Development of a workload estimator:
The influence of surrounding traffic behaviour on driver workload and performance

by

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The candidate confirms that the work submitted is his/her own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

The work in Chapter *4* of the thesis has appeared in publication as follows:

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I was responsible for performing the literature search, key ideas, primary contributions, experimental designs, recruiting participants, data collection, data analysis and interpretation. The study was conducted under the supervision of Samantha Jamson and Oliver Carsten, who had provided advices in the drafting stage of the paper. The coding scripts used for design implementation in the driving simulator was provided by Hamish Jamson.

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Abstract

The consumers' increasing desire to be connected at all times and the advancement of integrated functionality within the vehicle, increases the risk that drivers could be faced with information overload while driving. Given the importance of human interaction with technology within the vehicle, automobile manufacturers are introducing workload manager systems within the vehicles to help prevent driver overload. However the ability of the system to decide in a timely manner requires anticipation of changes in workload, depending on the capacity of the driver and matching it with the demand expected from the driving task such as the dynamic traffic environment.

In relation to the need to understand the influence of traffic demand on driver workload, the work here comprises the systematic manipulation of traffic complexity and exploration of workload measures to highlight which are sensitive to primary task demand manipulated. A within-subjects design was used in the studies explored in this thesis to allow comparison between different manipulated traffic conditions. In the first simulator test, the ability of various objective and subjective workload measures to tap into drivers' momentary workload was examined. Following the identification of a subjective measure that was sensitive to the influence of lane changes performed by neighbouring vehicle on drivers' momentary workload, the characteristics of the lane change were explored in the subsequent studies involving single and dual-task conditions. Overall, these studies suggested suppression of non-urgent communications by a workload manager during safety-critical conditions involving critical cut-ins would be advantageous to both younger and older drivers.

This thesis offers a novel and valuable contribution to the design of a workload estimator so as to ensure that the driving demand is always within drivers' capacity to avoid driver overload. Results of these studies have also highlighted the utility of vehicle-based sensor data in improving workload manager functionality.

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Abbreviations

ACP	Average change of pupil diameter
ADAS	Advanced Driver Assistance Systems
BD	Blink duration
CSR	Continuous Subjective Rating
DHW	Distance Headway
DVE	Driver-Vehicle-Environment
HFS	High frequency component of steering angle movement
HMI	Human Machine Interface
IDIS	Intelligent Driver Information System
IVIS	In Vehicle Information System
KSS	Karoslinka Sleepiness Scale
LOS	Level of Service
MBF	Mean blink frequency
MSP	Mean speed
NASA-RTLX	NASA Raw TLX
PDT	Peripheral Detection Task
RSME	Rating Scale of Mental Effort
SDSP	Standard deviation of speed
TDT	Tactile Detection Task
THW	Time headway
WLM	Workload Manager

Chapter 1

Introduction

Chapter 1 highlights the background of the research performed, providing a brief overview of the problems and the available design solutions relevant to the research. An outline of the remainder of this thesis is also provided.

1.1 The Vehicle Today

Automobiles are going through a transformation with infotainment systems providing more information and connectivity. With a tremendous appetite for new technology, car owners expect the latest telematics, infotainment and smartphone integration to be available in their cars. Progressing alongside the efforts of the designers and engineers who dream up new generations of infotainment features - GPS display, Internet radio, email and even Facebook apps - is a new generation of advanced driver safety assistance systems designed to increase comfort and avoid accidents. These available options for the modern automobile include lane departure warning systems and detecting obstacles on the road. While adoption of infotainment and assistance systems brings a lot of exciting features to cars promising comfort and potential reduction in traffic congestion (Barfield and Dingus, 1998; Matthews and Desmond, 2001; Alkim, Bootsma, and Looman, 2007), it presents another set of problems.

1.1.1 Problem 1: Internal Sources of Distraction

Matthews and Desmond (1995) identified the two themes of particular relevance to driver workload in the vehicle of the future: *overload of attention* and *disruption of control*. The overload of inputs from the in-vehicle systems, perhaps amplified by bad weather or demanding traffic, presents a real challenge to the driver and possibly a danger to all road users. There is a concern that telematics, infotainment and assistance systems could potentially overload and distract the driver and thus jeopardise safety (Verwey, 2000; Pauzie, 2002; Blanco et al., 2006).

The United States (US) National Highway Traffic Safety Administration (NHTSA) estimates that distraction and inattention contribute to 20% to 30% of reported crashes, although other sources estimate that this figure is between 35% and 50% (Stutts et al., 2001). Meanwhile, a study of naturalistic driving behaviour found that inattention contributed to 78% of crashes and 65% of near-crashes (Neale et al., 2005; Dingus et al,. 2006; Basacik, 2008). According to the data from the NHTSA Fatality Analysis Reporting System (FARS), the number of fatalities as a result of distracted driving has remained high for the past few years; for example in 2012, 3,328 people were killed in crashes involving a distracted driver on US roads, compared to 3,360 in 2011 and 3,267 in 2010 (National Highway Traffic Safety Administration, 2012).

According to Stutts et al. (2001), "distraction occurs when a driver is delayed in the recognition of information needed to safely accomplish the driving task because some event, activity, object, or person within or outside the vehicle compels or induces the driver's shifting attention away from the driving task". Such distraction may be in the form of visual (i.e taking your eyes off the road), manual (i.e. taking your hands off the wheel), or cognitive distraction (i.e taking your mind off what you are doing), depending on the type of in-vehicle task. The technologies which are commonly used within the vehicle include integrated vehicle systems (i.e. those that are factory-fitted or retrofitted) and nomadic (i.e portable) devices which provide a range of functions, such as entertainment, provision of information and communication. Examples of the integrated vehicle systems that provide pertinent real-time in-vehicle information about the elements of the driving (i.e traffic environment, the vehicle or the driver) include navigation systems, hazard warning and sign information systems. The portable systems refer to in-vehicle navigation systems designed to support the driving and mobile phones which have not been designed specifically for in-vehicle use. Due to the wide range of functionalities available and the vast differences in the designs of the human-machine interface (HMI) between devices, there is potentially a significant impact on the amount of time and effort required to interact with these devices which in turn, influences the level of distraction that it imposes on drivers.

In a UK-based study of police reports on fatal accidents, in-vehicle distraction was shown to be a contributory factor since mid-1980s, whereby 2% of fatal accidents between 1985 and 1995 were attributed to in-vehicle distraction (Stevens and Minton, 2001). With the growing number of mobile phone ownership worldwide as well as rapid spread of smart phones and rising introductions of new "in-vehicle" communications systems, this problem is likely to escalate globally in the coming years. A 2011 survey study performed by the Centers for Disease Control and Prevention found that at least 21% of drivers in the UK conversed on a mobile phone while driving, while in the US this percentage increased to 69% (Centers for Disease Control and Prevention, 2011). Some studies also attempted to assess the use of mobile phones at any given moment. For example, the 2011 national observational survey data and self-reported data on hands-held and hands-free mobile phone use estimated that at any moment, 9% of the US drivers were conversing on mobile phones (National Highway Traffic Safety Administration, 2013). Comparing this to the police crash report in one state in the US which estimated that 2.7% of drivers use the mobile phone while driving in 2001 and 5.8% in 2005 (Eby, Vivoda and St. Louis, 2006), there is clearly a growing body of evidence on the prevalence of mobile phone use at any moment while driving between 2001 and 2011.

Data from observational and epidemiological studies draw a clear picture about the impact of mobile phone conversations on the risk of being involved in an accident with increases in risk ranging from four-fold (McEvoy et al., 2005; Redelmeier and Tibshirani, 1997) to nine-fold (Violanti, 1998). Most researchers conclude that a significant contributor to mobile phone-related driver distraction is the engagement in the conversation, which leads to a withdrawal of attention from the immediate driving environment (Strayer, Drews and Johnston, 2003). In a high-fidelity simulator study, drivers conversing on a mobile phone (either handheld or handsfree) showed delayed braking reaction times and an increase in traffic accidents compared with the control group that was only driving (Strayer and Drews, 2006). In addition to signs of drivers adopting strategies to compensate for high task demands, such as slower response times to traffic events, participants also reported higher subjective workload. Some studies have attributed these findings to a reduction in situation awareness, which resulted from driver's attention being drawn

away from the road and the surrounding environment to concentrate on the phone conversation (Parkes and Hooijmeijer, 2000; Cooper et al., 2003). Some studies have also suggested that the "relative risk (of being in a traffic accident while using a mobile phone) is similar to the hazard associated with driving with a blood alcohol level at the legal limit" (Redelmerier and Tibshirani, 1997; Strayer and Drews, 2006). With much of the research focused on the negative safety impacts of driver engagement in secondary tasks, there were studies that have shown mobile phone conversation to be "protective" by supporting driving performance (Olson et al., 2009; Hickman, Hanowski, and Bocanegra, 2010), particularly during low levels of arousal (Fitch and Hanowski, 2011; Curry Meyer and Jones, 2013; Toole et al., 2013).

Apart from mobile phones, interactions with in-vehicle information systems are also prime examples of distracting activities. Most of the existing research on the effects of driver interaction with technology-based sources of distraction has so far been concerned with infotainment technologies that are embedded in the vehicle cockpit. For example, manipulation of the audiovisual entertainment systems such as the radio system controls has been shown to affect driving performance (Horberry et al 2006; Stutts et al, 2001). Due to the non-criticality of these activities, drivers are still capable of monitoring traffic continually and able to focus attention on the driving task at any given time. Little is known about the adverse effects associated with drivers' use of warning systems which provide real-time information about the status of the vehicle components (e.g. 'Bonnet Open', 'ACC sensors blocked', etc). While these systems are meant to support, inform and warn drivers, these systems may impose a demand upon the drivers. This may result in competition between driving and secondary tasks, inducing increased levels of distraction and workload. As both tasks fluctuate simultaneously, unsafe situations can develop rapidly and unexpectedly. If an unexpected event takes place within the time window the driver fails to monitor the ongoing traffic, failure to prioritise the driving task can have safety-critical consequences. This could mean longer times taken for the driver to detect the event and longer brake reaction times (Green, 2000).

1.1.2 Problem 2: External Sources of Distraction

Distracting activities can involve sources from either inside or outside the vehicle. As driving is a complex, multitask activity, the demand of one element of driving will interfere with another element. Often, a mismatch between the attention demanded by the road environment to drive safely and the attention devoted to it poses a threat of distraction. The level of distraction is dependent on the combined demand of the roadway and the competing activity relative to the available capacity of the driver. The lesser the degree to which the distribution of demands of roadway and the competing activity overlap, the less likely the roadway demands will exceed a driver's capability to respond (Figure 1.1). Mishap occurs when combined demand of both exceeds driver's capacity to respond (Lee et al., 2009).
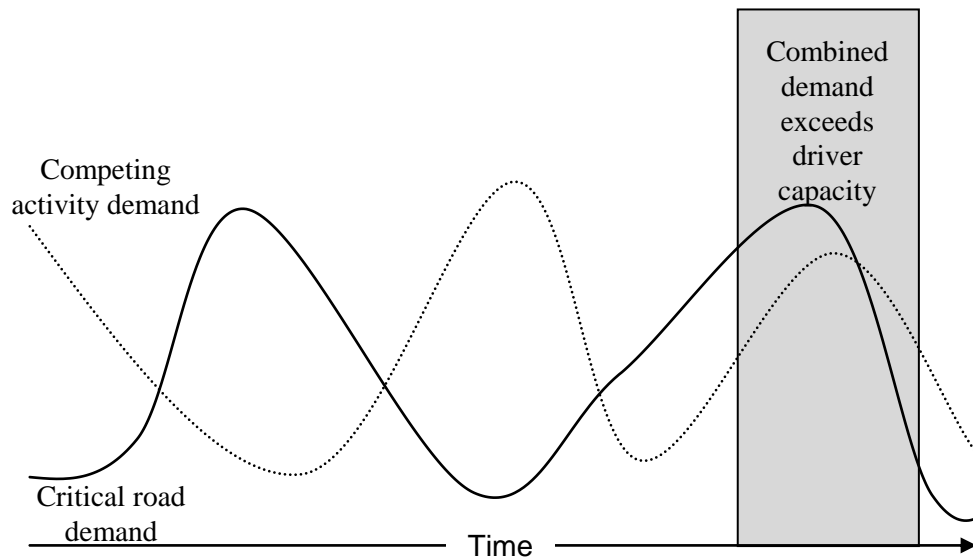
Figure 1.1: The distributions of attention demanded by the roadway and the competing activity (Source: Lee et al., 2009)

Due to the inherent variability in environmental sources of demand, for example if the traffic demand peaks suddenly and unexpectedly (such as when an obstacle moves suddenly into the driver's path), drivers may fail to respond to the hazard due to insufficient attentional capacity. Traffic density, surrounding drivers' behaviours and road geometry have been identified as contributory factors to accidents (Verwey 1993b; Verwey 2000). For example, Lerner and Boyd (2005) collected subjective risk ratings of varying driving situations and found that high risk ratings of a driving situation are often related to traffic demand with the highest three cited by drivers being merging or interacting with other traffic, high speed of traffic and behaviour of other drivers (Table 1.1). Inappropriate distribution of

attention however, does not necessarily guarantee a mishap or even a decline in performance. Hoyos (1988) concluded that the danger of a traffic situation depends on the amount of information to be processed and is frequently underestimated by drivers who tend to believe they have better control over traffic situations than is actually the case. Therefore drivers may be unaware that they are distracted, leading to drivers continuing to adopt unsafe practices that increase the chance for roadway demands to exceed the attention devoted to the roadway.

Table 1.1: Lists of reasons given by subjects for high risk ratings.
(Source: Lerner and Boyd, 2005)

Reason	Percentage of subjects citing the reason at least once	Demand
Merging/ interacting with other traffic	32	Traffic
High speed of traffic	26	Traffic
Behaviour of other drivers (improper, risky, hard)	24	Traffic
Difficulty of visual and temporal judgements	20	
Manoeuvre requires concentration, awareness	20	
Opposing traffic	19	Traffic
Limited sight distance	13	Visibility
Demands of vehicle control, staying on path	13	Road geometry
Volume of traffic	11	Traffic
Unfamiliarity	10	
Limited manoeuvre time	5	
Presence of children, pedestrians	4	Traffic
Slow or stopped vehicles	2	Traffic
Presence of roadside hazards	2	

Driving not only involves integrating and co-ordinating multiple discrete visual and motor actions, but also requires the driver to continuously sample and interpret the environment as well as other traffic participants' behaviour. Failure to detect an object or event is sometimes defined as attentional blindness which could be associated to the "looked but did not see" phenomenon. According to STATS19 data from Department for Transport (DfT), the most prevalent factor that contributes to road traffic collisions in the UK since 2007 was "failing to look properly", reported in 35% of accidents in 2007 and 42% in 2012 (with 14% of the those falling into this category were either killed or seriously injured). While a driving task requires speed control, lane keeping, curve negotiation, collision avoidance and motor control such

as gear shifting, the subtask of visual orientation i.e. looking in the right direction at the right time is deemed vital as it provides an overview of the traffic situation. However, coordinating these subtasks can be seen as a task itself (Aasman, 1995) and the fluctuating demand of the surrounding traffic environment which is less under the driver's control, may exacerbate the overall driving demand.

1.1.3 Design Solutions

Today, as drivers are exposed to an increasing amount of information flow provided by a number of in-vehicle systems (not exclusively related to the driving task) and the introduction of driver assistance systems (such as navigation systems, nomadic devices etc.), managing the demanding HMI interactions remains a challenge. With the increasing complexity of HMI, drivers could be overloaded if multiple systems want to attract their attention simultaneously, which could lead to potential accidents especially in critical situations. In order to handle this growing diversity and complexity of in-vehicle functionality, several types of workload management functions for human-machine integration and adaptation have been proposed to resolve potential conflicts between individual functions. Based on the interactions of these in-vehicle functions with the driver, information are prioritised or put on hold in demanding driving situations if the information are deemed non-critical (Engström et al., 2004, Broström et al., 2006).

So far only a few systems of this type have entered the market (e.g. Volvo Cars' intelligent driver information system (IDIS) and Saab's dialogue manager), but more advanced functions are being developed in different research efforts, both in-house at the companies and in collaborative efforts such as COMUNICAR (Amditis et al., 2002), AIDE (Engström et al., 2004) and SAVE-IT (SAVE-IT, 2002). These workload managers support drivers by resolving conflicts between different (driving and non-driving related) goals. One key objective is to promote safe driving by providing support to the driver in prioritising driving tasks in demanding driving situations. Workload managers adapt information flow based on the demand of the driving situations. Hence in order to ensure that these systems are effective, great care must be taken in the design of such functions in order to avoid unexpected usability and safety problems.

The behavioural effects of a specific driver support function is the result of a complex dynamic interaction between individual driver characteristics (motivation for driving, subjectively chosen safety margins, driving skills, personality, effort, etc), vehicle parameters (e.g. steering and braking dynamics) and the driving environment (road type, curvature, lane width, traffic density, etc). Most recent developments in workload management driver support systems by Scania (Osbeck and Åkerman, 2010) involves some form of characterisation of difficulty of use of different in-vehicle information functions while driving. In this study, the workload associated with each of the in-vehicle tasks was defined on the basis of amount of resources that the driver needs to perform the tasks, relative to a limited subjectively defined resource pool. Most studies conducted are based on traditional information processing models which tend to view the human as a passive receiver of information, subject to overload if the limited capability is exceeded. Moreover, different behavioural effects may result, depending on the type of secondary task. For example the HASTE EU-funded project (Engström et al., 2005; Östlund et al., 2004) showed that cognitively loading tasks lead to significantly improved tracking control in terms of reduced lane keeping variation compared to baseline driving, while the opposite effect is true for visually-loading tasks. Results also showed that the longitudinal safety margin, in terms of time-headway to a lead vehicle, was reduced during cognitive load (Jamson and Merat, 2005).

There is evidence that cognitively loading tasks, such as phone conversations, impair the ability to set appropriate safety margins and adapt accordingly. However, vehicle related messages also have the potential to cause cognitive load. The safety consequences of this are still unknown as the relation between driving performance and the risk (for an individual driver) is dependent on a driver's adaptation to the current complexity or difficulty of the driving task. Since the development of driver support functions is still to a large extent driven by technological possibilities rather than user needs, it is therefore important to link driver support functions to their intended purpose. In such dynamic and complex traffic environment, it is important that the self-paced, adaptive nature of driving is captured to ensure that driver support systems are able to provide assistance appropriately depending on the complexity of the driving condition and the type of secondary task involved.

1.2 Research Questions and Scope

This thesis studies the interaction between drivers and other road users in a motorway environment. Driver workload at a particular instance is highly related to driving behaviour and the driving task. According to De Waard (1996, pp. 15), workload is defined as "*the specification of the amount of information processing capacity that is used for task performance*". De Waard (1996, pp. 17) also posits that workload depends on the combination of task demands (what does the driver need to do), the available information processing capacities (how much can the driver handle), and the effort invested (how much effort is the driver willing to invest in task performance). As such, task demands can increase or decrease according to the situation and the pursued goals. Driving in dynamic traffic is a complex task as drivers continuously meet a sequence of different situations which are neither static nor similar. Occasionally drivers may encounter events requiring their full attention and quick reaction to avoid serious conflicts or accidents. Although research exists that reports the interaction between high traffic demand on driver performance and workload, these results are relatively few and there is still a need to study how changes of the traffic affect momentary driver response and fluctuations in subjective workload. Moreover, the determination of what constitutes high workload is largely driver-dependent and incorporates a number of contextual factors such as the point at which other road users enter the 'safe field of travel' (Gibson and Crooks, 1938) or the current level of distraction. Following the discussion above, this research aims:

- To explore how traffic complexity (i.e. traffic flows and the presence of lane changes) influences driver workload.

- To investigate to what extent resulting fluctuations in workload can be estimated via different measures.

- To explore the influence of lane change characteristics (i.e. criticality of a lane change, information availability) on driver workload.

- To investigate driver workload recovery and whether a driver is capable of managing his/her own workload in varying traffic demand conditions.

- To examine the ability of a workload manager to moderate driver workload via time-management of system-initiated distractions.

The research presented in this thesis attempts to examine how the surrounding traffic behaviour influences driver's momentary workload and how resulting fluctuations in driver workload are best captured by different workload measures. Such systematic manipulation of traffic complexity and utilisation of various workload measures to tap into these fluctuations in traffic have not been investigated before. This thesis is an attempt to fill this gap and present a set of findings on this topic which are useful to academia and the automotive industry (in particularly, in the design of a workload manager). In summary, the studies presented in this thesis are intended to contribute to the existing knowledge of driver workload in varying traffic complexity, with a focus on traffic flows and influence of other road users' behaviours.

1.3 Thesis Outline

This section provides a summary of the contents of this thesis:

Chapter Two addresses the definition of driver workload. To understand driver workload fluctuations, driving task models as related to driver workload effects are discussed. In addition, a review of the key methodologies used to study driver workload relevant to this research is provided. The chapter concludes by highlighting that driving is a self-paced task which poses a challenge in the estimation of driver workload in the driver-vehicle-environment interaction.

Chapter Three reviews the research on driver assistance systems, specifically the workload management systems which are designed to prevent driver overload. A critical review of existing workload manager system functionalities (i.e. to keep demand within operator capacities) and the deficiencies are provided. This chapter provides the rationale for the simulator studies described in Chapter Four to Chapter Six of this thesis.

Chapter Four describes an exploratory study carried out on a driving simulator, the first study conducted as part of this research. This study investigates the driver interaction with other road users in ambient traffic. The surrounding traffic was scripted to allow the examination of workload measures in a "naturalistic"

traffic environment. Appropriate measures of workload to be used in subsequent studies were defined based on their efficiency to capture changes in driver workload and driving performance.

Chapter Five details a second driving simulator study, which utilises the methods and advances from the findings of the first study. The effect of traffic demands on workload was further investigated by varying a range of characteristics of traffic behaviour, in particular focusing on the influence of a lane change performed by a neighbouring vehicle. To examine drivers' ability to manage their own workload in these traffic situations, the findings of the prior study were extended by incorporating an in-vehicle task in the dual-tasking domain. Drivers were presented with an in-vehicle task (i.e. a mental arithmetic task) which occurred concurrently with a change in traffic demand. The findings of the study are used to shape the design of the subsequent study which examines the potential benefit of coordinating system-initiated information with respect to the current driving demand and driver workload.

The final driving simulator study in this thesis is discussed in *Chapter Six*. It introduces surrogate in-vehicle tasks with higher ecological validity and explores the potential benefits of a workload manager to manage driving demand. Workload manager systems are compared in various dual-task conditions involving a preceding or a concurrent in-vehicle task alerts during critical traffic situations. Driver performance and driver workload are assessed to understand how in-vehicle tasks distract drivers in varying driving demand conditions. This information is used to make recommendations regarding the benefits of using a workload manager for in-vehicle task presentation in varying traffic scenarios.

Chapter Seven concludes this thesis by summarising the key findings. Using the results of the three studies in this thesis, recommendations are proposed for managing workload resulting from traffic density and the surrounding traffic behaviour both in primary and in dual-tasking conditions. The resulting recommendations aim to reduce the occurrence of distracted driving and mitigate its effects when it occurs. This chapter concludes with several suggestions for future work that could extend on the findings from this thesis and also to be applied in workload manager systems.

Chapter 2

Theoretical Frameworks of the Driving Task

Chapter 2 presents a detailed literature review on the underlying theories related to multiple task performance, its relationship to driver workload and their limitations. An overview of workload measurements pertinent to the driving task is also provided.

2.1 Operator Capacity and Workload

Car driving can be described as conducting a complex and dynamic control task (Rouse, 1981, Nilsson, 2005) within a traffic system, requiring the driver to perform a number of functional abilities simultaneously (Peters and Nilsson, 2007) in a timely and efficient manner. Although the traffic system is comprised of three interactive parts-vehicles, road users and the road environment- road user factors have been the sole or contributory factors in most of the traffic accidents. Early studies such as the Indiana Tri-Level crash causation research conducted during the mid-1970s identified human factors as the probable cause in 93% of the investigated crashes, while environmental factors and vehicular factors each attributed 34% and 13% to the accidents, respectively (Treat et al., 1979). Even though the most commonly reported cause of distraction-related accidents are associated with external distractions from outside persons, objects or events (Stutts et al., 2001), 95% of road collisions have been contributed by human error (Smart Motorist, 2000) suggesting the driver as a critical component of the traffic system. Since the driving task can be divided into multiple subtasks such as lane keeping, collision avoidance, speed control etc., understanding the theories relevant to workload may offer some explanations in regards to human errors while driving.

As illustrated in Figure 2.1, the concept of workload is "fundamentally defined by the relationship between resource supply and resources demanded" (Wickens and Holland, 2000, pp. 459). Changes in workload may thus result either from fluctuations of the operator's capacity or from the changes in the resource demands. In the following section 2.1.1, capacity-based theories and approaches are used to explain how limited human information processing capacity results in errors or slowed task performance.
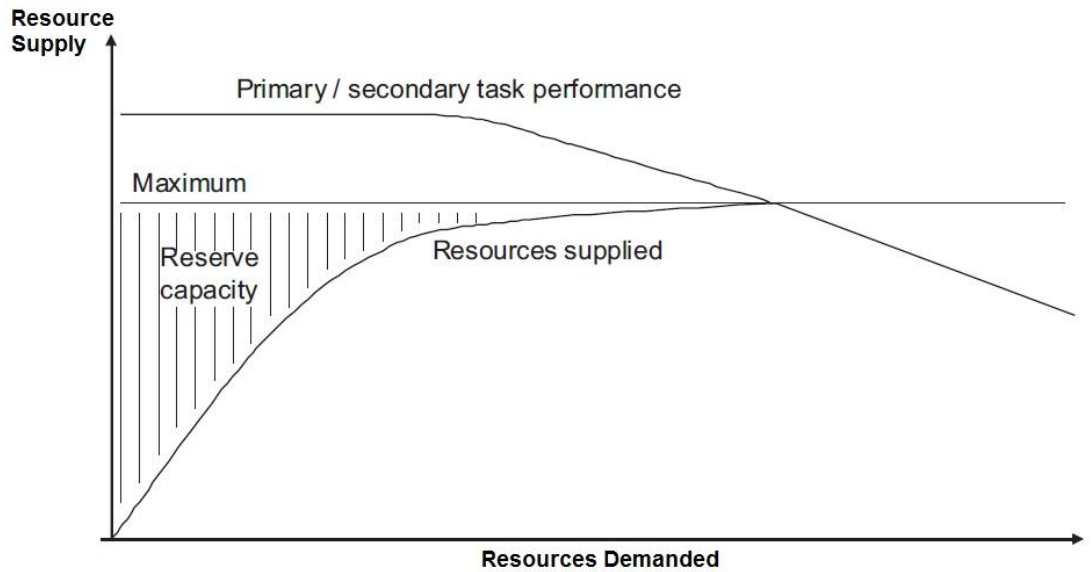
Figure 2.1: Relationship among resource demand, resource supply and performance. (Source: Wickens and Hollands, 2000)

2.1.1 Central Processing Limitations

Early models of capacity-based theories consider human processing capacity to be limited (Broadbent, 1958) but flexible (Moray, 1967) depending on the operator's physiological arousal mechanism (Kahneman, 1973). Numerous theoretical frameworks to explain the general limits of central processing have been presented, for example in experimental research on the structure of working memory (Baddeley, 1986), the limits of attention (e.g., Cowan, 2000), on bottlenecks in central processing (e.g., Pashler, 2000), or on specific resource theories (e.g. Wickens, 2002).

Baddeley (1986) defined working memory as the temporary storage of information that is being processed in a broad range of cognitive tasks. In the absence of rehearsal, the memory would decay thus suggesting its vulnerability to

interruptions by other tasks (e.g, Brown 1958). To keep several task components active in the working memory, additional workload is incurred from constantly refreshing these tasks in working memory to consciously process information. Cowan (1995) proposed that the human processing system is influenced by the limited focus of attention, which may represent lapses in the control and regulation of cognitive action in distracted driving. Cowan (1999) elaborates on how voluntary and involuntary mechanisms of the central executive interact to control and regulate the focus of attention. It is suggested that, when overloaded with visual information, a person may selectively focus attention on relevant aspects of the task environment while repressing the others (Haberlandt, 1997). Rather than focusing on working memory, Pashler (2000) found evidence for a bottleneck in the central-processing stage (i.e. response-selection or decision-making stage of human information processing), which is commonly referred to as the Psychological Refractory Period (PRP) (Telford, 1931). In essence, it shows that if two tasks require response selection or decision making at a particular time, at least one of them is delayed. However these models discussed earlier cannot explain all types of dual-task interference as it is possible that two tasks can be processed in parallel.

Adequate dual-task performance is achievable as long as the total amount of resources was not exceeded, by flexibly allocating the pool of resources between subtasks (Moray, 1967; Kahneman, 1973). Further empirical evidence found that dual-tasking performance can be improved by changing the qualitative demand of information processing (e.g, by changing the stimulus modality of one of the tasks) (Wickens, 1976). This subsequent research led to the concept of multiple resource theories in which multiple resource pools were defined (Wickens, 1980; 1984; 2002) which are both limited in capacity and can be allocated amongst difference tasks. These resources are defined along four dimensions: processing stages (i.e., perception, central processing and responding), resources for different input modalities (i.e., visual, auditory), responses (i.e., manual, vocal) and processing codes (i.e. spatial, verbal) as depicted in Figure 2.2.
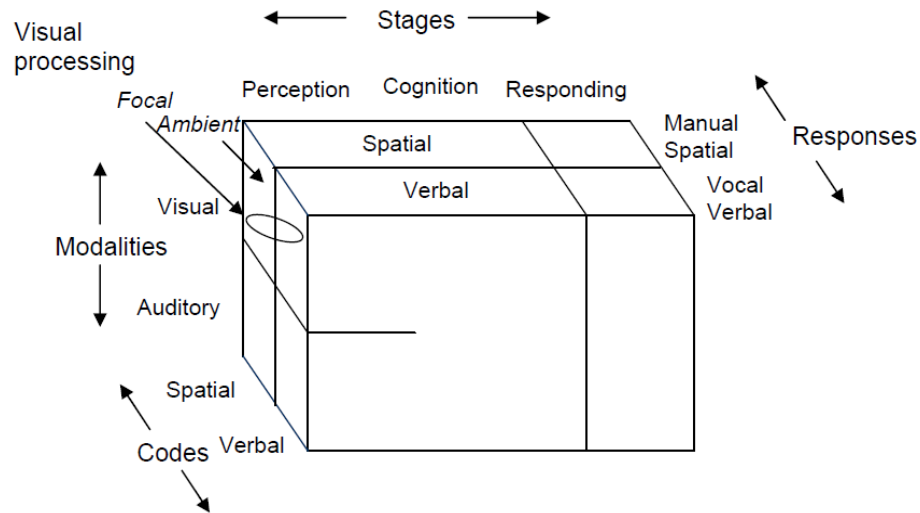
Figure 2.2: Wicken's four dimensional multiple resource model.
(Source: Wickens and Hollands, 2000, pp. 449)

Using the multiple-resource theory, the existence of serial processing in cognitive processes enables prediction of useful performance deterioration in dual-tasking or multi-tasking conditions. Although these theories may not be thoroughly applicable to complex tasks such as driving due to their development via simple laboratory tasks, they are useful as a framework to determine multi-tasking descriptions. For example, better overall performance of two tasks is expected when different resources are utilised. Therefore the primary task of driving will experience less interference if the secondary task has a different modality. For example, Verwey (2000) compared drivers' reaction times to a secondary task presented either auditorily or visually and found that visual presentation led to greater performance deterioration (i.e. longer reaction time) than auditory presentation.

In driving however, the relationship between the available resources and driving performance is not linear whereby driving demand may involve a variety of unknown variances imposed by the dynamic changing traffic environment and performance which can be enhanced by the development of skills (Fisk, Ackerman and Schneider, 1987). Although the capacity-based models above can explain part of the significant driving-related subtasks, their relevance can also be questioned as driving skills can be developed through learning and practice (Newell, 1991) which will be explored further in the following section.

2.1.2 Cognitive Models of the Driving Task

In an interactive environment, performance in longer continuous tasks may be better explained by time-sharing strategies (Gopher, 1993) as skills can be developed through practice. After sufficient practice, task completion can move from the limited-capacity conscious control to so-called automatic control (Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977; Groeger, 2000). Based on these observations, Rasmussen (1987) developed a popular model of skill-, rule- and knowledge-based information processing to explain the different types of human error (see Reason, 1990). This model was combined with the hierarchical control model of Michon (1985) to form the three behavioural levels of driving in Figure 2.3; i.e., control (skill-based behaviour), manoeuvre (rule-based behaviour), and strategic (knowledge-based behaviour).

The three levels can be differentiated based on the temporal level; the amount of processing time to define a goal and to make a decision varying from minutes to milliseconds. The discrepancy in terms of the time available and time required to make decisions can create time pressure for control level tasks where time to response is limited and constant adaptation of motor skills is required to avoid safety critical situations (Brouwer et al., 1988). With greater skill enhancements, more components of the driving task are performed through automatic control which demands relatively less attentional resources than controlled processing. Thus, the driving task becomes more routine, requiring less mental capacity. With extensive practice, experienced drivers are more efficient in allocating resources or scheduling tasks and thus have more spare capacity available to cope with the increasing difficulty of the driving task. By supporting lower levels in familiar tasks, more cognitive resources may be devoted to the strategic (i.e. knowledge-based behaviours) level which are important for managing unanticipated events.
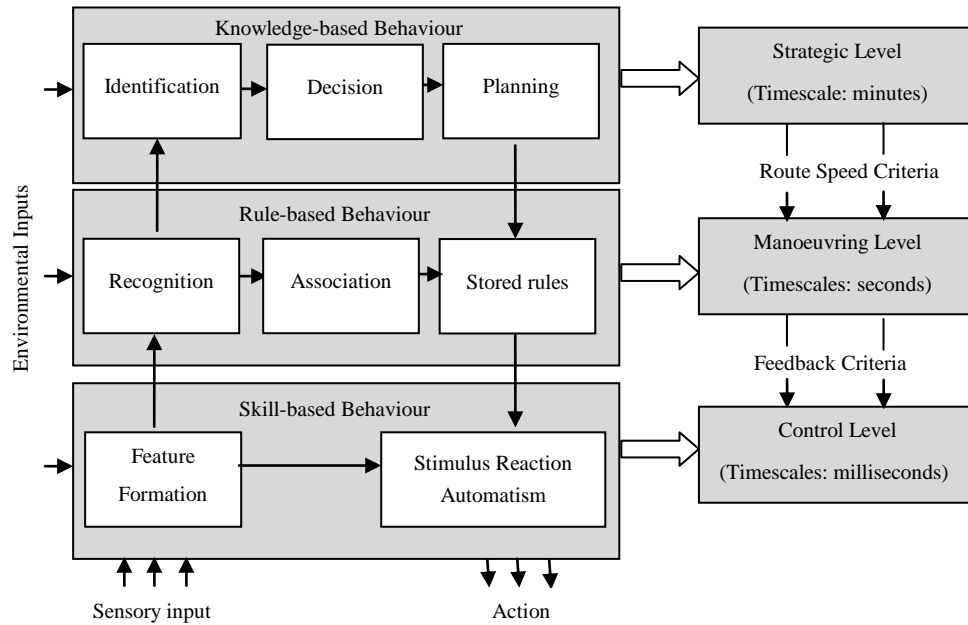
Figure 2.3: Combination of performance levels according to Rasmussen (1996) and the hierarchical model according to Michon (1985), modified by Donges (1999)

The ability to manoeuvre the vehicle safely is largely determined by the extent to which the individual is successful in adapting the planned motor behaviour to the changing environment. This adaptation is often extremely rapid and the driver must have different actions ready for implementation. In normal driving conditions, the complexity of the driving task is very much influenced by a driver's personal choices of driving speed, following distances or vehicle positions. Such personal choices are influenced by a driver's goal in maintaining a constant level of anxiety (Taylor, 1964), risk of collision (Wilde, 1982) or the more recently proposed theory of driving safety suggesting that driver's attempt to maintain a set level of task difficulty (Fuller, 2005). In Fuller's (2005) task-capability-interface (TCI) model (Figure 2.4), the driver is placed in interaction with external factors such as the vehicle and the environment which is largely outside the driver's control.
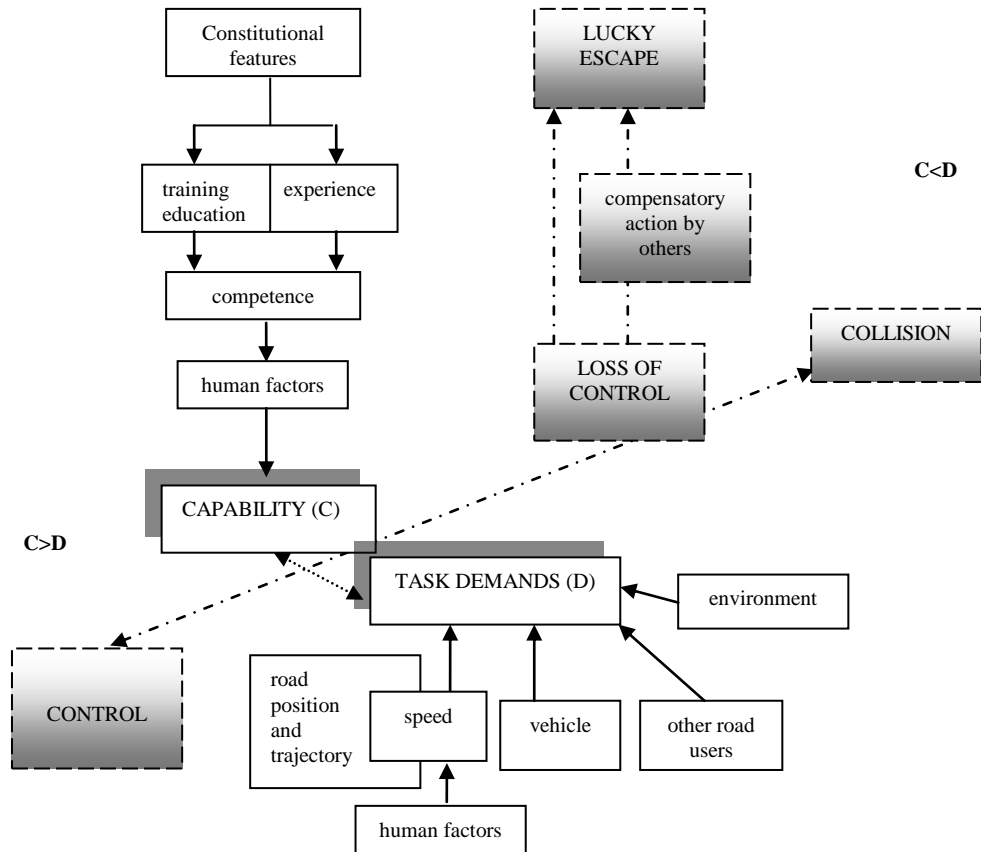
Figure 2.4: The task capability interface model from Fuller (2005)

When task demand exceeds the driver's capabilities, it results in task overload. The effect that this task difficulty has on the driver is commonly referred to as workload (e.g., De Waard, 1996). As the driving task requires continual interactions with a highly dynamic environment in real-time, the driving task difficulty fluctuates with roadway and traffic conditions, thus influencing the temporal driver workload. In a busy traffic environment, a driver may occasionally experience particularly high demanding situations due to unpredictable changes in the traffic. As driving demand fluctuates throughout the drive, driver capabilities also change with driver state (for example, inattentive, fatigued or distracted). In occasions where discrepancies occur, high workload may result thus increasing the likelihood of an accident occurring.

2.1.3 Sources of Driving Task Demand

The primary driving task demands are differentiated by the elements outside the vehicle namely traffic condition, road geometry and by driver status such as age, gender, fatigue and driving experience. However, the interaction between the driver and the environment is complicated by additional sources of demand either from the support systems already available within the vehicle or nomadic devices which are brought into the vehicle by the drivers such as the mobile phone. The following discussions are not intended to contain an exhaustive explanations of all possible influencing factors. Rather, they are provided to illustrate the key influencing factors examined in this thesis and to highlight the benefits of examining these relationships.
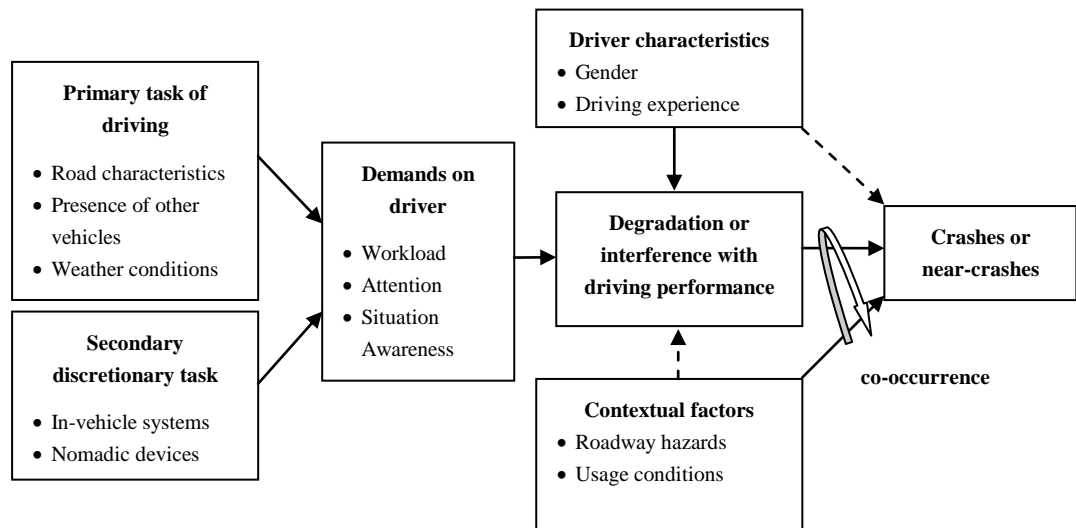
Figure 2.5: Source of demands on driver and their safety relevance with reference to CAMP driver workload metrics (Source: Hurts et al, 2011)

2.1.3.1 Primary Task Demands

Events which occur outside the vehicle such as traffic density, surrounding drivers' behaviours and road geometry, are attentional events that are less under the driver's control and may pose as contributory problem factors to accidents (Verwey 1993b; Verwey 2000). The magnitude of hazardousness in varying traffic situations is related to the amount of information to be processed (i.e., rate of information flow), for example, an emergency braking to avoid a vehicle pulling into the driver's lane is a high hazard potential driving condition as it requires high perceptual and cognitive selectivity as well as constant vigilance (Hoyos, 1988). However, drivers are confronted with various types of hazard while driving and this is complicated by

the fact that demands of the surrounding traffic environment on the perceptual capacities of drivers is constantly changing. Therefore, the driver would have less time to react to an event with increasing cues within the environment (Figure 2.5). Various previous studies have suggested the effect of traffic density on driver workload i.e. increase in attentional processing requirements of driving due to high traffic density (Lee and Triggs, 1976; Miura, 1986, 1990; Antin et al., 1990; Zeitlin, 1993; Dingus et al., 1989; Verwey, 1993a, 2000). The traffic flow and other road user behaviour in a particular road condition affect the driver workload via a number of possible routes; varying amount of information processing, feeling of comfort and time margin.

