possible conventional specification.(table 54,
right column). Assuming that all emergency tests on the closed track involved emergency braking, the adaptive system detected 12. Against that, the maximum achievable number of emergency instances a conventional system may detect is 11 . However, this number is achievable only after the best compromise is identified and the trigger is optimised according to the data.

Using the second method and examining the instances of system activation on the open-road section, yields instances of successful detection and false detection of an emergency (false-positives). During the case-bycase examination that preceded this section (figures 72-96), the adaptive system was engaged 13 instances. Examination of the concurrent video cues indicated that all 13 cases exhibited at least two of the characteristics of emergency braking according to the aforementioned definition: "perceived obstacle" (either actual vehicle/pedestrian or red traffic lights), and "imminent collision" unless the driver intervenes with the pedals. The third element of the definition, surprise, cannot be objectively extracted through the video data and requires the subjective report of each driver for each instance. Unfortunately, such data were unavailable in the current study. Nevertheless, it is still possible to compare against the number of false-positives of the optimised conventional brake assist system (table 54, middle column). The best possible conventional specification performs 9 additional false-positive activations of the system. The difference is much more obvious than in the test track, although this result is partly explained by the optimisation of the conventional solution for the test-track. Overall, of course, the true picture cannot be demonstrated by a tabulation of two characteristics; however it is indicative of the improvement offered by the adaptive function in the system.

Table 54: Comparative performance of the proposed system against a conventional one

| Type of brake assist | False-positives (road <br> section) |  | False-negatives (test track) |
| :--- | :--- | :--- | :--- |
| Conventional | 9 | 14 |  |
| Adaptive | 0 | 13 |  |

## Limitations

The definition of driver emergency braking is a decisive factor when judging the success of an emergency braking system. Under the present definition, it proved difficult to decide on each case without the subjective judgement of the participants. Therefore, the test-track data yielded an advantage, as it was decided in line with the definition and supported by the subjective reports of the participants after each session. By comparison, the open-road data was limited by the absence of the subjective judgement by the participants after each "activation" of the system. The collection of such data on-route was impossible in practice, as the "activations" were unknown until the data was analysed, long time after completion of the sessions.

Nevertheless, due effort was placed in setting the relevant strict criteria when judging on the success and failure of each case both on track and open road.

On a more general level, it is surprising that all previous studies on emergency braking, did not consider the provision of a definition within their scope. They considered suffice to assume any input associated to their "critical event" as emergency braking and considering all other inputs as "normal". Kassaagi (2001), Bouslimi (2005) and Schmitt \& Färber (2005) followed such an approach. In addition, all their data was collected either on a
closed track or in a simulator. Therefore, the validity of the success rates they report for their respective solutions is questionable.

Ideally, it would be useful to have the multi-variable methods for emergency braking detection by Schmitt \& Färber (2005) and Bouslimi (2005) compared against the adaptive version developed in the present Thesis. It is particularly interesting, as Schmitt \& Färber (2005) claimed that their fuzzylogic method correctly predicted $85 \%$ of emergency inputs and $97 \%$ of nonemergency braking inputs. It is further interesting as they compare it against a "conventional" system that according to them it predicts correctly 77\% of emergency and 99\% of non-emergency brake inputs. According to the data from the present study, those numbers are unachievable. Unfortunately, the exact particulars of the study were not published, so that fuzzy-logic method cannot be tested using the present data. Same applies to Bouslimi's (2005) study, although as mentioned in an earlier chapter, this model used postevent variables as well and consequently has limited practical use. The conclusion is that direct comparison with those studies is impossible.

Another point that needs to be mentioned is the possible alternative specifications of the adaptive system. For the reasons explained at the beginning of this chapter it was decided to test the specification described on figure 71. In theory, alternative specifications are possible according to the results in chapter 6. Initial brake-pedal displacement or force from particular areas of the pedal could be used instead of total pedal-force. The system used only inputs to each sensor that exceeded 5 N ; a criterion of $2 \mathrm{~N}, 10 \mathrm{~N}$ or any amount could be used alternatively, depending on how responsive the system is needed to be and how much noise the sensors suffer. There is no
strict guideline on this. The system could have an initial triggering-level or not; it could start with an "immunity" period for some length of time before being engaged. The possibilities are many. It is impossible to examine them all within this Thesis. In fact, it is quite realistic to think of a whole Thesis on these issues. There is a wealth of room for future research in this area and this cannot be addressed within the scope of the current Thesis. It is hoped though that this Thesis will stimulate the interest of other minds to build further the knowledge on the subject.

Finally, it should be acknowledged that every piece of evidence and every idea proposed so far refers to the initial part of the Human-Machine Interaction (HMI) loop (Oborne, 1987). All material reported to this point regards the inputs of the driver and the adaptation of the machine to human input. However, a huge area of research opens with regards to the feedback to the driver and the relevant adaptation he/she may commence in response. Even though the studies and solution developed within the present Thesis provided evidence of opportunities for adaptation of the machine (brake assist system in this case) to human input, it remains unknown what the possible adaptation of the human to this adaptation by the machine might be.

Collection of data regarding driver adaptation to the adaptive properties of the braking system is impossible until a prototype of the system is installed to a vehicle and studies commence examining exactly that. The issue is discussed further in the following chapter.

## Summary

This chapter presented a simulation-study to examine the behaviour of an adaptive brake assist system, based on the results of the controlled road study described in chapter 6. The proposed system incorporated an algorithm exploiting the relationship between normal and emergency braking. The system continuously calculates the instantaneous average brake-pedal force and employs the algorithm to estimate the respective "ideal" threshold for engaging maximum braking torque.

To test the behaviour of the system in practice, data from 25 drivers who took part in the controlled road study were employed. The function of the system was simulated in a Matlab environment, and the behaviour of the system during each trip was monitored for inappropriate activation on the open road and inappropriate non-activation on the test track (emergency test). Unfortunately, previous attempts to propose alternative solutions to conventional brake-assist systems did not publish enough data for a direct comparison with the system proposed in this chapter. However, results were encouraging in comparison to a constant-threshold system. The proposed system also exhibited the ability to adapt fairly quickly after a few braking inputs. Nevertheless, it was by definition unable to adapt to drivers who scarcely use the brake-pedal.

## Chapter 8: General Discussion

Each of the study-chapters concluded with a section titled "discussion". There, the implications and contributions of each study's results to the topic of this manuscript were discussed. Similar sections were also included in the early chapters too (chapters 1-2). In this chapter however, the aggregated results and limitations of the whole thesis are discussed within the general framework of road safety and driver ergonomics.

In the introduction of this Thesis, the title was analysed into its three main components and the associated areas for research were described.
"Ergonomics" was associated with man-machine interaction; "vehicle brake systems" was associated with driver longitudinal control and road safety; the term "intelligent" was associated with adaptive technology that is intended to accommodate the different characteristics of operators. It is hoped that most readers will agree that the present thesis has made contributions in all three areas.

The contribution and discussion of each study was presented in the respective chapter and further discussion regarding each chapter follows in the next pages. In summary, it is argued that the "naturalistic braking" study provided novel data regarding the general characteristics of driver braking, with the key characteristic being its variability, while the controlled road and closed track studies provided evidence of differences in driver braking in different conditions and, most importantly, revealed certain relationships between conditions. Both chapters contributed to both the knowledge regarding driver longitudinal control and that of man-machine interaction
regarding vehicle brake systems. The controlled study set the foundations and the "system simulation" chapter built on it by presenting a system articulation and specification, testing it virtually, and indicating the plausibility of the particular adaptive technology. Last but not least, the accident study of longitudinal control failures presented the core of the relevant real-world problem and put the current research output within its realistic limitations towards road accident mitigation.

The result of the above was the provision of good-quality evidence to address the research questions as they were set at the early chapters of this thesis. The naturalistic study provided microscopic data on the nature of driver braking and established a statistical definition based on the quantitative boundaries of normal driver braking. The controlled studies on public and closed roads provided evidence that iterates the results from previous studies (Perron et al., 2001), regarding the quantitative difference between emergency and non-emergency driver braking inputs to the pedals. Then, the controlled studies provided evidence of certain relationships between variables in two types of driver braking (non-emergency - emergency). Finally, based on one of those relationships, the design and virtual trial of an adaptive brake assist system provided evidence of the possibilities that arise to exploit such relationships for the evolution of brake assist systems.

## Placing the research into the context of previous literature

It is not easy to connect microscopic data, such as the majority of what was presented in this manuscript, to general theoretical models. The association can be made though, when the data are "translated" to
phenomena that as abstract instantiations can have implications within the respective theory or model. This "translation" was made in the final parts of the respective chapters where each study was described. There, results were interpreted in terms of their meaning and the consequences of the arguments they suggested. Thus, now it is possible to position them within the context of the various models of the driving task as described earlier in pages 17 to 32 .

As such, they can supplement the speed-control element in Gibson \& Crooks (1938). According to this theory, vehicle speed is influenced by the field of safe travel. The naturalistic study provided the range of inputs the drivers have on the brake pedal in order to keep the vehicle within the "safe field of travel". The controlled study and the subsequent system simulation suggested a technological development that effectively increases the safe field of travel. As this system can reduce the stopping distances, it increases the ratio of depth of the field of travel against the stopping distance. Therefore, although the field does not increase in space, it increases in time. On the other hand however, the benefit could be limited by possible behavioural adaptation of the drivers (Howarth, 1987). According to Gibson \& Crooks (1938), the index of cautiousness is defined by the ratio of the depth of field of safe travel to the minimum stopping zone. If the drivers systematically choose smaller safety margins after getting accustomed to the presence of the system, then they will effectively decrease the index.

In relation to the time-based model for the driving task, the naturalistic and controlled studies did not provide results that can be associated directly with the theory - such aims were not within the scope of the studies. However, the accident study indicated that inattention and distraction are common
contributors to longitudinal control failures by the drivers. This result is in accordance with previously reported contribution of distraction to rear-end collisions (National Safety Council, 1996). Empirical studies have suggested that this is partly explained by the late Brake Reaction Time associated with the presence of distractions (Harbluk et al., 2007/3; Strayer \& Johnston, 2001; Summala, 2000). It would be worth examining in the future whether distraction affects driver braking in ways other than by delaying the response (e.g. increase pedal force or initial pedal velocity). This could be done through studies of similar design to the ones presented in this thesis with the added element of distraction.