Although statistically, motorways are among the safest roads on which to drive, they are not crash free. The STATS19 Department for Transport road traffic survey, for instance, showed that in the year 2012, there were 626 Killed and Seriously Injured (KSI) casualties on UK motorways. Although motorways are highly standardised and much more predictable to the driver, 26% of fatal road accidents in the UK occur on the motorway. Factors including over-arousal such as higher traffic demand at a given speed or under-arousal due to monotonous driving on high-standard road, may create problems on driver in safety-critical situations where an almost instantaneous response from the driver is required. Thus, some safety-critical situations can be seen as reflecting a state of insufficient information in which the drivers must decide about manoeuvres and execute them although they do not have time to perceive and process all the necessary information. Additionally, motorways are demanding because they are multi-lane. On UK motorways, road users are often seen moving between the lanes to stay at a constant speed, either by overtaking slow traffic or giving way to approaching fast moving vehicles from behind. A naturalistic study of lane changes on 16 participants (who drove either a SUV or saloon car) conducted in the US (Lee, Olsen and Wierwille, 2004) reported 8667 lane changes over 24000 miles of driving. While saloon car drivers performed more lane changes than SUV drivers, results showed that male drivers perform more lane changes per mile on highway. Overall, 91% of the lane changes were low urgency and low severity (based on time-to-collision values and driver responses via subjective ratings).

However lane changing without understanding the surrounding traffic, can be dangerous and could be a hazard to other road users. An analysis of more than 50,000 accidents on UK roads by the accident management company, Accident Exchange, found that lane change manoeuvres account for more than 6% of the collisions (Automotive Industry Digest, 2011). Between the year 2009 and 2011, lane-change related accidents has increased by 48% and the annual cost of damage to vehicles is estimated to be more than £437 million (Automotive Industry Digest, 2011). The factor 'failed to look properly' is the most frequently reported contributory factor in traffic accidents in 2012 (42%) and the position of this factor has remained unchanged since 2007 (35%) (Department for Transport, 2012). In the majority of the incidents, drivers 'at fault' did not see or was unaware of the presence of another vehicle or crash hazard before lane change initiation. Therefore, several studies have looked into the benefits of the use of active safety equipment such as Lane Change Departure Warning systems implemented in the vehicles to assist drivers in maintaining awareness and reducing lane change crashes (Pomerleau et al., 1999; Abele et al., 2005; COWI, 2006). However there is a lack of literature on the perspective of the behaviour and workload of the drivers faced with the cutting-in of neighbouring vehicles. Data concerning this activity are limited and availability of such data can be used not only in developing models of human response in driving but also in designing and optimising driver aids such as Forward Collision Warning systems which could alert drivers of a potential pull-in from neighbouring vehicles. Moreover, the different aspects of the HMI can be adapted to optimise driver-system interaction to the current situation.

2.1.3.2 Secondary Sources of Demand

As discussed in the previous section, drivers perceive that driving on the motorway is considered relatively safe compared to other roads. Rural roads where design is less standardized, or urban roads where the presence of the other road users such as pedestrians or cyclists cause a higher increase in the complexity of the driving task. As drivers perceive motorway driving is more predictable and safer, they are more likely to interact with in-vehicle devices or communication devices that they have elected to bring in to the vehicle (e.g., mobile phones, GPS unit). Many of these devices including those readily available on-board the vehicles, are

taxing on the drivers' visual-manual channels, for example the embedded vehicle controls notification system which is design to inform or warn driver of potential faults within the vehicle. If this occurs when expectations in the primary task are violated (e.g., a vehicle pulling in front of the driver), the effect of the secondary task based distraction would be amplified, possibly causing sudden co-occurence of demands placed on the executive attention component of working memory (DeLucia and Tharanthan, 2009). Based on the multiple-resource model (Wickens, 2002), this simultaneous loadings of the primary driving task and a secondary task on the visual-manual channel would cause "structural overlap" (Hurts et al., 2011) depending on the modality of the secondary task.

Research has shown that the impact of using mobile phones while driving will result in varying profiles of interference, depending on the response required from the drivers. Earlier studies indicated that talking or listening on a phone while driving was no riskier than normal driving; therefore the assumption was made that the act of dialling or holding the mobile phone causes the driving impairment. However, recent work focusing mostly on the impact of using hands-free devices demonstrates that engagement in a conversation is a significant contributor that leads to a withdrawal of attention from the immediate driving environment (Drews and Strayer, 2009). Meta-analyses of mobile phone usage conducted by Caird et al., (2008) and Horrey and Wickens (2006) indicated that drivers responded more slowly to events (in the order of 130ms to 250ms) during a phone conversation. The mobile phone conversations have a negative impact on driving performance because the person who is remote from the driver has no awareness of the demand of the driving environment and as a consequence is unable to act as mediator by adjusting the conversation with the demand of the driving. Thus, cognitive demands may be unknowingly imposed when the traffic requires full attention from the driver. Moreover, drivers using mobile phones also demonstrate inattention blindness, suggesting the presence of a bottleneck in terms of simultaneous processing of the information from the driving environment and the conversation. A recent simulator study conducted by the Transportation Laboratory in the University of Padova (Rossi et al., 2012) examined the effect of processing a single, auditorily presented word on driver braking response. Their findings demonstrated that processing of a single word hinders driving performance whereby braking responses were substantially

slower as the overlap between tasks increased. As a result, this study of effects of presentation of just a single word to drivers highlights the potential implications of cell-phone ringing, visual information from navigation systems and auditory alerts from driver warning systems on driver's response time, leading to potentially safety-critical situations.

If the interpretation of auditory stimuli requires cognitive resources to process the content of information, then visual stimuli such as warning icons and text messages might have greater interference with the primary task due to the overlapping of resources used in processing the information from the vehicle and also the traffic environment. Another aspect that differentiates the mobile phone task from in-vehicle messages is that drivers are able to employ strategies such as delaying their response in answering the ringing mobile phone in high demand situations. This allows the drivers to allocate attention more flexibly and more effectively when required while driving. Vehicle-initiated messages such as information relating to equipment faults within the vehicle may be more difficult to be managed by drivers, as information presented is relevant to the driving task and may lead to potentially dangerous situations if the messages interfere with subtasks involved in driving such as braking, especially in an unpredictable emergency.

However the safe use of in-vehicle devices is debatable and mainly relates to the nature of the driving itself, drivers state, strategies employed by the drivers as well as the design of the secondary task investigated. To prevent the unwanted consequences of interference, understanding of the causes and the dynamic of the multitask interferences (caused by, for example listening, talking or using in-vehicle devices) has to be considered fundamental for designing and validating equipment (workload manager systems, human-machine interfaces, etc). Susceptibility to interference of secondary tasks with respect to the traffic demand such as traffic flow and other road users behaviour could also be investigated in single or dual-task conditions to provide a more thorough investigation on how the support systems could be improved in provide assistance to the drivers. For example, with the advancement of in-vehicle systems to increase driver comfort and driving experience such as the alerting system to notify the user of an event such as mobile phone call or text alert, it may prove difficult to prevent drivers from using such devices even when they are in a dynamic, high workload situation. With more and more people

owning mobile phones and coupled with the fact that drivers with higher mileage are more likely to engage in such distracting activity, the frequency of safety-critical events is likely to increase (Jamson, 2013). As such, enabling such functions while driving would require an active support system that manages these information available to drivers based on the driving situation.

Drivers' engagement with a secondary task may, however, influenced by drivers' characteristics such as age factor. While some studies have shown that driving performance degrades with age, especially with respect to the strategies of task coordination (McPhee et al., 2004; Chaporra et al., 2005; Makishita and Matsunaga, 2008; Stinchcombe, 2011; Thompson et al., 2012) in dual-task conditions, some studies however found conflicting results whereby no such age difference were found in dual-task performance (Strayer and Drews, 2004) and perceived workload (Fofanova and Vollrath, 2011). Horberry et al. (2006), for example, shown that older drivers engaged in self-regulatory behaviour by reducing their speed when performing a secondary task in complex highway environments. The authors reported that older drivers regulated their driving behaviour to offset the age-related degradation in their driving performance and to reduce their crash risk. Indications of older drivers to self-regulate were also highlighted in a survey research by McEvoy et al. (2006). Findings from the survey indicated that older drivers (aged between 50-65 years old) are less likely to engage in distracting activities while driving than younger drivers (aged between 18-30 years old) as they tend to be law-compliant, have a lower propensity for risk taking and are less inclined to drive aggressively. Therefore an exploration of driver workload fluctuations in response to the demands of joint driver-vehicle-environment may provide useful information on how in-vehicle support systems can assist in particular conditions, weighing the drivers' capability and the momentary driving demand. Comparisons of how driver workload differs between intra-individual variables such as systematically manipulated settings of traffic demands, designs of secondary task and inter-individual variable such as driver characteristics (age, gender) may provide relevant knowledge in developing and improving socially useful in-vehicle systems supports.

2.2 Understanding Driver Mental Workload

The study of workload is becoming an increasingly important topic in our society. Traditionally, the study of workload has been concentrated on physical workload but recent studies are more focused on other types of workload such as psychomotor, perceptual or mental workload (Wierwille, Rahimi and Casali, 1985). In the driving domain, mental workload is becoming one of the well known concepts to be examined when looking at human-technology interaction. However there is no clearly defined and universally accepted definition of mental workload due to the multidimensional nature of the topic. With workload being an aggregation of many different demands, it is therefore difficult to define workload uniquely. But there are several proposed definitions of mental workload as listed below, which are also cited in Cain (2007):

- "… the mental effort that the human operator devotes to control or supervision relative to his capacity to expend mental effort." (Curry et al., 1979)
- "...the difference between the capacities of the information processing system that are required for task performance to satisfy performance expectations and the capacity available at any given time." (Gopher and Donchin, 1986)
- "... the cost of performing a task in terms of a reduction in the capacity to perform additional tasks that use the same processing resource." (Kramer et al., 1987)
- "... the relative capacity to respond, the emphasis is on predicting what the operator will be able to accomplish in the future." (Lysaght et al., 1989)

Although a commonly accepted, formal definition of workload does not exist, workload can be characterised as a mental construct that relates to attentional demand (Kantowitz, 1987, Wickens, 1992) to explain the inability of human operators to cope with the requirement of a task (Gopher and Braune, 1984). From the perspective of cognitive-energetical theories, Gaillard (1993) viewed mental loads as the interaction between computational and energetical processes (Mulder, 1986), whereby the mental load induced by the task, is related to the mental effort and is influenced by the difficulty of task. Task difficulty is not only related to the processing effort required for performing the task at hand i.e. task demand, but also

dependent on individual factors such as operator's capacity, state and motivation which may influence the operator's strategy in allocating the resources involved in performing the task (De Waard, 1996). As such, workload is related to subjective task difficulty and thus related to effort invested. Workload measurement can therefore be employed to characterise effort invested in performance of the task. And for these reasons, the aspects of mental workload considered in this thesis are the effort invested (i.e. depending on driver's capacity and mediated by motivation in the allocation of processing resources) as the input and the task performance (i.e. primary or secondary task) as an output or result. These approaches represent alternative attempts to study workload and to allow greater diagnosticity, it is necessary to have more than one measure to be used when estimating mental workload.

2.2.1 Mental Workload Measurements

Over the past few years, there has been a great deal of research undertaken in developing and applying numerous mental workload assessment techniques. There are many techniques (e.g., Lysaght et al., 1989; Miller, 2001) available and some conceptual issues involved are very complex. To examine workload, it is first important to define exactly what kind of workload (i.e. residual capacity region, overload region, etc.) is to be estimated (Gawron, 2008; Tsang and Vidulich, 2006). From the perspective of multiple resource theory, overload can occur when either perceptual (i.e. visual, auditory), cognitive, or psychomotor resources are overloaded. For example in driving, the critical resources are usually visual and cognitive but the demand for those resources in driving are often coupled (Lee et al., 2007). Due to the potential dissociation of performance and mental workload (Yeh and Wickens, 1988) as well as the coupled effect of motivation, performance-based measurements alone may be insufficient to fully reflect mental workload. Therefore, subjective or physiological measurements of mental workload should be conducted in addition to the performance-based measurements. Subjective procedures are based on operator judgements of the workload associated with performance of tasks and operators are often capable of reporting the demands on separate workload dimensions. For physiological techniques, changes in physiological responses to task performance are used to determine the amount of workload imposed by performing

the task. However there are several criteria which a workload assessment technique should possess in order to be appropriate for use.

The most important criterion when examining the different measures of mental workload is sensitivity, which is the degree at which the measure is capable of detecting changes in levels of workload (Casali, 1983; Wierwille and Eggemeier, 1993; De Waard, 1996). Most subjective assessment procedures and certain primary task and physiological measures are capable of reflecting variations in different types of resource expenditure or factors that influence workload and thus qualify as globally sensitive measures of operator workload. Preferably, these measures should not degrade primary task performance (i.e. be non-intrusive) and provide reliable consistent results both within and across tests. If techniques are less intrusive and less artificial, operator acceptance will be higher and this can largely affects the reliability and accuracy of the measures (O'Donnell and Eggemeier, 1986; De Waard, 1996). Other things to considered include implementation requirements which includes any equipment or instrumentation that is necessary to present information (e.g., the stimuli required for data collection of primary and/or secondary task demand) or record data (e.g., operator eye behaviour). Implementation requirements also include expertise (i.e. knowledge to use a particular equipment, data processing and analysis), technique for data collection (e.g., time interval for data collection) or any operator training (e.g., familiarisation with rating scales). However, each measure has its own benefits and drawbacks whereby finding a perfect measurement is nearly impossible. It is therefore important to look into all areas to decide which measure is applicable for a given situation and often researchers use more than one method to get the most accurate measurement of mental workload.

In regards to the measure of temporal driver workload, various methods have been employed and investigated for the sensitivity in detecting variation in driver workload. Subjective measures, performance and physiology measures have been widely investigated in varying combinations of driving and secondary task demand conditions. Certain studies have investigated the effect of driving demand (i.e. driving environment) on certain measures such as workload ratings and response-time based performance measures. These on-line workload measures and few

potential physiological measures relating to driving demand relating to traffic changes are discussed in the following sections.

2.2.1.1 Subjective measures

Subjective measurements are relatively easy to implement, non-intrusive, inexpensive, and have a high face validity as they depend directly on the subject's actual experience of workload (Sheridan, 1980; Gopher and Dochin, 1986). With subjective workload being obtained from subjects' direct estimates of task difficulty obtained under repeated exposures to the same tasks, there are strong indications of uni-dimensional ratings being reliable subjective measures of mental workload (i.e. reliability coefficients as high or higher than 0.90) (Gopher and Browne, 1984). Subjective methods attempt to quantify the personal interpretations and judgements of experienced demand and generally have good user acceptance as these methods are easy to understand and to use. Depending on the task and demand explored, it is possible that subjective measures are more accurate in measuring fluctuations of driver workload in certain test environments as compared to some objective measures.

Uni-dimensional rating scales such as Rating-Scale Mental Effort (RSME), Modified Cooper-Harper Scale (MCH) and Sequential Judgement Scale (ZEIS) are considered the simplest to use because they do not involve complicated analysis techniques. The uni-dimensional scale, for example RSME scale developed by Zijlstra (1993) to investigate mental effort is rated on a 150mm long vertical line marked with nine anchors points, ranging from 'absolutely no effort' (close to the 0 point), to 'rather much effort' (approximately 57 on the scale) to 'extreme effort' (approximately 112 on the scale). The MCH scale is a 10-point scale enhanced version of psychomotor Cooper-Harper scale to account for the increase of range of applicability to situations, such as perceptual, cognitive and communications workload (Wierwille and Casali, 1983). MCH scale has demonstrated sensitivity in tasks during simulated flight (Wierwille and Casali, 1983; Wierwille, Rahimi and Casali, 1985; Skipper, Rieger, and Wierwille, 1986). This scale assumes that the two dimensions of performance (i.e. difficulty of aircraft controllability) and effort (i.e. pilot workload) are directly related, (Wierwille and Casali, 1983), whereby a pilot

answers questions regarding his/her performance of the aircraft-handling task under analysis to elicit an appropriate workload rating. As such, this uni-dimensional scale is less useful in other environments such as driving (Geddie et al., 2001). Moreover, the MCH scale is presented in the form of a category rating and therefore the values may result in ordinal data. In response to the need for a better scale to evaluate vehicle handling while completing the task, a 15-point form of the ZEIS scale (Pitrella and Käppler, 1988) was developed to measure task difficulty. The rating scale (Figure 2.6) requires participants to make two judgements in sequence; first judgement based on categories of difficulty (0-6), medium (5-9) or easy (8-14) then followed by making a finer rating within the scale of the appropriate first judgement. This scale has interval scale properties and thus the use of parametric statistics on rating data is permitted. This rating scale however has only been tested in flight simulation studies.
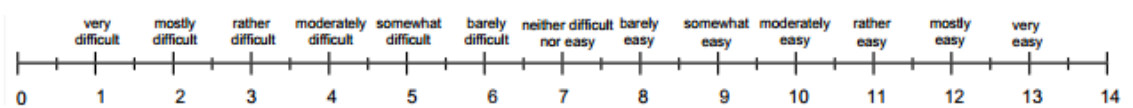
Figure 2.6: Fifteen point form of the Sequential Judgement Scale (ZEIS)
(Source: Pitrella and Käppler, 1988)

In the driving domain, a similar concept to the ZEIS scale was used to quantify driver workload measured in terms of stress factors with respect to the dynamic changes in traffic complexity (see Figure 2.7) (Schießl, 2008a and 2008b; Knake-Langhorst and Schießl, 2009). The 15-point scale also utilised the 2-step approach but with increasing numerical values with respect to increases in driver's perception of workload. Different from other rating scales which are pencil and paper-based, drivers were required to provide numerical values of their current workload verbally whenever they perceived a change in their subjective workload attempting to explore dynamic driver workload. Findings from Schießl's (2008b) study indicate that continuous subjective rating is capable of picking up short-term changes every few minutes. This concept of modelling dynamic workload has been previously investigated in the flight simulation studies (Speyer et al., 1987), whereby pilots were required to provide a rating based on a 5-point scale whenever requested by the observer. Although Speyer et al. (1987) found no direct relationship between scenario difficulty and rating, possibly due to the low number of sample (i.e. two

pilots) and flaws in the data collection (i.e. dependency on observer's assessment of workload in determining when to prompt pilots for rating), both Speyer et al. (1987) and Schießl (2008a; 2008b) studies suggest the potential use of workload ratings to measure continuous driver workload in a dynamic environment. This may reduce the effect of post-task workload ratings (i.e. delay in data collection at the end of task completion) where the operators may forget the amount of workload they were feeling during a particular segment of the task.

very little strenuous			little strenuous			moderate			strenuous			very strenuous		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Figure 2.7: Fifteen point form of continuous rating scale in driving domain (Source: Schießl, 2008a)

While a uni-dimensional scale is more sensitive than the multi-dimensional scale in accessing overall mental workload (Wierwille and Casali, 1983; De Waard, 1996), the multi-dimensional scale is generally more diagnostic (De Waard, 1996) and outperforms uni-dimensional ratings with a reduction in between-subject variability (Eggemeier and Wilson, 1991). The reduced version of NASA Task Load Index (NASA-RTLX; Byers et al, 1989) is an example of a commonly used subjective mental workload scale which reflects the multidimensional property of mental workload. The NASA-RTLX, a reduced version of the NASA-TLX originally proposed by Hart and Staveland (1988), was developed because the collection and analysis of the original TLX scale was cumbersome and labour intensive (Byers et al., 1989). The RTLX scale is the same as the original version but with a reduced procedure (i.e omitting the second step of the original TLX which requires a pairwise comparison and subsequent weighting procedure), thus producing unweighted mean of subscale scores. According to Byers et al. (1989), the RTLX is almost equivalent to the original TLX scale (R=0.977, p< 0.001) but with far less time involved for analysis (Lai, 2005). The scale measures mental workload with six rating subscales exploring mental demand, physical demand, time pressure, own performance, effort, and frustration levels. Each subscale is 10-cm long depicting a scale of 0 to 100, with the endpoints of the response scale anchored 'low' and 'high'. Park and Cha (1998) found that the RTLX scale was more sensitive to mental demand and difficulty in driving than the TLX. Due to the ease of applications and success in measuring small changes in workload (Jahn et al., 2005)

specifically in mental demand and effort, the NASA-RTLX has been widely adopted for evaluation of drivers' subjective workload across various research topic. This includes task management (e.g. Piechulla et al, 2003), dual-task performance (e.g. Horberry et al., 2006), driver impairment (e.g. Friswell and Williamson, 2008) and system design (e.g. Maltz and Shinar, 2007).

Although multi-dimensional measures were considered the best form of subjective measurement of workload in the past, recent studies have shown some evidence that uni-dimensional ratings of workload could be just equally adequate in determining how much workload a person 'feels'. Thus for simpler tasks, or while performing a task, a uni-dimensional rating is very appropriate because it is fast, easy and inherently not distracting. For a more exact estimate of workload at the end of the test, it may be beneficial to also use a multidimensional scale such as the NASA-RTLX when time is not a huge constraint.

2.2.1.2 Performance measures

"Performance may be roughly defined as the effectiveness in accomplishing a particular task" (Paas and van Merrienboer, 1993).

Performance measures of workload can be classified into two main types: primary task performance and secondary task performance. Based on the assumption that human have limited resources, "tasks demanding the same resource structure will reveal performance decrements when time-shared and further decrements when difficulty of one or both tasks is manipulated" (Derrick, 1988). Performance measures of the primary task will always be of interest and central to the study as it is a more direct way to measure workload. With direct assessment of operator's performance on the task of interest, primary tasks are useful where the demand exceed the operator's capacity such that performance degrades from baseline or ideal levels. As such, primary task measures are thought to be "global-sensitive and provide an index of variations in load across a variety of operator information processing functions" (Eggemeier et al, 1991).

However, primary task measures may be insufficient or inadequate if the variability of the task demands are insufficient to produce observable primary task performance changes (i.e. no information on remaining capacity can be inferred). Moreover, strategies employed during driving may affect performance and driver workload differently. Secondary tasks are therefore explicitly designed to probe "residual capacity" not used for a primary task, thus serving only to load or measure the spare mental capacity of the operator (Siveraag et al., 1993). Secondary task measures provide an index of the remaining operator capacity while performing primary tasks, and are more diagnostic than primary task measures alone.

i) Primary task performance

Primary tasks such as steering wheel movements (De Waard, 1996; Hicks and Wierwille, 1979; Boer et al., 2005; McLean and Hoffman, 1975; Östlund et al., 2004; Verwey, 2000), speed control (Wierwille and Eggemeier, 1993; Östlund et al., 2004) and lane-keeping (De Waard, 1996; Östlund et al., 2004) are examples of primary task measures taken to examine changes in driver workload. For driver workload estimation, these performance data are an indication of real-time driving conditions as measured by the vehicle sensors and can be used to quantify the factors influencing the primary task of driving. The mean gap from the lead vehicle (Green et al., 2007; Green et al., 2011), brake actuation rate (Zeitlin, 1998) and speed (Zeitlin, 1998; Fuller et al., 2008) are examples of driver behaviour which change with workload and are thus proposed to predict subjective task difficulty (i.e. driver workload).

While primary task measures are considered necessary measures of workload, they are insufficient on their own to adequately characterise workload. Speed for example, is able to reflect the amount of mental effort required to manoeuvre safely through the traffic (Wierwille and Eggemeier, 1993; De Waard, 1996; Cacciabue et al., 2007), whereby drivers proceed more cautiously with lower speed in more dense traffic conditions where space is restricted. However it does not take into account spare mental capacity and such measure can also be influenced by many other factors including motivation. Unless the workload is very high, it is hard to measure changes to performance due to workload. To assess the task difficulty, another

measure such as subjective measures or physiological measures may be collected concurrently to allow inferences regarding workload to be drawn. Although studies that do make comparisons between performance and subjective measures often find dissociation whereby "the pair of dual-task configurations differ in the degree of competition for common resources" (Yeh and Wickens, 1988), some agreement was found between secondary tasks and subjective measures of workload (Colle and Reid, 1999). Similarly, motivation may influence the performance whereby performance might not increase to the same extent (Vidulich and Wickens, 1986) as the workload increase when drivers are motivated. Therefore the upper limit of invested effort may be increased allowing behavioural stability to remain high under conditions of high workload. Effort remains within reserve limits, though the overall level of mental activity is increased (Hockey, 1997).

ii)   Secondary task performance

Typical variables for secondary task measures include signal detection rates, reaction time, time estimation variance, accuracy and response time (to mental arithmetic), etc. Depending on the task demand manipulated, the characteristics of the secondary task are used to infer the interaction between the primary and secondary task such that primary task performance is unaffected. In this secondary task approach, operators are instructed to maintain consistent performance on the primary task regardless of the difficulty of the overall task. The variation of the secondary task is measured as an indicator of the operator's reserve capacity, serving as a surrogate workload measurement under the various loading conditions.

An example is the peripheral detection task (PDT) which was first developed in the late nineties in response of the lack of good methods for measuring variations in workload (Martens and van Winsum, 2000). PDT measures attentional demand by recording the response times and/or hit rate to stimuli in the peripheral visual field reflected in the windshield or presented graphically on a simulator screen. Findings have demonstrate that reaction time to more peripheral stimuli increases as the functional visual field decreases with increasing complexity of the driving task (i.e. higher traffic density) (Miura, 1986; Williams, 1985; 1995). Numerous experiments found that visual tunnelling occurred with increasing foveal load, but performance

loss did not occur if the peripherally located stimuli were relevant to the performance of primary centrally located task (e.g. Cornsweet, 1969) and this phenomenon is "indicative of a shift towards increasingly selective patterns of attending" (Dirkin and Hancock, 1985) suggesting this as the 'cognitive tunnelling' effect. PDT is therefore a method sensitive to cognitive variation in both primary (driving) task demand and task demand induced by in-car support systems (van Winsum et al., 1999; Martens and van Winsum, 2000). Although it is suitable for measuring short-lasting peaks in cognitive workload, it lacks diagnosticity to account for the variances in driver performance resulting from changes in task workload (Van der Horst and Martens, 2010). It is unable to discern whether the effect is due to the operator's limitation or visual eccentricity (Engström et al., 2005). Moreover, background contrast and lighting conditions may also influence the measurement sensitivity.

To eliminate the limitations mentioned and to ensure a 'pure' measure of cognitive workload, Engström et al., (2005) proposed the Tactile Detection Tasks (TDT) which is a modification of PDT that presents stimuli in a different sensory modality (i.e. which is not used in driving or secondary task operation). These tactile stimuli are presented by means of vibrators attached either to wrists (Engström et al, 2005; Bengler et al. 2012) or neck (Merat, et al, 2006; Mattes, et al, 2007; Merat and Jamson; 2008) and a response button attached to the index finger.

Three major TDT studies were conducted; a field study at Volvo Technology in Sweden (Engström et al, 2005) and two simulator studies at the University of Leeds in the UK and at Daimler in Germany respectively (Merat, et al, 2006; Merat and Jamson; 2008; Mattes, et al., 2007). All three studies found similar results, indicating that TDT is at least as sensitive as PDT in measuring attentional demands of driving and secondary tasks. In general, driving demand had a small but significant effect on TDT response times (Engström et al., 2005; Mattes, et al., 2007). Results based on standardised effect size comparisons indicated that TDT was more sensitive than PDT in certain simpler cognitive load tasks such as answering biological questions (Engström et al., 2005) and as good as the PDT measure in more difficult tasks such as counting down by seven (Engström et al., 2005; Merat and Jamson; 2008). Mattes, et al. (2007) compared the effects of secondary task modality of varying difficulty (i.e. cognitive task either counting up

by two or counting down by seven, visual-manual task difficulty manipulated by varying the size of the distractor circles) on response times and found that TDT was sensitive to different levels of cognitive task difficulty as well as between different driving environments. There was a relatively large effect of the visual-manual task (i.e. response times to a visual-manual task were the highest among the different tasks in a highway and city environment) but no differences were found with visual-manual task difficulty levels. This thus further verifies that the TDT is a measure of cognitive load and is not affected by visual perceptual difficulty (Engström, 2010).

Therefore, TDT can be utilised as a real-time workload measure since TDT does not disrupt primary task performance and secondary task performance (Merat and Jamson, 2008) and this "tertiary task" does not use the same resource as the primary and secondary tasks (i.e. visual demand). However studies so far have only attempted to measure the differences in driving demand using TDT as a tertiary task measured over a longer period of time (i.e in minutes). There have not been any studies that attempt to measure TDT in smaller time intervals (such as in seconds) and there is a lack of extensive comparisons between performance and physiological measures. Additionally, there is also a concern of the best location to place the tactile stimulus and alternatives should be considered. For example, placing the stimulus on the neck (Mattes et al., 2007; Merat and Jamson, 2008) would minimise the wiring interference associated with putting it on the wrists (Engström, 2005; Bengler et al., 2010) but the sound vibration associated with secondary task involving verbal responses may however interfere with the tactile stimulus place on the neck (Engström, 2010).

2.2.1.3 Physiological measures

Among all the workload measures, physiological measures have been developed the most within the past forty years, thanks to the advancement in technology. The main motivation for physiological measures is the fact that direct responses from the operator can be measured accurately. Physiological measures may be needed in occasions where pure behavioural measures fail to provide fully satisfactory indexes of aspects of cognition for example cardiac activity, brain activity through electroencephalography (EEG) or the less obstructive measure of eye activity collected with remote eye trackers. However, it is still an open question in regards to determining which of these techniques is the most sensitive to the differential effects of driving demand (Young and Regan, 2007). Data interpretation may be difficult as the body also response physiologically to things other than mental workload. Depending on the task demand manipulated and the physiological measure employed, skewed data may result if the mental demand is coupled with other increased demand such as physical effort (Brünken et al., 2003). Moreover the choice of the measures is dependent on the cost and expertise required in utilising the equipments to collect data.

Cardiac activity measured through mean heart rate and heart rate variability is the most common measure of workload with the longest history among the physiological measures due to its fairly reliable indication of workload and continuous availability (Wilson, 1982). In a simulator study examining the influence traffic density on driver workload, mean heart rate was found to be associated with subjective ratings of strain from low to moderate traffic density conditions. In high traffic density conditions, these two measures however dissociate (Schieβl, 2008b) whereby subjective strain increased while mean heart rate decreased possibly influenced by relatively higher mental load than physical load in high density traffic situations. Mulder et al. (1999) reported that heart rate measures, particularly heart rate variability in the 0.07-0.14 Hz range, are sensitive to effort invested. However this band is also associated with blood pressure regulation and compensatory effort may result due to the presence of stressors such as fatigue (Veltman and Gaillard, 1998). Therefore cognition and emotion may be too tightly coupled to distinguish effect.

EEG is a measurement of brain electrical activity recorded from electrodes placed on the scalp. Measures of EEG such as the P300 component of Evoked Response Potential is thought as a good measure of residual capacity (Wickens, 1992) because it is one of the largest components and relatively easy to evoke using a secondary task. According to Wilson and O'Donnell (1988), the P300 amplitude ERP is associated with the degree of sudden and unexpected events while P300 latency is more related to the difficulty of a task. EEG can also be used to measure the magnitude or power of ongoing oscillatory activity such as alpha band power which is found to be sensitive to task demand (Kramer and Strayer, 1988; Wilschut, 2009). The alpha-band power can be used as a complementary measure of driver workload to account for driver fatigue and time-on-task while driving (Schier, 2000; Wilschut, 2009). Although EEG provides multiple methods to obtain insight into cognitive processes, approaches are prone to artefacts and results should be interpreted with great caution. For example, amplitude of the true P300 is hard to measure because it strongly depends on the baseline chosen (i.e. mean amplitude of the entire period or pre-stimulus baseline) (Wilschut, 2009).

Eye movements have the advantage of being unobtrusive since they can be collected with remote eye trackers. Measurements of eye activity such as eye blinks (duration and frequency) and pupil dilation are believed to be an indicator of both fatigue and workload. While the number of blinks increases as a function of time-on-task (i.e. fatigue) and it has been observed to increase with increased mental workload (Holland and Tarlow, 1972; Recarte et al., 2008), Castor et al. (2003) suggests the link between blink rate and workload to be tenuous. Besides blink rate, blink duration has been shown to be affected by visual task demand whereby blink closure duration appears to decrease with increased workload resulting from visual stimuli or gathering data from a wide field of view (Veltman and Gaillard, 1996; Ahlstrom and Friedmand-Berg, 2006). Blink latency increases with memory and response demands (Castor et al., 2003), often related to sustained attention (Ahlstrom and Friedman-Berg, 2006; Ingre et al., 2006).

Pupil diameter generally increases with higher cognitive processing levels and it is sensitive to rapid changes in workload. Although the pupils dilate for other reasons such as emotions and loads on working memory, it has been successfully used for distinguishing different levels of difficulty of various cognitive tasks

(Beatty, 1982; Beatty and Lucero-Wagoner, 2000; Recarte and Nunes, 2008; Bailey and Iqbal, 2008) as well as between-subject differences (Goldwater, 1972; Kahneman; 1973). The two most common use of pupillometry as a measure of cognitive load are the index of cognitive activity (ICA) and the average change of pupil diameter (Palinko et al., 2010). ICA uses the frequency of dilation of the pupil per minute (Marshall, 2002; Marshall et al., 2004) and used almost exclusively with head-mounted eye trackers for high precision data. However, Marshall et al. (2004) have patented this measure and therefore, only an approximation of this variable can be used. Ewing and Fairclough (2011) attempted to infer mental effort using an approximation of this method and remote eyetrackers but without success. The average change of pupil diameter, on other hand, can be easily calculated for estimating rapid cognitive load changes and this method has been found to correlate well with cognitive load (Bailey and Iqbal, 2008, Palinko et al., 2010). Although these measurements need to be quite precise (in the order of tenths of a millimetre) making application difficult in an environment with uncontrolled lighting conditions, such measures are more viable in strictly controlled simulated-environment as the percentage change of brightness varies by less than ±5% (Palinko et al., 2010). Moreover pupil diameter can become unresponsive to changes or even reverse its responses when overload occurs.

2.2.2　Situation Awareness

It is worth noting that the concept of situation awareness is constantly coupled with mental workload (Vidulich, 2003). Endsley (1995) defined situation awareness as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future". According to Wickens (2001) these two concepts of workload and situation awareness can be differentiated by the quantitative properties of mental workload (i.e. 'how much') and qualitative properties of situation awareness (i.e. 'what kind') of the cognitive processes. While the operator's skills and ability influences the level of mental workload and the quality of situation awareness, external factors such as task demands, situation complexity and uncertainty also play an important role in achieving a delicate balance of workload level and situation awareness. This is because the more demanding the task, the more complex the situation and the more work is required to get the task completed and the situation assessed. Therefore more attention is required for task performance and less resources is available to keep abreast of the situation. Parasuraman et al. (2008) indicated that mental workload and situation awareness constructs have useful roles in improving the performance of human-machine systems by being both predictive of performance in complex human-machine systems and diagnostic of operator's cognitive state.

To take better account of the regulation activity in a dynamic traffic environment, situation awareness is assimilated with an occurring mental representation. In the driving domain, drivers construct a mental representation of what they see in the road environment and with this understanding, they can then estimate and predict what will happen. However, environmental determinants on driver workload for example, traffic density (e.g., Verwey, 1993b; De Waard, 1996; Liu and Lee, 2006; Verwey, 2000; Trick et al., 2010) or road geometry (e.g., Miura, 1986; Green et al., 1993) are dynamic and change rapidly. The mental construct is constantly updated and with increasing environmental cues to be processed, it is assumed that level of workload will increase as a result and thus also influence the driver's ability to maintain situation awareness. To maintain adequate situation awareness, strategic management is needed. This involves strategic coordinating, planning, chunking or reorganising of multiple tasks to optimise resources and

inhibiting irrelevant information. Such strategic management is skill-based and depends highly on a driver's apprehension of the situation (Vidulich and Tsang, 2012). Therefore, an effective strategic management would require high-quality situation awareness. However a driver's quality of situation awareness is dependent on their ability to continuously engage in a spectrum of estimations as to what is currently happening in their driving environment and what is liable to happen in the immediate future.

Drivers make estimations in relation to a multitude of objects in the driver's environment: driver's own field of travel, the possibility of intruding objects and the roadway surface. Earlier studies have established some fairly stable and commonly acceptable boundaries for the detection of movement in other vehicles (Mortimer et al., 1974), but events outside the car are attentional events that are less under the driver's control. Traffic density and surrounding drivers' behaviours have been identified as contributory factors to accidents (Verwey, 1993b and 2000; 100-car study of Dingus et al, 2006) whereby time available for drivers to make accurate estimates of the potential hazards within the driving environment may rapidly shift from being primarily relative to mostly absolute. In these situations requiring drivers to have high perceptual and cognitive selectivity and constant vigilance (Hoyos, 1988) to safely transverse the roadway, driver's accuracy in decision making and ability of estimations in uncertainty would depend strongly on the explicit and implicit "awareness" a driver has of the situation (Morgan and Hancock, 2009).

However drivers occasionally may be surprised and frightened when suddenly realising that their own awareness of the situation was not on par with objective reality. The surprise effect is greater when the driver was initially convinced of being in control of a familiar situation but that situation suddenly becomes critical. Bellet (2006) conducted a field study on ten participants to examine driver's risk awareness of varying criticality of situation relating to the presence of obstacle occurrences. Risk awareness was assessed based on the risks of path conflict with other road users and on the anticipation of hazard depending to other road users' behaviours and action. The participants assessed the criticality level of each of the situations via a double scoring (i.e. a score from 0 to 100%) and findings indicated that in higher criticality situations, drivers tended to feel that they "suffered the situations" and felt less often in control of events.

2.2.3 Envelope Zones: the concept of safety margins in the road environment

The road environment requires constant adaptation from the driver. To progress safely in the road environment, drivers are guided by the envelope zones when managing their interactions with other road users. In car driving, this concept of envelope zones can be found in the notion of safety margins (Gibson and Crooks, 1938). Safety margins reflect the amount of time drivers allow themselves in the interaction with other road users and the environment. Summala (1988) defined safety margins in terms of temporal distance of an agent to a hazard. The idea of safety zones was first developed by Kontaratos (1974) and Ohta (1993) further defined these safety zones by time-based following distances namely, a danger zones (time headway < 0.6s), a critical zone (between 0.6 and 1.1s) and a comfort zone (between 1.1s and 1.7s). Similarly, Van der Horst (1990) used time-to-collision which is defined as "the time required for two vehicles to collide if they continue at their present speed and along the same path" (Hayward, 1971), to differentiate the criticality of the situation when drivers start braking. Under normal driving conditions, the envelope zones play a decisive role in the modulation of interactions with other road users, for example in maintaining safe distances between vehicles as well as risk diagnosis (Figure 2.8) and management of conflicts in the event of safety-critical situations.
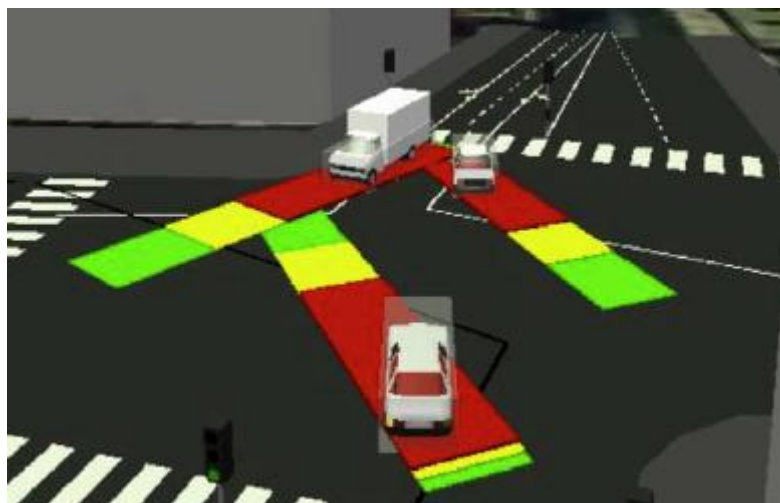
Figure 2.8: Examples of danger (red), critical (yellow) and comfort (green) zones in COSMODRIVE project (Source: Bellet et al, 2009)

The distance to a lead car is an important safety margin that has to be maintained continuously for prolonged periods of time. Occasionally, drivers may experience small safety margins and are under-pressure due to the smaller time frame available to react to potential hazards. In such occasions, driver may need to regulate the distance that they judges as safe and maintain the driving situation to an acceptable limit while managing their cognitive resources within the given time to deal with the current situation. Following difficulties either with perceptual thresholds or lack of expectation, driver error may occur (Rumar, 1990). Depending on drivers' anticipation abilities (i.e. mental simulation of the driving situation future statues) and skills, failure to detect the relevant information (such as late detection of decelerations of the lead car) in danger or critical zones could impose a longer time to recover following an error (Brown, 1990).