Regarding the three-level models for the driving task, the output of the present research seems to fit them well; the quantification of driver braking as performed in the previous pages affects decisions made at the strategic level, choices made at the tactical level, and rapid actions made at the manoeuvring/control level. The way and how much one brakes might affect not only the concurrent inputs on the other vehicle controls (steering, changing gear etc.) directly, but also what route he/she chooses for a destination or even what type of car she/he prefers to drive. Although Lee (2005) suggests the importance of behaviour at the higher levels as main force affecting the performance requirements at the lower levels of the driving task, it is still worth examining the other side of the interaction: from the lower level to the higher. The extent of the impact braking has on the upper levels of the driving task remains to be systematically explored.

## Implications for technology

In pages 8-13 the major contemporary active safety technologies were presented. Evaluation of some of these technologies have already provided concrete results of their potential for accident mitigation (Breuer et al., 2007; Lie, Tingvall, Krafft, \& Kullgren, 2006; Page et al., 2005; Thomas, 2006). However, the level of accident reduction is below the projected potential of the systems as originally conceived (Emberger,1993). The present thesis described studies descending from a human-centred philosophy for technology and showed how this philosophy can lead to the development of an adaptive brake assist system; a system that continuously adapts to driver braking and reduces the number of false interventions. Such a system may have a greater probability of achieving its potential for accident reduction. The same philosophy can be applied to other safety systems as well. Lane change support could adapt to the lane deviations of the driver, ACC could adapt to the preferred time headway of the driver and ESP could adapt to the oversteering characteristics of each driver's style. Successful specification of such systems can take driving interfaces to another level.

In the shorter term, adaptive brake assist and ACC can support each other quite well in achieving collision mitigation; ACC controls time-headway and TTC the variables that matter before the brake reaction takes place, while adaptive brake assist controls the variables that matter during the braking reaction: brake force and brake torque on the wheels, thus controlling braking distance. These systems can be further integrated with passive safety systems - e.g. seat belt pretensioners - to further support casualty
reductions, even when a collision finally takes place. All these of course require further studies of possible behavioural issues during the integration.

## Driver-braking research

The driver-braking studies from the literature presented in pages 32-53 provided evidence regarding basic characteristics of driver longitudinal and braking control. Van der Horst (1990), van Winsum and Heino (1996) and van der Hulst (1999) addressed the issue of TTC and time-headway during car following. Van Winsum (1997) further investigated the relation with brake reaction time (BRT). The studies in the present thesis quantified the braking control input itself studying detailed characteristics under normal and emergency conditions. There was a shift from the factors that matter before the braking input takes place to the characteristics that matter when it does take place.

There is also a clear shift in the methods undertaken. In the early nineties, van der Horst (1990) video recorded actual vehicles on the street, but the studies of driver braking during that period are dominated by simulator-based studies (Hoedemaeker \& Brookhuis, 1998; van der Hulst, 1999; W. van Winsum \& Heino, 1996; W. van Winsum \& Brouwer, 1997; W. van Winsum, 1998). Subsequently, more instrumented-vehicle based studies on test track have been undertaken (Bouslimi et al., 2005; Curry et al., 2003; Kassaagi, 2001; Schmitt \& Färber, 2005). Now, this thesis presents a controlled and a naturalistic braking study, so the trend towards realism is continued. It is hoped that more studies will replicate such realism while improving on the limitations of the present studies.

## Methods

The trend to move towards more ecologically valid research method has been supported by the evolution of data-collection tools and utilities. Hardware and software that required the space of a proper building decades ago has equal data-logging and processing power as a modern laptop with a multi-channel, multi-mode (digital/analogue) data acquisition card. The relative cost has also shrunk in proportion to size. Sensors and transducers have also evolved in terms of precision, reliability and cost. Intrusion, which is critical when sensors are used on human subjects, has been minimised too. More data can be collected with improved precision, validity and reliability.

However, beyond the hardware-issues, approaches where "the field is the laboratory" remain financially demanding. Long working hours are required for the support of the logistics and researchers have to be flexible and ready to intervene when problems. As naturalistic and on-the-road studies tend be prolonged, staff-time adds up to a significant number and, consequently, cost. In addition, there is a level of detail in driver research (neurophysiology/psychology), where despite technological developments, data of this quality cannot be collected in naturalistic environments. There are some attempts however to use low-intrusion methods in closed-road studies (Pettit, Clarion, Ramon, \& Collet, 2009). Still, though, the introduction of more intrusive methods like electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) out of the lab environment has not materialised and
even low-intrusion methods like electro-dermal activity (EDA) measurement have been applied in closed environments only.

At the same time there is an opposite movement where rapidly advancing simulation technology aspires to turn the laboratory into a realistic "field" environment. The fidelity of driver simulators is advancing quickly and for many types of driver research the necessary realism can be found there. However, unlike the technical equipment for vehicle instrumentation, there has not been so big a reduction in the costs associated with purchasing, running and maintaining high-fidelity simulators. Anything above a fixed-base, standard-controls, wide-screen simulator requires technical staff dedicated to doing the required programming, maintaining its components and supervising its operation during studies.

In parallel, the depth of accident data accessible is deepening. The developments from the early road accident investigation up to the microscopic, on-the-spot contemporary studies show an evolution of methods. While the breadth of data remains large, with datasets now including thousands of accident cases, the depth goes deeper and deeper and more detail is possible. However, as was discussed in the road accident study chapter, the necessary depth and type of data required for contributions to the specification of safety systems is still missing. It is a technically demanding and time consuming procedure to extract "black-box" data (precise history of inputs on controls, vehicle speed, lateral acceleration etc) from a crashed vehicle, and authorised in special cases only. However, the technology is there, it has recently been standardised (IEEE, 2009), and when the stakeholders come to an agreement over the particulars of the related
legislation, accident studies will be taken to another level. Accident reconstructions will be less relied on indirect transformation estimates and witness' perception for vehicle velocities, impact forces, driver reactions etc. Precise values of vehicle dynamics and driver inputs will be available instead. Then, studies like the one presented here (chapter 7 ) will contribute not only as a validating benchmark for the empirical studies and the general framework within which the related technology will come into effect, but also as a source of data directly useful to the design of the technology itself. A lot of potential arises in this area.

## Accident Study

As mentioned in the relevant chapter, due to its methodological nature, results from the accident study are not directly comparable with those from the other studies. Nevertheless, the study provided the context within which the thesis is positioned. The need for technologies alternative to the currently proposed adaptive and existing brake assist systems was concluded. In addition, results from this study validated the design of the emergency test as well as drivers' reaction during the test.

The most microscopic data available, those of driver reactions during accident occurrence, showed that in about 50\% of cases driver's reaction did not include a significant input to the brake pedal. In the relevant cases where failure to stop the vehicle promptly was the main factor in the accident - steering inputs were extremely rare too. So, essentially this limits the maximum effectiveness of any system based on the input on the brake pedal by about $50 \%$. On the other hand, accident cases showed interesting similarity to the instances when the adaptive system was "activated" during
the simulation study (chapter 7). Junction overshooting and rear-end shunts were among the most common type of collisions and these correspond to the controlled junction instances on the public road and emergency test on the closed road when the system was "engaged".

Finally, the accident study suggested that many factors contribute to longitudinal-control failures and accidents which most of the current technologies fail to address. These factors can be grouped into two categories: cognitive failures - where drivers are distracted, fail to look or to see something in the road environment - and emotional failures - where drivers are stressed, panicked or uneasy. At the moment, there is negligible technology addressing such issues.

## Naturalistic Study

The naturalistic study in chapter 5 provided the quantitative characteristics of "normal braking", validated the results of the controlled public road study and complemented the previous driver braking studies. The "anthropometrics" of brake-pedal operation in terms of force and pedal displacement were provided and normal braking can statistically be defined as the range between $5^{\text {th }}$ and $95^{\text {th }}$ percentile pedal force and displacement. This range was compared to the one provided by the controlled public road study (chapter 6) and showed very similar characteristics, thus validating it. Further, the study was the most extensive in time and depth of all the driver braking studies quoted in this thesis.

This was not without issues and limitations though. First, by definition, a naturalistic study has no control over the type of trips and distance the drivers
travel. The accompanied ecological validity of such a study though limits the capability to identify what sort of roads each participant used. Therefore, the sort of research questions that can be addressed with such a study-design is limited in this aspect. Indirectly, this can be balanced through the employment of a controlled study like the one described in this thesis, but only if the general profile of the target variables is similar and the results transferable between the two studies. This problem is cured if the study-vehicle is equipped with a Global Positioning System (GPS) device and its position monitored constantly. Such a solution was beyond financial boundaries of the current project, however it may well be included in future studies. Finally, the study could benefit from an increase in sample and vehicle-fleet size. There can be no certain satisfactory number, however in this case "more is more". A better funded study could employ more participants, more instrumented vehicles and, potentially, the instrumentation of the participants' own vehicles. Such a design would further increase the external validity of the study and allow for the valid comparison of sub-groups within the sample (gender, level of experience, age etc).

Overall though, face validity for the current study was high and included all levels of processes according to the driving models described in the early chapters of the thesis (pp 17-32). Looking at table 2, which combines the two major vectors of the relative models, for example, most of the spectrum of processes, decisions and actions was included in the study. Participants did not decide on the vehicle they would drive (knowledge - strategic), but they probably knew the type of trips they would drive before entering the vehicle. Some of them consciously discussed whether to change the route when
facing traffic along the way (knowledge - tactical). Others had to think to select reverse, because they were accustomed to a different layout of the gear-selection (knowledge - operational). Some participants encountered roadwork diversions and followed them (rule-tactical) and most applied brakes prompted by traffic lights or give-way signs at some point (rule-operational). Some of the more experienced drivers in the area followed the works diversions without having to pay attention to the signage, as they had been exposed to the particular road environment repeatedly during that period (skill - tactical). Finally, in most cases, basic vehicle control was an automatic process, and did not require conscious thinking (skill - operational).