Experiences from other actions of traffic (such as a cut-in from a neighbouring vehicle) are examples of factors which are used to build up usable mental rules or models for behaviour in traffic situations relating to envelope zones. When one is confronted with an increasing variety of traffic situations and more of the driving tasks are integrated in mental models, attention can be diverted towards interaction with other road users. At this rule-based stage of development, behaviour will initially be greatly governed by formal rules and regulations, but gradually the formal rules and control skills will become more integrated and perceptions and experiences from the road and interaction with other road users will play an increasingly dominant role in determining driving behaviour. For experienced drivers, their implementation of skill-based behaviours enable them to allocate the cognitive resources required for driving monitoring and the management of their interactions with the nearest events more effectively than novice drivers. Studies have shown that experienced drivers are comparatively better than novice drivers in detecting potential risk situations (Soliday and Allen, 1972; Finn and Bragg, 1986). In situations where drivers are approaching an urban intersection, for example, Bellet et al, (2009) suggests that experienced drivers would anticipate behaviours of surrounding vehicles up to 50m ahead (including the opposite traffic), while novice drivers tend to pay greater attention to the nearby environment of the vehicle (i.e. 15m or less). With better anticipation abilities, experienced drivers may therefore be more aware of potential path conflicts in the future than the novice drivers.

2.3   Factors Moderating Dynamic Temporal Workload

There are many factors mediating mental workload that make a definitive measurement difficult. As described by Jex (1988), mental workload is a function of coping with interacting goals, strategies, adjusting to task complexity, etc. In the real world, drivers play an active role in the initiation and management of driving and in-vehicle tasks (Lee et al., 2009). Drivers' multi-tasking performance at a particular instance is dependent on the real-time demand of the driving task, and therefore both the driver characteristics related to regulation of own driving (such as driving experience, gender or personality) and the driving context (i.e. unexpected hazards, level of distraction) (as shown in Figure 2.5), should be considered when estimating driver temporal workload.

2.3.1   Self-regulation strategy

Drivers are active receivers and can actively adjust their driving behaviour in response to changing task demands to maintain an adequate level of safe driving (Haigney et al., 2000). Due to information processing limitations, drivers will adapt their strategies with changing task demand by processing more elements simultaneously in the focus of attention (e.g., Cowan, 2000) or investment of more effort, changing working strategy (e.g., Wilde, 1982; Fuller, 2005; Fastenmeier and Gsalter, 2007) or neglecting less important tasks or information (Cnossen et al., 2000; Hockey, 1998). The ability of the driver to prioritise between primary and secondary tasks is intrinsically linked to the spare mental capacity (i.e. the ability to conduct a number of tasks simultaneously) and also influenced by the level of interest (motivation) which determines how drivers select and persist in processing certain types of information in preference to others. With more spare capacity, drivers are able to attend to and process input rapidly.

At the highest level (i.e. strategic level), drivers can moderate their workload by choosing not to engage in potentially distracting activities, for example a driver can make the decision not to use the mobile phone from the start of the drive. This self-regulation behavioural adaptation at a strategic level is more commonly seen in older drivers who have greater tendency purposely limit or restrict their driving in order to reduce accident risk (e.g. Ball et al., 1998; Hakamies-Blomqvist and

Wahlström, 1998; Baldock et al., 2006; Lang, Parkes and Fernández-Medina, 2013). According to the recent STATS19 Department for Transport UK survey, in year 2012, accident involvements for older drivers (13%; age > 60 years old) are generally lower in comparison to young (17%; age < 25 years old) and middle age groups (49%; 25-50 years old). Despite lower involvement in accidents than other groups, older person can be seen as a vulnerable road user group. In the UK, among those road users who were killed or seriously injured in a road traffic accident, the fatality rate for older person (12%) is the highest of all age groups (i.e. fatality rate for other age groups varies up to 8%) (Department for Transport, 2012). Due to their frailty and vulnerability to injury in the event of a crash, older road users therefore have distinct risk factors relative to young and middle-aged groups. However there is an indication that older drivers have more difficulty extracting relevant information from road signs, particularly when driving in complex traffic and in time-limited situations (Schieber et al., 1997). A related finding is that older adults have more difficulty than younger adults in management or coordination of multiple tasks, but many older drivers who are aware of their decline in functional capacities may adapt their driving patterns to match these changes by self-regulating when, where and how they drive, to an extent that does not interfere with their lifestyle (Ball et al, 1998; Baldock et al., 2006) .

In addition, experience may also play a part as regular drivers are more adept in with the rules of the road, better in perceiving or predicting the dynamics of the road (Kaempf and Klein, 1994) and perhaps more skilful in their driving manoeuvres in varying circumstances. While there is a high correlation between age and driving experience (for example, young drivers are inexperienced drivers, and older driver typically have many years' of driving experience), numerous studies have found conflicting results (Catchpole et al., 1994; Cooper et al., 1995; Levy et al., 1990) due to difficulties in discriminating the relative effects of age versus driving experience on driving performance and crash involvement. To overcome the significant discrepancies of driving performance loss between older drivers and younger drivers when the complexity of the tasks being performed increases, studies have suggested using "average" drivers aged between 25-50 years old with at least 5 years driving experience as the general group of drivers in studies (Östlund et al., 2004). Within the drivers, fatigue and arousal (i.e. motivation) may also lead to differences in

driving task demand. A fatigue driver for example, may perform worse than his/her usual level of performance in the driving task despite being an experienced driver and researchers attributed between 2% and 25% of car crashes to fatigue (Brown, 1994).

Apart from age and experience, several studies have also demonstrated gender and personality factors as influencing factors in adoption of risk avoidance strategy. For example, women drivers are more likely to embrace stricter rules and driving habits than men (Bauer et al., 2003; Gwyther and Holland, 2012) and studies had suggested that this may be due to women having less experience than male counterparts since men are traditionally the main driver (Kostnyniuk and Shope, 1998). In terms of personality, theorists have suggest that extroverted drivers tend to opt for non-avoidance in order to boost arousal, which accounts for their higher involvement in traffic accidents and violations (Eysenck, 1965; Fuller, 1984). At tactical and operational levels, research has shown that driver conducting secondary tasks attempt to reduce workload by decreasing speed, increasing inter-vehicular distance or by reducing or ceasing to engage in certain driving task, such as checking mirrors.

The level of driver performance at any given moment is also dependent on the motivational (i.e. arousal) factors and driver's prioritisation between different tasks, whether primary or secondary. In real world situations, drivers have different and varying motivations for undertaking concurrent in-vehicle activities (Lerner and Boyd, 2005; Hancock et al., 2009). Horrey and Lesch (2009) conducted a study where drivers were instructed to perform a task before a given deadline. Drivers were found to initiate a secondary task in all driving demand conditions. Although this could be due to the limitation whereby the experimenter's instructions forms the driver's motivations to comply with the experimental rules, it indicates that drivers may be likely to distract themselves in real driving situations. Studies have also shown that drivers are motivated to complete a task with increasing exposure and practice with the task even in demanding driving conditions (Horrey et al., 2008).

2.3.2   Driving context

In normal driving conditions, drivers are able to adjust their pace downwards by shedding irrelevant input and tasks, which can be done with information provided in advance. However this may not be possible in safety-critical situations involving sudden increases in demand or extraneous demand where quick decisions from the driver is required. The criticality of the event influences drivers to switch skill-based driving towards rule-based or even knowledge-based (i.e. conscious control over the driving task). Drivers switch from a lower level of automaticity to exert more conscious control (i.e. more active role) on the driving task in an unexpected situation. In more highly critical events, drivers evoke more active control of the brake to decelerate and keep a larger safety margin.

Studies have indicated that different traffic environments can have different effects on driver workload and driving behaviour. High workload conditions, for example are associated with more disruptive gas pedal operation, i.e. frequent corrections on the gas pedal (Malta, 2010), increased safety margins or lowering driving speed. Liu and Lee (2006) found that drivers in general adopted greater safety margins and lower driving speeds when faced with heavy traffic. However heavy traffic was generally defined based on the peak hours as data were mostly obtained via on-road studies. Thus, a clear identification of the traffic factors that truly influence drivers' momentary workload could not be achieved.

Additionally, workload history plays a role in drivers momentary workload and subsequent driver behaviour. Schaap (2012) found that two groups of drivers (high mental workload and normal circumstances i.e. low mental workload) responded differently to different categories of critical events. It was found that those under normal circumstances (i.e. low mental workload) responded to all levels of events, while high mental workload drivers responded selectively only to the critical ones. Such presence of workload history effects, also referred to as hysteresis effect on task performance, was first studied in the aviation domain in the 1960s. Earlier studies indicated that task performance varies with task demands up to a certain demand level and differs with the loading directions (i.e. increasing or decreasing levels of demand). In a study in which Hancock et al., (1995) examined the effect of prior workload history on current task performance and workload in Air Traffic

Control scenarios, it was demonstrated that workload history has a strong effect on current perceived workload suggesting presence of lag within operator's perception of the level of task demand and interpretation of workload. In the driving domain, Morgan (2008) conducted a simulator study to examine the interaction between workload history and driver workload in the driving task. In this study, participants were instructed to follow pre-set routes in the simulated environment and the navigation system failed at a certain point within the drive. Driver workload ratings were collected three times: once during the drive before the failure, immediately after the failure of the system and at the end of the drive. Results from the simulator studies indicated that the increase in driver mental workload resulting from the navigation system's failure was prolonged and did not reduce significantly by the end of the drive. However due to the short drive in the study, it is unknown for how long the workload effect was present or simply how long the driver would take to recover from the incident. The author concluded with remarks that future systems should include some manner of accommodating the immediate past as well as the immediate present demands from the drivers. The design recommendations for advanced driving cognitive load-levelling technologies include reducing message transmission rate after a high demand situation or provide highly reliable cue to upcoming high demand situation.

2.4 Summary

This chapter has highlighted the concept of workload which is used in discourse of human interaction with technology and organisations. Although the definitions of workload vary quite considerably, in this thesis, driver workload is defined as the effort invested (i.e. the input as the amount of effort mediated by driver's capacity and motivation) in performing a task (i.e. primary or secondary task performance as output or result) (refer Section 2.2).

Despite several methods for measuring workload (as discussed in Section 2.2.1), there is a lack of good methods for measuring variations in workload (i.e. short-lasting peaks of workload). Performance measures, for example, may be the most direct indication of driver workload but substantial variability of the task demands are required to produce observable changes in performance. Physiological

measures, on the other hand, may have an advantage over the performance measures with them providing continuous data over time. However, changes in physiological measures may differ for a lot of reasons that are not related to workload. Thus, rather than using the physiological means to determine workload differences, subjective techniques for direct assessment of how a driver would "feel" about the task may be a potential option. After all, the difficulty of a driving task is to a large extent dependent on drivers themselves and may be moderated by other motivational factors (refer Section 2.3). Of course, current available subjective measurement tools have their own shortcomings of being ill-suited for measuring real-time workload. But with further simplification of the rating scale (such as using a 10-point rating scale) and by collecting subjective appraisal of the "feeling" of workload verbally, this imperfect subjective tool may be the best available technique to probe driver workload. In the absence of one-size-fits-all technique and with room for further improvement, a combination of information from different candidates of measures may be much more attractive at the initial stage prior to determining the most suitable workload measure for the intended area of investigation. This will be discussed and investigated further in Chapter 4 of this thesis.

Due to the increments in traffic density, the number of roadside sources of data and the new additions of in-vehicle equipments such as mobile phones and automotive displays in recent years, there are growing concerns in regards to the amount of information flow to drivers while driving. The ability of drivers themselves to manage their own workload is questionable and therefore, vehicle manufacturers are looking into introducing intelligent workload manager systems within the vehicle to ease drivers' management of information. This has gained interests not only from the vehicle manufacturers, but also from the human factor community to examine whether a workload manager is useful in reducing driver workload and improving driving performance. In the next Chapter 3, the concept and functionality of a workload manager system will be provided. The limitations in the current designs of workload manager systems will also be discussed.

Chapter 3
Workload Management

Chapter 3 describes the concept of workload management systems which are designed to prevent driver overload. A review of existing workload manager system functionalities is provided. The chapter concludes by discussing the limitations of existing studies in relation to the design of workload manager systems, thus forming the rationale for the simulator studies described in Chapter Four to Chapter Six of this thesis.

3.1 Introduction

To assist drivers and improve the operation and safety of the traffic system, there has been a rapid increase in research activity devoted to the design of new in-vehicle support systems over the past 20 years. These driver support systems mediate drivers' interactions with the road environment by creating new sources of information such as visual or auditory alerts to warn drivers or by directly intervening by for example, automatically applying the brakes. Examples of these systems are lane departure warning (LDW), forward collision warning (FCW) and intelligent speed adaptation (ISA) all designed with the goal of preventing or mitigating crashes. To ensure that the end-product is adapted to user needs, the development phase of most advanced driver assistance systems (ADAS) include an evaluation of their human machine-interaction (HMI) (Norman and Draper, 1984; Nielsen, 1994; Norman, 1998; Cacciabue, Hjälmdahl, Lüdtke, and Riccioli, 2011). While each system is evaluated during the development phase for a good basic knowledge background to understand which is the best way to give information to systems, the collaborative impact is unknown when more than one of these systems (such as ADAS, telematics and on-board information messages) are used simultaneously. Hence, with the vast amount of technologies introduced in the vehicle, drivers may encounter situations involving high a large amount of

information to be processed simultaneously within a limited time, resulting in higher task difficulty and higher driver workload.

As discussed in Chapter 2, driver workload is subject to variation over time and if not carefully managed, additional tasks in the vehicle can adversely affect performance (Donmez et al., 2007; Horberry et al., 2006), particularly if workload is already high. In highly demanding situations, drivers can actively try to cope with the increased demands and protect performance by investing more effort in it (De Waard, 1996), for example by constant corrective steering wheel movements in order to maintain lateral control as well as keeping a safe distance from lead vehicle by continuous pressure changes on the brake and a accelerator. However, things may deteriorate if the driver tries to use more than one in-vehicle device at the same moment. Other than increased task demands alone (i.e. higher number of information), the capabilities of the task performer, i,e the driver also play a major role. If the driver has a lower capacity to respond due to impairment or lack of experience (May et al., 2006; Wilschut, 2009), these factors can affect the reactions of the overloaded driver since their spare capacity has been absorbed by the secondary task. Moreover, errors in judgement of a driver's own driving capabilities in relation to the vehicle control and to the external environment and traffic conditions are factors in causing road accidents. Hence, there is a need to design and develop a workload manager assistance system which is capable of modulating the flow of oncoming messages to a driver, from both the newly developed and readily available functions in the vehicle.

3.1.1 How much workload is too much?

The Yerkes-Dodson Law developed in the early 20th century is the foundation of workload that plots the relationship of workload and performance on a bell curve, i.e. the inverted-U hypothesis (Figure 3.1). At both ends of the curve, there are risks of an accident due to either an inattentive or an overworked driver who may be incapable to safely manoeuvre the vehicle. In the under-challenged (to low task demand) conditions, drivers may see no reason to be fully attentive to the driving task or they are in the danger of approaching their driving task in an unmotivated way. On the other end, drivers could be overwhelmed by the volume and scale of the competing demands on their attention thus influencing their performance either

in the driving task or subsidiary tasks. In both conditions, mental workload is high (see Figure 3.1) compared to normal optimum performance level represented by the middle of the curve which is ideal for the drivers. In this highly productive state, drivers are sufficiently loaded in tasks but not so overloaded that they struggle to maintain safe driving. However, based on task performance alone, the high workload conditions cannot be distinguished from each other. Therefore, investigators have found it useful to divide the Yerkes Dodson inverted-U function into 6 task performance-related regions (see Figure 3.1) as a way to determine safe limits of workload. Based on Figure 3.1, driving performance in both high workload conditions can still be protected from deterioration by effort investment i.e. trying harder to counteract a sub-optimal state (region A1) or deal with high task demands (region A3) (De Waard, 1996). In the under-loaded condition, transitions from region A2 into region A1 due to reduced task performance would rely heavily on increased operator vigilance to maintain performance. However, to maintain an optimal performance (i.e. within A1 region), the operator would need to make sure his/her vigilant state is adequately resourced. In low workload scenarios (i.e. region A1), effort is thus needed for the maintenance of a vigilant state to ensure that the operator's cognitive system is in the state of "ready to respond" when required. In contrast, in high workload scenario (i.e. region D), effort is required to direct attention towards the incoming task demand (Caggiano and Parasuraman, 2004).
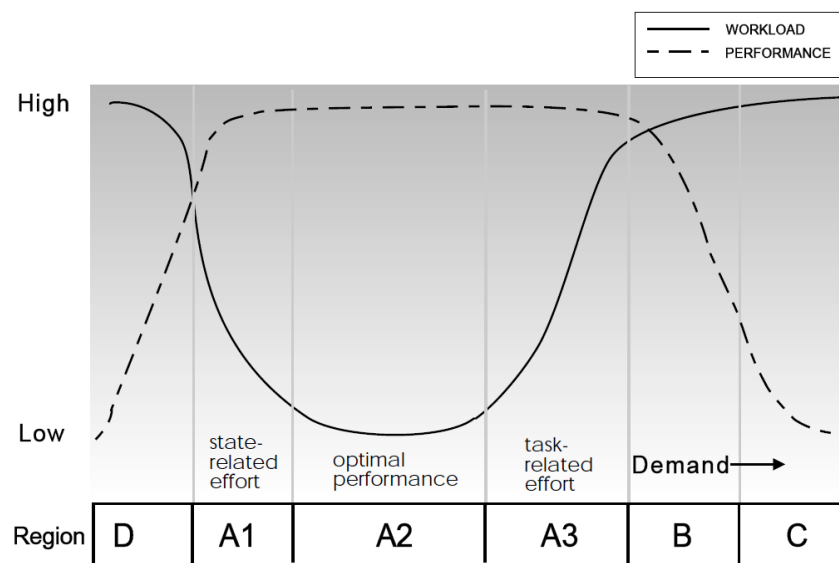
Figure 3.1: Task performance and workload as a function of demand (Source: De Waard, 1996)

In region A3 operator is able to maintain adequate task performance levels by increasing cognitive effort or by allocating more mental resources to processing activity. However there are costs and limits to investment of efforts. Although such effort investment is a voluntary and a conscious process, it is preferred for short-lasting rather than prolonged effort as extended period of time spend in this region can be harmful in emergence of peak loads which could give rise to heightened workload which are to be avoided wherever possible (Mulder et al., 1988). Quality of task performance begins to decline in region B because demands begins to exceed the operators' tolerable capacity. Operators thus experienced higher workload with increasing task demand and performance errors become increasingly commonplace. Therefore individuals no longer have the mental resources to recover the situation without adopting coping strategies which in some situations involve reducing demand by shedding some of the work activities contributing to cognitive overload. Beyond region B, the operator is at risk of losing control of the situation due to high workload levels.

With the divisions of the inverted U function, useful qualitative discussions of cognitive workload in practical contexts and estimation of mental workload levels in particular situations, are more viable. The simplest way to use this inverted-U model is to be aware of it when allocating tasks to drivers by considering the driver's current workload and the additional load to be employed on the driver by the subsidiary tasks. With the growing amount of information coming from on-board information messages, telematics and advanced driver assistance, there is a need to understand how well the driver is managing workload in various driving situations especially in demanding driving periods when the driver may not have sufficient spare attentional capacity to handle the amount of information given. The interaction between the driver and the systems is critical since each additional task taken on board while driving would increase driver workload. NHTSA for example, has issued design guidelines in an effort to reduce distraction and banning use of hand-held mobile phones while driving, while in the UK, using hand-held mobile phones while driving is illegal. But this does not stop accidents relating to use of hands-free mobile phones from occurring. Given consumers' hunger for gadgets and car-makers introducing new generations of infotainment features and safety systems into the vehicle, driver overload is becoming harder to manage.

3.1.2 Countermeasures to Prevent Driver Overload

With the availability of workload measures (as discussed in Section 2.2.1), driver support systems can be designed to consider drivers' workload and driving demand to ensure that they do not present in a way that overloads the drivers while the car is in operation and also reduce any load it placed on the driver when the driver is busy. As such, these support systems manage driver workload in real-time by preventing distractions but also mitigate distraction. Moreover, mental workload is not determined solely by the task demands but also reflects large individual differences in capability and state. Although humans are very adaptable at responding to continuously changing local situations when driving and can easily cope with increases in workload, in combination with decreased capability (such as from an elderly, less skilful or inexperienced driver), workload can be too high resulting in driver overload. Therefore workload managers have been introduced as a support system to modulate the levels of information available to drivers to avoid overloading drivers in situations when the driver is already under high demand.

There have been numerous initiatives in Europe (Michon, 1993), the United States (SAVE-IT, 2002) and Japan (Uchiyama et al., 2002) investigating the optimisation of HMI and the integration of multiple ADAS and IVIS by means of integrated and adaptive interfaces techniques. These initiatives look into estimating drivers' workload or developing static situation-dependent rules for the interaction between the driver and the vehicle. To prevent mental overload or distraction from occurring in the first place, system initiated information can be prioritised or scheduled according to the current driving situation or driver state. According to Carsten and Brookhuis (2005), the amount of information has to be adapted to the traffic situations and road-user requirements (i.e. providing the required 'dose' of information to the driver at a given situation) to avoid information overload at one moment. This issue can be managed by adaptive systems that possess a level of intelligence which may provide support to the driver by changing the level of information presented to the driver, or even alter the system thresholds and parameters in real time. The type of function which utilises this information scheduling is commonly known as a workload manager.

This idea of adaptive systems was first highlighted in the Generic Intelligent Driving Support (GIDS) project (Michon, 1993) which proposed adding a scheduling system that plans information presentation (Verwey, 1993a) based on the local situations. The scheduling of the tasks was to be based on prior knowledge of the effects the tasks have on the driver workload (i.e. previously stored model of the driver or the task context) which were assessed independently and in combination with other tasks that require simultaneous performance. Since the workload imposed on the driver and the associated potential for distraction changes dynamically with the driving situation, the GIDS concept prevented overload by scheduling resource demanding tasks (such as an incoming phone call) which may coincide with the sudden workload peaks in demanding driving situations (for example when overtaking). Depending on the assessment of the complexity of the road layout, the GIDS system might then decide whether to re-route the incoming phone directly to voicemail without informing the driver.

Following this EU-funded project which was conducted between 1989 and 1992 as part of the DRIVE programme in the automotive domain that implemented adaptivity to the driver (Onken, 1993), there have been efforts in the area of workload management systems. However research that demonstrates the effectiveness of workload managers to reduce driver workload is less common. The benefit of the use of the information management system was examined in the COmunication Multimedia UNit Inside CAR (COMUNICAR) project, whereby Hoedemaeker et al. (2003) compared the subjective workload measured using the RSME method in two conditions: (1) without the Information Management system, the message was presented exactly during the event, (2) with the Information Management system, the message was postponed to right after the event. Although no significant differences between the conditions were found, recent studies have shown otherwise. For example, the study performed in the Adaptive Integrated Driver-Vehicle Interface (AIDE) project which featured more overt behavioural indices or stored models of the driver, whereby situational factors were detected by an on-board geographical database and a computational workload estimator compared these data to a complex task-based model in order to assess those situations, demonstrated that workload management can indeed improve driving performance. Results however indicated that effects were only obtained in more

difficult driving scenarios (where driving difficulty was varied in terms of traffic density and curvature). In the US, NHTSA funded the SAfety VEhicles(s) using adaptive Interface Technology (SAVE-IT) project which investigated the impact of locking (i.e. disabling or lock-out entry system when vehicle is in motion) and advising strategies on driving performance (Donmez et al., 2006b; Tijerina et al., 2011). Although this study indicated that a locking strategy improves driving performance, the effects differed between the type of information scheduled. Therefore, more research is needed to better understand the mechanisms underlying drivers' responses to workload management functions in different traffic conditions and how the potential safety benefits of these types of systems can be quantified.

The more commonly known workload manager systems that have entered the market are: the Saab Dialogue Manager in the Saab 9-3 and 9-5 models (Green, 2004) and the Volvo Car Intelligent Driver Information System (IDIS) in S40 and V50 models (Broström et al., 2006). These are focused on an information-rescheduling function depending on the demands of the driving situation on the basis of real-time workload estimation from the sensor information already available on the vehicle's data bus. The complexity of the current driving environment is gauged based on the vehicle behaviour (i.e. lateral and longitudinal acceleration or velocities) and driver inputs (such as brake pedal position, steering wheel angle, windshield wiper, indicator usage, etc). The flow of information to the driver is then regulated based on these conditions to minimise the risk of driver distraction, for example if the driver enters a roundabout, incoming phone calls are delayed until the driver has completed the manoeuvre.

Although there are still very few workload management systems in the market, the automotive industry is working to realise the workload management function by looking into various ways of improving the estimate of driver workload as well as identifying the situations where a certain type of information presentation should be rescheduled. The Swedish truck manufacturer Scania (Osbeck and Åkerman, 2010) for example, has conducted a project to develop a system that presents only relevant and desired information to drivers of trucks and buses in critical traffic situations. Drivers' responses of the criticality of the traffic situation and the secondary tasks involved were collected and classified. However the workload ratings could not be verified as the prototype was not tested in real-life situations. Although the

effectiveness of the workload manager system in preventing crashes is completely unknown, analysis of data from naturalistic driving studies in heavy vehicles appears to indicate that total removal of distraction due to higher risk tasks (i.e. tasks relating to dispatching devices, interaction with mobile phones and navigation aids) would reduce the incidence of "safety-critical events" by about 6 percent (Olson et al., 2009). Therefore, efforts to feature more advanced workload estimation of the dynamic driving situation as well as centralised management of information from all types of onboard applications to improve the efficiency of workload managers may have merit.

3.2 Workload Manager and Functionalities

According to Engström and Hollnagel (2007), workload management functions can be viewed as "meta-functions" responsible for coordinating individual functions by, for example, prioritising or putting non-critical information on hold in demanding driving situations (Engström and Victor, 2008). These systems typically use sensors to detect some parameter of the task context, and will infer the driver's state based upon this information. Depending on the data that have been collected, the interface itself then adapts the amount of information by providing more or less information depending on the situation. Thus with these adaptive interfaces, mental workload can be regulated to achieve an optimal operator state (Byrne and Parasuraman, 1986; Hancock and Verwey, 1997). Green (2004) categorizes workload manager systems into four broad categories depending on what they measure:

i)   the driving situation

ii)   driver input

iii)   vehicle performance and response

iv)   the driver state

An optimal workload manager would cover all relevant parameters involved in assessing driver state and the various demands to successfully determine driver overload and distraction. However, there remains the crucial open issue as to what is measurable within each category and how the parameters combine in affecting driver workload and driving performance. If these categories are to be used by a real-time

on-board system such as a workload manager system, then appropriate sensors (vehicle CAN Bus in Figure 3.2) will be required to generate information about the current conditions and depending on the diagnostic of the workload estimator on the driver's current workload (Low, Medium or High), the information is filtered and it is decided whether adaptation of the action to the workload conditions (is needed).
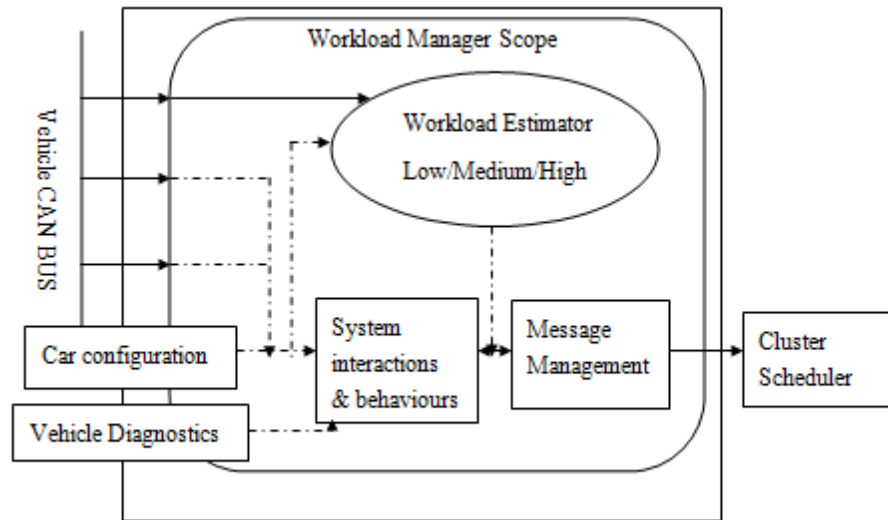
Figure 3.2: Simple diagrammatic representation of workload manager obtained from a vehicle manufacturer

Traffic density for example, can be provided from radar or image processing. Secondary task demand, as opposed to driving task demand, can be inferred from interaction with entertainment systems, navigation systems and other in-vehicle devices. Use of the mobile phone by the driver can be identified provided that there is an interface between vehicle and mobile phone. Using these readily available sensors in the vehicle, driver workload can thus be estimated and be managed accordingly to ensure that the driver workload is within manageable level (below A as shown in Figure 3.3). Assuming that E is the estimated workload and D is the actual workload, driver's workload range should be within A and C for optimum performance.
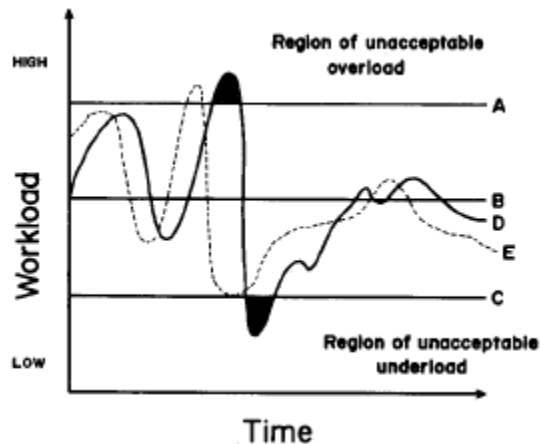
**Figure 3.3: Illustration of driver's workload transition while driving
(Source: Hancock and Chignell, 1988)**

However, accurate estimation of driver workload is not sufficient for realising workload management functions. Due to the variability of human responses both between and within individuals, it is virtually impossible to predict from one precise moment to the next what the driver is likely to do. Rather than predicting precisely and reliably what a driver will do at any moment, it is perhaps more sensible to attempt to predict the probability of error or failure (Carsten, 2007). An example would be to identify traffic situations where a workload manager system might need to intervene in order to prevent performance from deteriorating drastically.

With the need for a driver model which is predictive and can be applied in the long run to produce a well-designed advance driver assistance system, a dynamic real-time driver model which includes five major categories of driver capability, performance and behaviour with the associated variables was proposed initially by Carsten (2007) and later adapted by Cacciabue et al. (2007), as shown in Table 3.1. Each of these five categories of driver capability, performance and behaviour are related to accident risk, with workload associated with demand from road layout to driver performance. If the workload is used by a real-time on-board system, appropriate sensors will be required to generate information about the current conditions including vehicle behaviour (i.e. lateral and longitudinal velocity or acceleration), weather conditions (i.e. wet, snow or fog), traffic complexity (i.e. traffic flow), etc (see Table 3.1). Estimation of some of these task demands in real-time has been the focus of vehicle manufacturers in the design of a workload manager and also the focus of previous projects such as COMUNICAR (Amditis et al., 2002) and CEMVOCAS (Bellet et al., 2002).

**Table 3.1: The proposed five main parameters which play important role in the dynamic Driver-Vehicle-Environment interaction
(Source: Carsten, 2007; Cacciabue et al., 2007)**

Parameters	Definition	Measurable Variables
Experience	The accumulation of knowledge or skills that result from direct participation in the driving activity	1. Annual Mileage 2. Number of years with driving license
Attitudes	A complex mental state involving beliefs and feeling and values and dispositions to act in certain ways. Sensation Seeking and Locus of Control have been identified as personality based predictors of accident involvement.	1. Speed 2. Lane keeping 3. Overtaking 4. Headway
Task Demand (workload)	The demands of the process of achieving a specific and measurable goal using a prescribed method. When Task Demand is focused only on driving, then Task Demand = Driving Demand	1. Traffic complexity 2. Weather 3. Light 4. Speed 5. Driving direction
Driver State (impairment level)	Driver physical and mental ability to driver (fatigue, sleepiness etc). A set of dynamic parameters representing aspects of the driver relevant for the human-machine interaction	1. Lane keeping; headway control 2. Duration of driving; time-on-task 3.Weather; road conditions 4. Traffic complexity 5. Speed
Situation Awareness	Perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near futures	1. Distraction 2. Driver state 3. Task demand

To estimate task demand in real-time in order to manage driver workload, AIDE has also used similar approach by assuming that different workload management functions may require different or specific driver-vehicle-environment (DVE) parameters (Engström, Arfwidsson et al., 2006) such as driving demand, secondary task demand, driver impairment, traffic risk and individual driver characteristics to decide the specific workload management function to be implemented (i.e. information-rescheduling function). Although it was never really built, Figure 3.4 illustrates the general principles behind the AIDE architecture and examples of workload manager systems developed based on similar principles are discussed in Section 3.2.1. In AIDE, the main part of the theoretical workload

manager functionality is controlled by the Interaction and Communication Assistant (ICA) which works on logic whether to execute the list of prioritised action from the Application Request Vector (ARV) or delayed/cancel depending on the real-time information gathered from the DVE modules. If needed, the action is adapted to the DVE conditions before allocated to the appropriate input or output devices.
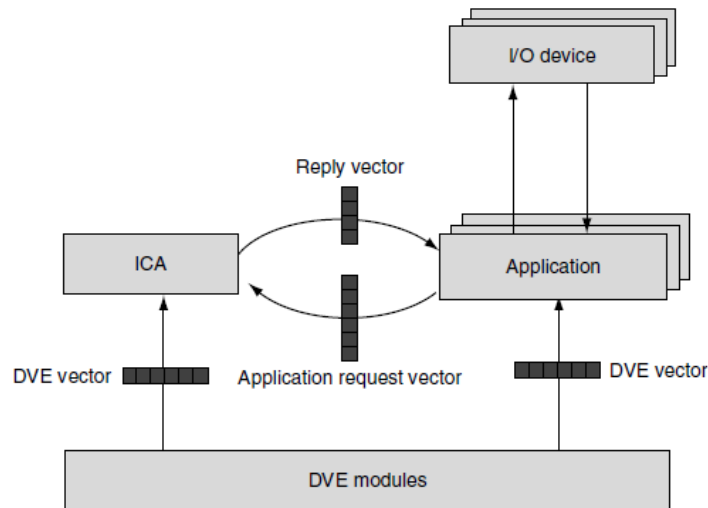
Figure 3.4: Illustration of the basic principles behind AIDE workload management system concept (Source: Engström and Victor, 2009)

3.2.1 Examples of workload manager systems with information-scheduling function

Information-scheduling functions aims to minimise the number of non-driving related tasks that can be performed in high load situations. For example, under high demand driving conditions and depending on the criticality of the situation, the incoming phone calls can either be filtered (not letting the phone ring) or prioritised (allowing only the calls that are listed by the driver as highly important). Parasuraman et al. (2000) suggest that organizing information sources by prioritisation or representing the information by highlighting decreases workload and thus enhance performance. However, a potential downside of this strategy is that the driver's attention may be drawn to inappropriate elements of the driving task when multiple number of information is available simultaneously (e.g. notification of the next exit when the car ahead is braking).

The list of prototypes of workload manager systems discussed below are selectively chosen to highlight the simulator and on-road studies regarding information-scheduling workload manager systems. Although the list is not exhaustive due to the limited availability of information, this list provides an idea of the current workload manager prototypes used in the automotive industry and thus highlight the research gaps which are to be discussed in relevance to this thesis contribution in this research field as discussed in Section 3.3.

I.   BMW - SANTOS Project

Piechulla et al. (2003) conducted on-road study of a workload manager with 12 university drivers (6 novices and 6 experienced drivers) who drove a 27 km experimental route three times. The participants were required to respond to incoming phone calls that involved 10 mental arithmetic questions while driving in a variation of situations involving the use of driver support systems such as adaptive cruise control, lane keeping aid and a workload manager. In the study, incoming calls were automatically sent to voice mail when the estimated driver workload was over a certain threshold value (i.e. a value of 0.35 was chosen for study). Driver workload was estimated to increase in situations where a lead vehicle was present within a certain range of interest (i.e. 120m), an intersection was present within drivers' view or hard braking was taking place. For example, if the car was approaching an intersection within the next 5s, a factor of 1.1 was multiplied to the current driver workload value. This estimated workload was then determined whether it is was higher than a certain threshold value (i.e. 0.35) to suppress incoming phone calls (see Figure 3.5).

Physiological measures such as heart rate, heart rate variability, facial muscle tone as well as subjective measures such as offline rating from observers watching video scenes and NASA-RTLX scores from participants were recorded. Observers ratings suggest that only the experienced group of drivers benefited from the workload manager system. Both NASA-RTLX and physiological workload measures (heart rate, heart rate variability, and facial muscle tone) however were found to be not significantly different with the use of a workload manager. This study is an example of a prototype real-time workload estimation operational in a demonstrator vehicle which showed that experienced drivers benefited from the use of a workload manager (i.e. reduction of subjective workload) which automatically

directed incoming telephone calls to the mailbox without notifying the driver. Although this study focused on exploration of information-scheduling HMI based on traffic complexity, it had also highlighted the importance of subjective assessments in the development of a workload estimator.
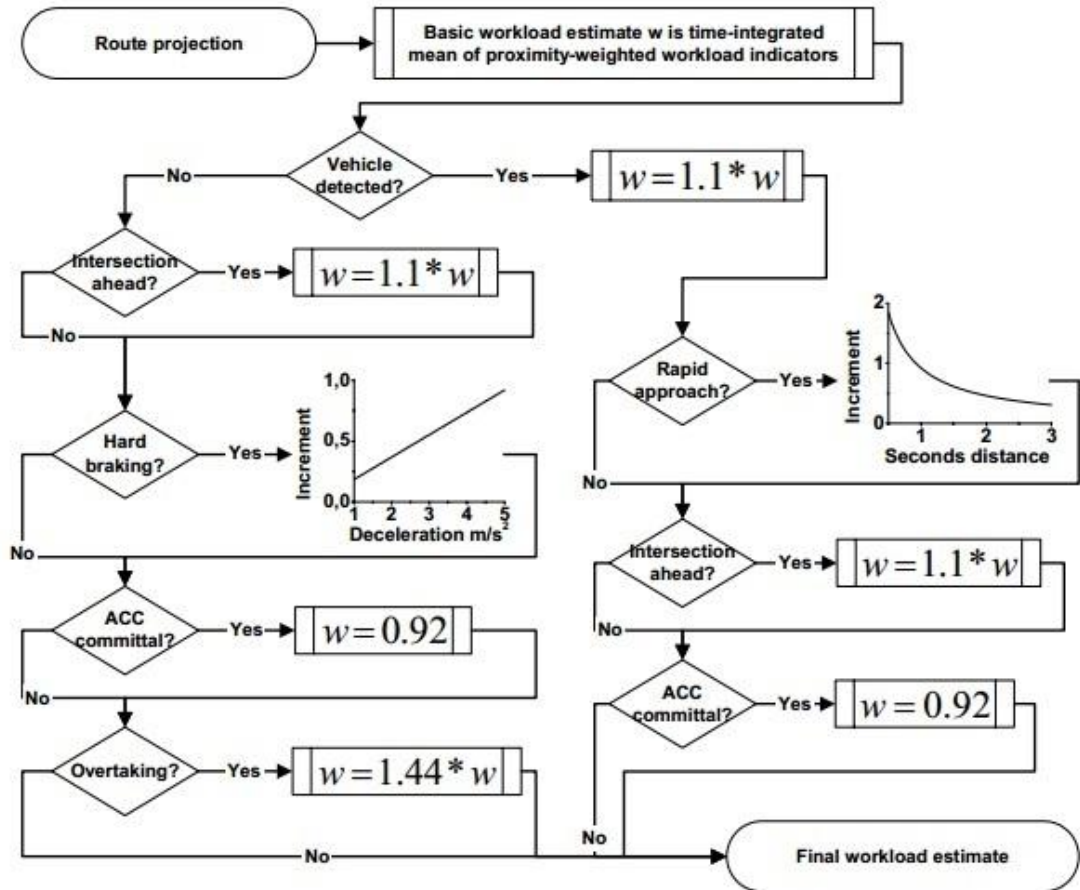
Figure 3.5: Piechulla's (2003) workload estimator

II. Toyota

In Japan, Uchiyama et al. (2002) developed a workload estimator based on accelerator pedal release to predict when the driver was under high workload. Based on results from nine test participants who were engaged in a mentally demanding memory test, the researchers found that accelerator pedal releases were able to predict high mental workload situations with 85% accuracy. Following this finding, Uchiyama et al. (2002) conducted an on-road study with two drivers whereby the voices messages (with duration of each messages between 2 to 3 seconds) were delayed in most conditions involving high driver workload such as when encountering a stopped or slowed vehicle ahead, curves ahead or approaching left or

right turns. In the study, the increase in workload was estimated to be valid for 5 sec and during that time, all voice messages were delayed (Figure 3.6). This on-road study provides an interesting correlation between driver workload and the time release of accelerators pedal in estimating driver workload recovery period following the high demanding conditions. The workload recovery was estimated to be approximately, 5 seconds. However, the issue here is that the accelerator release might be too late as a signal to be useful as the estimation of driver workload.
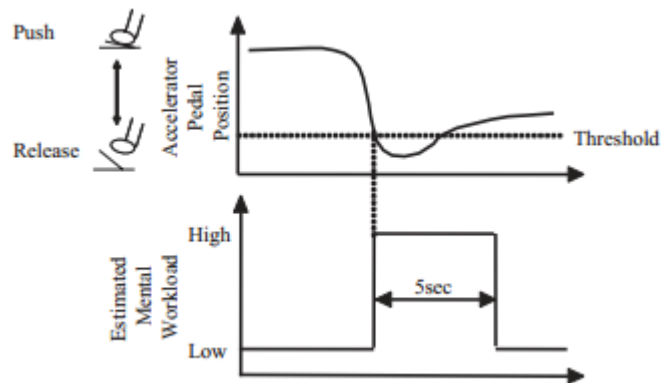
Figure 3.6: Workload Estimator (Source: Uchiyama et al., 2002)

III. Volvo Cars

Volvo's interaction management system, IDIS consists of a workload estimator and an information manager. The workload estimator continuously monitors the driver's activity via the vehicle's CAN bus network for example, by checking on brake pedal position, vehicle speed, turn signal indicators, steering wheel angle and engagement of infotainment controls (Broström et. al. 2006). When a signal exceeds its threshold value, such as when the driver is performing an overtaking, the IDIS which has a built-in delay function will automatically hold incoming phone calls for up to 5 seconds (i.e. until the workload is estimated to have decreased to an acceptable level). This common method of managing incoming phone calls based on the inputs from sensors is also implemented by other automotive car makers such as General Motors and Mercedes-Benz.

IV. General Motors

Saab's Dialog Manager developed in the Intelligent Vehicle Safety Systems (IVSS) research project, could delay or cancel information from infotainment or other non-critical systems when the driver was considered to be under high workload. The five critical scenarios investigated were operating radio while driving in a roundabout, turning into a road while presented with a warning message, initiating a phone call, answering a phone call in a restriction area such as within a school or hospital areas with and without the presence of a hazard (i.e. pedestrian crossing the street). The system was also able to adapt information according to the complexity of the traffic situation, i.e. vehicle speed was given audibly to the driver in complex traffic environment (IVSS, 2007). However warning messages of high priority such as 'brake fluid level low', are allowed. It is however unknown the duration of delay implemented.

V. Mercedes Benz

Similarly, Mercedes is also working on a workload manager that prioritises the messages based on some set of parameters such as criticality and urgency and improving the comfort for drivers which include personalisation of application such as allowing download and update of applications and interfaces (Wex et al., 2008). Although no details on the information-scheduling of the messages are available, it suggest the importance of prioritising messages based on driving demand. Moreover, future advanced system will be able to handle information from several types of sensors and devices such as an eye and head tracker.

3.2.2 Examples of workload manager systems with locking- or advising-function

As well as an information-scheduling function, some workload managers have a locking function (i.e. a high level mitigation function) which interrupts by locking-out system that is associated with non-driving activities, to help drivers to focus on primary driving task. This strategy is preferred in situations where drivers are found to engage in in-vehicle tasks as long as the driving demand is relatively low. It does however has the disadvantage of potentially increasing driver annoyance and thus

the degree of distraction especially when the driver attempts to resume engagement with the non-driving related task that was interrupted or locked (Donmez et al., 2006b). An example of a such support system recently on market is the Ford's Do Not Disturb feature (Ford Motor Company, 2011) which is aim to reduce distraction among teenage drivers.

Alternatively, the workload managers developed by Delphi Electronics under the SAVE-IT Program, could provide feedback to drivers regarding the degree to which they are engaged in a non-driving task. For example, an "advising" background sound could become more intense as vehicle speed and traffic density increase. This real-time function is commonly coupled with other strategies such as a locking function which is available in the Delphi Electronics workload manager system. Provision of feedback on how well driver's performed in driving is also available in certain workload manager system such as the Scania Driver Support system. Although an advising-function is a lower level of intervention as compared to a locking-function, such a strategy may increase driver annoyance and possibly distraction if the demands of ignoring the "advice" become a burden. A list of workload manager systems discussed below are selectively chosen to highlight the current work alternative workload manager system who examine locking and advising functions. It is worth noting that the list is not exhaustive and serves the function on emphasising research gaps which are to be discussed in relevance to the work contribution of this thesis as discussed in Section 3.3.

I.   Delphi Electronics- SAVE-IT Project

Donmez et al. (2006b) conducted a simulator study to compare the effects of an advising strategy and a lockout strategy to mitigate the demand of visual and auditory IVIS tasks following the approach of triggering conditions such as a curve ahead or lead vehicle braking events. In both strategies, the workload manager presented either visual information (a red bezel on the IVIS that stayed lit during a triggering condition) or auditory information (a periodic clicking noise that persisted during a high demanding condition). Results indicated that mitigation strategies have mixed effects depending on the type types of in-vehicle system and the system demands. In the study, the visual advising strategy was found to be more disruptive as compared with the visual locking strategy, whereby drivers were maintaining

higher speeds when manoeuvring the curve sections, leading drivers to more risky behaviour.

Following these findings, Tijerina et al. (2011) conducted a simulator based study to investigate several different workload mitigation strategies on driver braking response to a surprise forward collision hazard. The strategies included no in-vehicle task or distraction (baseline); task allowed; task interrupted (i.e. locking of the screen following presence of a hazard); and task denied. Participants were requested to conduct a visual in-vehicle task and during the conduct of the task, a vehicle parked on the side of the road would suddenly pull into the participant's lane requiring the participant to brake to avoid a collision. Results indicated that the task interrupted condition was more disruptive as the variability of braking reaction times were larger than in task denied conditions, indicating that drivers were taking longer time to process the reason underlying the task interruption. The study concluded with suggestion to avoid task interruption strategy (i.e. locking of the screen) if a task is already underway and in situations where driving conditions suddenly grow more intense.

II. Ford

In 2011, Ford introduced the 'Do Not Disturb' function (Ford Motor Company, 2011) in their vehicles, which aimed to reduce driver distractions among teen drivers. With the function enabled, the system would automatically sent all incoming calls from a bluetooth-paired phone to voicemail and stores new text messages for later viewing. Different from the information-scheduling workload manager systems, the driver has the choice to choose to have this function enabled by having the driver support system named the SYNC to be paired with all nomadic devices such as cell phones and mp3-players.

III. Scania (Heavy Good Vehicles- Trucks and Buses)

The instrument cluster (ICL2) used in the latest Scania trucks is capable of handling three levels of criticality of messages; red (for high priority messages relating to serious vehicle damage which may compromise traffic safety), yellow (warnings or active functions) and white (for general informational messages which are non-critical) (Osbeck and Åkerman, 2010). If there is a queue of messages to be presented, the highest priority messages will be presented first for at least two

seconds followed by the next highest priority message in order. This way the driver never misses any information since it is just delayed until the highest priority messages have been acknowledged. Recent development in Scania trucks' workload manager systems involves expanding the traffic situations and varying modality of secondary tasks which are considered extra demanding.

3.2.3   Simulation techniques related to driver workload estimation

Following the examples discussed in Section 3.2, it can thus be concluded that workload managers are now attempting to account for the fluctuations of driver workload in the dynamic traffic conditions to improve the efficiency of the systems in managing real-time driver workload. With the increments in traffic density and the inherent fluctuations of traffic demand, it is becoming important to be able to predict or anticipate sudden increases in workload or short but high peaks workload which are potentially dangerous (Figure 3.7). Moreover, the mismatch of drivers' capability and driving demand (i.e. usually due to errors in drivers' own judgement) is often the key issue in the occurrence of road accidents (Amditis et al., 2006).
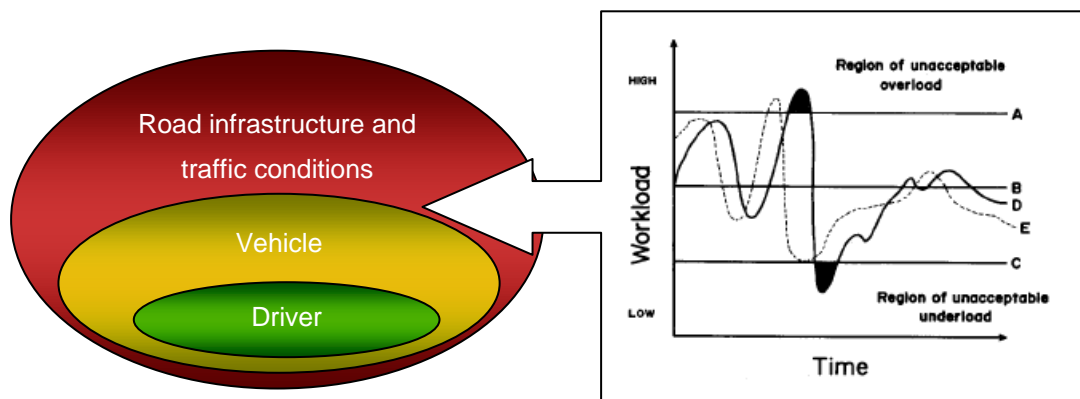
Figure 3.7: Estimation of epochs of driver workload in dynamic traffic condition (Source: Hancock and Chignell, 1988)

To predict operator's mental workload, there are some studies that use an analytical method. Although the analytical workload method is beyond the scope of this thesis, it is worth noting that cognitive architectures such as Adaptive Control of Thought- Rational (ACT-R, Salvucci et al., 2001) and Queuing Network- Model Human Processor (QN-MHP, Wu et al., 2008) have been used in several studies to predict mental workload. For example, Wu et al. (2008) developed a driver workload manager based on a queuing network model of human cognitive processes.

This model used micromodels of elementary perceptual, cognitive, and psychomotor processes arrayed in a queuing network that sampled data about the driving environment and carried out operations on the data. The processing times were estimated from the micromodels and the benefit of this cognitive modelling approach was that it could optimally delay task sequencing rather than simply lock out functions or reroute messages. This simulator based study investigated the benefit of a workload manager by addressing performance on a secondary task performed by police interceptors and found that subjective workload assessment was lower when the workload manager was active (i.e. optimal delay of tasks based on the driving demand i.e. straight or curved road segments at either 45 mph or 65 mph). Overall, the average utilisation of a sub-network of QN-MHP was regarded as a natural index of mental workload and their QN-MHP workload model could predict each NASA-TLX sub-factor rating with good accuracy. While these results contribute to the road safety, a more common technique i.e. empirical testing is preferred in this thesis.

As discussed in Chapter 2, empirical measures of mental workload are the most common, useful and reliable methods to be applied as they provide a genuine reflection of the real-world happenings. In this kind of approach, a variety of methodologies can be implemented, for example primary task, physiological and subjective measures. In the evaluation of different workload management functions for instance, empirical technique provides useful information regarding the beneficial effect of information-scheduling function on driving performance in both longitudinal and lateral controls as well as both objective and subjective workload as discussed in Section 3.2. Since the objective of this research is to explore the real-time detection of driver workload in varying traffic conditions and then to offer guidance regarding the time-scheduling of information to avoid overload or distracted situations, the primary approach in this thesis is to explore the empirical measures of mental workload namely, primary task, physiological and subjective measures in detecting temporal workload transitions. The problematic traffic situations will be identified through a moment-by-moment analysis of driver state and the management of workload will be based upon accurate predictions about how certain tasks will impact upon driver state (in terms of workload).

3.3 Gaps in the Literature on Workload Manager Systems

Following the current development of workload manager systems as discussed in Section 3.2, it can be concluded that there is still a lack of research in this area especially in investigating the influence of traffic demand on driver workload. The traffic conditions examined are limited and requires a more systematic exploration of the traffic demands. Also, given the complexity of the proposed model in Table 3.1, the number of relationships within it and the number of potential parameters, it is thus sensible to decompose the model so that not all parameters are tested and verified at once. A good workload manager system would be required to have the ability to determine the driver's actual workload level by estimating and differentiating the load; for example it is important the system is capable of distinguishing between driving on a curvy road or negotiating a dangerous intersection as well as the load incurred on the driver. With the availability of varying types of sensors in a vehicle (Figure 3.8), the analysis of the vehicle surroundings has become more reliable and widely available. The workload manager however cannot be omniscient about the environmental situation and may make errors in interpreting driver actions and capabilities.
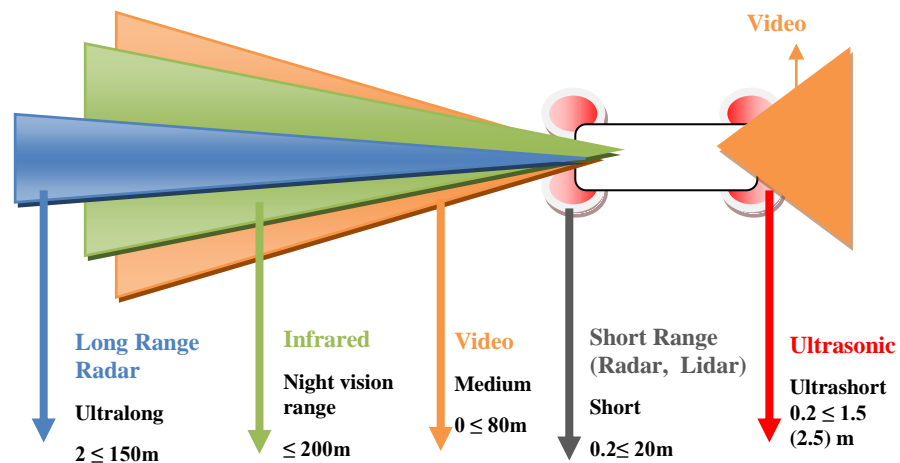
Figure 3.8: Range of some of the sensors available in the vehicles to analyse the vehicle surroundings (Source: Erséus, 2010)

In some situations, drivers may manage high workload peaks by adapting to the driving situation by, for example, slowing down or refraining from conducting secondary tasks such as answering the phone. Studies however have shown that

drivers may not always be able to anticipate a demanding or risky situation and adapt accordingly and some drivers find it hard to resist answering an incoming phone call even in very demanding driving situations (Green, 2004; Lansdown, 2012; Jamson 2013). It is therefore important to empirically predict mental workload through various measures during the early stages of system development to ensure full benefits of the support system to the driver. Although this would be a substantial task requiring large number of drivers to be observed over a considerable amount of driving, the benefit gained would be the delivery of a truly intelligent workload manager system.

In the next section, the research gap with examples of current available systems will be highlighted and discussed, which also forms the objective of the simulator studies examined in Chapter 4 to 6 of this thesis.

3.3.1 Quantitative standardised measures of the traffic complexity

With the advancement in current available sensor systems to assess drivers' physiology and traffic environment, there is a great effort to explore and interpret the interaction of DVE systems on drivers' mental workload. Some recent literature which examined the human-vehicle interactions focused on investigating the effect of IVIS on driver's mental workload and exploring the effect of individual differences such as age, skill and experience. However driver perception of workload is affected by factors such as road geometry, road type, lane driven, and traffic volume (Tsimhoni and Green, 2004; Schweitzer and Green, 2006). And thus, it is important to be able to model driver workload perception and prediction because the perceived workload will influence a driver's willingness to engage in secondary tasks (Schweitzer and Green, 2006).

Many specific road characteristics concerning the traffic environment (including road curvature, road marking, roadside advertising, etc) have also been considered. For example visual demands on the driver increase linearly with the road curvature, and maximum demand occurs near the point of curvature (Nowakowski et al., 2002; Tsimhoni and Green, 2001). Early studies (Brown and Poulton, 1961; Harms, 1986, 1991) have shown that driver performance varies according to the driving environment. Harms (1991) found that mean reaction time in responding to

targets (i.e. attentional demand) was strongly related to the complexity of the driving environment. Results showed that in higher surrounding traffic density and more complex driving environment (such as a village), the time response to visual signals increased due to greater tendency of drivers' eyes directed toward the surrounding driving scene rather than the road ahead. Similarly, the study of Zhang et al. (2009) suggests that driving task demand increases when the number of objects in the forward scene increases. Demands also increased in sharp curves, highway entrances and exits, narrow lanes, higher speeds, and during braking manoeuvres.

Apart from road infrastructure, various studies have suggested that traffic density increases driving task demands (Antin et al. 1990, Zeitlin 1993, Dingus, Antin et al. 1989). For example, Zeitlin (1998) proposed a micromodel of driver behaviour to predict subjective task difficulty. In this study, the participants performed two subsidiary tasks while travelling on a mix of rural secondary roads, express highways and high density urban roads. Using data which includes road characteristics, time, traffic density, speed, weather, brake applications, subsidiary task performance, and subjective difficulty ratings, it was suggested that it is possible to equate the mental workload differences imposed by the same system under different conditions. In this study, driving workload was defined as having two components, a steady state load dictated by roadway conditions, speed, and traffic density and a transient load determined by the braking actuation rate.

Similarly, Verwey (1993b, 2000) attempted to investigate the traffic density factor by measuring performance on a secondary task at different times of the day (associated with traffic density) but found no significant effect of traffic density on driver's mental workload. Evidence of increased mental workload during rush hour was however reported by Fairclough (1997) in which a decrease of frequency in overtaking was associated with reducing opportunity to select following headways and perform manoeuvres at leisure due to greater volume of vehicles in early-morning journeys. In relation to this, Hanowski et al (2009) studied the relative frequency of critical incidents where participant drivers were at fault, as a function of time of day and found that there was a strong positive linear relationship. This suggests that as the number of vehicles increases, there is an increase in the number of possible encounters and so does the chance of being involved in a multi-vehicle incident. However using time of day to represent different levels of traffic density

may be too crude a method to investigate the size of this effect on driver mental workload. This thus calls for a systematic approach in estimating real-time driver workload.

The model proposed by Piechulla et al. (2003) suggests that workload is due to the road segment being approached. Although it suggest only very modest increases in workload due to external factors such as darkness (2.6%), rain (5%), a wet surface (2.5%), and ice (10%), it presents quantitative workload estimates for real roads and for a wide range of driving situations involving a single lead vehicle. In contrast to the work of Piechulla et al. (2003), Green et al. (2007) considers multiple vehicles as traffic and reported that the Level of Service (LOS) i.e. an ordinal measure of traffic flow using letter A through F, with A being the best road condition (i.e. free flow) to F being the worst (i.e. force or breakdown flow) substantially affects driver's rating of workload. The study showed that free-flow conditions (LOS A) imposed low workload, while LOS E (unstable flow) imposes the highest workload (LOS F represents stopped traffic in a queue). While Green (2007) highlighted the association of driver subjective workload with few parameters including mean distance between the participant and lead vehicle as well as traffic count (Figure 3.9), the study did not address the question of how dynamic traffic situations in real traffic would affect driver workload as the participants were providing ratings based on short video clips.

Mean Workload Rating = 8.07 – 2.72(LogMeanRange125) + 0.48(MeanTrafficCount) + 2.17(MeanAxFiltered) - 0.34(MinimumVpDot(0 removed))

where:
LogMeanRange125 = Logarithm of the mean of the distances to the lead vehicles in the same lane as the subject averaged over 30 sec. If there was no vehicle within 125 m, the range of the radar, the distance was set to 125 m.
MeanTraffficCount = Mean number of vehicle detected by the subject vehicle radar (15 degree field of view) averaged over 30 s.
MeanAxFiltered = Mean longitudinal acceleration (m/s2)
MinimumVpDot(0 removed) = Minimum acceleration of a lead vehicle in m/s2 averaged over a 30 s interval, with deceleration of the lead vehicle being negative values. Cases where there was no lead vehicle were not included in the computation.

Figure 3.9: Green's et al. (2007) workload estimator equation

Hence, a quantitative standardised measure of primary task difficulty is required as studies tend to manipulate the driving environment qualitatively.

Moreover, it is also difficult to link the available findings of driver-vehicle interactions as the traffic conditions considered are not standardised. This makes association between other and own research findings rather difficult. Not to mention that results would differ between types of studies for example, definition of high density traffic on-road track would differ from the simulated high density traffic in simulator studies, but also between different simulator studies.

3.3.2 Exploration of the benefits of workload manager in managing dual-tasking conditions

Most studies demonstrate adaptive behaviours in the driving task in single experimental sessions (e.g., Strayer and Drews, 2004; Strayer, Drew and Johnston, 2003; Liu and Lee, 2006; Haigney et al., 2000) whereby drivers engaged in a cell phone conversation increased the headway distance. However it is unknown whether drivers would adapt their driving behaviour (with respect to in-vehicle activities) in response to changes in traffic over a relatively short time frame. Drivers generally perceive that they can effectively partition the task into more manageable chunks (e.g., Wierwille, 1993). While this strategy may be effective the majority of the time, there are obviously instances where it would be expected to break-down (e.g., Hancock and Ganey, 2003). Moreover, drivers do not tend to be well-calibrated to their own level of performance and tend to be overly optimistic about their ability to perform in-vehicle activities (Horrey, Lesch and Gabaret, 2008; Wogalter and Mayhorn, 2005). As such, drivers may not be effective at gauging the appropriate times to perform in-vehicle tasks. For example, in an on-road study conducted by Verwey (2000), the participants were found to be incapable of judging the traffic situation as participants were found to conduct non-driving related tasks in unsafe situation despite being asked to postpone the task following an occurrence of unsafe situation. Similarly, Horrey and Lesch (2009) also found no interaction between the distracter task (i.e. initiating a hands-free phone conversation) and subjectively-rated demanding road sections (such as narrow roads, curve road sections or signalised intersections). In the study, Horrey and Lesch (2009) found that participants did not postpone their decision in initiating any in-vehicle tasks in all highly demanding traffic conditions, despite being aware of the demand of the driving situation.

Additionally, it is possible that increasing the number of objects (for example, billboards and buildings, Horberry et al., 2006) that are not central to the driving task has little effect on increasing the demands of the driving task because drivers simply ignore environmental features that are not essential to the driving task when already under increased load (e.g., when performing a secondary activity).

To mitigate distractions, some vehicle manufacturers employ 'lock-outs' on navigation systems to prevent drivers from using the in-vehicle applications in driving situations deemed unsafe or critical. Research has shown that a locking strategy was beneficial in improving driving performance during engagements in visual distraction (Donmez et al., 2006b). However studies have indicated that such intervention on a task that is already underway is not advisable in driving conditions which have suddenly grown more intense as task interruption could potentially lead to higher workload. Thus in the design of an optimum support system, it is important to identify the problematic traffic situations and to account for the possible mitigation functions. It is also equally important to understand how a driver thinks about the system while driving the vehicle with the system enabled. While it is indeed difficult to provide a balanced approach between controlling the environment and optimising the operation of infotainment features, engineers and researchers from both academia and industries have recognised the importance of utilising mental workload in designing support systems to prioritise information within the vehicle and are altogether heading in the same direction towards optimising the support system which provides **the right level of information at the right time**.

3.3.3 Summary

Overall, the results from the current literature have demonstrated that surrounding traffic condition such as traffic density can have an impact on driver workload and potentially safety critical impacts on driver responses in dual-tasking conditions. Although various industrial and academic organisations have attempted to quantify the activities in car and driving situations as a way to generate workload estimates, there is a lack of understanding about how driver's workload fluctuates with the current traffic situations. Most workload estimators utilise sensors that determine speed, throttle position, steering wheel angle and transmissions gear as surrogates for monitoring traffic on the road and driving situations. Additionally, physiological metrics such as heart rate, skin conductivity and temperature have been combined with analysis of the driving situation to gauge fluctuations in driver workload, but some car manufacturers have not embraced biometrics as a practical way of measuring driver workload. Some researchers believe that biometrics only work in a laboratory. To ensure that the system includes the 'driver-in-the-loop', subjective rating techniques are employed as they offer the advantages of not disrupting the task and ease of application. However current measures of subjective workload such as NASA-TLX and SWAT do not capture all the relevant aspects of their tasks and their application not considered appropriate for use in real-time where demand changes are dynamic.

Thus the research in this thesis will extend the studies on the area of estimating driver workload in varying traffic behaviour condition by exploring a variety of different measures to capture the epochs of driver workload. Based on the findings from Chapter 4, Chapter 5 and Chapter 6 attempt to advance on the work described in Chapter 4 to produce recommendations for information-scheduling strategies in demanding traffic conditions.

Chapter 4

Exploratory Study: Effect of Traffic Complexity on Driver Workload

4.1 Study Aims

This chapter outlines the first of three studies conducted on a driving simulator. This study was undertaken to develop and test the following: the traffic behaviour required for the driving simulator experiment and the effects that these traffic behaviours might have on driver workload by collecting a wide range of data. This study also provided the opportunity to refine the workload measures to be used in later experiments.

4.1.1 Identification of measures

A significant amount of driving occurs in traffic and the amount of traffic not only influences the visual demand imposed on drivers but also to some degree the behaviour of the drivers (Zaidel, 1992). The traffic environment represents an important and commonly experienced social space that constitutes of anonymous individuals with a variation of driving behaviour traits, who interact with one another within a set of written and unwritten rules. The collective behaviours of other drivers represents the driving culture and has direct interaction and impact on an individual driver. While for an individual driver, his skills and experience play important roles in structuring his expectations and enable him to formulate hypotheses about the adjustment that other road users may force him to make in his driving (Saad et al., 1999). Wilde (1976) provides an extensive review of social interaction patterns which places various social factors in perspective and discusses how they interact with other factors in driving. For example, the presence of other drivers may increase attention when driving, especially when driving in heavy traffic. Others factors include expectations about the behaviour of other road users in obeying rules of the road and knowing how to drive properly, communication between drivers through use of signalling lane change as well as the social aspect of

invasion of one's personal space in particularly when other drivers follow or pull-in too closely. Nonetheless, the number as well as the repeatability and controllability of studies that involve driving in dynamic traffic has not been overwhelming. This first experiment aimed to define an appropriate indicator for driver workload in varying traffic demands under the assumption that driving is demanding due to the amount of attention required in processing external inputs involving the surrounding traffic and also the need to make predictions about the roadway situation based on expectations about other drivers' behaviour. In this study, visual workload is considered as part of mental workload which is often used interchangeably with the terms cognitive workload in the literature. Since the distinction between them is vague (De Waard, 1996) and they are often used for the same concept, it will be referred to as mental workload in this study.

As far as research in transport is concerned, there are no reported studies that have systematically varied complexity factors and measured the resulting workload in a dynamically changing traffic environment. This study has attempted to do just that, albeit in a simulated context. For the advancement of knowledge in the modelling of driver workload, it was more efficient to undertake the study using a driving simulator; in an on-road study it would not have been possible to control the surrounding traffic or expose the participants to identical experimental conditions. Although simulator studies can invite criticism on the grounds of validity, the lack of fundamental understanding in the domain of traffic complexity and workload is partly due to the difficulties in manipulating it in the real world. In this case, a simulated environment was therefore ideal for this purpose.

Assessment of mental workload calls for using multiple measures together. De Waard (1996) described a variety of possible measurement tools for measuring mental workload including primary task, secondary task, self-report measures and physiological measures. Workload studies in traffic adopt an operator-based approach which consider the characteristics of the driver and interactions between the driver and the driving environment. With this approach, the causes of high workload could be examined; strategies to reduce workload can be identified and ultimately improve the quality of driving and driver safety.

Since the sensitivity of workload measures are dependent on the road and driving conditions, there is a need to identify valid and reliable methods for

assessing the fluctuations in workload while driving. Peaks in workload while driving might have immediate safety implications. However the ability to detect these workload epochs are dependent on the driving conditions. Since this study aimed to explore continuously the influence of the external traffic complexity on drivers' workload, a variety of selected measures were identified for their suitability in tapping into these changes in workload. The measures considered in this study are highlighted in the following paragraph with the detailed descriptions of the measures available in Section 4.3.

The test is the Tactile Detection Task (TDT), a secondary task that is used to measure "headroom" on the primary task. This objective workload measure was chosen over the Peripheral Detection Task (PDT) due to a number of practical advantages. Firstly, TDT is suggested as a better measure of workload than PDT as PDT has the limitation of surrounding lighting and background contrast effect which may introduce additional variance in detection performance and thus influence the measurement sensitivity (Engström, 2010). Additionally, PDT detection performance may also be impaired due to attention switching as visual resources are also utilised in monitoring the changes in surrounding traffic. This may lead to inaccurate results as the aim of the measure is to enable discrimination of demands in 'just driving' rather than discriminating the effect of driving of both with and without secondary task load. Since the measures utilised in this study should not interfere with the visual demand required in driving task, TDT may thus in this case, thought to be more appropriate detection task.

Subjective measures of workload are valid, easy to use and widely adopted (Sheridan, 1980 also cited in Wickens, 1984; Gopher and Browne, 1984, Gopher and Donchin, 1986). To probe the perceived workload as a whole, both uni-dimensional and multi-dimensional subjective workload questionnaires i.e. RSME (Zijlstra, 1993) and NASA-RTLX (Byers et al., 1989) were administered at the end of a each of the three runs in this study. To explore the temporal workload imposed by the traffic demand while driving, a continuous subjective rating task (CSR) was administered during driving, whereby participants were requested to provide a workload rating via a 10-point rating scale (as described in data collection Section 4.3.1(ii)). This is to enable the collection of subjective workload without interrupting the driving tasks and possibly jeopardising objective performance. Moreover, in a

highly controlled experimental setting, the ability to prompt participants to provide a workload rating to a pre-specified schedule is superior to that of conventional post-drive scales, given the natural fluctuations in traffic complexity that can be observed in real-life settings.

Additionally, physiological measures provide an alternative and more objective perspective on workload and effort. Although there are various selection of physiological measurements which are sensitive to driver workload such as heart rate (Mulder et al., 1999), brain activity (Wilshut, 2009) and eye behaviours (Recarte et al., 2008) (refer Section 2.2.1.3 for the descriptions of physiological measures), the feasibility of the measures in momentary analysis of driver workload may influence the choice of the measures. Heart rate, for example, would require wider window length (i.e. at least 30 s to 40 s) to detect momentary changes in mental effort (Mulder, 1992) and thus to distinguish changes in mental effort in the mid-frequency band. Since the momentary workload is measured at shorter intervals (i.e. every 8s in the present study), comparison between measures such as heart rate variability (HRV) and other measures such as subjective workload ratings, may prove to be difficult due to the unequal window length. Other factors to be taken into consideration include the availability of equipment and the expertise in utilising the equipments to collect data. Since the remote eye-trackers were readily available in the simulator, eye behaviour such as blink frequency, blink duration and pupil diameter were also measured. Eye blinks are believed to be an indicator of both fatigue and workload. Number of blinks (Recarte et al., 2008) and blink duration (Veltman and Gaillard, 1996; Ahlstrom and Friedman-Berg, 2006) were suggested to be related to aspects of visual attention required by the driving task. Pupil dilation has also been found to reflect changes in task variation such as cognitive tasks (Beatty and Lucero-Wagoner, 2000) and mental tasks (Recarte and Nunes, 2000).

With the use of multiple measures together in this first experiment, the relationship between the dynamic traffic behaviours and driver workload was thus explored. It was hoped that relationships could be found between workload measures within particular traffic conditions.

4.1.2 Experimental hypotheses

The main experimental hypothesis was that the changes in surrounding traffic complexity would affect driver workload. Driver workload was predicted to increase with increasing traffic flow and presence of lane changes.

The secondary experimental hypothesis was that the momentary traffic complexity can be tapped into using different workload assessment techniques. This present study compared techniques encompassed of three rating scales (RSME, NASA-RTLX, 10-point rating scale), six driving parameters (mean speed, standard deviation of speed, distance headway, time headway, high steering frequency component, and standard deviation of lateral position), secondary task performance (tactile detection task reaction time) and three physiological measures (blink frequency, blink duration and pupil diameter). Detailed insight into the merits of these workload assessment techniques for the driving task will aid in understanding workload in varying traffic complexity manipulated in this study and also in the design of subsequent studies of driver workload.

4.2 Methods

4.2.1 Simulator

The experiment took place in the moving-base, high-fidelity University of Leeds Driving Simulator (UoLDS) as shown in Figure 4.1.
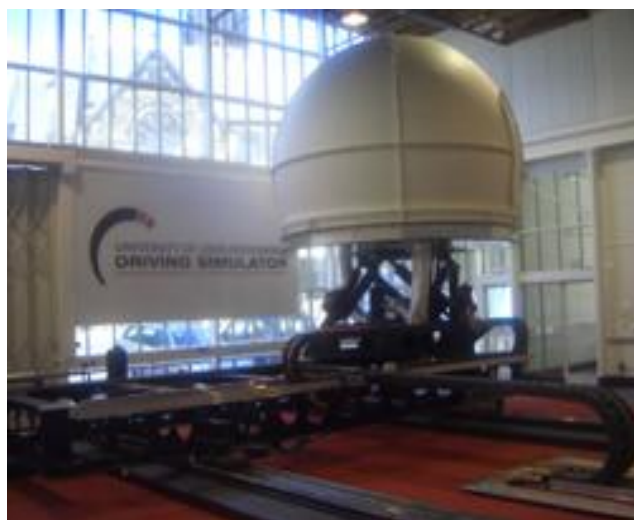
Figure 4.1: The University of Leeds Driving Simulator

The UoLDS is based on a complete 2005 Jaguar S-type vehicle housed within a dome, with all of its basic controls and dashboard instrumentation fully operational. The vehicle's internal Control Area Network (CAN) is used to transmit driver control information between the cab and one of the eight Linux-based PCs that manage the overall simulation. The simulator system collects data relating to driver behaviour (vehicle controls), the vehicle and other autonomous vehicles in the scene at a rate of 60Hz.

To simulate realistic driving cues, the 80W 4.1 sound system is used to provide audio cues of engine, transmission and environmental noise. The projection system within the dome provides a seamless total forward field of view of 250°. The central rear channel (60°) is viewed through the vehicle's rear view mirror, whilst LCD panels are built into the Jaguar's wing mirrors to provide the two additional rear views. The vertical field of view of 45°.

Additionally, driver's visual behaviour is tracked using remote cameras mounted on the dashboard. The Seeing Machines faceLAB (version 4) eye-trackers housed within the vehicle cab collect data at 60Hz. The quality of eye tracking was monitored throughout the experiment, and calibration undertaken before each drive.

4.2.2 Participants

Drivers were recruited on the basis of a volunteer sample scheme, drawn from both an existing database, responses to University of Leeds' website and local poster advertisements seeking volunteers. Forty six drivers participated in the study (22 males, 24 females, $Range_{age}$ = 25-50 years old; M_{age}= 36; SD_{age}= 7.1). All participants were holders of a valid driving license for over five years, with reported minimum annual mileage of 10000 miles. They all had normal or corrected-to-normal vision. Ten participants did not complete the experiment due to simulator sickness and simulator technical complications. The breakdown of the thirty-six participants (18 males and 18 females; $Range_{age}$ = 25-50 years old; M_{age}= 37; SD_{age}= 6.9) who successfully completed the experiment is reported in Table 4.1. All drivers were paid for their participation (£15). A sufficient number of participants is important for reducing between-subject variance in task performance. According to the central limit theorem in statistics, the distribution of a sample will be close to the

normal distribution when the sample size is larger than 30, regardless of the distribution of the population.

Table 4.1: Statistics of participants' demographic details

Gender	N	M_{age}	SD_{age}	$M_{annual\ mileage}$
Male	18	37.0	5.709	20428
Female	18	37.4	8.081	15333

Note: N= number of participants; M_{age}= mean age; SD_{age}= standard deviation of age ; $M_{annual\ mileage}$= mean annual mileage.

4.2.3 Experimental design

Three roads were modelled, each being a 38km two-lane divided motorway where the behaviour of the traffic was dynamically scripted to change lanes, overtake and stay in front of or behind the participant's vehicle. The three roads; Low, Medium and High Traffic Complexity varied in their average traffic flow and therefore the number of lane changes that occurred as shown in Table 4.2. Examples of the three simulated drive are depicted in Figure 4.2.

Table 4.2: Average traffic flow and number of lane changes for each drive

	Low Traffic Complexity	Medium Traffic Complexity	High Traffic Complexity
Average Traffic Flow (vehicles/lane/hour)	416	810	1654
Total No. of Lane Changes (count)	1065	1428	2688

Figure 4.2: The three simulated roads with varying Traffic Complexity (left to right: Low, Medium, High)

Due to the naturalistic nature of the choreographed traffic, for the purposes of data analysis each road was divided into 252m long sections, i.e. the tile size of the traffic road used in the simulation. These road sections were defined according to their traffic complexity in terms of Traffic Flow and Lane Change Presence, Proximity and Direction.

i. Traffic Flow was characterised according to the Level of Service (LOS) as defined in the Highway Capacity Manual (2000); these range between LOS A (minimal traffic) and LOS F (traffic congestion). According to the Highway Capacity Manual (2000), the traffic in LOS F can be considered as erratic and unstable. As there were very few instances of LOS F present in this study, it is difficult to draw statistical robust conclusions. Therefore, the LOS F data were excluded from the analysis, leaving five levels of this independent variable (LOS A-E).

ii. Presence of one or more lane changes performed by neighbouring vehicle in front of the participant's vehicle were considered for every 252 m travelled. This created a dichotomous independent variable (Lane Change Present, Lane Change Absent).

iii. When a lane change performed by a neighbouring vehicle occurred, its proximity to the participant was subsequently categorised as being in either the near-zone and far-zone. The near-zone was defined as the area between the participant's vehicle and the lead vehicle within 252 m, whilst the far-zone was defined as the area between lead and preceding lead vehicle within a distance of 252 m from participant vehicle (see Figure 4.3). This resulted in two levels of independent variable (Near-Zone and Far-Zone).

iv. Lane Change Direction was also varied, with vehicles either moving away from the participant's lane or towards it, thus creating two levels of independent variable (Towards and Away).
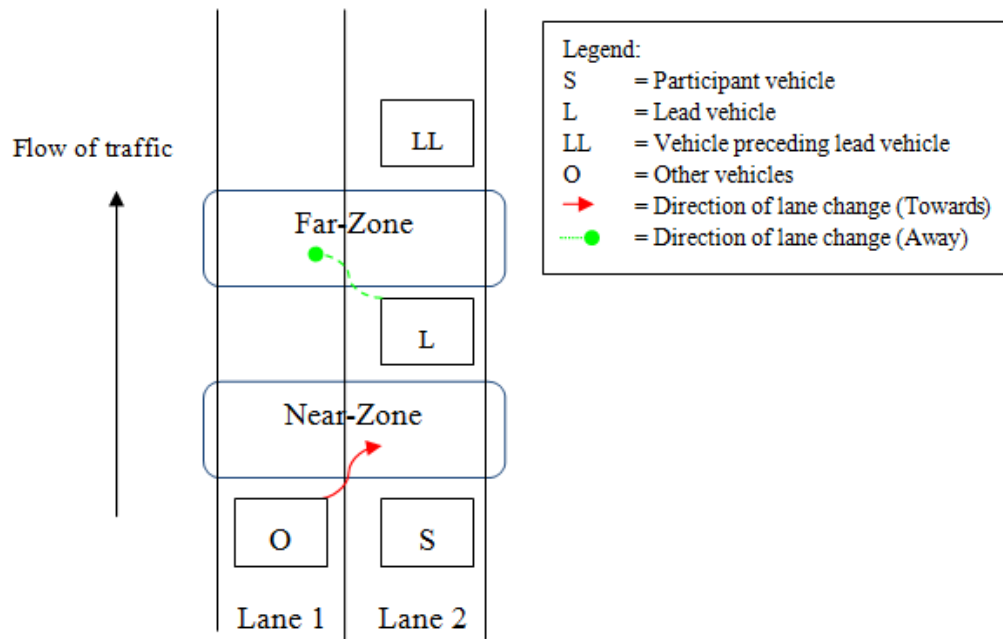
Figure 4.3: Description of type of Lane Change

4.2.4 Driving task

A within-subjects design was used, whereby all participants drove all three roads, each at a differing traffic complexity and the order in which the participants drove the roads was counterbalanced among the participants. The surrounding vehicles consisting of passenger vehicles, highway maintenance vehicles and heavy good vehicles were scripted to change lanes when certain conditions were met (e.g. available gap). To encourage participants to interact with the surrounding traffic, they were instructed to drive as they would in the real world. They were instructed that driving in a hurried manner whilst adhering to the traffic regulations (i.e. they should not exceed the speed limit) would ensure that they arrived at the meeting on time. No extra reward was offered for compliance with the instructions. The following instructions were given to the participant prior to the start of the drive,

"You are late for a meeting. You will arrive on time if you drive at 70mph."

A 10 minute practice of the experimental road preceded the experiment to ensure a certain level of competence with the simulator controls and familiarisation with the rating scales and tactile detection task.