## Controlled Road Study

The controlled studies on public and closed roads had to be well planned and executed to provide meaningful results within the time and resource constrains of a PhD project. The sample of drivers employed was of substantial size and was representative of the local driver population. Multiple nationalities, ethnic backgrounds, ages, lengths of mileage, experience and people-sizes were included. The apparatus worked with precision and reliability up to the expected standards. The validity of the design for the emergency test was supported both objectively by the achieved decelerations of the auto-brake trailer as well as subjectively by the participants after the test. The results supported arguments regarding the second and third research questions, as these were set at the early part of this Thesis, and set the foundations for the study (system simulation) that addressed the fourth question.

In contrast to previous results reported by Kassaagi (2001), throttle-off exhibited comparatively better properties than brake-pedal force or initial displacement in distinguishing between non-emergency and emergency braking inputs. However, that study employed slightly different methods to extract the relevant information (force was estimated from the pressure in the brake cylinder and pedal position was measured directly through the CAN bus of the vehicle) and instead of data from actual braking on public roads, used data from the test track as non-emergency/normal braking. This bias is obvious on table 40 in chapter 5 , where the respective statistic parameters from the most important driver-braking studies are presented.

Probably the most important result in the thesis is the relationship of brake-pedal force between normal/non-emergency and emergency braking. The shape of the two distributions is such, that unlike other variables, it allows for a successful model and algorithm for their relationship to be developed. And this lead to the "System Simulation" chapter that followed.

Of course, the study would have benefited from a few more resources, as video had to be used to monitor brake-pedal position and displacement and the sampling frequency of all sensors was limited to 50 Hz by the data acquisition module. Better resourced studies could employ special highfrequency data acquisition equipment and/or a direct link to the vehicle central processing unit could be established. In a contemporary vehicle, this would provide pedal-position data directly and enhance precision.

## System Simulation Study

The system simulation study acted as an example application and a testbench for the exploitability of the results in the previous study. Simulation of system function during actual journeys, showed good results avoiding activation during non-emergency braking and identifying the need to stop the vehicle on the closed track. Equally significant was the ability it demonstrated to engage during rapid stops at controlled traffic junctions on public roads. In fact, if the instantaneous time-headway is taken into account, it identified most emergency-braking inputs during the emergency test on the closed track as well. This finding suggests improved effectiveness of an integrated system, combining pedal-inputs with time-headway/TTC information. For example, if cutting point was set at about 2.5 s for time-headway in the simulations in chapter 7 , then the success rate for identification of emergency and normalbraking inputs would approach $100 \%$. Of course, such approach would further limit the number of eligible cases to be included in the study.

As mentioned on several occasions in this manuscript, the simulation study in chapter 7 is both a test and an example of a possible system articulation. Although the heart of the system, the relationship-algorithms, remains constant, the surrounding functions (e.g. initial threshold, initial idle period, minimum force-inputs taken into account, etc) allow for further changes and testing. Also, the combination of multiple variable histories might lead to even more accurate identification of emergency inputs; or it might not. There is plenty of room left for further research in this area.

Furthermore, even if this was the best possible system specification, it has only been tested on a virtual setting, in which the system was not
operational. Thus, the method employed did not allow for examination of feedback issues and behavioural adaptation of the human operator in the long term (Howarth, 1987). Since the participants had no cues of the systems intervention, when this was virtually engaged, there are no means to tell whether the actual system could be associated with behavioural side-effects, untraceable by the current method used. Most of the work presented in this Thesis is focused on the Driver-Vehicle side of the interaction loop and little is implied about the Vehicle-Driver side of the loop.

However, by definition even a conventional Brake-Assist is a system that is not expected to intervene regularly - in most cases it rarely intervenes. According to Howarth (1987), the level of behavioural adaptation depends on how much the technology makes its presence obvious. Therefore, a system with rare intervention, such as Brake Assist of Stability Control, is expected to yield less behavioural side-effects than a system which has regular or continuous function, such as Headway Control systems. On a similar line, some researchers suggest a distinction between "above" and "below the line" systems (Young, Stanton \& Harris, 2007).

On a more theoretical level, normal driver braking was defined statistically and distinguished form emergency braking. This is an important advancement compared with previous approaches (Kassaagi, 2001;Bouslimi, 2005) where "normal" is considered as the sum of test-track braking outside the emergency test or other studies that avoided providing a definition. However, the wide variety of braking instants grouped under the umbrella of normal braking, might include sub-groups of braking inputs with different intentions behind them. For example, vehicle speed or desired deceleration might be
associated with certain driver-braking parameters and this might open another opportunity for adaptive braking systems. It remains to be explored in future studies.