4.3   Data Collection

The first 3km of data in each road were excluded to allow participants to adjust to the traffic conditions and to allow the simulated traffic to build up to the appropriate flow level (see Figure 4.4). The following 35km road geometry was consistent across the three roads, with 75% of the sections being straight and 25% being curved. In order to eliminate the carryover effects between sections (e.g. accelerating out of a curve or decelerating into one), the data recorded in the first and the last 26m of each 252m straight section were excluded from the analyses, as detailed in Figure 4.4. This resulted in there being 126 road sections for inclusion in the analysis.
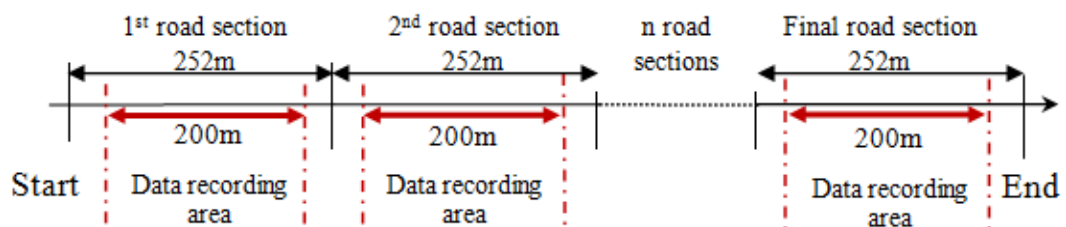
Figure 4.4: Data recording at each road section

4.3.1   Subjective workload measures

Overall (i.e. after each drive) and continuous (i.e. during each drive) measures of subjective workload were elicited. An informal post-study interview session was also conducted at the end of study to expand the understanding of ease of use of workload ratings and to discuss factors that influenced driver's ratings.

i.   *Overall workload (NASA-RTLX and RSME).* It is common to assess workload over a long period of time (Verwey and Veltman, 1996) as a global measure of operator demand. In this study, after the completion of each of the three drives, the two most commonly used techniques of eliciting subjective mental workload were administered; the Raw NASA-Task Load Index (NASA-RTLX; Byers, Bittner, and Hill, 1989) and RSME (Zijlstra, 1993). The NASA-RTLX is a multi-dimensional instrument consisting of six subscales exploring Mental Demand, Physical Demand, Temporal Demand, Own Performance, Effort, and Frustration Level. Each subscale is 10-cm long depicting a scale of 0 to 100, with the endpoints of the response scale

anchored 'low' and 'high'. The NASA-RTLX has successfully been used to measure small changes in workload (Jahn, Oehme, Krems, and Gelau, 2005), specifically in mental and temporal demands. Another multidimensional workload scale that has been developed to assess the level of workload in the automotive environment is the Driving Activity Load Index (DALI) (for example, Pauzié, 2008). Although DALI is a modified version of the NASA-TLX, DALI is less preferred for this study as it is specifically tailored to the assessment of in-vehicle systems/ tasks, which is not the task demand being investigated in this study. The RSME is a uni-dimensional rating scale developed by Zijlstra (1993) to investigate mental effort only. Perceived mental effort is rated on a 15-cm long vertical line marked at 1-cm intervals and reflects a scale of 0-150. The scale has nine anchor points ranging from 'absolutely no effort' (close to the 0 point), to 'rather much effort' (approximately 57 on the scale) to 'extreme effort' (approximately 112 on the scale). This scale has been widely used in traffic research (De Waard, 1996) since it is a fast and easy method; however it provides no diagnostic information about the sources of workload (Zjilstra, 1993).

ii.   *Continuous Subjective Rating (CSR).* As well as the workload measures taken post-drive, in the present study ratings were also collected continuously during each drive to assess the fluctuations in participant's workload. De Waard (1996) noted that where performance measures might be insensitive to increases in workload, changes in continuous workload ratings may well give an indication of effort exerted. A pilot study using a 15 point rating scale similar to that of Schieβl (2008a; 2008b), suggested response-bias with participants' scores clustering around multiples of 5. Participants also indicated a preference for a smaller scale and therefore a 10-point scale was used here. The rating scale consisted of a 1-10 point scale and was explained verbally to the participants as follows, "Please provide a rating on how easy or difficult to drive in the traffic. Low difficulty is between 1 to 3, medium difficulty is between 5 to 6 and high difficulty is between 8 to 10". Participants were asked to provide a workload rating by an auditory prompt, approximately every 8 seconds (i.e. in each 252m road section).

4.3.2 Tactile Detection Task

Performance was measured in terms of response time (RT) and error rate. An error is defined as a response less than 200 ms or more than 2000ms from the stimulus onset (Engström, 2010, pp. 93). RTs are defined as the time between stimulus onset and response, and are calculated for correct responses only. RT is used as the main performance metric, since it is difficult to interpret RT data at low hit rates (Engström et al., 2005). According to Merat, et al. (2006), the hit rate must be above 70% for a data segment to qualify for analysis. Therefore, hit rate is mainly used as an indicator of the quality of the measure (i.e. to identify whether the set of data from a participant can be used for analysis).

Engström et al. (2005) has shown that TDT is sensitive to small variations in non-visual cognitive loads such as answering biological questions (Engström et al., 2005) or counting up by two (Mattes et al., 2007). Results also indicate that TDT does not seem to have any major impact on driving performance and any major impact on visual behaviour (Engström et al., 2010). Since this study attempts to examine the short-lasting variations in workload induced by increasing complexity of driving task (higher traffic density), TDT was investigated to see whether this approach was sensitive to short lasting peaks in workload.

4.3.3 Physiological measures

Van Orden et al. (2001) found oculomotor parameters such as eye blink frequency and pupil diameter could be combined in multi-factorial index to detect overload conditions. The challenge is to determine whether these oculomotor metrics can be generalised across tasks and varying levels of task difficulty. In order to optimise the significance of the pupil data, the luminance of the screen was kept at a constant level of 100 lux. Both mean blink rate and average change of pupil diameter were measured over each road section as described in Figure 4.4.

i. *Blink Frequency and Blink Duration*

Studies have shown that blink of the eye (i.e. the rapid closing and reopening of the eyelid) is affected by both mental workload and visual demand, with the former leading to blink frequency increase and the latter to blink frequency inhibition (Recarte et al., 2008). This thus suggests that an increase of visual demand required by the driving task could lead to a

decrease in blink frequency. Apart from the blink frequency, the blink durations, typically between 40 and 200 milliseconds in length, were also examined in this study.

ii. *Pupil Diameter Changes*

Pupil dilations have been observed to increase with increased cognitive loading, such as processing of discrete sentences (Just and Carpenter, 1993), or talking and calculation (Recarte et al., 2008). Since human pupils dilate as a consequence of mental and emotional events (Beatty and Lucero-Wagoner, 2000) and tends to be indicative of increase demand for information processing (Kahneman and Beatty, 1966; Beatty and Wagoner, 1978), fluctuations of the pupil diameter can thus be associated with changes in workload. As discussed in Section 2.2.1.3, the mean pupil diameter or average change of pupil diameter, is a common pupillometric measure and is suggested to be more resistant to noise than the ICA method in tracking load changes on time scales of seconds due to the averaging process (Palinko et al., 2010; Ewing and Fairclough, 2010). A remote eye tracking system was utilised to collect pupil diameter measure, owing to it being less obtrusive and easier to use than head-mounted eye trackers. Baseline pupil diameter was measured for 1 minute for which participants were required to look straight ahead. Pupillometry data were pre-processed to remove blinks and artefacts due to tracking failures (i.e. eliminating readings of 0 or near 0). The change of pupil diameter measured in this study was adapted from Palinko et al., (2010), as follows:

Pupil Change (PC) = (Pupil diameter - Baseline)/Baseline

An average change of pupil diameter (ACP) for each road section (as described in Figure 4.4) was calculated by taking the average of this measure over a time period.

4.3.4 Driving Performance

During the trials, driving behaviour in terms of speed, steering and vehicle position (lateral position, time headway) was sampled and calculated for each road section (each 252 m) as detailed previously in Figure 4.4. Curved sections (which comprise of 25% of the total sections) were removed when examining the lateral control measures.

i.   *Mean and Standard Deviation of Speed.*

Ratings of workload systematically increase with speed (Fuller, McHugh and Pender, 2008) since task difficulty has been suggested to be analogous to mental workload (Fuller, 2005). Since very little change of speed occurs in the case of roads with constant geometry (straight or low curvature roads), standard deviation of speed would be an indication of changes in traffic conditions (Cacciabue, 2007) suggesting variation in driving demand while controlling the vehicle. This is particularly applicable in more dense traffic conditions where space is restricted, causing drivers to proceed more cautiously with lower speed.

ii. *Mean Distance Headway and Time Headway*

Headway is a measure of longitudinal control to understand whether a following vehicle is travelling too close to a lead vehicle compared with a recommended safe following distance (Roskam et al., 2002). In previous studies of estimating driver workload, Green et al. (2011) suggested that distance from the lead vehicle should be considered when measuring the influence of other road users on driver workload and this measure of distance was included in workload estimator equations in the SAVE-IT project (Green, 2011). Since the continuous workload ratings collected in this study requires the driver to constantly monitor the surrounding traffic, distance headway is selected for in-depth analysis to investigate the possible influence of overall distance headway on driver workload. In this study, distance headway is defined as the distance from the front bumper of lead vehicle to the front bumper of the following vehicle. Additionally, time headway which is defined as the time taken to pass the same point by taking into consideration of the vehicle speed, is also considered in this study for comparisons over conditions.

iii. High Frequency Component of Steering Angle Movement

A detailed analysis of lateral deviation performances can be conducted by examining the variation of steering wheel angle. Analysis of the means of a spectral analysis of the steering signal requires an initial transformation of the signal to a frequency domain (by means of Fourier transform), prior to analysing those frequency bands affected by different factors. Mc Lean and Hoffman (1975) found that the frequency content in the 0.35-0.60 Hz band is sensitive to variations in both primary and secondary task load, and is thus an effective indirect measure of the driver workload since any variations on drivers' attention affect the steering wheel frequency variation (Östlund et al., 2004). In this study, the high frequency component is defined as the proportion between the power in the frequency band between 0.3 and 0.6 Hz and the total steering activity signal (i.e. power of frequency band between 0 – 0.6 Hz).

iv. Standard Deviation of Lateral Position

Lateral position variation is influenced by unintentional lateral variations caused by the difficulty to drive within the safe path of travel. SDLP is a primary task performance measure which is sensitive to high workload in conditions where driver performance is not optimal (De Waard, 1996). In this present study, it is hypothesised that significant changes in lateral position would be observed when driver workload increases with the changes in traffic conditions. In a study conducted by Green et al. (1993) that examined the relationship between road geometry and workload ratings, standard deviation of lateral position was found to correlate with workload ratings whereby workload was low when traffic was light or absent. In the present study, it is assumed that this variable is capable of detecting the driver workload changes caused by the impact of the surrounding traffic conditions.

4.3.5 Procedure

Upon arrival at the simulator, participants were given the participant briefing sheet and a consent form to fill in. Following a short briefing on the study, participants were escorted to the simulator and fully briefed of the operation of the simulator. The base and lumbar support of the seat were adjusted to ensure a comfortable driving position and the view of the warning messages are within the peripheral sight. They then drove the simulator vehicle on the motorway used in the later experiment and were encouraged to familiarise themselves with the use of the throttle brake and steering wheel. After completing a ten minutes practice drive, the participant then performed the first experimental drive which involves two sets of tasks. Figure 4.5 describes the administration of the tasks (Subjective Ratings, CSR; Tactile Detection Tasks, TDT) within each of the three drives (approximately twenty minutes each).
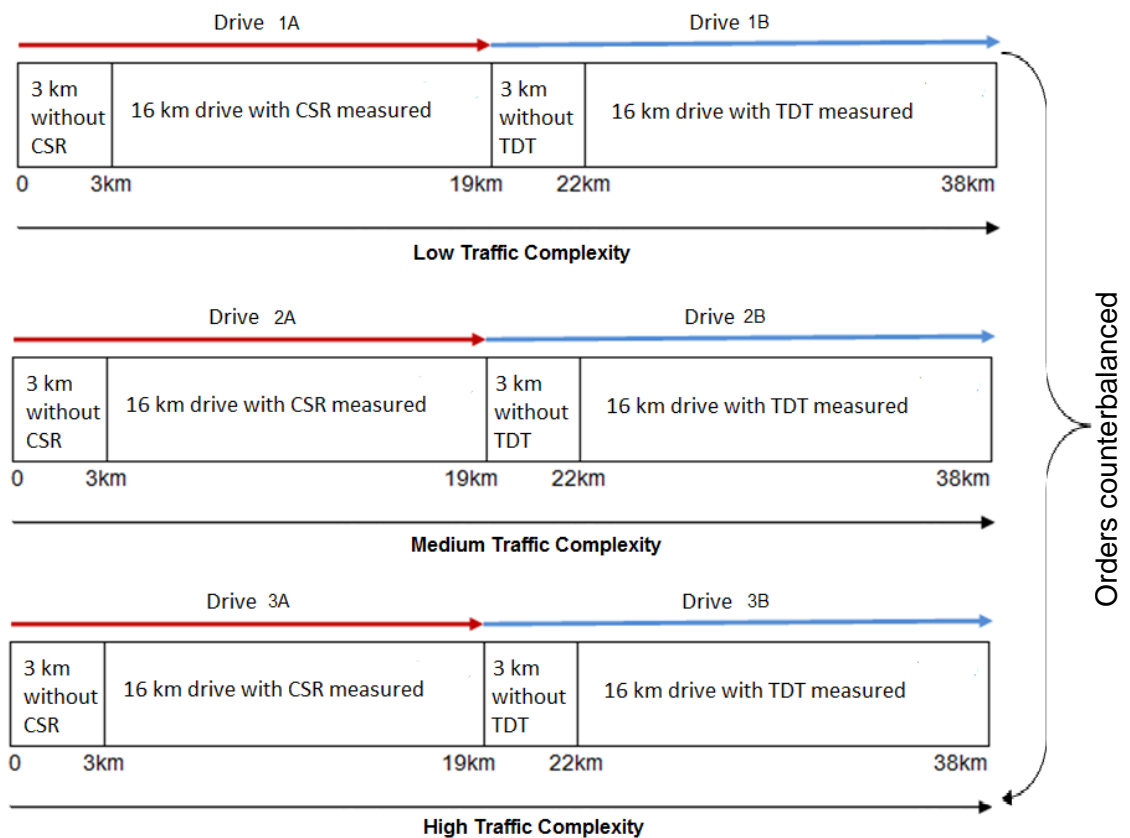
Figure 4.5: Administration of the secondary tasks within each drive

Participants were required to first produce the subjective self-reported ratings (CSR) in the first half of the drive (i.e. Drive A) and then the tactile detection task (TDT) was presented in the second half of the drive (i.e. Drive B) (refer to Figure

4.5). For the SR task, participants were asked to verbally provide a rating of their driving demand using the 1-10 point rating scale (as shown in Figure 4.6), explained as representing low (1-3), medium (5-6) and high (8-10) workload. Participants were asked to provide this workload rating, prompted by an auditory signal, approximately every 8 seconds (i.e. in each 252m road section).

1	2	3	4	5	6	7	8	9	10

Figure 4.6: Ten-point workload rating scale

Upon completion of the SR task, participants were then required to respond to the TDT. The detection task was presented via a small vibrating mechanism, 5.8 cm x 5.8 cm x 2.5 cm (as shown in Figure 4.7) which was strapped on the driver's seat and placed directly below the participants' left thigh outside their clothing. Participants received a short vibration pulse of one second (at approximately every 8 second interval) and a response was required via pressing a button nearest to the left index finger on the steering wheel. Detection performance was measured in terms of response time (s) and missed signals (%).

Figure 4.7: The position of the vibrating mechanism for tactile detection task during study

During piloting, the tasks were counterbalanced among the participants. However results indicated that data were contaminated as with participants became confused about the order of the next task. To avoid this issue in this present experiment, each of the drive began with the rating task followed by the tactile detection task.

After the completion of the first drive, participants were required to fill in the NASA-RTLX and RSME questionnaires to indicate their perceived level of

workload in the drive. Participants were also required to fill in the nine-point Karolinska Sleepiness Scale (KSS) to evaluate their level of alertness before and after each drive (1=very alert, 9=very sleepy). There were two purposes for this measurement; firstly to evaluate whether the duration of the task was too long and secondly to enable changes in driving performances and subjective workload which are not associated to driving difficulty, such as fatigue, to be identified and to be taken into consideration in the analysis if required. These are repeated for the second and last drive. Participants were required to complete a post-study questionnaire after the third drive. They were then debriefed and paid for their time.

4.4   Results and Analysis by Traffic Complexity

As outlined in Section 4.2.3, there were three levels of Traffic Complexity (Low, Medium, High). Within each of the three traffic complexity conditions (Low, Medium and High), two main workload measures were administered, namely continuous subjective rating (CSR) and tactile detection task (TDT). Drivers' physiological behaviour such mean blink frequency, mean blink duration, and average pupil change as well as driving performance were also measured.

To explore the sensitivity of the chosen measures mentioned above in tapping into the changes across traffic complexity, highly validated subjective measures such as NASA-RTLX and RSME questionnaires were administered at the end of each traffic condition. These questionnaires will be used to benchmark the workload associated with each traffic complexity.

The exploratory data were analysed for normality of distribution and homogeneity of variances using the Kolmogorov-Smirnov test and the Levene's Test of Equality of Error Variances, respectively. Following any violation of these tests ($p<0.01$), transformations were conducted on the data. For reporting purposes in this thesis, the results of these transformed data were back-transformed and interpreted on the original measurement scale. In the event that the Mauchly's test indicated that the assumption of sphericity was violated ($p<0.05$), the Greenhouse-Geisser correction was applied to produce a more conservative p-value (Field, 2005).

4.4.1 Relationship between NASA-RTLX, RSME, CSR and TDT

To compare the workload measures, means and standard deviations of the measures across the traffic conditions are presented in Table 4.3. Due to the number of missed TDT responses, the total number of data points associated with this measure is less than CSR and varies across the three traffic conditions.

Table 4.3: Descriptive statistics of workload measures between traffic complexity conditions

Workload measure		Low Traffic Complexity			Medium Traffic Complexity			High Traffic Complexity		
		N	Mean	SD	N	Mean	SD	N	Mean	SD
CSR		2268	2.88	0.92	2268	4.66	1.35	2268	6.37	1.09
RT		2192	0.66	0.39	2090	0.62	0.38	2136	0.65	0.39
RSME		36	31.61	14.57	36	51.28	18.71	36	82.42	20.01
NASA_RTLX	MD	36	25.03	18.41	36	44.47	21.49	36	73.01	16.28
	PD	36	15.53	11.85	36	27.19	15.45	36	47.94	20.62
	TP	36	23.39	18.58	36	40.08	21.92	36	68.56	17.71
	OP	36	20.06	17.68	36	28.42	14.94	36	52.28	20.21
	EF	36	24.36	20.50	36	47.00	22.60	36	68.14	15.21
	FR	36	18.92	20.60	36	41.44	26.66	36	67.97	16.70
NASA OW		216	21.21	13.48	216	38.10	14.89	216	62.98	11.91

Note: Abbreviations: CSR = Continuous Subjective Ratings
                             RT = Tactile Detection Task Response Time (s)
                             RSME = Rating Scale of Mental Effort
                             MD = Mental Demand
                             PD = Physical Demand
                             TP = Time Pressure
                             OP = Own Performance
                             EF = Effort
                             FR = Frustration
                             NASA OW = NASA Overall Workload

Analysis of variance was performed to find out to what extent indices of mental workload varied as a function of the objective changes in driving demand (varying from low to high traffic complexity). All the data were entered into a repeated measures ANOVA analysis with one within subject factor (i.e Traffic Complexity) and one between participant variable (i.e. Gender). Table 4.4 shows the results of the ANOVAs for each measure.

Statistical analysis of the measures of workload showed a main effect of Traffic Complexity on the workload measures. Simple effects analysis showed that only the subjective ratings increases with increasing Traffic Complexity

(Low<Medium<High, p<0.05). TDT response times (RT) was not found to vary significantly with increasing traffic complexity.

Table 4.4: Summary of ANOVAs for each workload measure

Workload measure		Traffic Complexity			Gender		
		F(2,68)	Sig.	η^2	F(1,34)	Sig.	η^2
CSR		153.05	**<0.001**	0.818	1.94	0.173	0.054
RT		1.09	0.341	0.031	1.98	0.168	0.055
RSME		128.28	**<0.001**	0.790	0.96	0.333	0.028
NASA_RTLX	MD	132.75	**<0.001**	0.796	1.30	0.262	0.037
	PD	61.25	**<0.001**	0.643	6.75	**0.014**	0.166
	TP	81.23	**<0.001**	0.705	0.02	0.896	0.001
	OP	44.35	**<0.001**	0.566	0.01	0.916	0.000
	EF	73.43	**<0.001**	0.684	0.11	0.743	0.003
	FR	75.21	**<0.001**	0.689	0.35	0.556	0.10
NASA OW		175.86	**<0.001**	0.838	0.36	0.553	0.010

Note: **BOLD** denotes significance < 0.05

There was significant main effect of Traffic Complexity on all six NASA-RTLX dimensions. However, main effect of gender was only significant for physical demand, whereby female drivers reported significantly more physical demand as shown in Table 4.5. Additionally, no interaction was found.

Table 4.5: Descriptive statistics of the physical demand across traffic complexity

Gender	Low Traffic Complexity		Medium Traffic Complexity		High Traffic Complexity	
	Mean	SD	Mean	SD	Mean	SD
Male	13.06	12.544	21.94	11.096	40.39	19.722
Female	18.00	10.890	32.44	17.601	55.50	19.117

To explore the sensitivity of CSR and TDT in tapping into workload, correlations with the two highly-validated workload measures (i.e. RSME and NASA-RTLX) were computed as shown in Table 4.6. Results show that CSR being highly correlated with RSME (r=0.720, p<0.001) and the NASA OW (i.e. overall NASA-RTLX) (r=0.739, p<0.001), which confirm the convergent validity of CSR. TDT response times, on the other hand, has shown a moderate correlation with RSME and Overall Workload in Low Traffic Complexity only. For an appreciation of the relationships between CSR and the overall workload measures (i.e. RSME and NASA-RTLX), comparisons between these subjective measures are depicted in Figure 4.8, with RSME and Overall NASA standardized to 100 point scale for

graphing purposes. Figure 4.8 shows CSR being as good as RSME and NASA in tapping into workload induced by primary driving task (i.e. traffic complexity)

Table 4.6: Pearson correlations between workload measures

Measures		CSR			RT		
		Traffic Complexity			**Traffic Complexity**		
		Low	**Medium**	**High**	**Low**	**Medium**	**High**
RSME		0.646**	0.553*	0.589*	0.409**	0.034	0.058
NASA_RTLX	MD	0.231	0.655**	0.513**	0.101	0.122	0.202
	PD	0.080	0.214	0.078	0.162	0.017	-0.286
	TP	0.176	0.352*	0.065	0.106	0.026	0.155
	OP	0.193	0.133	0.019	0.433**	0.183	0.297
	EF	0.114	0.176	0.241	0.076	0.054	0.281
	FR	0.224	0.453**	0.232	0.031	0.024	0.101
NASA OW		0.632**	0.583**	0.666**	0.310*	0.025	0.060

Note: 1. N = 36
         2. Figures shown in cell are correlation coefficients
         3. * denotes the correlation is significant at the 0.05 level.
         4. ** denotes the correlation is significant at the 0.01 level.
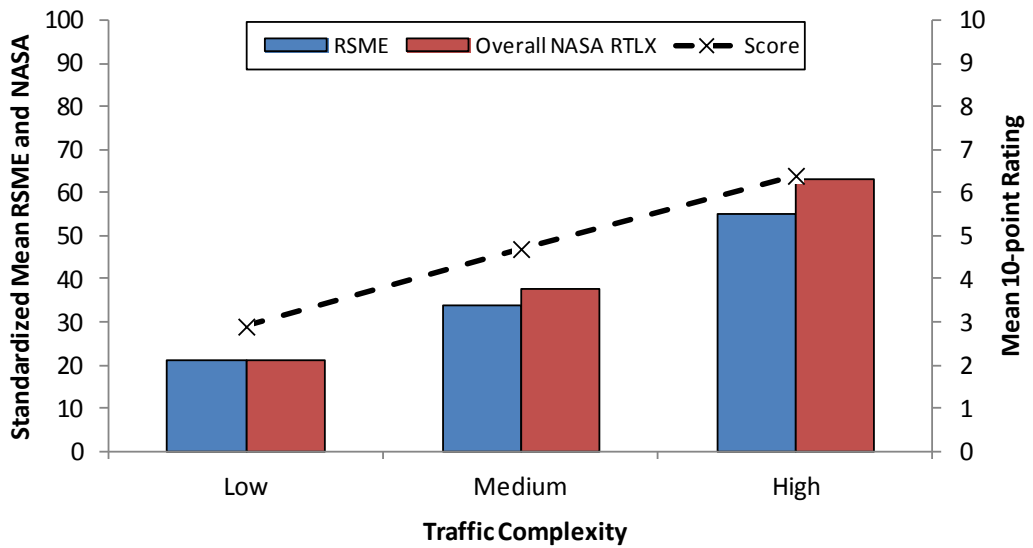
Figure 4.8: Workload scores across Traffic Complexity

4.4.2 Relationship between CSR, TDT and behavioural parameters

The descriptive statistics for the behavioural parameters measured within each drive are shown in Table 4.7. Since CSR and the TDT were performed separately within each traffic drive (refer Figure 4.5), two-way ANOVA analyses (with Traffic Complexity as a within-subject factor and Gender as a between-subject factor) were conducted individually for each of physiological and driving performance measure. For SDLP and HFS, only straight sections were analysed (refer Table 4.8).

Table 4.7: Descriptive statistics of behavioural parameters between traffic complexity conditions

Measures	Drive A: CSR			Drive B: TDT		
	Traffic Complexity			Traffic Complexity		
	Low Mean (SD)	Medium Mean (SD)	High Mean (SD)	Low Mean (SD)	Medium Mean (SD)	High Mean (SD)
MBF	0.42 (0.21)	0.42 (0.25)	0.40 (0.18)	0.41 (0.18)	0.42 (0.19)	0.39 (0.18)
BD	0.17 (0.05)	0.18 (0.06)	0.18 (0.06)	0.17 (0.06)	0.18 (0.05)	0.17 (0.06)
ACP	0.11 (0.03)	0.12 (0.04)	0.11 (0.02)	0.12 (0.03)	0.12 (0.04)	0.11 (0.02)
MSP	34.63 (2.15)	31.74 (1.19)	27.74 (0.77)	34.40 (1.85)	31.56 (1.16)	27.66 (0.77)
SDSP	0.28 (0.10)	0.41 (0.10)	0.81 (0.14)	0.28 (0.11)	0.42 (0.13)	0.75 (0.16)
DHW	348.85 (156.6)	56.41 (17.87)	31.68 (13.11)	374.39 (134.4)	59.52 (21.49)	30.65 (14.63)
THW	9.33 (5.76)	4.17 (2.13)	1.46 (0.40)	9.42 (5.13)	4.16 (1.91)	1.62 (0.51)
HFS	0.46 (0.05)	0.45 (0.05)	0.46 (0.06)	0.47 (0.05)	0.47 (0.05)	0.47 (0.06)
SDLP	0.09 (0.03)	0.10 (0.03)	0.10 (0.02)	0.08 (0.03)	0.10 (0.03)	0.09 (0.02)

Note: 1. Abbreviations: MBF = Mean Blink Frequency (Hz),
BD = Blink Duration (s),
ACP = Average Change of Pupil Diameter,
MSP = Mean Speed (m/s),
SDSP = Standard Deviation of Speed (m/s),
DHW = Distance Headway (m),
THW = Time Headway (s),
HFS = High Frequency Steering,
SDLP = Standard Deviation Lateral Position (m)

The aim of these analyses was to examine the effects of Traffic Complexity and Gender on eye measures, driving performance, and workload. As shown in Table 4.8, CSR was more sensitive than TDT as CSR increases with increasing traffic complexity. Additionally, driving performance measures such as mean speed, standard deviation of speed, distance headway and time headway which achieved significance, were similar regardless whether the CSR or TDT was administered during the drive. This thus suggest no influence of workload measure on the driving task. No main effect of gender was found for all measures.

Table 4.8: Effect of Traffic Complexity and Gender on primary task measures

Workload Measure	Measure	Traffic Complexity			Gender		
		F(2,68)	Sig.	η^2	F(1,34)	Sig.	η^2
Drive A: CSR	CSR	**153.05**	**<0.001**	**0.818**	1.93	0.173	0.054
	MBF	0.55	0.581	0.016	1.34	0.210	0.088
	BD	1.32	0.443	0.123	0.55	0.582	0.018
	ACP	0.32	0.691	0.035	2.05	0.161	0.057
	MSP	**291.39**	**<0.001**	**0.896**	0.59	0.449	0.017
	SDSP	**225.54**	**<0.001**	**0.869**	0.94	0.340	0.027
	DHW	**156.58**	**<0.001**	**0.822**	0.13	0.718	0.004
	THW	**54.14**	**<0.001**	**0.614**	1.19	0.283	0.034
	HFS	0.26	0.772	0.008	3.36	0.076	0.090
	SDLP	3.08	0.047	0.094	1.50	0.052	0.039
Drive B: TDT	RT	1.09	0.341	0.031	1.98	0.168	0.055
	MBF	1.76	0.180	0.055	0.23	0.632	0.008
	BD	1.21	0.542	0.030	0.40	0.672	0.004
	ACP	0.89	0.661	0.092	0.32	0.731	0.002
	MSP	**166.01**	**<0.001**	**0.847**	0.00	0.964	0.000
	SDSP	**132.93**	**<0.001**	**0.758**	0.01	0.923	0.000
	DHW	**94.92**	**<0.001**	**0.695**	1.79	0.192	0.056
	THW	**5.73**	**0.023**	**0.103**	2.96	0.080	0.110
	HFS	0.55	0.581	0.016	0.96	0.335	0.031
	SDLP	2.73	0.063	0.083	0.46	0.503	0.015

Note: 1. **BOLD** denotes significance < 0.05

2. Abbreviations: MBF = Mean Blink Frequency (Hz),
BD = Blink Duration (s),
ACP = Average Change of Pupil Diameter,
MSP = Mean Speed (m/s),
SDSP = Standard Deviation of Speed (m/s),
DHW = Distance Headway (m),
THW = Time Headway (s),
HFS = High Frequency Steering,
SDLP = Standard Deviation Lateral Position (m)

Since CSR, TDT, driving performance and eye measures were measured continuously across the whole drive, correlations were computed to examine whether relationships between these measures can be established within certain Traffic Complexity. Correlations were computed to investigate whether variances in the CSR data (i.e. workload peaks and troughs) can be accounted by certain primary task measures. Table 4.9 shows that CSR significantly correlates with the SDSP, THW and DHW across all traffic complexity conditions while TDT only significantly correlating with certain driving parameters in low traffic complexity conditions (such as SDLP, MSP, THW and DHW). Among the eye behaviour measures, only mean blink frequency showed some significant correlations with CSR and TDT and were present only in moderate traffic complexity condition.

Table 4.7: Pearson correlations between workload and behavioural measures (by Traffic Complexity)

Measure	CSR			RT		
	Traffic Complexity			Traffic Complexity		
	Low	Medium	High	Low	Medium	High
Eye Behaviour						
MBF	-0.058	-0.095*	-0.068	-0.108*	-0.106	-0.020
BD	-0.102	-0.023	-0.087	-0.095	-0.089	-0.054
ACP	0.022	0.103	0.122	0.032	0.0988	0.056
Primary Task Performance						
MSP	-0.034	-0.261**	-0.211**	-0.157*	-0.003	0.020
SDSP	0.098*	0.173**	0.168**	0.049	0.077	-0.008
DHW	-0.255*	-0.354**	-0.207*	-0.171**	-0.187**	-0.015
THW	-0.144*	-0.342**	-0.083	-0.153**	-0.160**	-0.019
HFS	0.005	0.002	0.071	0.020	0.056	0.080
SDLP	0.023	0.154*	0.063	-0.100*	-0.066	-0.062

Note: 1. Figures shown in cell are correlation coefficients
       2. * denotes the correlation is significant at the 0.05 level.
       3. ** denotes the correlation is significant at the 0.01 level.

4.4.3 Karoslinka Sleepiness Scale (KSS)

To identify presence of fatigue in the study, participants were required to rate their level of alertness by filling in the nine-point KSS, before and after each drive. The order of the runs (T1, T2 and T3) were counterbalanced among the participants with an overall of six order combinations in total. On average, all the participants were at a level of alertness between first and third point at the start of the drive. Although there were reductions in alertness (i.e. on average, one point reduction)

with increased number of drives per participant, these data were not statistically significant. This is due to fluctuations in the level of alertness among the participants, depending on the type of traffic involved. For example, there were five participants who showed an increased level of alertness (an average change of two points) following the completion of T3. Additionally, participants' level of alertness was reduced by an average of one point following the completion of T1 due to low-demand monotonous driving. Since the order of the drives was counterbalanced among participants and all participants were given a short break following the completion of each drive, the effect of fatigue is therefore negligible. Moreover, all the KSS scores did not exceed four points and changes in KSS score did not exceed two points.

4.4.4 Overview of the Traffic Complexity Analysis

In this study, the effect of Traffic Complexity was investigated for all measures with the aim to provide an overview of how the workload measures and driving performance would vary with increasing Traffic Complexity. However, no relationship could be established between workload and driving performance as correlations between these measures were variable. This may be due to the limitation of comparing the means between the traffic complexity drives which is too gross a measure which may limit the generalisation of findings. By examining the changes in workload and driving performance by traffic complexity conditions (i.e. drive completed by each participant), average changes were computed, as opposed to the momentary change in workload and driving performance. Additionally, such method does not allow for looking at whether lane changes were absent or present at a particular time or within each traffic flow condition.

Since the aim of the study was to investigate the fluctuations in workload and to determine which of the workload measures were sensitive to the momentary changes in Traffic Complexity, it may thus prove to be beneficial to subdivide each of the three traffic complexity drives based on road sections (as previously outlined in Figure 4.4) and categorise these traffic demand by Traffic Flow and Lane Change Presence. As shown in Figure 4.9, each traffic complexity drive consists large number of road sections covering all five levels of Traffic Flow (A to E). With the

high amount of datapoints within each traffic complexity drive, traffic complexity and thus momentary workload, can be tapped into more accurately. Moreover, categorisation of the manipulated traffic complexity by Traffic Flow (i.e. categorised based on the standard LOS concept) permits more reliable comparison of outcomes across all measures.
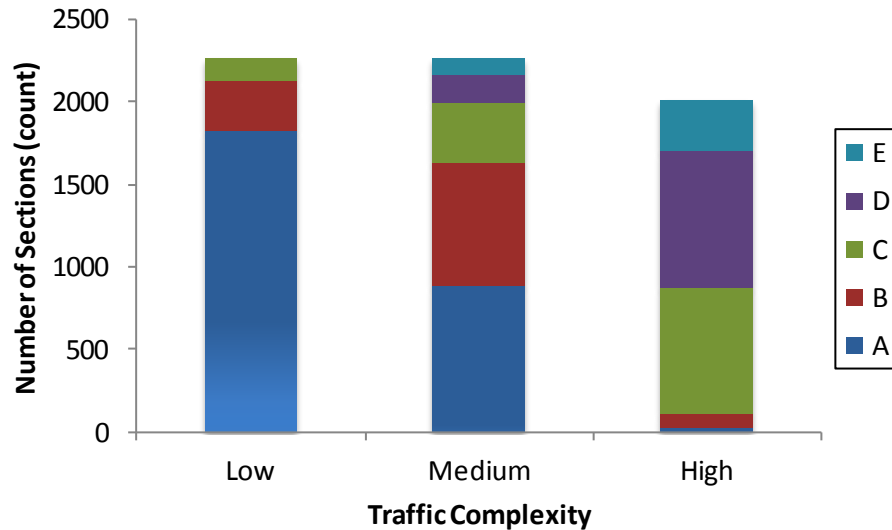
Figure 4.9: Post-hoc analysis of the distribution of number of sections per LOS

4.5   Results and Analysis by Road Section

As shown in Figure 4.4, each 38 km traffic complexity (including 6 km without workload measures) was divided into 252m long sections. This resulted in there being 126 road sections for inclusion in the analysis. In this part of the analysis, all the data from the three traffic complexity drives were pooled together for data stratification. There were two parts of analysis in this section; Section 4.5.1 investigates the effect of Traffic Flow, Lane Change Presence and Workload Measure and Section 4.5.2 investigates the effect of lane change characteristics.

In Section 4.5.1, these road sections were defined according to their traffic complexity in terms of Traffic Flow (five levels: A, B, C, D, E) and Lane Change Presence (two levels: Present, Absent) as well as Workload Measure (two levels: CSR, TDT).

In Section 4.5.2 which depicts the results on the effect of lane change characteristics, the road sections were defined according to Lane Change Proximity (two levels: Near-Zone, Far-Zone) and Lane Change Direction (Towards, Away).

4.5.1   Effect of Traffic Flow and Lane Change Presence

The following analysis consists of four parts; Section 4.5.1.1: Continuous Subjective Ratings, Section 4.5.1.2: Tactile Detection Task, Section 4.5.1.3: Eye Measures, and Section 4.5.1.4: Driving Performance Measures. Data transformation were conducted on the data which violated the normality of distribution and in the event of violation of the sphericity assumption, Greenhouse-Geisser corrections were used.

In Section 4.5.1.1 and 4.5.1.2, a three-way (5x2x2) repeated measures ANOVA was conducted on the CSR and TDT data respectively, with Traffic Flow and Lane Change Presence as within-subjects factors and Gender as between subject factor. The aim of the analysis was to examine whether the two workload measures are sensitive to the changes in the independent factors.

Since two workload measures were included in this study (as indicated by A and B in each traffic complexity as shown in Figure 4.5), the effect of workload measure on eye behaviour and driving performance was assessed by subdividing all road sections into two groups defined by Workload Measures (CSR or TDT). This addition of the Workload Measure (two levels) was conducted on the eye behavioural and driving performance data, in Section 4.5.1.3 and 4.5.1.4 respectively, to investigate whether both datasets (related to CSR or TDT) showed identical patterns of main effects. A significant difference in traffic complexity effect across workload measures would imply the need to separate the road sections based on the Workload Measures administered. Therefore, a four-way (5x2x2x2) was conducted on the eye behaviour and driving performance data, in Section 4.5.1.3 and 4.5.1.4 respectively, with Traffic Flow, Lane Change Presence and Workload Measure as within-subject factors and Gender as between subject factor.

4.5.1.1 Continuous Subjective Ratings

First, the segmented CSR data were subjected to three-way ANOVA repeated measures analyses. There were significant main effects of Traffic Flow $(F(3.02, 102.61)=124.978, p<0.001, \eta^2=0.786)$ and Lane Change Presence $(F(1,34)=45.758, p<0.001, \eta^2=0.574)$ on CSR ratings as shown in Figure 4.10. CSR was found to increase with increasing Traffic Flow and was found to be higher when lane changes were present as compared to lane changes were absent.
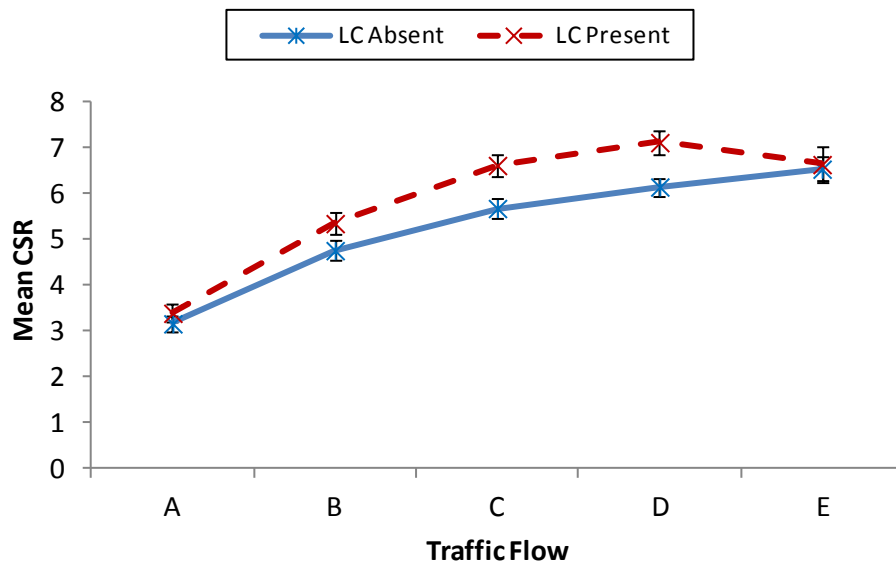
Figure 4.10: Mean CSR (with standard errors)

Post-hoc polynomial contrasts showed a significant linear $(F(1,34)=255.509, p<0.001, \eta^2=0.883)$ and quadratic effect of Traffic Flow $(F(1,34)=69.504, p<0.001, \eta^2=0.672)$ on CSR. Post-hoc pairwise comparisons of CSR indicated that the effect of Traffic Flow on CSR was significant up to LOS D, suggesting that workload increases with increasing Traffic Flow (A-D) and then levels off beyond LOS D. This suggest that a higher Traffic Flow (i.e. from Traffic D to E), changes in this variable have little effect on this measure of workload. Additionally, the non-significant interaction between Traffic Flow and Lane Change Presence (p=0.063) suggests that the effect of Traffic Flow on the CSR is not dependent upon the presence and absence of lane changes. However, there was no significant effect of Gender (p=0.234).

4.5.1.2 TDT Response Times and Percentage of Missed Signals

The TDT represents the objective workload measure used in this study. The mean response times and percentage of missed signals rate for the total of 6418 datapoints collected were analysed using a three-way repeated ANOVA (Traffic Flow, Lane Change Presence, Gender), respectively. For TDT response time, no significant main effects were found. There was no significant interaction between Traffic Flow and Lane Change Presence as well as no significant effect of Gender.