Similarly, the issue of what emergency braking really is and what EBA and similar systems really refer to, has never really been addressed. The often quoted previous studies (e.g. Perron et al., 2001; Bouslimi, 2005; Schmitt \& Färber, 2005) did not consider it necessary to provide a definition upon which they based their experiments. In the present Thesis, a definition was provided and formed the basis for the design of the emergency-braking test. The provision of a definition and the subsequent comparison of the findings against it, make it possible to realise that what is commonly marketed under the title of "Emergency Brake Assist", is actually a system (which aims at) identifying the intention to stop the vehicle. The element of "perceived obstacle" in the definition allows for the subjective nature of what an emergency is and what is not, under various circumstances. The objective parameter is the "intention to stop", irrespective of the presence of an imminent collision or not. Therefore, brake-assist systems essentially measure the "intention to stop" through the pedal-input.

It could be argued that in practice this differentiation has not got any significant implications; the title does not affect the essence of things.

However, it affects human perception of things and may lead to misunderstandings. Unless the differentiation is acknowledged, it is reasonable to question the engagement of a brake assist system, when the collision is otherwise avoidable. In chapter 7 for example, the simulated system should only be activated if a collision did take place. On contrary,
understanding that all measurements refer to the "intention to stop" the vehicle promptly, leads directly to the established expectancies about the system function: a system that augments braking torque when the driver perceives an emergency.

## Summary of Limitations

The limitations of the original studies presented in the current Thesis can be summarised in:

- The inability of the Accident-Study to yield data microscopic enough (e.g. "black-box" data) for direct comparison with the results from the instrumented-vehicle studies.
- The temporal restrictions the Naturalistic Braking study to just one day per participant.
- The use of a single instrumented vehicle (Ford Fiesta) and the inability to measure participants' braking inputs in their own vehicles (applies to both the Naturalistic and the Controlled-Road Study).
- The restricted speed during the emergency braking study (limited to $30 \mathrm{mph} / 50 \mathrm{kmh}$ ).
- The limited number of meaningful simulations (25) from the pool of participants in the controlled-road study.
- The weakness of the proposed solution/system to adapt to drivers who do not make significant use of the brake-pedal.


## Conclusions and Future Work

In summary, the results of the studies provided evidence in support of 4 main arguments:

1. There are differences between normal and emergency braking inputs in terms of the throttle-release rate, the initial displacement of the brake pedal and force applied to it.
2. At the same time, there are relationships between normal and emergency braking parameters and these can be modelled systematically.
3. These relationships can be integrated into an adaptive brake assist system and further improve its success rate in identifying whether an input is normal or emergency - braking.
4. Such a system could contribute to the reduction of certain types of accidents; however, there is a variety of factors contributing to these accidents that is addressed neither by this system nor by any other known active safety systems.

The future of vehicle braking and control ergonomics: systems integration
The work presented in this thesis should be viewed as the beginning of a research area rather than as a piece of work that completes one. The proposed system remains to be prototyped and tested in the field through further field operational trials and naturalistic studies. Such studies would benefit from extra resources compared to the present studies, as discussed earlier. Additional/alternative variations of the system could be developed and tested as well; nonetheless, the fact remains that any implementation of the
findings would require extensive testing before the solution is distributed widely.

Adaptive brake assist can also be integrated with ACC, Collision Mitigation Systems and even passive safety systems (e.g. seat-belt pretensioners). Such an approach would lead to a more spherical solution against the consequences of longitudinal control failures and collisions. During the system simulation study, it became obvious that people who adopted long headways to the vehicle in front, had too gentle inputs for the system to intervene. On the other hand, Pauwelussen \& Minderhoud, M. (2008) report that drivers prefer to deactivate ACC during low-speed driving (speeds between 2040kmh). When their limits are exceeded or they have been deactivated by the driver, headway-control systems need a successful braking-assist system to reduce stopping distances. A (adaptive) braking assist system can be more successful if it incorporates headway-data. The combination of the above results suggests an opportunity for a reduction in rear shunts, if the two systems are integrated.

Integration, nevertheless, is not an easy process (Engström, Arfwidsson, Amditis, Andreone, Bengler, Cacciabue, Eschler, Nathan \& Janssen, 2004). Possible conflicts between system functions, interventions and effects on the human operator/driver are the main issues to deal with. There are some research projects dealing with these issues and suggesting some solutions, albeit limited to adaptive prioritisation of IVIS systems (Amditis, Kussmann, Polychonopoulos \& Andreone, 2006). In the case of adaptive brake assist systems and integration with headway-control systems, it remains to be
investigated what the fine details of such integration are and how the relevant integrated systems should be specified.

Finally, on a more theoretical level, the results presented in the present Thesis exhibited the benefits of human-centred philosophy and adaptive technology employment within this context. An adaptive brake assist system was proposed and a method to continuously adapt its trigger in accordance to the previous inputs by the operator/driver. Similar principles could be applied for the development of other vehicle control systems: steering, stability control, lane change support etc. Steering response could adapt to the steering style of the driver, depending how sharp or gentle her/his input is in general. In parallel, lane departure warning and/or lane change support systems could adapt the alarm-timing and the level of interference depending on the driving style of the driver. The same adaptive principle can be employed for the specification of future stability control systems. In such case, the system will decrease or increase the envelope of its interference depending on how the instantaneous vehicle-dynamics compare to the previous history with the particular driver on-board.