Of the 36 participants, 9 made no errors (i.e. missed stimuli) during the driving scenarios and only 4 participants made more than 15 errors (out of a maximum of 189 stimuli). Missed rate was calculated based on the percentage of missed stimuli within each Traffic Flow per participant. The results indicate that the average percentage of missed stimuli increased significantly with the increasing Traffic Flow ($F(2.14,72.88)=7.059$, $p=0.001$, $\eta^2=0.172$) and the Lane Change Presence ($F(1,34)=7.087$, $p=0.012$, $\eta^2=0.172$) (Figure 4.11). No significant effect of Gender as well as interaction between Traffic Flow and Lane Change Presence was found.
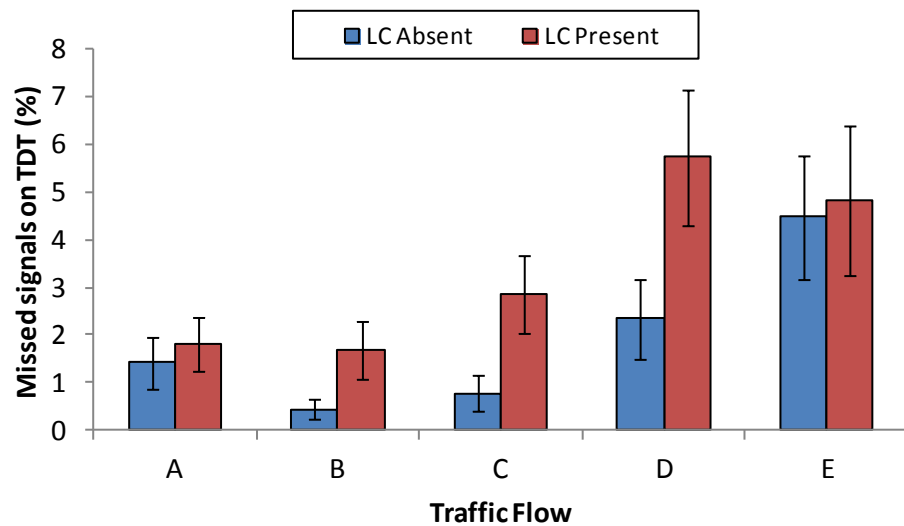
Figure 4.11: Mean TDT percentage of missed signal (with standard errors)

4.5.1.3 Blink Frequency, Blink Duration and Pupil Diameter

In addition to CSR and TDT, other objective measures were evaluated to determine their suitability for use as measures of workload. Eye movement activity metrics such as blink frequency and pupil diameter could serve in this capacity, by evaluating whether they were sensitive to the changes in traffic demand such as Traffic Flow and Lane Change Presence. The average pupil diameter change, mean number of blink per second and blink duration were measured throughout the drive. Since CSR and TDT were administered while the eye behavioural data were collected, a factor of Workload Measure was also examined to investigate whether the workload measures had an effect on these eye behavioural data. Thus, a four-way (2x5x2x2) repeated ANOVA was computed for each of the measure with Workload Measure, Traffic Flow and Lane Change Presence as within-subject factors and Gender as between-subject factor.

Results showed that blink frequency did not vary with Workload Measure (p=0.380), Traffic Flow (p=0.114) and Lane Change Presence (p=0.595). These null effects of workload measure, traffic flow and lane change presence were also present for the blink duration (Workload Measure, p=0.986; Traffic Flow, p=0.768; Lane Change Presence, p=0.326) and average pupil diameter change (Workload Measure, p=0.338; Traffic Flow, p=0.117; Lane Change Presence, p=0.732). Workload Measure did not take part in any significant interactions suggesting that it has a consistent effect on eye behaviour across the range of experimental conditions tested. Additionally, the non-significant main effects of Traffic Flow and Lane Change Presence suggest that the eye behaviour measures were not sensitive to the manipulation in traffic complexity. Similar to findings using workload measures of CSR and TDT, there was no significant effect of Gender on eye behaviour. No two, three or four way interactions were found.

4.5.1.4 Driving Performance

The effect of Workload Measure, Traffic Flow, Lane Change Presence and Gender on longitudinal and lateral measures of driving performance were analysed in this section. Each of the longitudinal and lateral data was analysed with a four-way ANOVA with Workload Measure, Traffic Flow and Lane Change Presence as within-subject factor and Gender as the between-subject factor.

Mean Speed and Standard Deviation of Speed

The four-way ANOVA described above found a main effect of Traffic Flow on average mean speed ($F(1.79, 61.00)=193.108$, $p<0.001$, $\eta^2=0.850$) and standard deviation of speed ($F(2.52, 76.55)=59.106$, $p<0.001$, $\eta^2=0.635$).

The mean trend is consistent with the traffic complexity effect, with increasing Traffic Flow causing a decrease in driving speed. This is because as traffic builds up, drivers were forced to cruise less. Post-hoc pairwise comparison analysis found that all significant differences ($p<0.001$) between the Traffic Flow (A to E). A similar trend was also found with main effect of Lane Change Presence on average mean speed ($F(1,34)=48.737$, $p<0.001$, $\eta^2=0.589$) and standard deviation of speed ($F(1,34)=113.63$, $p<0.001$, $\eta^2=0.770$). As drivers responded by rapid adjustment of own speed (for example, shown by lower average mean speed) in the presence of lane changes, this led to greater variations in mean speed in higher traffic complexity conditions.

Since the main effect of Workload Measure did not approach significance for both mean speed ($p=0.06$) and standard deviation of speed ($p=0.41$) which suggests no significant difference between the two dataset for CSR and TDT, the whole dataset for both mean speed and standard deviation of speed is shown in Figure 4.12. No significant interaction between Traffic Flow and Lane Change Presence on standard deviation of speed and mean speed suggesting that the main effect of Lane Change Presence is prominent regardless of Traffic Flow and vice versa. No two-way, three-way or four-way interactions reached significance.
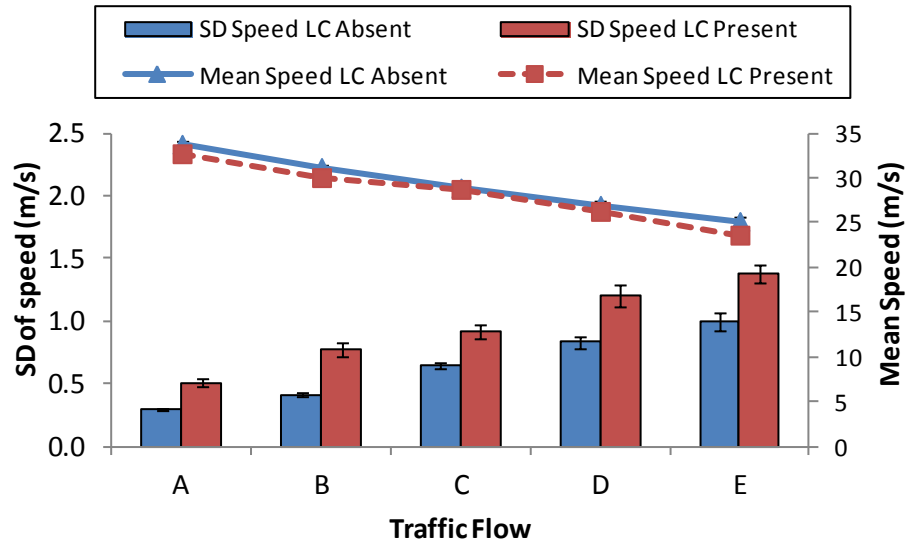
Figure 4.12: Mean and standard deviation of speed (with standard errors)

Mean Distance and Time Headway

For the headway measures, there was significant effect of Traffic Flow, $F(1.13, 38.36)=239.20$, $p<0.001$, $\eta^2=0.876$) on mean distance headway. Post-hoc pairwise comparison analysis found that all comparisons showed significantly lower distance headway with increasing Traffic Flow conditions.

Taking into consideration of the drivers' driving speed, there was also a significant main effect of Traffic Flow on drivers' time headway ($F(1.79, 60.97)=154.571$, $p<0.001$, $\eta^2=0.820$). Post-hoc comparisons showed that time headway was significantly different only in Traffic Flow A to C. Beyond Traffic Flow C, drivers' did not achieve significantly lower time headway with increasing traffic flow. This indicates that drivers had compensated the reduction in distance headway in increasing traffic flow by reducing their driving speed, which thus resulted in non-significant reduction in time headway between Traffic Flow C, D and E.

There was also main effect of Lane Change Presence on mean distance headway, ($F(1,34)=135.864$, $p<0.001$, $\eta^2=0.800$) and time headway ($F(1,34)=46.864$, $p<0.001$, $\eta^2=0.580$), respectively. Results showed that mean distance was smaller in the presence of lane changes but participants generally kept an overall larger time headway. There were no significant main effects of Workload Measures and Gender on the headway measures.

Significant two-way interactions of Traffic Flow x Lane Change Presence on headway measures were found; distance headway (F(1.72, 58.37)=31.119, p<0.001, η^2=0.478) and time headway (F(2.55,86.57)=11.89, p<0.001, η^2=0.259). To examine the interaction of Traffic Flow and Lane Change Presence, simple effects analysis involving pair-sampled t-tests were conducted separately for distance headway (Table 4.10) and time headway (Table.4.11).

T-test results of mean distance headway revealed significant effect of Lane Change Presence in all Traffic Flow conditions whereby significant reductions in mean distance headway were observed when lane changes were present (Table 4.10). Pearson's correlation coefficient (r) was used to give a measure of the effect size for each significant results (Equation 4.1). All five Lane Change Presence effects were strong, accounting for at least 34% - 64% of the variance in the data.

$$r = \sqrt{\frac{t^2}{t^2 + df}}$$

Equation 4.1: Paired sample t-test effect size calculation
(calculated using Field, 2005, pp. 294)

Table 4.8: Paired sample t-test comparisons of Lane Change Absent and Lane Change Present distance headway

Traffic Flow	Mean difference of distance headway (m)	t	Sig.	Effect size (r)
A	106.32	t(35)= 7.784	**<0.001**	0.796
B	46.16	t(35)= 6.752	**<0.001**	0.752
C	17.36	t(35)= 4.900	**<0.001**	0.638
D	11.98	t(35)= 4.230	**<0.001**	0.582
E	11.78	t(35)= 5.709	**<0.001**	0.694

With Lane Change Present, the mean distance headway is reduced by an average of 106.33m (95% CI - 78.60m to 134.06m) in Traffic Flow A to 11.78m (95% CI – 7.59m to 15.97m) in Traffic Flow E (Figure 4.13).
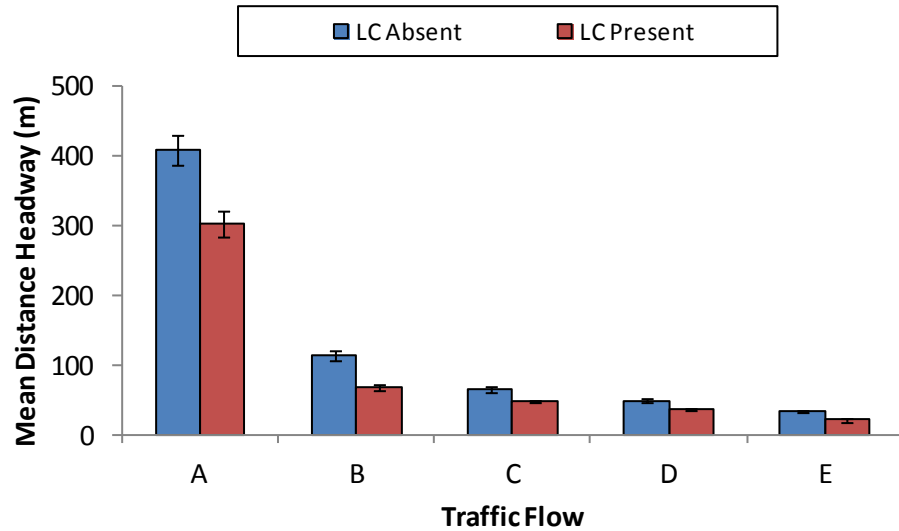
Figure 4.13: Mean distance headway (with standard errors)

For time headway (i.e. headway with consideration of drivers' driving speed) measure, t-tests results showed that the effect of Lane Change Presence was significant for all Traffic Flow conditions except Traffic Flow D (p=0.114) and Traffic Flow E (p=0.062) (Table 4.11). The mean increment in Traffic Flow A (M=3.35s) was the highest in comparison to other traffic flow conditions (B and C). As the time headway in LOS A is larger than a threshold of 6 s (which is considered as non-car following), LOS A is therefore excluded from Figure 4.10 for a better representation of data from LOS B to LOS E. Although participants kept a longer mean time headway whenever lane changes were present (as shown in Figure 4.14), this effect of Lane Change Presence was non-significant in Traffic Flow D and E.

Table 4.9: Paired sample t-test comparisons of Lane Change Absent and Lane Change Present time headway

Traffic Flow	Mean difference of time headway (s)	t	Sig.	Effect size (r)
A	-3.353	t(35)= -6.874	**<0.001**	0.757
B	-0.569	t(35)= -5.132	**<0.001**	0.655
C	-0.172	t(35)= -2.524	**0.016**	0.393
D	-0.852	t(35)= -1.621	0.114	0.264
E	-0.722	t(35)= -1.929	0.062	0.310
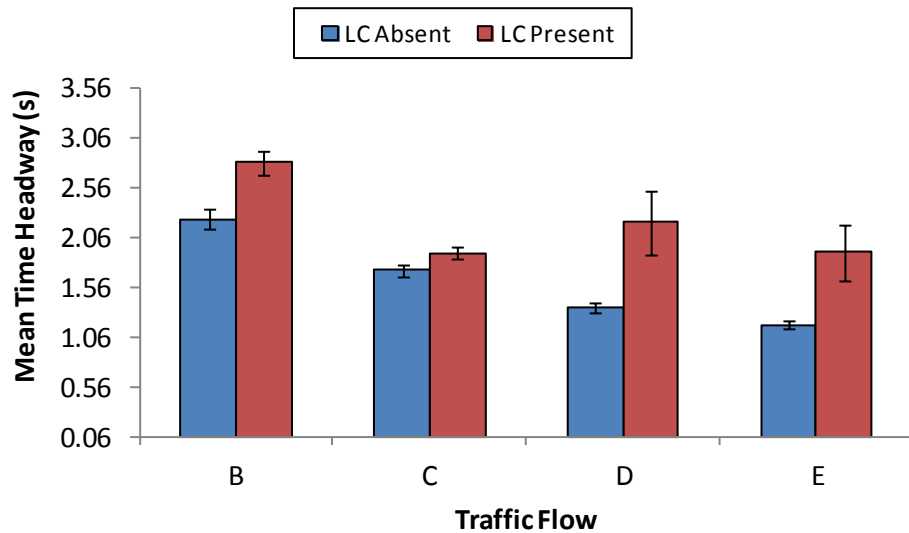
Figure 4.14: Mean time headway (with standard errors)

Standard Deviation (SD) of Lateral Position

Analysis of the lateral measures data (i.e. high steering frequency component and SD of lateral position) showed that there was significant main effect of Traffic Flow ($F_{(4,136)}$=5.397, p<0.001, η^2=0.137) on standard deviation of lateral position. Post-hoc pairwise comparison analysis found only significant differences between the lowest Traffic Flow A and non-adjacent Traffic Flow pair (C and D). All other comparisons showed non-significantly higher deviation in lateral position in response to higher Traffic Flow conditions (Figure 4.15).
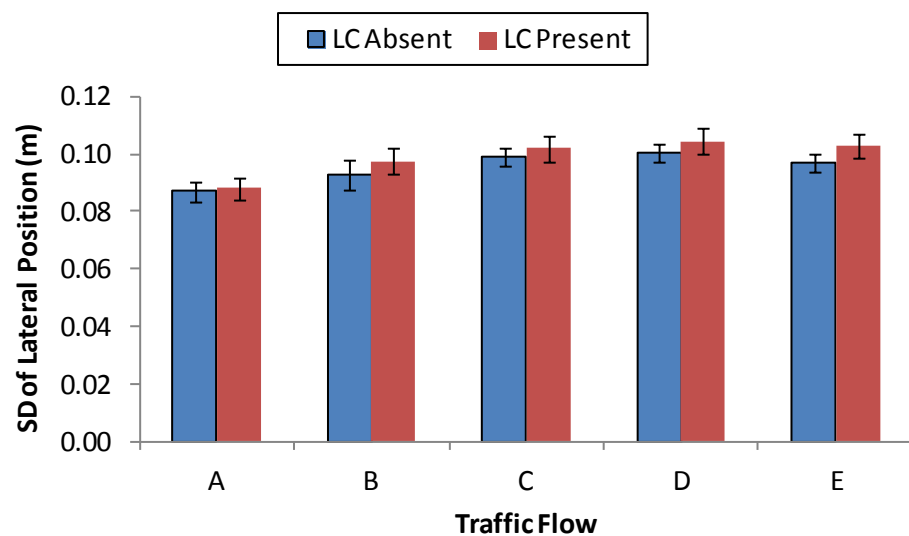
Figure 4.15: SD of lateral position (with standard errors)

It is worth nothing that the SDLP values presented in Figure 4.15 were values derived from the means of small segments (i.e. every 252m). Although the SDLP values are smaller than commonly reported values (i.e. 0.15 m to 0.25 m) due to the averaging, the main effect of Lane Change Presence ($F_{(1,34)}=5.592$, $p=0.024$, $\eta^2=0.141$) was also found to approach significance, thus indicating that participants deviated more in lateral position when lane changes were present (M=0.103m) than when absent (M=0.093m).

Although there was no main effect of Workload Measure, there was a significant two-way interaction of Workload Measure and Lane Change Presence ($F_{(1,34)}=6.29$, $p=0.017$, $\eta^2=0.156$). Simple effect analysis of the significant interaction effect involved paired sample t-test comparison of Lane Change Present and Lane Change Absent standard deviation of lateral position for each workload measure (CSR and TDT). Results showed that the effect of Lane Change Presence on standard deviation of lateral position only significant for CSR, $t(35)=-3.97$, $p<0.001$ with an effect size of 0.557. On average, participants deviated 0.012m (95% CI - 0.006 m to 0.018 m) more during presence of lane changes than they did during non-lane change conditions. For TDT, the increment in SD of lateral position was however non-statistically significant ($p=0.175$) (Refer to Figure 4.16). No other two-ways, three-way or four-way interactions reach significance.
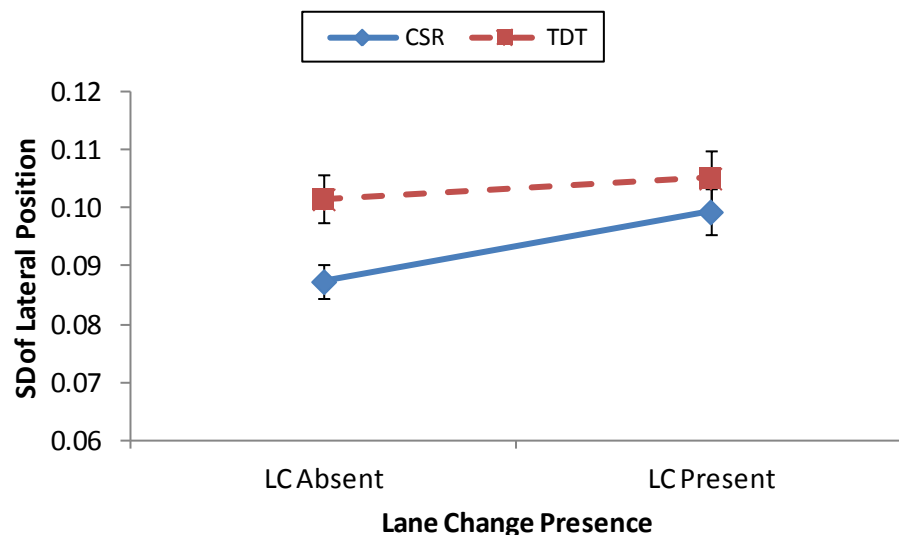
Figure 4.16: SD of lateral position (with standard errors) by Workload Measure and Lane Change Presence

In regards to high steering frequency component measure, no significant main effects and interactions of the independent factors were found.

4.5.1.5 Summary of statistical ANOVA analysis

The summary of the statistical ANOVA analysis for each of the measure is provided in Table 4.12 for comparison purposes. Results of the statistical analysis were found to be similar for both Drive A (CSR as workload measure) and Drive B (TDT as workload measure) whereby the associated measures showing significant main effects of traffic behaviours were similar, regardless whether the driver was conducting CSR or TDT task. This shows that the workload measures do not influence the driving behaviour.

Results on overall have indicated the sensitivity of CSR of tapping into the changes in traffic complexity. Few driving parameters such as speed, headway and lateral position, were found to vary with the independent variables, suggesting a possible relationship between the workload measures and the driving parameters in certain traffic complexity conditions. To investigate the relationship between the workload measures and driving parameters, correlations were computed in Table 4.13.

Table 4.10: Summary of ANOVAs for each measure

Measures	Data	Workload Measures $F(1,34)$			Traffic Flow			Lane Change Presence $F(1,34)$			Gender $F(1,34)$		
		F	Sig.	η^2	F	Sig.	η^2	F	Sig.	η^2	F	Sig.	η^2
Workload Measures	CSR				F (3.02,102.6)=124.98	**0.00**	0.79	45.76	**0.00**	0.57	1.47	0.23	0.04
	RT				F(2.51,85.26)=2.24	0.10	0.06	0.15	0.70	0.01	0.61	0.44	0.02
	ER				F(2.14,72.88)=7.06	**0.00**	0.17	7.09	**0.01**	0.17	2.02	0.17	0.06
Eye Measures	MBF	0.79	0.38	0.02	F(2.15,73.01)=2.20	0.11	0.06	0.29	0.60	0.01	4.73	0.08	0.10
	BD	0.94	0.34	0.03	F(2.55,86.97)=0.11	0.77	0.00	0.47	0.33	0.01	0.03	0.91	0.00
	ACP	1.94	0.34	0.05	F(4,136)=1.94	0.12	0.05	0.12	0.73	0.01	0.07	0.79	0.00
Driving Performance	MSP	3.89	0.06	0.10	F(1.79,61.00)=193.11	**0.00**	0.85	48.74	**0.00**	0.59	0.57	0.46	0.02
	SDSP	0.71	0.41	0.02	F(2.52,76.55)=59.11	**0.00**	0.64	113.63	**0.00**	0.77	1.62	0.21	0.05
	DHW	0.09	0.76	0.00	F(1.13,38.36)=239.20	**0.00**	0.88	135.86	**0.00**	0.80	0.12	0.73	0.01
	THW	0.99	0.33	0.03	F(1.79,60.97)=154.57	**0.00**	0.82	46.86	**0.00**	0.58	0.02	0.88	0.00
	HFS	0.44	0.512	0.01	F(1.09,37.10)=2.08	0.16	0.06	3.52	0.07	0.09	0.02	0.90	0.00
	SDLP	3.50	0.07	0.09	F(4,136)=5.40	**0.00**	0.14	5.59	**0.02**	0.14	0.63	0.43	0.02

Note: 1: **BOLD** denotes significance < 0.05

4.5.1.6 Correlations between workload measures and behavioural parameters

Figures presented in the cells in Table 4.13 are Pearson correlation coefficients; correlations which are significant at level 0.01 and 0.05 are highlighted in bold. As shown in Table 4.13, the workload measures correlated with the behavioural data (both objective and physiological measures) in certain traffic complexities. A comparison between Table 4.9 in Section 4.4.2 and Table 4.13 showed that relationships between certain measures were found to be more significant in certain traffic conditions when road sections were categorised by Traffic Flow (i.e. Traffic Flow was categorised according to the LOS, refer to Section 4.2.3(i)). For example, in Table 4.13, relationships between CSR and speed measures (i.e mean and standard deviation of speed) were found to be more significant in Traffic Flow B-D. Prior to this technique of categorising the traffic demand, presence of such relationship could only be generalised as being present in medium and high traffic complexity (as shown in Table 4.9). With a more refined way of categorising the data, the inherent fluctuation of Traffic Flow to be taking into consideration and thus enables the workload peaks to be detected by certain measures more accurately.

On overall, both the ANOVA analysis and correlations have shown strong indications of CSR being a better measure than TDT in tapping into the traffic demand manipulated in this study. Only CSR was also found to be sensitive to effect of traffic behaviour, namely the presence of lane changes. Therefore, only significant measures such CSR and driving performance parameters were explored in the following Section 4.5.2 Effects of Lane Change Characteristics.

Table 4.11: Pearson correlations between the workload measures and behavioural parameters

Workload Measures	Data	Lane Change Absent					Lane Change Present				
		Traffic Flow A	Traffic Flow B	Traffic Flow C	Traffic Flow D	Traffic Flow E	Traffic Flow A	Traffic Flow B	Traffic Flow C	Traffic Flow D	Traffic Flow E
CSR	*Eye Behaviour Measures*										
	MBF	-0.18	-0.20	-0.15	-0.14	-0.17	-0.06	-0.18	-0.06	-0.25	-0.35*
	BD	-0.05	-0.02	-0.03	-0.06	-0.08	-0.11	-0.08	-0.01	-0.03	-0.04
	ACP	0.07	0.12	0.05	0.02	0.09	0.12	0.02	0.14	0.018	0.11
	Primary Task Performance										
	MSP	-0.01	-0.31*	-0.31*	-0.32*	-0.31*	-0.09	-0.33**	-0.35**	-0.31**	-0.29
	SDSP	0.15	0.30*	0.41**	0.49**	0.33	0.06	0.50**	0.58**	0.52**	0.33
	DHW	-0.35*	-0.07	-0.01	-0.06	-0.15	-0.43**	-0.19	-0.03	-0.06	-0.28
	THW	-0.35*	-0.04	-0.05	-0.11	-0.15	-0.38**	-0.15	-0.04	-0.07	-0.33*
	HFS	0.08	-0.15	-0.07	0.01	0.05	0.11	0.000	-0.07	0.35*	-0.13
	SDLP	0.15	0.18	0.32*	0.46*	0.44*	0.04	0.03	0.14	0.43*	0.46**
RT	*Eye Behaviour Measures*										
	MBF	-0.24	-0.22	-0.15	-0.01	-0.20	-0.35*	0.00	-0.20	-0.22	-0.18
	BD	-0.04	-0.08	-0.11	-0.07	-0.18	-0.14	-0.09	-0.04	-0.07	-0.08
	ACP	0.03	0.15	0.12	0.00	0.13	0.45**	0.08	0.08	0.03	0.25
	Primary Task Performance										
	MSP	-0.30	-0.17	-0.01	0.10	0.29	-0.05	-0.35	0.13	0.11	-0.05
	SDSP	-0.17	0.30	0.19	-0.01	-0.01	-0.03	0.46**	0.18	0.05	0.28
	DHW	-0.30*	-0.30	-0.02	-0.01	-0.21	-0.34*	-0.04	-0.03	-0.24	0.27
	THW	-0.27*	-0.08	-0.18	-0.11	-0.14	-0.16	-0.01	-0.04	-0.09	-0.01
	HFS	-0.06	-0.06	0.13	-0.04	-0.07	-0.01	0.06	0.13	-0.02	0.08
	SDLP	-0.33*	-0.07	-0.22	-0.6	0.04	-0.07	-0.18	-0.19	0.11	0.03

Note: 1. Figures shown in cell are correlation coefficients

2. * denotes the correlation is significant at the 0.05 level, ** denotes the correlation is significant at the 0.01 level.

3. Abbreviations: CSR = Continuous Subjective Ratings, RT = Tactile Detection Task Reaction Time,

MBF = Mean Blink Frequency, BD = Blink Duration, ACP = Average Change of Pupil Diameter,

MSP = Mean Speed, SDSP = Standard Deviation of Speed, DHW = Distance Headway, THW = Time Headway,

HFS = High Frequency Steering, SDLP = Standard Deviation Lateral Position

4.5.2   Effect of Lane Change Characteristics

Given that the presence of lane changes has an impact on driver workload and driving performance, further analyses were undertaken to establish what characteristics of the Lane Change Proximity and Lane Change Direction (see Section 4.2.3) were included as relevant characteristics of the lane change that affected workload. This analysis was only computed for the CSR measure and the corresponding driving parameters which were shown to be significantly influenced by the presence of lane change in the previous section (i.e standard deviation of lateral position, mean and standard deviation of speed as well as distance headway and time headway). With regards to Lane Change Proximity, the near-zone was defined as the area between the participant's vehicle and the immediate lead vehicle (569 lane changes took place here), whilst the far-zone was defined as the area between lead and preceding lead vehicle (2147 lane changes) (see Figure 4.3). The lane changes performed by neighbouring vehicle were also categorised by Lane Change Direction (Towards or Away) (refer Figure 4.3) which is dependent on whether the vehicles were moving away from the participant's lane or towards it. However only 31 participants experienced both characteristics of lane changes, therefore data for the 5 participants were excluded.

To examine the influence of the characteristics of a lane change, only mutually exclusive conditions were considered. Data relating to occurrence of lane changes in both zones were excluded to ensure that the effect of near-zone lane changes on driver workload can be differentiated from the effect of far-zone lane changes. Two way repeated ANOVA showed a significant main effect of Lane Change Proximity, ($F_{(1,30)} = 8.445$, $p<0.005$, $\eta^2=0.236$) on CSR scores. When the lane change occurred in the near-zone, CSR scored were higher than when the lane changes occurred in the far-zone (Figure 4.17). There was, however, no significant main effect of Lane Change Direction on CSR ratings. No significant interaction between Lane Change Direction and Proximity was found.
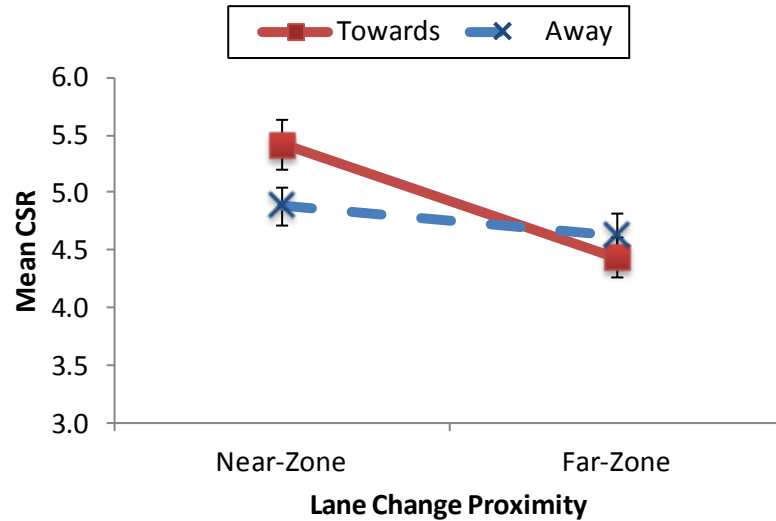
Figure 4.17: Mean CSR (with standard errors) by lane change characteristics

Although no significant effect of Lane Change Direction was found on any of the performance measures, there was an effect of Lane Change Proximity on mean speed $(F(1,30)=19.586, p<0.001, \eta^2=0.395)$ and standard deviation of lateral position $(F(1,30)=8.430, p=0.007, \eta^2=0.219)$. Results indicate that participants drove at a lower mean speed of 2.182m/s and performed more poorly in maintaining lateral position with an average increase of 0.024 m when experiencing lane changes in the near-zone. Although other factors such as the criticality of these lane changes (for example, time-to-collision at which they occur) could offer an explanation to changes in primary task performance, this factor was not explored further due to insufficient data for statistical testing. Table 4.14 shows a summary of the main effects of Lane Change Proximity and Lane Change Direction on the workload and driving performances.

Table 4.12: Summary of ANOVAs for each measure with respect to Lane Change Characteristics

Measure	Proximity			Direction		
	F(1,30)	Sig.	η^2	F(1,30)	Sig.	η^2
CSR	8.445	**0.002**	0.236	1.180	0.286	0.038
SDLP	8.430	**0.007**	0.219	0.000	0.990	0.000
MSP	19.586	**0.000**	0.395	0.215	0.647	0.007
SDSP	1.864	0.182	0.059	1.409	0.245	0.045
DHW	0.421	0.521	0.014	3.341	0.078	0.100
THW	0.425	0.519	0.014	3.066	0.090	0.093

Note: **BOLD** denotes significance < 0.05

4.6 Discussion

The present study investigates the relationship between dynamic traffic behaviour factors and workload measures and compares the sensitivity of different workload assessment techniques in measuring the momentary traffic complexity.

4.6.1 Influence of traffic flow

Measures of self-reported workload elicited after each of three twenty-minutes drives significantly increased as Traffic Complexity increased. Based on the correlations between the three subjective workload measures (RSME, NASA-TLX and CSR) and objective performance measure (TDT reaction times), it can be concluded that the CSR is a reliable measure of overall driver workload as shown by its significant correlations with the widely validated uni-dimensional RSME ($r=0.720$, $p<0.001$) and multi-dimensional NASA-RTLX ($r=0.739$, $p<0.001$) workload scales.

To further establish the feasibility of using different modality of measures to tap into workload changes, the subsequent analysis of temporal fluctuations (by 252m road section) in workload involved dividing the road into 252 m sections. Each road section was characterised by its momentary traffic flow and lane changes. Among the three measures, namely CSR, TDT and eye measures, only CSR was found to vary in the hypothesised direction, increasing systematically as traffic flow increased. Schieβl (2008b), who also found similar results, argued that mental load is higher in high traffic flow due to drivers being restricted in the actions available to them. Feedback from the post-study interviews in the present study indicated that participants rated workload higher when they experienced a 'boxed-in' effect with the presence of the vehicles, especially heavy goods vehicles in dense traffic. Participants also indicated higher ratings when a highway maintenance vehicle (misjudged as a traffic police vehicle) was present in the nearby surroundings. Other traffic factors which influenced their ratings included frustration when traffic was operating at non-normal speed i.e. when vehicles in the slow lane were moving faster and more freely than in the fast lane. The driving performance measures demonstrated changes in longitudinal and lateral control, an effect that was linear up to moderate traffic. However from moderate traffic to high traffic density conditions,

the driving task is more heavily influenced by other vehicles that required participants to adapt their speed and headway distance with respect to the surrounding traffic. Thus continuous control input from the driver as measured by the longitudinal driving performance measures such as standard deviation in speed and average headway may imply fluctuations in driver workload.

The two TDT measures on the other hand, were found to respond differently in different Traffic Flow conditions. TDT reaction times were found to vary only within low traffic complexity conditions (i.e. Traffic Flow A and B). Despite variation of demand in traffic flow conditions, the TDT response times were unable to differentiate the Traffic Flow conditions as good as using the subjective rating. A possible explanation for this might be that responding to the TDT stimuli does not require an evaluation of the driving demand and therefore performance in this task may be associated with other factors rather than workload from variations in traffic complexity. In this study, the measure of TDT percentage of missed signal was however found to be more sensitive than the reaction times whereby the percentage of errors increases with Traffic Flow. Literature indicating that the percentage missed signals measure being slightly more sensitive than the response times measure in detecting changes in the attentional demand, can be found in some studies that utilised the peripheral detection task (Martens and van Winsum, 2000; Feenstra, Hogema and Vonk, 2008) (see Section 2.2.1.2(ii) for a description of the peripheral detection task). However, these studies utilised the method to measure attentional demand imposed by the secondary task, rather than the primary task demand (i.e. traffic flow) as measured in this study. Moreover findings may vary depending on the design of the study and therefore, Van der Horst and Martens (2010) recommended that both measures (i.e, reaction time and percentage error) should be used when utilising an event-detection task for reliable conclusions to be made.

In addition to the measures discussed, eye behaviour measures were also found to be non-significant to the main effects of density and lane changes. Although there is a decreasing trend in the number of blinks and an increment trend in average pupil change with increasing traffic demand by visual inspection, these were statistically non-significant. The dual resource; mainly visual and cognitive aspect, utilised while driving in a dynamic changing environment may possibly provide an

explanation for these findings. In general, drivers not only have to monitor the traffic but also make hypotheses and predictions about the roadway situation. Due to these conflicting effects, these demands may have impacted on the overall eye behaviour measures, for example increment of the relevant amount of visual attention required by the driving task could lead to blink reduction (Recarte et al., 2008) but interaction with the surrounding traffic can be stressful and may contribute to an increment in blink rate. Studies have shown that blink rate slows after relaxation while increased in blink rate generally reflects negative mood states such as nervousness, stress and fatigue (Tecce, 1992). Moreover, the NASA-RTLX questionnaire findings in this study had also indicated an increase in frustration in relation to higher traffic flow. Therefore, the increase of visual demand and emotions (i.e. frustration) elicited in demanding traffic may off-set each other's effects, resulting in non-significant effects on measures of eye behaviour.

4.6.2 Influence of the presence and characteristics of lane changes

Additionally, this study not only wished to establish how the flow of traffic influenced workload, i.e. the number of vehicles that drivers were required to monitor, but also whether the specific behaviour of those vehicles was influential. Whilst undoubtedly there are other behaviours that can be considered, such as a lead car braking, we chose to focus on lane changes due to the relative lack of research observed in the literature. Moreover, drivers reported increases in workload when a lane change occurred in their forward field of view, with further increases when that lane change occurred in close proximity. This is congruent with the notion of a safety margin (Endsley, 1995) which influences a driver's interactions with other road users under normal driving conditions (e.g. distance keeping) and in their risk assessment if a critical situation occurs. This concept was first conceived as the "field of safe travel" by Gibson and Crooks (1938) and later adapted by e.g. Kontaratos (1974) who defined two safety zones (termed collision and threat zones). If another vehicle entered these zones, then the driver undertakes an emergency reaction. Ohta (1993) defined these safety margins as four zones, with the most critical being when a following vehicle is within 0.6 s of a lead vehicle. In this zone, drivers experience feelings of being in danger of colliding with the vehicle ahead.

Ahead of this critical zone is the danger zone (0.6 s to 1.1 s headway) whose upper border corresponds to the minimum subjective safe following distance. The normal (or comfort) driving zone then extends to 1.7 s headway, beyond which is the pursuit zone.

In the current study, among the two lane change characteristics investigated; Lane Change Proximity (Near-Zone, Far-Zone) and Lane Change Direction (Towards, Away), only Lane Change Proximity was found to have significant effect on CSR. The lane change events occurred in all four levels of lane change characteristics), thus allowing the possibility of measuring the criticality of these lane changes and evaluating the effect of this factor on driver workload. Investigation of the near- and far- zone lane change indicates that proximity of an event has an influence on driver's perceived workload. On average, driver's workload rating was approximately one-point higher in the events of presence of lane changes in higher traffic demand conditions. Additionally there were significant standard deviation of lateral position in response to the proximity of the lane changes. Table 4.15 below indicates that standard deviation of lateral position and subjectively perceived difficulty is higher in the presence of lane changes within the near-zone. An investigation of the criticality of the lane changes with near-zone may provide some explanation on the influence of lane changes, but there were insufficient number of data to conduct any inferential testing.

Table 4.13: Descriptive statistics and paired-sample comparison of Lane Change Proximity

Measure	Mean (SD)		Paired-sample t-test		
	Near-Zone	Far-Zone	t(30)	Sig.	Effect Size (r)
CSR	5.111 (1.245)	4.556 (1.196)	3.235	0.003	0.508
SD of lateral position (m)	0.102 (0.024)	0.080 (0.036)	2.924	0.007	0.471
Mean speed (m/s)	30.293 (2.149)	32.476 (1.895)	-4.426	<0.001	0.628

Results from the post-study questionnaire (refer Appendix III) also supported the findings above whereby 50% of the participants indicated that the factor of 'adjacent vehicle pulling into your lane' as the most important factor in influencing their driving task difficulty (i.e. subjective workload ratings). The factor of 'lead vehicle braking' was rated by 58.3% of the participants as the second most important

factor influencing driving task difficulty. Additionally, 11% of the participants indicated both factors as the main influencing factor. Overall, the 'number of vehicles in front' is the least prioritise in the perceived driving task difficulty as compared to the behaviour of imminent traffic such as adjacent and lead vehicle. Figure 4.18 shows the percentage distribution of the four factors in influencing participants subjective ratings. Below are example of comments from the participants in explaining these findings;

Participant 2:   *'Sudden lead vehicle braking and adjacent vehicle pulling into your lane are both main priority as I usually prioritised based on whether the lead vehicle or adjacent vehicle is nearer when changes occur.'*

Participant 4:   *'Adjacent vehicle plays a big role as I can adjust my braking when lead vehicle speed changes. But unpredictability of adjacent vehicle moving in and out the lane requires me to monitor more often.'*

Participant 13: *'I would say the adjacent vehicle pulling into your lane. The black BMW pulled into my lane when I wasn't aware that I had to brake to avoid collision. That certain made me more aware of the traffic around throughout the drive.'*

Participant 27: *'I disliked vehicle pulling into my lane because I need to adjust speed accordingly. Thus I would rather change lane following an experience.'*

Participant 33: *'I usually keep a long distance from the lead vehicle and constantly check of up to 3 vehicles ahead of me. I gave higher ratings when the adjacent vehicle moved in and out without signalling.'*
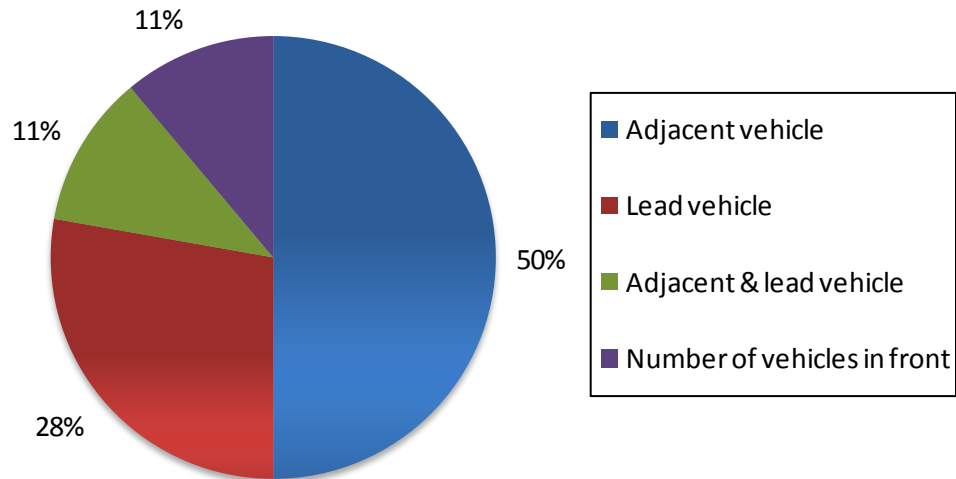
Figure 4.18: Most important factor in influencing driving task difficulty

4.6.3 Sensitivity of Workload Measures

This study shows that workload is a multi-dimensional and multi-faceted construct whereby sensitivity of measures were found to vary according to the demand of traffic behaviours. Although self-report measures can be prone to response bias (for example, Green et al. (2011) found ratings tended to be clustered at lower ends of the range and significantly favoured rounded numbers), this issue was not found in this study as sufficient piloting was conducted to ensure that the scale can provide diagnostic value. The simple CSR method developed in this study was found to be capable of differentiating the level of workload and had proven to have high-face validity (as indicated by the high correlations with the highly validated RSME and NASA-RTLX). Findings in this study have shown that this method can be used not only in assessing the effect of traffic on driver workload but also measuring these effects in real-time.