The same philosophy can be applied and tested in applications outside the current framework. It has already been suggested as beneficial against automation-related issues (Steinhauser, Pavlas, \& Hancock, Spring 2009), however there is room for development of more direct and quantitative solutions in many areas. The human operator has been adapting to the technical environment for some time now. At best, it has been considered sufficient to accommodate individual differences under a single
"representative" average. It is time to realise the potential for actively adapting
technologies. It is time for the technical environment to start adapting to the human operator.

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Appendix A: The design of the trailer

Project title: Quantification of driver emergency braking
Proposal Number: R07-P114
Equipment Specification

Part 1: the trailer

This document describes the proposed design for the trailer to be used in the main experiment. It aims at providing a guide to any prospective fabricators and documents the necessary details to serve the purpose of the study. The design is heavily based on the successful design of the trailer used in a similar study in France (Bouslimi, Kassaagi, Lourdeaux, \& Fuchs, 2005; Perron, Kassaagi, \& Brissart, 2001) with necessary changes to minimise risk and keep cost at reasonable levels. Before going down to the details, it is useful to give a broad description of the study it is designed to serve.

## The study

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Figure 1: The study design
The study is expected to take place in a closed road track (old airfield). Participants drive the instrumented vehicle to the test track - normal braking measurement.
In the track, they are instructed to follow the leading vehicle which tows the trailer as close as they feel comfortable. The leading vehicle accelerates to 30 mph when the trailer is released by the lead driver.

## The trailer

To serve the purpose of the study a lightweight trailer needs to be manufactured. Figures 2 and 3 present the particular dimensions of it. Its base is an aluminium sheet across which aluminium triangles are welded to support another aluminium plate - where card box is attached (grey area in figures 2,3 ). The main aluminium sheet is cut open in three points for the wheels to fit in as indicated on figure 2. Additional brackets are bolted on the sheet, so that the wheels can be easily mounted and removed. 20 " wheels and $V$-brake mechanisms are to be mounted when the aluminium sheets are cut and welded together according to the designs in figures 2 and 3 . An additional hole is to be drilled right in front of the front wheel, for the towrelease mechanism to be fitted (see figure 4).


Figure 2: Plan view of the trailer


Figure 3: Side view of trailer

## Front hole



Figure 4: The wheel mount design for quick replacement

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Appendix B: Printed materials used during the studies

## Participant demographics sheet

Date of session $\qquad$
Participant Number $\qquad$
Gender $\qquad$
Age $\qquad$
Height $\qquad$
Weight $\qquad$
Ethnicity $\qquad$
Driving Experience $\qquad$
Annual Mileage $\qquad$
Licence Points $\qquad$
Current Vehicle $\qquad$
Desirable Vehicle $\qquad$

## Generic health screen for study volunteers

It is important that volunteers participating in research studies are currently in good health and have had no significant medical problems in the past. This is to ensure their own continuing well-being and to avoid the possibility of individual health issues confounding study outcomes.

Please complete the questions in this brief questionnaire to confirm fitness to participate:

If YES to any question, please describe briefly in the spaces provided (eg to confirm problem was/is short-lived, insignificant or well controlled.)

1 At present, do you have any health problem for which you are:
(a) on medication, prescribed or otherwise
(b) attending your general practitioner
(c) on a hospital waiting list
(Please tick as appropriate)


2 In the past two years, have you had any illness which required you to:
(a) consult your GP
(b) attend a hospital outpatient department
(c) be admitted to hospital
(Please tick as


3 Have you ever had any of the following:
(a) Convulsions/epilepsy
(b) Asthma
(c) Eczema
(d) Diabetes
(e) A blood disorder
(f) Head injury
(g) Digestive problems
(h) Heart problems
(i) Problems with bones or joints
(j) Disturbance of balance / co-ordination
(k) Numbness in hands or feet
(I) Disturbance of vision
(m) Ear / hearing problems
(n) Thyroid problems
(o) Kidney or liver problems
(p) Allergy to nuts
(q) Migraines
(Please tick as appropriate)


## Optional questions for female participants

(a) are your periods normal/regular?
(b) are you on "the pill"?
(c) could you be pregnant?
(d) are you taking hormone replacement therapy (HRT)?


Thank you for your co-operation!
Date of Birth: D/ M / Y

## Declaration Of Consent

I, hereby volunteer to be an experimental participant in a driver ergonomics experiment during the period of $/$ on

My replies to the above questions are correct to the best of my belief and I understand that they will be treated with the strictest confidence by the experimenter. The purpose of the experiment has been explained by the experimenter and I understand what will be required of me.

I understand that I may withdraw from the experiment at any time and that I am under no obligation to give reasons for withdrawal or attend again for experimentation. I also understand that the experimenter is free to withdraw me from experimentation at any time.

I undertake to obey the laboratory regulations and the instructions of the experimenter regarding safety, participant only to my right to withdraw as declared above.

Signature of Participant
Date

Signature of Experimenter Date

## General Driver Application Form (for driving University vehicles)

# Loughborough University 

## GENERAL DRIVER APPLICATION FORM

## IMPORTANT

It is an offence under the Road Traffic Act to make a false statement or withhold any material information. Great care must be taken to ensure that this form is completed correctly in every particular detail.

A copy of your UK driving licence in card and paper form MUST be attached to this form.

| FULL NAME: |  |
| :--- | :--- |
| ADDRESS: |  |
| TEL. NO: |  |
| DATE OF BIRTH: |  |
| OCCUPATION: |  |
| Klist fulltime and any part.time nown) |  |
| DEPARTMENT: |  |

PLEASE ANSWER "YES" OR "NO" AS APPLICABLE - A DASH IS NOT ACCEPTABLE.

| Are you suffering from any physical defect, infirmity, impaired vision or hearing? |  |
| :--- | :--- |
| If "YES", please give full details (including medication). |  |
| Do you hold a full UKDring Licence? |  |
| For how long? | Type/class of vehicles. yrs <br> Do you have any motoring convictions?  <br> State conviction code(s) noted on driving licence.  <br> Date of conviction.  <br> Fine imposed  <br> Give full details of offence.  |


| Have you ever had your licence suspended or withdrawn? |  |
| :--- | :--- | :--- |
| If 'YES', please give full details. |  |
|  |  |
| Have you been involved in an accident within the last 3 years? |  |
| If 'YES', please give full details and costs incurred. |  |
| Has any company or underwriter in respect of any motor insurance proposed or effected by |  |
| you or on your behalf: |  |
| - declined such a proposal? |  |
| - cancelled or refused to renew a policy? |  |
| - increased the premium or imposed special conditions? |  |
| - required you to bear any part of any loss? |  |
| If 'YES', please give details. |  |
| Date: |  |

Applicant: A copy of your driving licence in card and paper form MUST be attached.
Send completed form to Hiten Patel, Insurance Officer, Admin. 1, Sir Arnold Hall Building.

## Appendix C: the basic MatLab code for system

## simulation

```
Clc
X=MeanForce;
n=length(X);
Tr keep=zeros (n,1);
B=zeros(n,1);
Tr=20.9392;
for counter=1:n
    X_mean=sum(X(1:counter))/length(X(1:counter));
Tr_1=0.2646435288626*X_mean^2-2.43381551641*X_mean +22.90;
%Tr=(Tr+Tr_1)/2;
Tr_keep(counter)=Tr_1;
end
criteria=+(B>Tr_keep);
```


[^0]:    1 The total of $\$ 164.4$ billion rises to 432 billion per year when derived valuations of loss of life and pain and suffering are included.

[^1]:    ${ }^{2}$ Chapter based on two research studies published in:
    Gkikas, N., Hill, J.R., and Richardson, J.H, (2008). Getting back to basics: using road accident investigation to identify the desirable functionality of longitudinal control systems. In D. de Waard, F.O. Flemisch, B. Lorenz, H. Oberheid, and K.A. Brookhuis (Eds.), Human Factors for assistance and automation (pp. 203-216). Maastricht, the Netherlands: Shaker Publishing
    Gkikas, N., Hill, J.R., and Richardson, J.H., (2009). Reset to zero and specify active safety systems according to real-world needs. Journal of Transportation Engineering. Submitted August 28, 2008; accepted April 27, 2009;posted ahead of print April 29, 2009.
    doi:10.1061/(ASCE)TE.1943-5436.0000042

[^2]:    "Failure to stop"

[^3]:    ${ }^{3}$ Part of this study was published here: Gkikas, N., Richardson, J., \& Hill, J. (2009). A 50driver naturalistic braking study: Overview and first results. In P. D. Bust (Ed.), Contemporary ergonomics 2009 (pp. 423-431). London: Taylor \& Francis.

[^4]:    ${ }^{4}$ This variable represents the average of all participants' average input during their trips

[^5]:    ** Correlation is significant at the 0.01 level (2-tailed).

[^6]:    ${ }^{5}$ average

[^7]:    ${ }^{6}$ Parts of this study were published in: Gkikas, N., Richardson, J., \& Hill, J. (2009). Towards a driver-centred brake assist. Braking 2009, St Williams College, York, UK. 85-92.
    And:
    Gkikas, N., Richardson, J. H., \& Hill, J. R. (2009). Exploitable characteristics of driver braking. Proceedings of the 21st International Technical Conference on the Enhanced Safety of Vehicles (ESV), Stuttgart. (Paper Number 09-0247)

[^8]:    Dependent Variable: test_ brake_force_lower
    The independent variable is pub_road_brake_force_lower_avg.
    a The dependent variable (test_brake_force_lower) contains non-positive values. The minimum value is .00. Log transform cannot be applied. TThe Compound, Power, S, Growth, Exponential, and Logistic models cannot be calculated for this variable.

[^9]:    Dependent Variable: Emergency foot displacement time
    The independent variable is Typical foot displacement time.

[^10]:    ${ }^{7}$ The basic Matlab code used for the simulation can be found in Appendix $C$