On overall, TDT did not demonstrate the same sensitivity as CSR in measuring traffic effect. While studies have prove the sensitivity of TDT in detecting change in cognitive load associated with secondary tasks (Engström, 2010), this measure was however not found to be sensitive in detecting short-lasting variations changes in workload associated with changes in traffic demand manipulated in the present study. Similarly, the physiological measures utilised (i.e. blink frequency, blink duration and average pupil diameter) in this study did not vary with the

fluctuations in driving demand, possibly due to these measures being more suitable to tap into other types of effort. Moreover, it is possible that these physiological measures are more suitable for measuring workload over a longer period of time (rather than a short time interval i.e. 8s as measured in this study).

From the selected candidates of measures investigated in this study, CSR was the only measure that was found to be sensitive to all levels of Traffic Flow. Using a simplified rating scale (10-point rating), verbal ratings were collected on a frequent basis, requiring participants' to actively assess their own workload. Therefore, participants' subjective appraisal of their "feeling" of workload could be measured real-time using this technique. Additionally, relationships between CSR and vehicle parameters such as speed, headway and standard deviation of lateral position, could be found in certain traffic conditions. Apart from being indicators of the vehicle status, these parameters can be good indicators of workload change and were found to be in agreement with the CSR with respect to the changes in traffic demand. Although CSR were found to be sensitive to the influence of traffic flow across the different LOS, TDT was found to discriminate low traffic demand conditions only (as indicated by the correlations with driving performances). With a more refined way of categorising the data (by LOS and Lane Change Presence), results on the sensitivity of measures are more conclusive, whereby CSR was found to be comparatively more sensitive than TDT to the influence of Lane Change Presence. Moreover, some participants failed to respond to TDT but there were no observations of participants failing to respond to the prompt for CSR. This is possibly due to the interaction of the noise and vibration environment within the vehicle in the virtual environment that could lead to participants being less sensitive to the TDT stimuli, which further support the decision to adopt CSR as a tool to measure workload in subsequent experiments (Chapter 5 and Chapter 6). Despite the fact that there are indications that TDT is a sensitive method of measurement for cognitive workload (Engström, 2010), future research is still needed in order to specify some absolute criterion against which driving demand can be accurately determined, particularly in the context of international standardization.

Brookhuis et al. (2003) highlighted that each measure of driving performance has its value in determining the differing level of driver impairment. In other words, it is possible to capture changes in momentary workload from vehicle control

parameters. For example, CSR can be used to benchmark the relevant situations and apparent improvement or deterioration in several vehicle control parameters such as steering performance, speed maintenance, etc. can be examined. Jamson (1999) suggested that steering behaviour can be used as an indicator of driving experience and therefore it is possible that drivers' momentary workload can be estimated from a variety of refined indicators such as steering reversal rate and steering entropy or other indicators such as headway maintenance (Carsten, 2007). The ability to estimate drivers' momentary workload from vehicle control parameters (based on measures from several vehicle sensors) would help improve the management of driver workload in real-time and thus preventing driver overload.

4.7 Implications of Study for the Thesis

This study has indicated that categorising the traffic complexity variables that influence driver workload and driver performance may prove useful in estimating driver workload as traffic demands could now be determined and weighted accordingly. Results from this study have validated CSR as a simple method for measuring real-time driver workload and have indicated traffic behaviour (i.e. Lane Change Presence) as being more important than Traffic Flow in causing high workload. Following the findings from this study, lane change characteristics could be explored further to examine the varying criticality on driver workload. Since this study showed that driving task related to changes in the traffic such as weaving traffic may increase momentary driver workload as measured subjectively and objectively, this factor can be examined further by taking into consideration of other variables affecting the influence of a lane change. The impact of the lane change on driver workload warrant further study based on this investigation.

While current study has shown the influence of lane change characteristics on driver workload, further research is needed to examine these lane change characteristics, such as lane change proximity, the origin of the pulling-in vehicle and the use of indicator, more systematically. This is to ensure that the increase in driver workload in this study is not a consequence of experimental settings and these changes can be tapped into more accurately in a more systematically manipulated driving environment. For example, this study was unable to accurately measure the

impact of a lane change as the workload rating obtained was a reflection of the overall driver workload every 8s interval, and not when the lane change occurred.

Additionally, interference from an in-vehicle task presented during a lane change event should be considered, especially to determine whether lane change effect on driver workload is shown in dual-task driving scenarios. If the presence of a distracter task during lane change events can have an effect on driver workload, there is a possible merit in the prioritising the in-vehicle task to reduce the lane change effect.

To conclude, understanding of possible problematic traffic behaviours may help in optimising the design of a real-time workload estimator which considers not only the driver's distraction within the vehicle but also the dynamic workload resulting from surrounding traffic demand. Assessing and predicting poor performance states on a moment-to-moment basis would be useful towards improving an individual's performance level, particularly on tasks such as driving which requires ongoing vigilance and decision-making. As such, both of these characteristics will aid the design of a workload manager that is reliable and acceptable to drivers.

Chapter 5

The Influence of a Lane Change Performed by a Neighbouring Vehicle on Driver Workload and Performance

5.1   Study Aims

This chapter reports on the second of the three studies presented in this thesis and examines whether drivers can assess their own level of workload and where appropriate, delay their response to a secondary task. The study again uses a motion-base, high fidelity driving simulator and seeks to explore the findings detailed in Chapter 4 with regards to the effect of lane changes on workload. The aims of the study are:

- To determine the magnitude of the effects of a lane change in a single-task scenario by systematically manipulating three lane change characteristics, namely the distance gap from the participant vehicle during the cut-in (5m, 10m, 15m, 20m, 25m, 30m), location or lane origin of the neighbouring vehicle (slow lane, fast lane) and use of the indicator by the neighbouring vehicle before the start of the lane change (indicator on, indicator off).

- To quantify the influence of the varying lane change behaviour performed by neighbouring vehicle on driving difficulty using the subjective workload ratings and objective driving performance. Additionally, workload recovery time, i.e. the time required for the participant to recover from each increase in driving demand associated with the lane change presence is examined both subjectively and objectively.

- To explore whether drivers would modify or regulate their driving behaviour to reduce the driving difficulty. For example, whether drivers would delay or postpone their engagement in a secondary task (i.e. exhibit adaptive behaviour) such that they coincided with the lower driving demands.

5.1.1 Study rationale

Based on learning and experience within this rather complex social environment, drivers develop their own expectations for the self and others following their experience of the typical speed, volume, flow and style of traffic within their area. One of those expectations that develop over time is the desired proximity to other vehicles.

Personal spaces has been defined as "the area immediately surrounding an individual, which is regarded as his or her own" (Sommer, 1959). Depending on the environment and social factors, this personal space varies in size and serves to avoid arousal and overload, minimise stressors, privacy, as well as serving as a form of defence and protection from harm (Fisher et al., 1984). The notion of personal space in a traffic environment (also commonly known as driver space) was introduced more than 20 years ago (Marsh and Collett, 1987). Recent studies have shown that personal space can extend from the body to possessions such as computer (Bassolino et al., 2010) and extend visually far from the body through extrapersonal space (Holmes and Spence, 2005). Similarly, driver space may also extend beyond the physical boundaries of the vehicle itself, and the mobility and variability of this space make it especially unique. However driver space in the rapid context of the traffic environment may be too subjective and too variable for specific dimensional measurement or identification of spatial evaluations. For example, drivers in specific traffic would adjust expectations based on the situation (i.e. drivers generally prefer a large space, but under a bumper-to-bumper traffic situation would adjust expectations to a smaller size based on the situation) (Hennessy et al., 2011). As such, it would be useful in understanding how drivers perceive these driving situations (measured via workload) and their interaction with the other road users in order to establish the situational factors that can accurately determine driver workload level and to predict the performance degradation following an event.

To help drivers manage difficult situations on road, traffic safety researchers and automobile system engineers are looking into developing intelligent system to regulate driver workload in varying traffic situations. These potentially demanding situational factors could be incorporated the workload manager 'watch-list' as these scenarios can be detected or monitored via the radar or sensors readily available in a

vehicle. Data captured by the vehicle can be leveraged to determine the amount of external demand and workload upon a given time and apply an intelligent decision-making system (i.e. a workload manager) to simplify the driving experience.

One issue of pressing importance following the findings reported in Chapter 4 regarding traffic behaviour is what characteristics of a lane change performed by a neighbouring vehicle influences driver workload and if so can the magnitude of this influence in fact be measured. Previous research has found that drivers would alter space preference. For example, under crowded conditions, drivers expected lower personal space (Baum and Greenberg, 1975). However, traffic congestion would alter interpretations and reactions of drivers (for example, increasing driver stress, revenge motivations and aggressions) and research predicted that the size of driver space preference would thus be greater in higher congestion conditions. This is in line with the finding of Lewis-Evans et al. (2010) who found that the feelings of risk, task difficulty and discomfort in a simulator increase only when drivers were within 2.0 seconds of another vehicle, while Fraine et al., (2007) found that some drivers identified cutting in and tailgating as a "violation of personal space". As Chapter 4 in this thesis has shown that the driver workload increased in the presence of lane changes possibly due to the influences on driver's personal space, this present study attempted to explore this effect by examining the fluctuation in temporal workload across a variety of lane change situations (i.e. whether the driver obtains information from the surrounding traffic either explicitly through use of formal signals such as the indicator, or implicitly through their behaviour such as positioning on the road).

Studies have already established the effect of distracter tasks on workload and driving performance and this study is looking to build on this by assessing the fluctuations in driver workload and driving performance in traffic events involving a cut-in performed by an adjacent vehicle. This study also attempted to explore the driver's self-regulating behaviour in respond to additional distracter task in varying lane change conditions. For example, will the drivers be able to recognise their own workload in dual-task conditions and possibly delay their response to answering a mobile phone call in high workload conditions. In recent years, workload manager systems have been developed for vehicles, in order to manage distractions within the vehicle during driving; this study attempts to extend this work albeit in specific conditions relating to lane changes. Research has showed that the effects of task

interruptions occurring during driving are disruptive and further magnified when the interruption involves a secondary task requiring driver response (Monk et al. 2004). For example, while studies have shown that conversing using a hands-free mobile phone during motorway driving increases subjective workload (Parkes et al. 1993; Alm and Nilsson, 1994) and heart rate (Brookhuis et al., 1991), Lerner and Boyd (2005) found that drivers are not dissuaded from engaging in a series of in-vehicle activities even in challenging and traffic-heavy driving situations. Similarly, a questionnaire survey conducted by Lansdown (2012) found that 32.4% of surveyed drivers use hands-free mobile during a typical week and would still attempt to use it despite being aware that this activity is distracting.

5.1.2 Experimental hypotheses

- The primary experimental hypothesis is that subjective workload ratings will vary according to the three lane change characteristics; lane change proximity, lane origin of the cutting-in vehicle and indicator usage. Firstly, it was hypothesised that the nearer the lane change cut-in occurs, the greater driver workload will be. Secondly, there will be differences with respect to the origin of the pulling in-vehicle i.e. between vehicle pulling in from the slower lane and from the faster lane. Thirdly, driver workload is moderated by the use of the indicator i.e. driver workload is lower when the neighbouring vehicle uses the indicator use prior to starting the lane-change.

- The secondary experimental hypothesis is that driver response to the secondary distracter task would not vary across lane change conditions. This hypothesis was constructed based on the question whether drivers are sensitive to the increased task demands as reflected in drivers' ratings of workload.

5.2 Pilot Study: Testing of Scenarios

There were two aims of this pilot study. Firstly, piloting was conducted to test the script and the realism of the lane change characteristics simulated. Secondly, it was hoped that the piloting would provide some evidence of whether the use of an auditory prompt is efficient for measuring workload variation in relation to the lane change characteristics manipulated.

5.2.1 Participants

Participants consisted of twelve experienced male drivers, recruited on the basis of a volunteer sample scheme, drawn from both an existing database, responses to University of Leeds' website and local poster advertisement seeking volunteers. Participants were aged between 25 to 40 years old (mean age = 31 years, SD age = 5.15 years) and they all possessed a valid UK driving license and had been driving regularly for the previous 5 years with a minimum annual mileage of 10,000 miles. Drivers were awarded a payment of £15 for their participation.

5.2.2 Apparatus

The study used the same apparatus as utilised in Study 1, which was the motion-base, high-fidelity University of Leeds Driving Simulator. The driving simulator's vehicle cab is a complete 2005 Jaguar S-type model with all driver controls fully operational. Participants had full control of the longitudinal and lateral motion of the vehicle and were encouraged to operate the controls as they would in their own vehicle. The vehicle is right-hand drive and uses an automatic transmission (refer Chapter 4, Section 4.2.1 for the description of the simulator controls and sound systems).

5.2.3 Method

5.2.3.1 Experimental Design

A three-lane motorway was simulated with occasions of adjacent vehicle (either from the slow or the fast lane) pulling in front of the participants. Vehicles in the slow lane were programmed to maintain 60mph while fast lane vehicles travelled at 70mph. Three characteristics of the lane changes performed by the neighbouring vehicles were manipulated: Lane Change Proximity (5, 10, 15, 20, 25 or 30 metres in front of the participant), Lane Origin(Slow or Fast Lane) and Indicator Usage (On or Off). The adjacent vehicle was programmed to pull in at a certain distance measured as the gap (LC_p, measured in metres) between the participant vehicle and a cutting-in vehicle as shown in Figure 5.1. To minimise fatigue, the lane change events were divided into two shorter drives; each contained twenty-eight events involving a mix of lane change conditions to avoid predictability of the event. The two drives were counterbalanced among the participants.
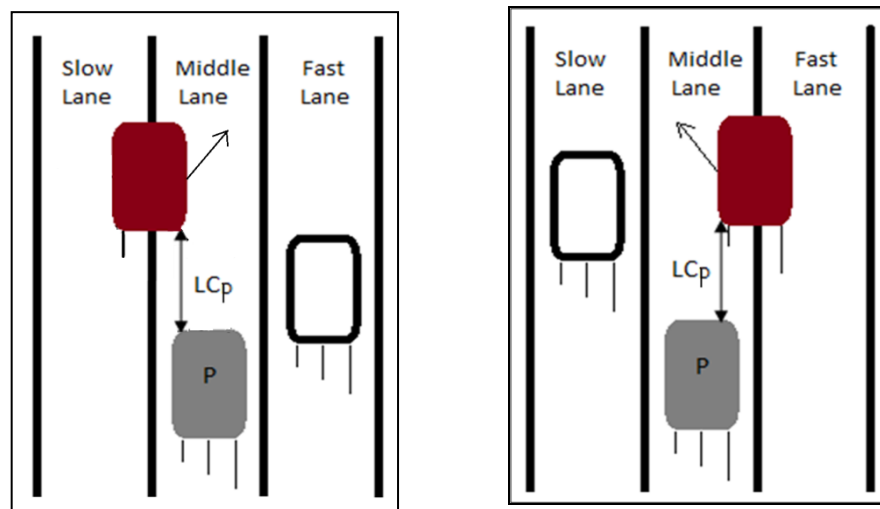
Figure 5.1: Lane change descriptions showing vehicle overtaking either from slow lane (left figure) or from fast lane (right figure), LC_p = Lane Change Proximity, P= participant vehicle

5.2.3.2 Traffic Manipulation

Traffic was dynamically scripted to change lanes when certain conditions were met (e.g. available gap). To ensure that the workload measured accounted for all possible scenarios, a mix of lane change events originating either from the fast or slow lane, with and without use of indicator was provided. Drone vehicles had their indicators switched on approximately 1.9s before crossing the lane divider. To ensure that the indicator usage was visible, the respective drone vehicle was always ahead of the participant vehicle before starting the lane change manoeuvre. There was an average buffer period of forty nine-seconds between the lane changes to eliminate cross-contamination effects.

5.2.3.3 Rating Task

For the rating task, participants were prompted with an audible beep to provide a rating between 1-10 to indicate their overall workload based on the events which they had recently experienced or any events that had occurred since the last rating (approximately seven seconds). The rating scale consisted of a 1-10 point scale and was explained verbally to the participants as follows, "Please provide a rating on how easy or difficult to drive in the traffic. Low difficulty is between 1 to 3, medium difficulty is between 5 to 6 and high difficulty is between 8 to 10". Baseline ratings were collected at the start of the drive (ten data points) before the first lane change event and at the end of the drive (ten data points). The lane changes and audible 'beep' prompts were scripted such that the ratings of the driving difficulty were collected continuously before and after a lane change. With these ratings, the relative changes in driver workload (pre-, during and post-lane changes) can be examined. ***Relative Workload*** was defined as the difference between pre-lane change rating and during-lane change rating. A ***Workload Recovery Period*** was also calculated, defined as the total time taken to achieve a constant workload (i.e. the level of workload ratings achieved and has not changed since the last three ratings of workload) or baseline workload (i.e. the level of workload measured at the start of the drive), following a lane change.

5.2.3.4 Procedure

Upon arrival at the simulator, participants were given the participant briefing sheet and a consent form to fill in. Following a short briefing on the study, participants conducted a short practice drive to ensure that they were adept at handling the vehicle controls and familiar with the task involved. Participants were instructed to maintain at 65mph in the middle lane and not pass the new 'lead vehicle'. After completing a 15 minutes practice drive, the participant then performed the first experimental drive and periodically the rating task. After completion of the first drive, they were given a short break to freshen up before they were allowed to conduct the second drive. Following the completion of the second drive, participants were then debriefed and paid for their time.

5.2.4 Examination of Subjective Workload

The relative changes in driver workload (pre-, during and post-lane changes) were examined. ***Relative Workload*** was defined as the difference between pre-lane-change rating and during-lane-change rating. A ***Workload Recovery Period*** was also calculated, defined as the total time taken to achieve constant workload or baseline workload, following a lane change.

5.2.4.1 Effect on Relative Workload

The data were tested for normality and suitability to conduct ANCOVA testing. Since the data fulfilled all the assumptions for ANCOVA including the assumption of homogeneity of regression slopes (i.e. no interaction between the covariates and the independent measures, a three way repeated measure (6x2x2) ANCOVA with the baseline workload at the start of the drive as the covariate (baseline) was used to examine the effect of the independent measures on Relative Workload (RW). Assumption of sphericity was violated and Greenhouse Geisser correction was used. Workload at the start of the drive was used as the covariate.

After accounting for the covariates, significant main effects of Lane Change Proximity (F(1.996,19.958)=36.430, p<0.001, η^2=0.928) and Lane Origin (F(1,10)=8.428, p=0.001, η^2=0.657) on Relative Workload were found. Effect of indicator use was however non-significant (p=0.226). Post-hoc pairwise comparisons of the Relative Workload across the Lane Change Proximity indicated that the effect of lane change distances on Relative Workload was significant up to 20 m; beyond this distance the effect started to plateau. Participants overall experienced higher Relative Workload when encountering a pull-in from the slower lane compared to pull-in from the faster lane (Figure 5.2). There was however no interaction between Lane Change Proximity and Origin of the Overtaking Vehicle.
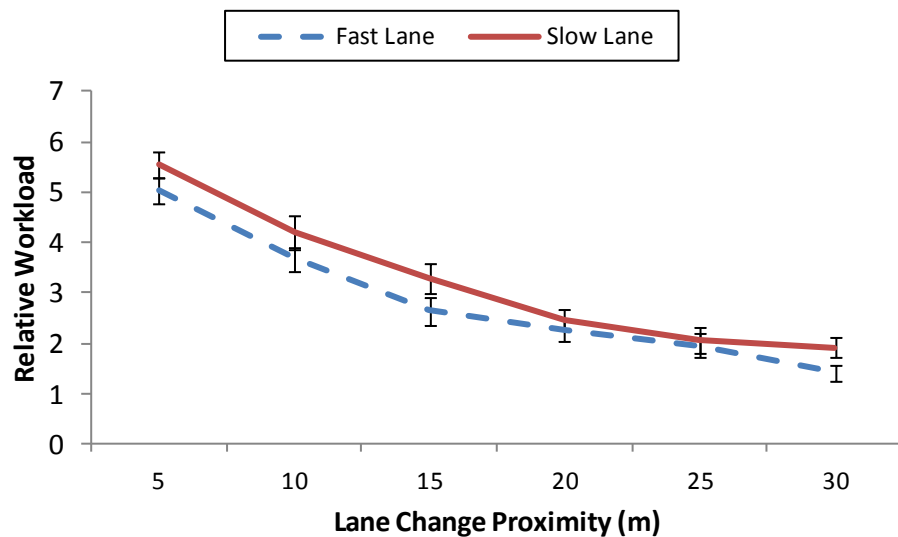
Figure 5.2: Relative Workload (with standard errors) in pilot study

5.2.4.2 Effect on Workload Recovery Period

The Workload Recovery Period (WRP) was measured as the time elapsed from the point the lane change occurred to the first instance the baseline workload ratings were achieved or constant static workload, was achieved (i.e. the point where the reduction of workload ratings remained constant for last three workload ratings). The latter was measured as there were occasions where workload did not reduce to baseline.

Data were examined for normality and a three way (6x2x2) repeated ANOVA was conducted to examine for the effect of Lane Change Proximity, Lane Origin and Indicator Usage. Similar to the finding on Relative Workload, a main effect of Lane Change Proximity ($F(5,55)=11.894$, $p<0.001$, $\eta^2=0.574$) on Workload Recovery Period was found. Post-hoc pairwise comparisons demonstrated that the effect of Lane Change Proximity significantly influenced driver's recovery time between Lane Change Proximity 5 and 20m.

Additionally, there was also a main effect of Lane Origin ($F(1,11)=5.218$, $p<0.001$, $\eta^2=0.326$) on Workload Recovery Period. Pairwise comparisons indicated that drivers in general took a few seconds longer to recover from the lane change originating from the slow lane (M=13.177s) in comparison to lane changes originating from the fast lane (M=11.776s) (Figure 5.3). No significant main effects of Indicator Usage and interactions between the independent variables on Workload Recovery Period were found.
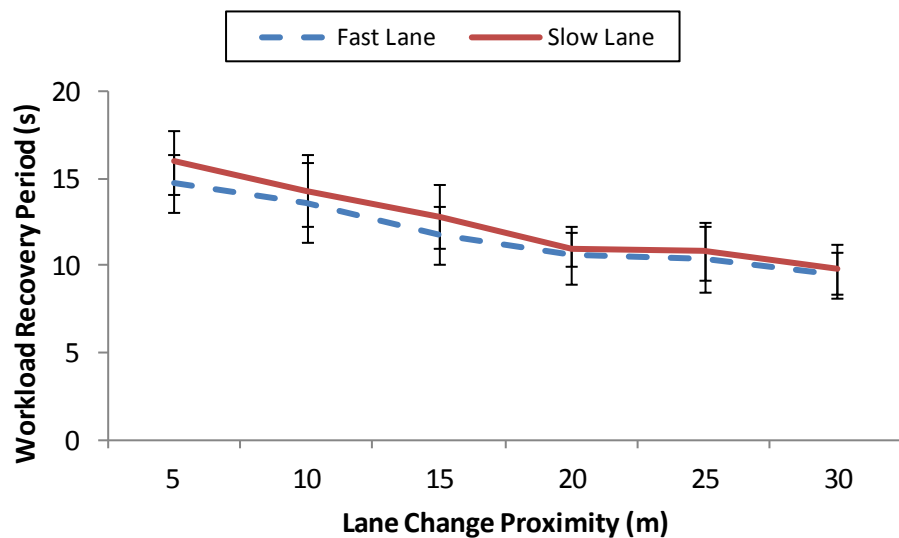
Figure 5.3: Workload Recovery Period (with standard errors) in pilot study

5.2.5 Implications of the Pilot Study

Results of the pilot study showed that even with a very small sample size, the design was sufficiently sensitive to differentiate the effect of proximity of lane changes (i.e. criticality). The examination of Relative Workload and Workload Recovery Period suggested that the presence of a lane change was influenced by the different characteristics of the lane change: mainly the Lane Change Proximity and possibly Lane Origin of the overtaking vehicle.

A modification to the simulator script in the study was added following the findings from the pilot study. In the pilot study, the drone vehicle started moving away from the participant's vehicle two seconds after pulling-in to create gap for the preparation of the next lane change to occur. Although this increases the probability of a lane change occurring, it reduced the realism of the lane changes experienced on-road. To improve the realism of the lane change events, the pulling-in drone vehicles were scripted to stay in front of the participant's vehicle for ten seconds after pulling-in.

To examine how would drivers react in response to a secondary task such as an incoming mobile phone during varying Lane Change Proximity and Lane Origin, a third drive was added into the main study. In this drive, an incoming phone alert was given simultaneously to the lane change. The participants were required to respond to the incoming mobile phone call when they perceived the driving demand as low and thought if appropriately safe to conduct the task. To take into account of driver's experience and their preference for using mobile phones while driving, only drivers who use hands-free while driving were recruited in the subsequent study.

5.3 The Main Study

The main study in this chapter focused on the research questions that was examined in the pilot study in a higher scale (i.e. larger number of participants).

5.3.1 Participants

Twenty-eight users of hands-free mobile phones drivers were recruited via responses to the University of Leeds' website and local poster advertisement seeking volunteers. Twenty four participants successfully completed the study with ages ranging between 24 to 45 years old (mean age = 32.2 years, SD age = 6.05 years: 14 males, 10 females). Four participants did not complete the study due to simulator sickness. The minimum number of participants selected was based on a power analysis using sample size and effect size from the pilot study dataset. Participants were permitted to take part in the experiment if they held a valid UK driving license and had been driving regularly for the past five years with a minimum annual mileage of 10,000 miles. Participants were randomly allocated to a particular trial order. Drivers were awarded a payment of £20 for their participation. The study advertisement offered a £15 reward with a further £5 based on performance. The reward was used to motivate participants to engage with the task. However, every participant received the full reward payment, regardless of performance.

5.3.2 Method

Stimuli, procedure, apparatuses and experimental conditions were the same as those used in the pilot study, with the following additions:

- *Traffic script*: The difference concerning the traffic script in the present experiment was that the adjacent vehicle was scripted to stay in front of the participant's vehicle for ten seconds after pulling-in.

- *Experimental design*: The difference regarding experimental design was that each participant in the present study was required to complete three drives (as compared to two drives in the pilot study), each lasting approximately thirty minutes. The first two drives were the same as in the Pilot Study which involved only the rating task and were counterbalanced among the

participants. Following the completion of the second drive, participants were given a briefing regarding the third drive and the nature of the secondary task involved. The secondary task was added into the third run to investigate how drivers would respond to a distracting task in varying lane change conditions. Since the participants were unaware of the true purpose of the study and to ensure participants were fully familiarised with the traffic behaviour (following one hour of interaction with the traffic in the driving simulator), the drive involving the secondary task was administered as the last drive for every participant.

- *Apparatus*: Due to the absence of synchronized voice recording capabilities in the simulator software, the dependent measures relating to the secondary vocal response task were collected manually via a voice recorder and the data were processed using the Praat audio playback program with sound spectral analysis capability. The vocal responses were recorded using a Sony ICD-200X Digital Voice Recorder attached to a Griffin Lapel Microphone. To measure the vocal reaction time using Praat, originally stored in Windows Media Audio (WMA) format, were required to be in WAV format. Therefore the recording files were converted to MP3 using the Jodix Free WMA to MP3 Converter and then followed by conversion to to WAV format using the Audacity digital audio editor. Using Praat's software sound spectral analysis capability, the sound stimulus and speech response could then be identified and thus the vocal reaction time measured to +/-1 millisecond accuracy.

5.3.2.1 Secondary task

Apart from the addition of the third run, a secondary task was used in the third run to investigate how drivers respond to a distracting task in varying lane change conditions. To assess drivers' prioritisation in dual-tasking, participants were presented with a numerical operations task as a surrogate for a phone conversation (a two choice, self-paced response task) at different times in the driving task. The mathematical operation task has been used in many previous studies (McKnight and McKnight, 1993; Shinar, Tractinsky and Compton, 2005) and has been shown to be sufficiently taxing to interfere with driving performance. In this study as in other

research (Treffner and Barrett, 2004) the decision to use mathematical problems as materials was motivated by the need for an engaging task that offers a degree of experimental control as well as cognitive effort.

In this third drive, each participant experienced six single tasks involving driving only (with lane changes) and eighteen dual-task conditions (with and without lane changes). The eighteen dual-task conditions involving the surrogate mobile phone tasks consists of six no-lane change conditions and twelve dual-task conditions (with lane changes between 5 and 30m). In dual-tasking conditions, a 'ding-dong' sound was played to indicate an incoming phone call at certain points during the drive and this prompt occurred only once. The participants were instructed to respond as they would in real life. As soon as participants responded by pressing the button on the steering wheel, five numbers were presented via the audio system, followed by a sum or product question[1]. For example,

> *9, 5, 3, 2, 1*   *What is the sum of the first and the fifth number?*
>
> *8, 4, 2, 0, 1*   *What is the product of the second and fourth number?*

The time taken to answer the call (i.e. Acceptance Time, AT), the time taken in responding with an answer verbally to the arithmetic question (Response Time, RT) and the questions answered wrongly (percentage of error) were recorded. Participants were informed that their performance on the secondary task would be monitored and rewarded based on how many questions they answered correctly. To increase the ecological validity of the driving scenario and allow participants to decide how to manage the dual-task scenarios, participants were not instructed on how to respond to a surrogate mobile phone task in the event of lane change event so as not to prime the participant on how to respond to this type of event.

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[1] According to Card, Moran and Newell (1986), the human auditory storage capacity (i.e. the capacity of the auditory image store) is 5 characters.

5.3.2.2 Procedure

Participants were required to attend the driving simulator for one testing session. They were briefed about the content of the study before giving their informed consent. Participants then drove the simulator four times, one practice run (approximately ten minutes) and three experimental runs (approximately thirty five minutes each). During the practice drive, participants were encouraged to ask questions if they were unsure of any aspect of the driving. Participants were fully debriefed on simulator safety protocol before the experimental stage of the study.

Participants performed three drives, with the first two drives aiming to evaluate workload responses to the lane change events. The first two drives; each consisting of twenty four lane change events with four non-lane change conditions to avoid predictability of the events, were counterbalanced among the participants. Prior to the start of the third drive, participants were briefed on the secondary task and shown the control button to press in the event of wanting to respond to the in-vehicle task.

Participants exited the simulator vehicle between the runs to counteract fatigue effects and to maintain the illusion of the virtual world during the set-up of the following drive. After the experiment, participants were fully debriefed and paid for their time.

5.3.3 Data Collection

Apart from the subjective measures (Relative Workload and Workload Recovery Period) as described in Section 5.2.4, three additional measures of secondary task performance and driving behaviour were collected in the present experiment.

5.3.3.1 Subjective Workload

Similar to the measures investigated in the pilot study, this present study also examined the relative changes in driver workload (i.e. Relative Workload) as well as the recovery time (i.e. Workload Recovery Period) following a lane change. Based on the pilot study findings, this present study hypothesised that the Relative Workload and Workload Recovery would vary with the characteristics of the lane changes (i.e Lane Change Proximity and Lane Origin).

5.3.3.2 Secondary task performance

The Acceptance Time (AT) measured in seconds is defined as the time that elapsed between the offset of the interruption (i.e. 'ding-dong' prompt of secondary task) and the first press on the steering wheel button which indicated participants' readiness to engage in the secondary task.

Response Time (RT) which is also measured in seconds, is defined as the time taken to respond to the arithmetic question. The RT were recorded on a digital recorder and processed manually using spectral software ('Praat'). RT is the time that elapsed between the end of the voice message and the first correct answer provided by the participant, as illustrated by the following equation:

Vocal response time (RT) = Vocal response onset - End of auditory stimulus onset

Additionally, the accuracy of each of the responses was also measured (i.e. correct or wrong) for the computation of percentage error (%).

5.3.3.3 Driving Performance

This study not only wished to quantify the effect of the lane change characteristics on driver workload subjectively but also attempt to examine the effect of lane change on driving performance. To account for the influence of increased driver workload on driving behaviour, driving performance indicators such as mean speed and brake pressure were examined for each lane change event. The measurement of speed is of interest as the participants were encouraged to maintain speed at 65mph through the run. In addition, some of the lane change events manipulated in the study required the participants to brake. Therefore examination of the speed and braking may provide some illustration on how much change in vehicle control was involved in varying traffic demand situations. To examine the relationship between changes in driving behaviour with Relative Workload, the changes in driving behaviour (i.e. the difference of driving behaviour 7s before and after a lane change) were computed. For example, if mean speed 7s before a lane change is 28 m/sec, and the mean speed 7s after a lane change is 18m/sec, the relative change in mean speed of -10m/sec indicates a reduction in speed following a lane change.

Braking profiles and driving speed profiles were examined to understand better the differences between conditions. The maximum brake pressure, minimum speed and the half recovery time were computed for each traffic conditions. Half recovery time is defined as the time for participants to recover 50% of the speed that was lost during braking (e.g. if the participant's car was travelling at 28m/sec before braking and decelerated to 20m/sec after braking, then half recovery time would be the time taken for the participant's vehicle to return to 24m/sec). Since all participants were required to maintain a speed of 65mph throughout the drive, participants speed were investigated for the half recovery time following a lane change. As such, examination of driving profiles and recovery from interruption may provide better understanding on how these adjacent lane changes influences driver workload and driving performance.

5.3.4 Data Analysis and Results

5.3.4.1 Subjective Measures

Subjective measures of Relative Workload and Workload Recovery Period were examined from the first two runs (Run 1 and Run 2). The data were pooled together and the average of responses for each Lane Change Characteristics (i.e. Lane Change Proximity, Lane Origin and Indicator Usage) were computed for each participant. The data were checked for normality and homogeneity of variance using the Kolmogorov-Smirnov and Levene tests respectively and tested for sphericity for all ANOVA and ANCOVA analyses. Greenhouse Geisser correction was applied where necessary.

Relative Workload

Data were subjected to a three-way Repeated Measure ANCOVA analysis with Lane Change Proximity, Lane Origin, and Indicator Usage being the independent factors. After accounting for the workload at the start of the drive (i.e. the covariates), main effects of Lane Change Proximity, $(F(3.18, 66.70)=71.917, p<0.001, \eta^2=0.794)$ and Lane Origin, $(F(1,21)=93.513, p<0.001, \eta^2=0.873)$ on Relative Workload were found.

Similar to the findings in the pilot study, post-hoc pairwise comparisons indicated that the effect of Lane Change Proximity on Relative Workload were not significant beyond 20m, see Figure 5.4.
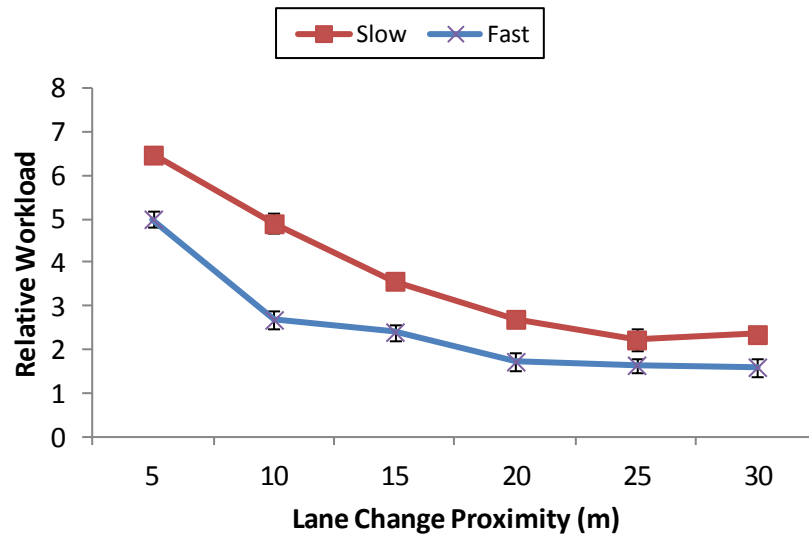
Figure 5.4: Relative Workload (with standard errors)

An effect of Lane Origin on the mean Relative Workload was found whereby change in workload was higher when drivers experienced a cutting-in vehicle originating from the slow lane (M=3.707, SD=0.307) as compared to a vehicle originating from the fast lane (M=2.514, SD=0.321). On average, participants indicated an increase of 1.193 (95% CI-1.052 to 1.335) in workload when they experienced vehicle cut-ins from the slow lane. No significant main effect of Indicator Usage was found in this study whereby driver did not report significant differences in workload depending on whether the cutting in vehicle used the indicator or not. Additionally, no two-way and three-way interactions were found.

Workload Recovery Period

Data were subjected to a three-way Repeated Measure ANOVA analysis with within-subject factors of Lane Change Proximity (5, 10, 15, 20, 25, 30m), Origin of the Lane Origin (Slow/ Fast Lane), and Indicator Usage (On/Off). Significant main effects of Lane Change Proximity, $F(2.59,59.51)=69.245$, $p<0.001$, $\eta^2=0.751$ and Lane Origin, $F(1,23)=88.452$, $p<0.001$, $\eta^2=0.794$ were found. Pairwise comparisons showed that Workload Recovery Period increased with decreasing Lane Change Proximity up to 20 m. Beyond 20m, the increase of Workload Recovery Period was not significant. Similarly, drivers recovered significantly slower after experiencing a Lane Change from the slow lane (M=17.865, SD=1.8915) as compared to the

overtaking vehicle originating from the fast lane (M=13.637, SD=1.644) (Figure 5.5).

These findings were similar to those obtained in pilot study whereby the origin of the cutting-in vehicle had an influence on the Workload Recovery Period on all lane change distances even though drivers' Workload Recovery Period was not significantly influenced by distal lane changes (i.e. lane changes which at occurred at distances beyond 20m). Among all levels of Lane Change Proximity, the workload recovery for the 30m trials is the smallest and particularly if the cutting in-vehicle originates from the fast lane. Since the minimum average workload recovery period obtained in this study is 11.188s, the minimum amount of time that a driver requires to recover from this traffic event can thus be estimated to be approximately 12 seconds.
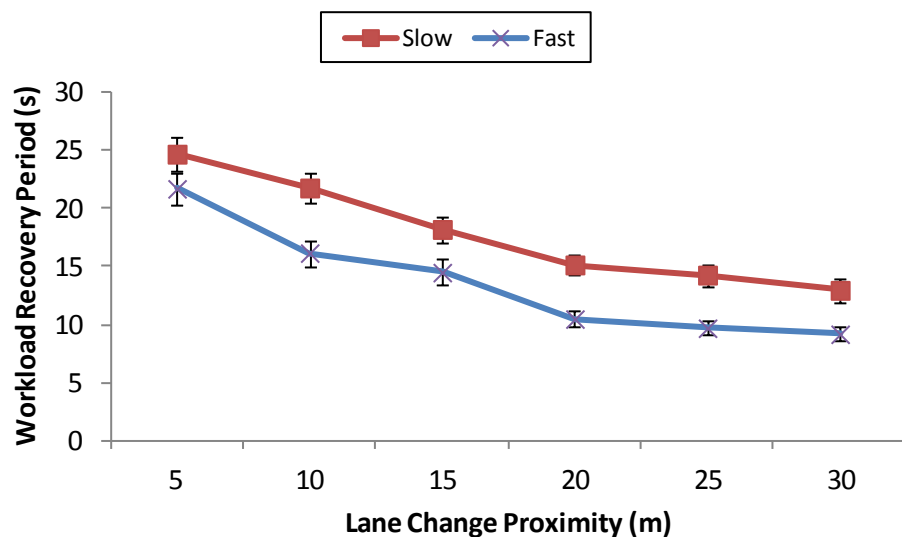
Figure 5.5: Workload Recovery Period (with standard errors)

Similar to the findings on Relative Workload, no main effect of Indicator Usage (p=0.649) was found. Pairwise comparisons of Indicator Usage showed that the recovery time for absence of Indicator Usage events (M=15.825) was not significantly higher than for presence of Indicator Usage events (M=15.677). Therefore the variable of the Indicator Usage was not investigated further. Additionally, no effect of interactions between the independent variables were found.

5.3.4.2 Secondary Task Performance

While Section 5.3.4.1 examines the effect of the presence of lane changes on driver workload, this section investigates the effect on driving behaviour and secondary task performance. This section uses the data obtained from the third run (Run 3) which investigates the manipulation of two independent variables (i.e Lane Change Proximity and Lane Origin).

Surrogate mobile phone task acceptance time

The Acceptance Time (AT) was not normally distributed. Reciprocal-transformation was effective in reducing problems relating to the skew and kurtosis of the variable distribution. Therefore, parametric testing was performed on the transformed data set. The Acceptance Time (s) data was subjected to ANCOVA with two within factors; Lane Change Proximity (six levels) and Lane Origin (two Levels) and control condition Acceptance Time (i.e. where no lane change occur) as covariates.

These analyses showed statistically significant main effects of Lane Change Proximity, $F(5,110)=16.690$, $p<0.001$, $\eta^2=0.326$ and Lane Origin, $F(1,22)=19.704$, $p<0.001$, $\eta^2=0.447$) on in-vehicle surrogate task acceptance time. Drivers initiated the in-vehicle surrogate task more slowly when the lane change performed by the neighbouring vehicle occurred at a shorter Lane Change Proximity distance. Inspection of the Figure 5.6 suggests that the effect of Lane Change Proximity on acceptance time dissipated at a longer Lane Change Proximity.
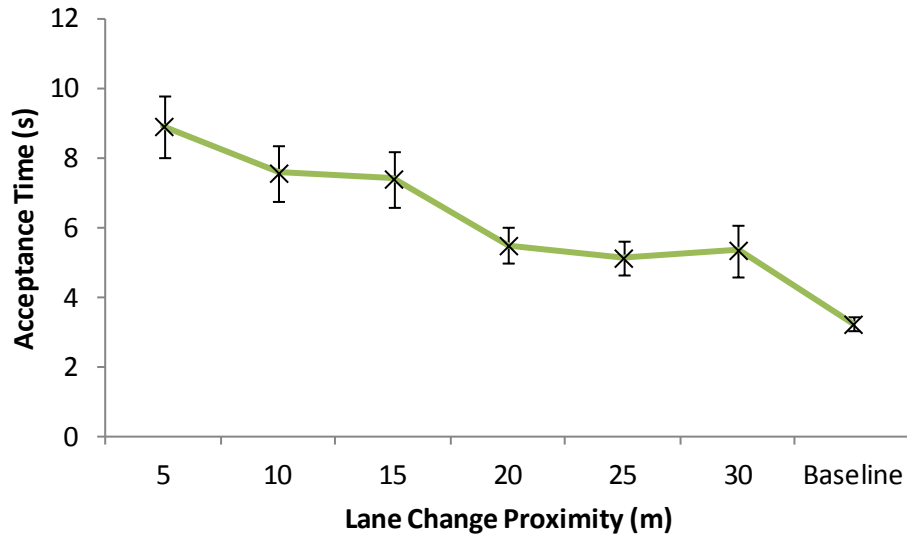
Figure 5.6: Mean Acceptance Time (with standard errors)

Post-hoc pairwise comparisons (with Bonferroni adjustments) showed that longer Acceptance Time was significantly associated with shorter Lane Change Proximity (i.e. less than 15m). Beyond 15m Lane Change Proximity (i.e. 20m, 25m or 30m), the planned contrasts results showed that the reduction in Acceptance Time were not significant. Mean Acceptance Time for cut-ins originating from the slow lane (M=7.818s) differed from those where cut-ins originated from the fast lane (M=5.560s) (Figure 5.7). The analysis showed that the interaction of Lane Change Proximity x Lane Origin on acceptance time was not significant (p=0.051).
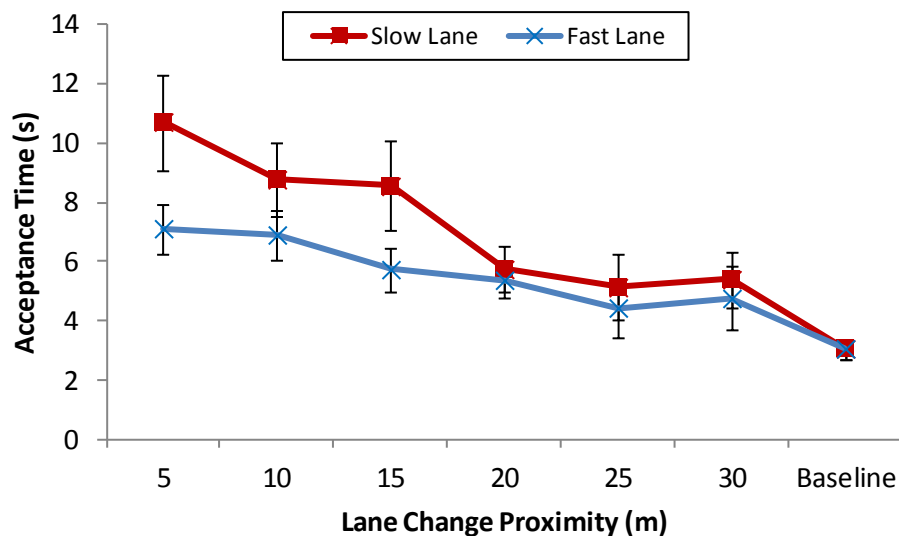
Figure 5.7: Effect of Lane Origin on Acceptance Time (with standard errors)

Secondary task response time and performance accuracy

Upon acceptance of the secondary task, the mean time taken to respond to each arithmetic question was measured. The Response Time was defined as the time elapsed from the end of the voice message until the driver responded verbally. The data were subjected to ANCOVA analysis with Lane Change Proximity and Lane Origin as within-subject variables and response time in control events as covariates. No significant main effects of Lane Change Proximity, ($F_{(3.15, 95.35)}=1.147$, $p=0.133$, $\eta^2=0.026$) and Lane Origin, ($F_{(1,23)}=11.609$, $p<0.000$, $\eta^2=0.0.447$) on Response Time were found.

Incorrect responses to the surrogate mobile phone task were rare. Each participant performed six trials involving the in-vehicle task alone (i.e. baseline) and twelve trials where it was presented concurrently with a lane change event. Of the 24 participants, only one participant made more than three errors (out of a maximum of 18). Despite the overall high level of accuracy, it is clear that, where errors did occur, they were largely confined to high demand conditions involving small Lane Change Proximity. The percent error data differed significantly from the normal distribution and transformations were ineffective for normalisation. The percent error data were therefore subjected to non-parametric analysis. Wilcoxon Signed Rank tests confirmed that differences were found between baseline and the near Lane Change Proximity scenario (5m), $T=0$, $p<0.05$. The percent error and mean response times for each of the scenarios are shown in Figure 5.8.
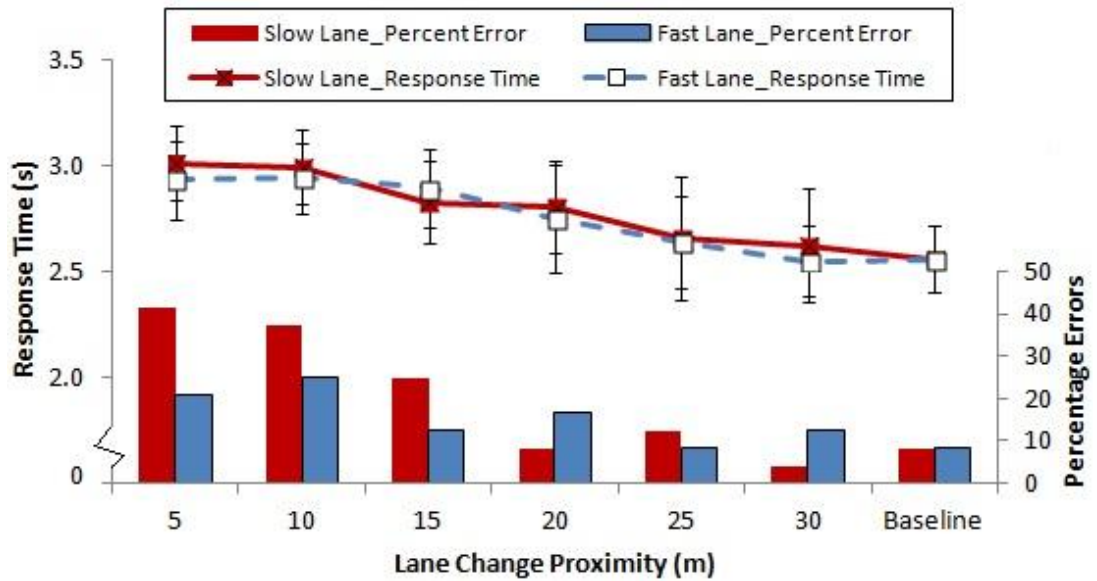
Figure 5.8: Mean secondary task response times (with standard errors) and mean error rates (right ordinate)

Since the secondary task involved a driver-paced response, the Response Times were unaffected by driving demand. Visual inspection of the number of errors from Figure 5.8 indicated that errors were highly associated to demanding traffic scenario such as Lane Change Proximity at 5m and 10m. Considered in relation to Response Time, these data indicate a speed-accuracy trade off whereby responses to the secondary task were made more quickly in the baseline situation and in conditions requiring braking but tended to be less accurate. Despite Response Times being longer under more demanding conditions (i.e. lane change at proximity of 5m), there was a marked increase in error. These findings indicate that the inclusion of a distracting task is inappropriate in certain traffic events deemed as cognitively demanding to drivers, specifically requiring drivers to brake in order to maintain their safety margin.

5.3.4.3 Driving Performance

In this section, the effects of lane change characteristics on mean speed and braking were examined. Two way repeated ANOVA analysis were conducted on the changes in mean speed and braking force across Lane Change Proximity (six levels), Lane Origin (two levels), Indicator Usage (two levels). To understand the driving performances in different conditions, the speed and braking profile were computed.

Speed

There were significant main effects of Lane Change Proximity ($F_{(3.14, 59.98)}=36.124$, $p<0.001$, $\eta^2=0.440$) and Lane Origin ($F_{(1,23)}=25.939$, $p<0.001$, $\eta^2=0.775$) on mean speed reduction. There was also a significant interaction of Lane Change Proximity x Lane Origin, $F_{(2.307,68.83)}=6.886$, $p=0.011$, $\eta^2=0.087$) (Figure 5.9) indicating a higher reduction in mean speed when experiencing a lane change from the slow lane.
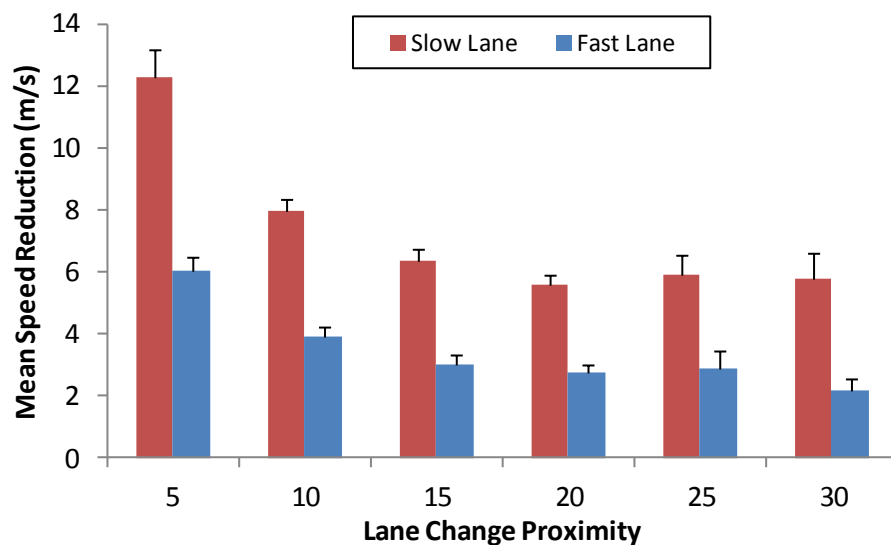
Figure 5.9: Mean speed reduction (with standard errors)

Pairwise comparisons showed that the effect was significantly different for Lane Change Proximity less than 20 m whereby drivers did not slow down when experiencing lane changes performed by an adjacent vehicle at distances beyond 20m. Similar to the findings in relation to relative workload, this suggests that the drivers were influenced by the presence of the vehicle when the cutting-in vehicle

encroached into their safety zone. On the other hand, no main effect of Indicator Usage on mean speed was found (p>0.05).

Speed profiles were examined for each independent variable (i.e. Lane Change Proximity and Lane Origin), in order to better understand the differences between conditions. Indicator Usage was not examined as this main effect was not found in any driving performance measures. Since the cutting-in vehicle started moving laterally 2 s before crossing the lane divider and stayed in front of the participant vehicle for 10 s after pulling-in, driving profiles were thus created by extracting 12s-epochs of driving performance from the onset of the cutting-in vehicle moving laterally. The data for the ensuing 12 s measured at 60 Hz were then entered into a 24x720 data matrix (i.e. on the *j*th occasion that the drone vehicle indicator on, data from the 1st, 2nd, 3rd ...and 720th observations following the onset of the drone vehicle signal lights were entered into the matrix $X_{[j,1]}$, $X_{[j,2]}$, $X_{[j,3]}$,... $X_{[j,720]}$, in which j ranges from 1 to 24 reflecting the 24 occasions in which the participant reacted to the overtaking vehicle).

Figure 5.10 presents the driving speed profiles. In the near lane change distances (i.e. 5 m and 10 m), participants began reaching minimum speed 2 s after the drone vehicle began to move laterally across the lane, whereupon participants began a gradual return to pre-braking driving speed. When traffic was demanding (i.e. lane change proximity 5 m and 10 m), participants drove more slowly; thus the shape of the speed profile differed compared to when traffic demand was low (i.e. lane change proximity between 15 m to 30 m). By contrast, when participants experienced an overtaking vehicle originating from the slow lane, it took them longer to recover their speed following braking.

Overtaking vehicle from slow lane

Overtaking vehicle from fast lane
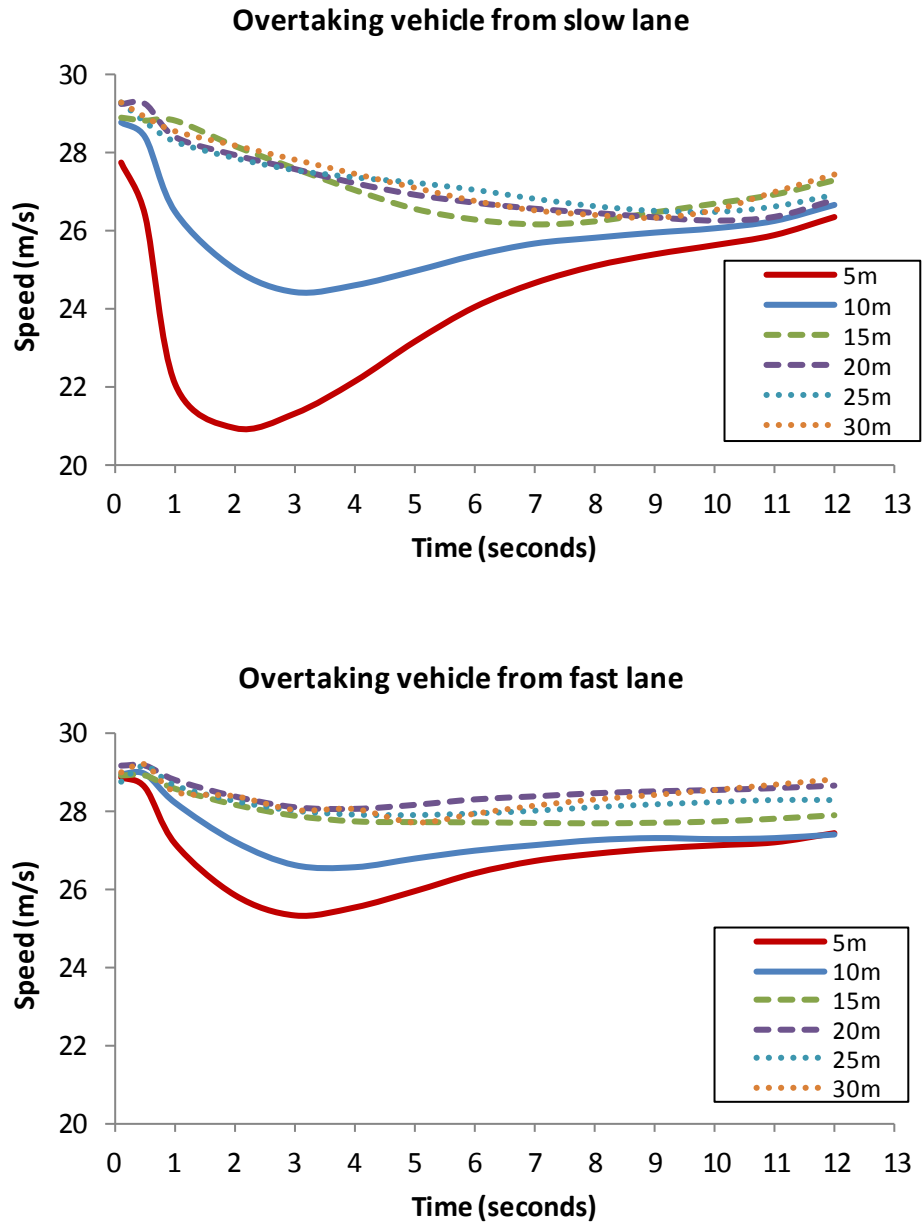
Figure 5.10: The speed profile by Lane Change Proximity and Lane Origin; slow(top) and fast (bottom)

Braking

There were significant main effects of Lane Change Proximity (F(3.352, 54.190)=12.319, p<0.001, η²=0.211) and Lane Origin (F(1,23)=21.318, p<0.001, η²=0.317) on maximum brake pressure depression. Pairwise comparisons showed a significant increase in maximum brake pressure was exerted for Lane Change Proximity between 5m and 10m (Mean difference= 10.897N, p=0.013). Figure 5.11 shows the distribution of relative change in Maximum Brake Pressure where significant higher brake pressure was applied when the overtaking vehicle originated from the slow lane within 10m.
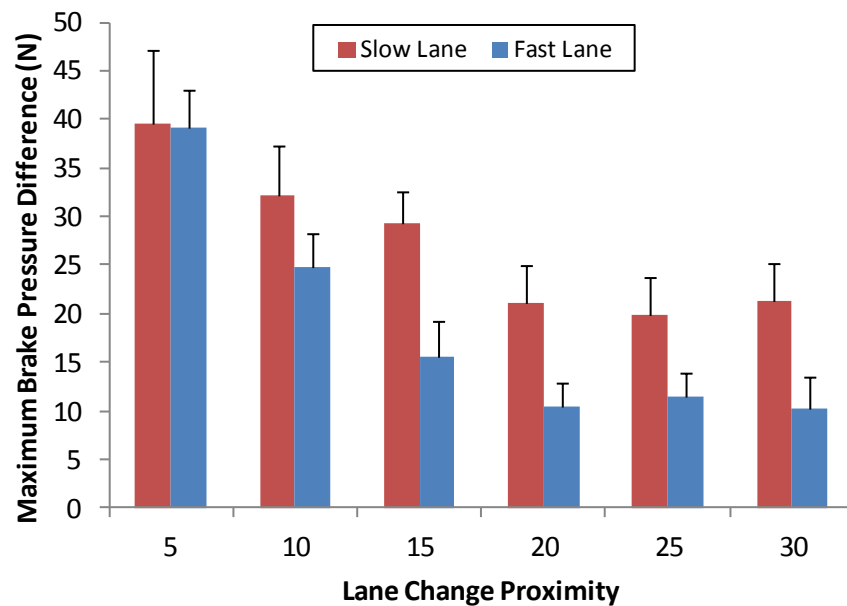
Figure 5.11: Maximum Brake Pressure Difference (with standard errors)

Figure 5.12 presents the braking profiles of different lane change characteristics. As illustrated, participants' braking responses were slower for longer Lane Change Proximity cut-ins. The Lane Origin effect could also be seen whereby the median of time to maximum brake depression shifts to the right, indicating longer response time when experiencing a lane change originating from the fast lane. For example, as shown in Figure 5.12, the braking for 25 m and 30 m was almost negligible in the event approaching an overtaking vehicle originating from fast lane, suggesting that participants were able to negotiate without the need to brake. There were occasions where participants would apply a braking force of less than 10 N, which is comparatively negligible in the examination of urgency to brake.

Overtaking vehicle from slow lane

Overtaking vehicle from fast lane
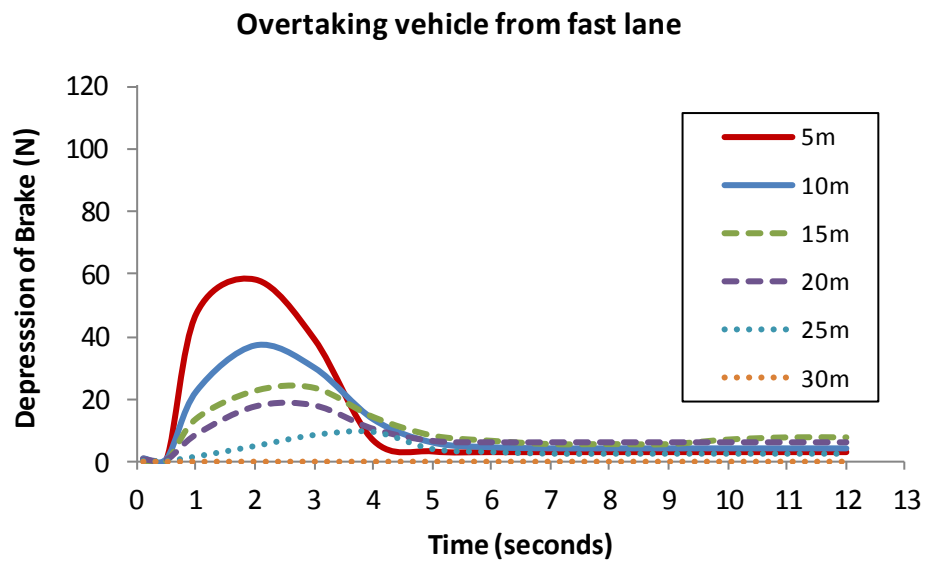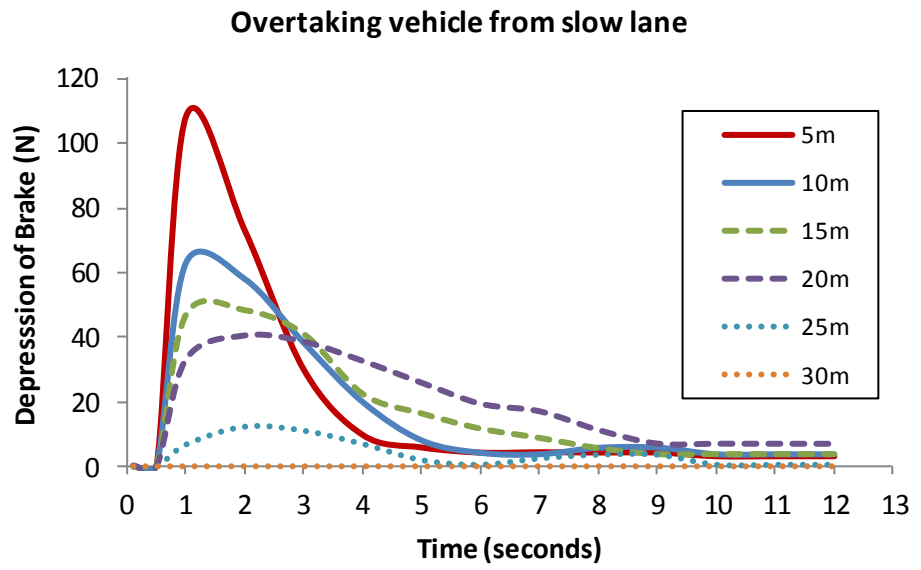
Figure 5.12: The braking profile by Lane Change Proximity and Lane Origin; slow(top) and fast (bottom)

Half-time recovery, Maximum Brake Force and Minimum Speed

Following the examination of the brake pressure and speed, half-time recovery was measured. Half-time recovery which is defined as the time taken for the participants vehicle to recover 50% of the speed that was lost during braking were also investigated. Strayer, Drews and Crouch (2006) used this method to evaluate the effect of alcohol and distraction of mobile phone on driving performance. Although this method has been widely use in biological sciences studies evaluating human recovery from physical demand task such as running, this has not been widely researched in the automotive domain.

Since this study attempted to quantify the traffic demand based on subjective measures, findings associated with objective parameters may provide conclusive evidence of the multi-dimensional aspect of driving workload. In the attempt to examine workload recovery period using driving performance parameters, half-time recovery is calculated to differentiate the differing level of demand associated with each lane change characteristics. As the baseline speed may be different before and after a sudden change in demand, thereby influencing the measurement of full-recovery time, a half-recovery time measure was adopted instead for more reliable results. Since half recovery time is the time participants take to recover 50% of the speed that was lost during braking, this measure is only calculated for each lane change where braking was applied. There were occasions where participants did not need to exert brake pressure. Table 5.1 shows the percentage of trials which were excluded from the analysis of half-recovery rate.

Table 5.1: Percentage of trials excluded in the analysis of half-recovery period

Trial Type	% Trials Excluded
5m	0
10m	0
15m	0
20m	2.6
25m	26.0
30m	32.8

Since not all participants braked in all events (especially in low demand conditions such as Lane Change Proximity 30 m) and Indicator Usage was not found significant in this study, the half-recovery time was thus grouped by traffic demand

(as manipulated by Lane Change Proximity and the Lane Origin) for analysis. Additionally the maximum brake force and minimum speed associated with each of the lane change were also analysed. This was to allow interpretation of the half-recovery time data. The data were grouped by Traffic Proximity as measured by Lane Change Proximity; high proximity (Lane Change Proximity 5 m and 10 m), medium proximity (Lane Change Proximity 15 m and 20 m), low proximity (Lane Change Proximity 25 m and 30 m).

Data were analysed individually using a 3x2 repeated measure ANOVA (three level of Traffic Proximity and two level of Lane Origin). Results indicated a significant main effect of Traffic Proximity on all three measures of Maximum Brake Force, ($F(2,46)=69.57$, $p<0.001$, $\eta^2=0.737$), Minimum Speed, $F(2,46)=57.132$, $p<0.001$, $\eta^2=0.713$) and Half Recovery Time, ($F(2,46)=8.938$, $p=0.007$, $\eta^2=0.280$). When drivers were in closer proximity traffic conditions, they exerted a higher brake force resulting in the significantly lower average minimum speed due to more hard braking involved, relative to lower proximity traffic conditions. However participants who were in high traffic proximity situations reacted more quickly to recover the speed that was lost during braking due to the lane change involved. This could possibly be translated to the greater urgency of the lane change at near distances involved, thus increasing participants level of arousal during lane change. Therefore, participants were more aware of the need to increase their speed to keep up with the surrounding traffic and also to meet the requirement of maintaining speed at 65mph (as instructed to the participant in the briefing).

Although no significant effect of the Lane Origin on half recovery time was found, a main effect was found on braking force, $F(1,23)=8.185$, $p<0.01$, $\eta^2=0.525$) and minimum speed, $F(2,46)=57.132$, $p<0.001$, $\eta^2=0.713$). Average minimum speed achieved when the overtaking vehicles originated from the fast lane was higher as compared to adjacent vehicles pulling in from the slow lane (see Table 5.2). The higher urgency to brake when responding to a slower lane vehicle could result in increased braking force and thus the high maximum braking force exerted. Overall, speed reduced with the increase of braking force and although not all braking force would result in the same speed reduction (for example, the minimum speed), this relationship was not surprising due to significant correlation between brake force and speed at the particular time ($r=-0.174$, $p<0.01$).

Table 5.2: Descriptive statistics of mean and standard deviation of measures collected following a lane change

Proximity	Origin	Maximum braking force (s)		Minimum speed (s)		Half recovery time (s)	
		Mean	SD	Mean	SD	Mean	SD
5	Slow	108.182	54.221	20.71	6.956	7.82	7.344
	Fast	58.16	3.601	25.13	4.675	9.27	6.868
10	Slow	63.09	22.937	24.22	4.671	13.52	6.968
	Fast	48.71	20.929	26.37	0.689	14.21	6.897
15	Slow	46.70	28.340	25.94	0.709	14.33	6.088
	Fast	23.44	23.439	27.52	0.775	14.52	6.580
20	Slow	40.01	27.931	26.01	0.738	14.89	7.564
	Fast	17.14	20.794	27.88	0.825	15.04	6.579
25	Slow	11.97	19.300	26.26	0.964	15.22	7.523
	Fast	8.26	16.483	27.72	1.021	15.36	6.579
30	Slow	4.01	9.482	26.21	0.814	15.24	4.608
	Fast	2.71	1.324	27.86	0.656	14.24	0.608

Figure 5.13 depicts the relationship between the half recovery time measured objectively based on mean speed and the workload recovery period obtained subjectively via workload rating (1-10). Following the finding that workload was influenced by the presence of lane changes, drivers in general required a minimum time duration of 12 s or 15 s (as measured by subjective and objective measure respectively) to recover in low Traffic Proximity situations following an experience with an adjacent vehicle pulling-in. Overall, Figure 5.13 depicts a dissociation between the objective half-time measure and workload measure in high and medium traffic difficulty i.e. associated with presence of Lane Change proximity of less than 20 m. Between Lane Change Proximity 5 m and 15 m, the subjectively measured workload recovery period is on average higher than the objectively measured half-time recovery by 7.40s (ranging between 1.98 s - 14.90 s). From medium to low traffic difficulty, (i.e. Lane Change Proximity 20 m to 30 m), the subjective

workload recovery time is lower than the measured objective half-time by on average 3.28 s (3.05 s - 3.57 s). As shown in Figure 5.13, both measures showed constant values of recovery period beyond Lane Change Proximity of 20 m, which suggest dissociation of the subjective and objective measure of workload recovery period only in higher lane change proximity (i.e. less than 20 m).
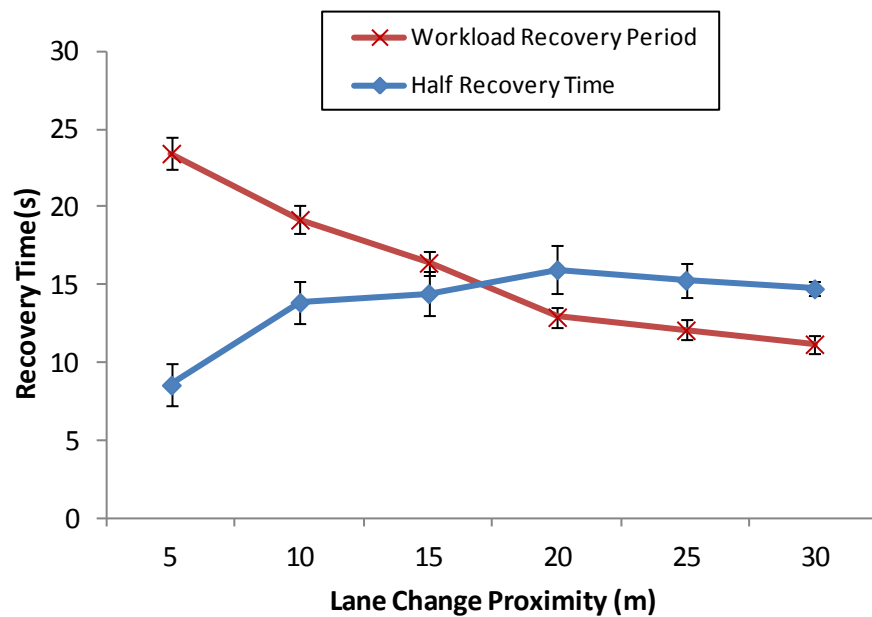
Figure 5.13: Comparison of mean workload recovery time (with standard errors) measured subjectively and objectively

5.3.5   Summary of Results

This study produced a number of important results:

- Lane changes at close proximity of up to 20 m have significant effects on driver workload. Findings showed that lane changes within 20 m or less, influence both participants' relative workload and workload recovery period significantly.

- This effect of this cut-in was particularly strong when the overtaking vehicle originated from the slow lane as compared to the fast lane. This is probably due to drivers generally being concerned about vehicles in the slow lane being unable to keep up with the speed in the middle lane after pulling in, hence an increase of workload with respect to the presence of the vehicle involved. However, no effects of indicator usage was found.

- Despite the secondary task being driver-controlled and participants being able to decide when they would like to respond to the secondary task, participants' were found to perform poorly (i.e. higher percentage error) in the secondary task in traffic conditions associated with lane change proximity 5 m and 10 m.

- Additionally, participants were found to only employ an average delay of 10s at maximum in all traffic conditions. The suggests participants' insufficient self-pacing as a minimum workload recovery time of 12 s is required to recover following a lane change.

5.4 Discussion

The present study aimed to explore the influence of the surrounding traffic in a simulated environment, with a focus on examining characteristics of a cut-in performed by an adjacent vehicle. This study utilised subjective workload measures to capture the driver's perceived driving difficulty of various manipulated traffic events. Hence, participants were required to actively assess and differentiate their own momentary loads via verbal ratings collected on a frequent basis. The subjective workload measures showed that drivers were sensitive to increased driving task demands as defined by the characteristics of the pull-in manoeuvre (Lane Change Proximity and Lane Origin). From the point of driver training and awareness, this is encouraging as this indicates the ability of drivers to evaluate own level of workload constantly, but there is little evidence to prove that drivers are able to manage their own workload in the presence of secondary tasks, in a particularly highly motivating task such as the use of a mobile phone while driving.

As discussed in Section 5.1.1, such intrusion into this safety zone arouses discomfort (Summala, 2005) and may account for the increases in workload. The presence of a lane change performed by the neighbouring vehicle not only increased the visual demand associated with the more frequent traffic monitoring, but may also lead to heightened arousal. Results showed that apart from increases of visual monitoring and possibly heightened arousal, the changes in workload ratings also suggest increasing variation in vehicle control as variation in traffic especially in moderate to heavy traffic situation requires the driver to continuously update their

speed, lane position and headway in order to maintain their own safety. In normal driving, drivers try to keep themselves within a certain range of "comfort zone" and therefore, when a conflict occurs in the "view to the front" channel of a driver's trajectory, the driver is removed from the "comfort zone" as they are now required to make adjustments to changes in task demand (Summala, 2007). Greater adjustments in vehicle control are thus required when the presence of conflicts was less anticipated or possibly more threatening which could result in high demanding conditions.

While the use of the indicator signal may improve the predictability of an event, this study however found no significant improvement in workload changes in regards to the use of signal indicator. Throughout the study, sufficient care has been taken to ensure the visibility of signal indicator to participants in the simulated environment, for example, the cutting-in vehicle is always ahead of the participant vehicle prior to the cut-in and the colour contrast of the signal indicator enables it to be easily differentiated from the surrounding traffic. In addition, the duration (i.e. 1.9 s) of the signal indicator being switched on (i.e. to indicate a lane change intent) is sufficiently long as findings from an on-road study (Hedrick, 1997) found that most turn-signal onsets tend to occur close to lane change start (for example, as early as 2.42 s before the start of a lane change to as late as 3.62 s after the start of a lane change). Therefore, despite that participants in this study having higher anticipation of a cut-in with the use of signal indicator, their perceived workload did not differ with indicator usage. This thus highlights that the relationship between workload and situation awareness is multifaceted as changes in drivers' comprehension of the driving situation (i.e. situation awareness; Endsley, 1995) may not be necessarily reflected on driver workload.

Drivers are viewed as an active operator who is not only capable of assessing and differentiating their own momentary load but also plays an active role in the initiation and management of distracting in-vehicle activities (Lee and Strayer, 2004). Some studies have noted that secondary take engagement may support performance (Olson et al., 2009, Hickman, et al., 2010), which is particularly true at low arousal levels (Fitch and Hanowski, 2011, Curry et al., 2013). However, studies have also shown that despite drivers being aware of the increasing driving demand, drivers still choose to engage in secondary task (Horrey and Lesch, 2009) in the

event of high workload conditions. As such, it is interesting to investigate whether drivers would employ any form of behavioural adaptation in initiating a secondary task despite that drivers have shown capabilities of differentiating driving difficulty, (measured as Relative Workload in this present study). For example, this study attempts to investigate whether drivers would employ any delays in initiating the secondary task, in order to compensate for the addition of secondary task demand on mental resources. To explore drivers' behavioural adaptation to an engaging secondary task, a surrogate mobile phone task was simulated using arithmetic questions to cognitively load them temporarily in occasions of high traffic demand. In such circumstances, drivers' task prioritisation of the driving and surrogate mobile task were evaluated for any form of adaptation. Since the participants were prompted with incoming calls at intervals to coincide with mentally loading conditions, it was hypothesised that drivers would strategically postpone in-vehicle activities until the driving difficulty was perceived as manageable. To examine this form of adaptation with respect to the interaction with secondary tasks to the demands of driving, numerous response variables including percentage of errors were also evaluated.

Drivers were, in general, found to apply some form of delay (i.e. in seconds) in responding to a concurrent secondary task in demanding traffic conditions deemed as the presence of lane changes within close proximity. Despite the varying effect of lane change distances on driver workload, participants on overall were found to respond to the task alert within 10 seconds or less, from the first prompt in all driving demands. While the delay duration increases with increasing driving demand (i.e. Lane Change Proximity), it was found that the motivation of answering a phone call is relatively prevalent as the delay time (ranging between 6s to 10s) is comparatively shorter than the workload recovery period (ranging between 12s to 24s). Although this shows that drivers would attempt to regulate their workload by making deliberate decisions to delay their response time to attend to a secondary task in more demanding traffic situations, there is a lack of understanding of whether drivers were still capable of controlling the vehicle within such condition at that particular time. Findings of higher secondary task percentage error in higher traffic demand conditions (i.e. Lane Change Proximity 5m and 10m) indicated that the adoption of delay on the task was not adequate. Visual examination of Figure 5.14

depicts that the percentage error is roughly equated to the difference between the Workload Recovery Period and the Total Response Time to the surrogate in-vehicle task. The Total Response Time is defined as the sum of Acceptance Time and Response Time in completing the secondary task. While the average mean difference of the Workload Recovery Period and total Response Time increased with lower Lane Change Proximity, the increase of percentage error suggests that the delays implemented by drivers were possibly insufficient. This is particularly relevant in the demanding traffic conditions involving Lane Change Proximity such as 5m and 10m.
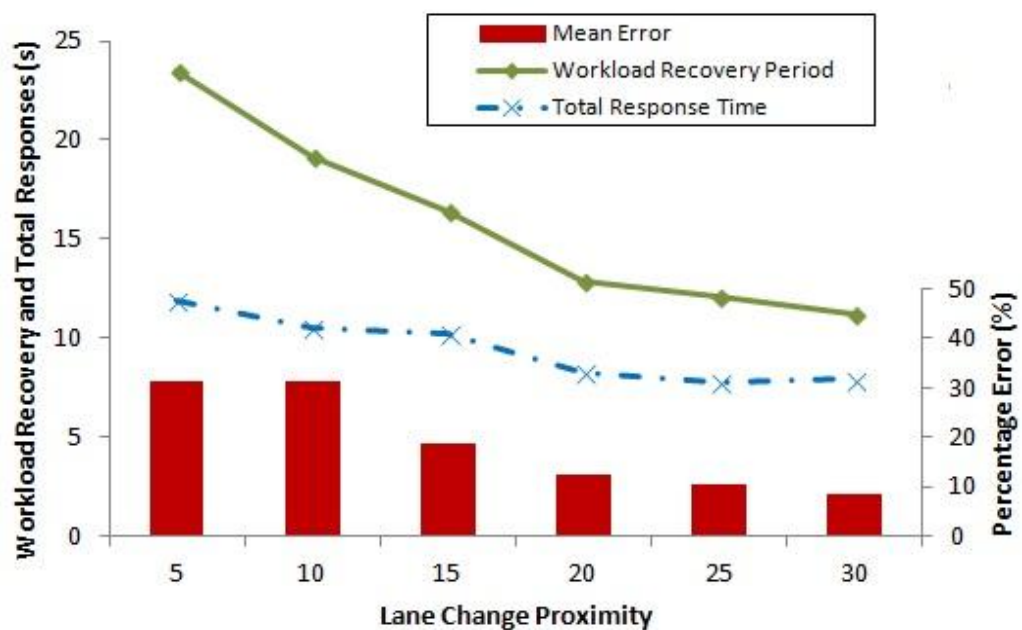
Figure 5.14: Workload Recovery Period, secondary task Total Response Time and Percentage Error

Overall, this study found two important findings. Firstly, driver workload fluctuated with the behaviour of surrounding vehicle. As each driver keeps a safety zone around them in all environments, drivers experienced intrusion of space when this boundary is trespassed. Secondly, drivers strategically regulated their overall workload by delaying their response to a secondary task, especially in high workload traffic conditions. Assessment of subjective workload indicated that drivers were capable of differentiating traffic demands in terms of safety margin. However, when placed in dual-task conditions, driver judgements seemed to be impaired as evidenced by the degraded performance of the secondary auditory task examined in this study. Use of a phone resulted in perceptual and decisional impairment due to

division of drivers' attention between different sensory modalities (Brown et al., 1969) and the act of being involved in a conversation while driving detracted attention away from the primary task of driving (Strayer et al., 2005). While Brown et al. (1969) concluded that talking was likely to have only a minimal effect on the more automatized driving skills such as steering, Almor (2008) has shown that the act of speaking increases the level of interference with performing a visual task by as much as four times in relative to listening-only conditions. Thus if there is a need to perform a response, the perception and decision-making abilities could be critically impaired by drivers having to switch their attention between eyes and ears (Spence, Nicholls, and Driver, 2001). Additionally, the intensity of the conversations could further impair the drivers' ability to drive (Violanti and Marshall, 1996; McKnight and McKnight, 1993).

Therefore, it can thus be concluded that drivers do not tend to be well-calibrated to their own level of performance and tend to be overly optimistic about their ability to perform in-vehicle activities (Horrey, Lesch and Gabaret, 2008; Wogalter and Mayhorn, 2005) in the traffic demands investigated in this study. Despite the implementation of delay, errors were still prominent. New forms of assistance systems such as workload managers have been implemented in vehicles to help drivers to cope with the increasing amount of information that a driver would need to deal with while driving. Since such distraction could be detrimental especially in situations where the traffic changes required an immediate changes for example lane changes at close proximity, the workload manager may provide assistance to the driver by suppressing non-urgent communications when drivers experience critical lane changes. This study suggests that a delay of 12 seconds or more may be advantageous to drivers.

5.5 Conclusion

The influence of the lane change performed by a neighbouring vehicle on driver workload was observed in subjective workload ratings and driving performance measures. This effect was largely due to the occurrence of the lane changes at close proximity such as 5m and 10m. These lane changes were perceived as urgent and difficult due to the amount of work in braking in maintaining a safe

margin from the overtaking vehicle. As such, participants took longer to recover (measured as workload recovery period) following these events. The relative workload measuring drivers' assessment of the driving difficulty suggests that drivers are aware of the interruption that the change in traffic demand may have on their own driving. Further examination of the dual-tasking conditions found that participants employed delays (measured as acceptance time) in initiating a secondary task. Comparison of the measure with workload recovery period obtained via the subjective rating measure suggests that the delay duration was lower than the amount of time taken to recover (Figure 5.15). Additionally vehicles pulling in from the slow lane were more threatening (as reflected in the Relative Workload) and required a higher amount of time to settle down (i.e. workload recovery period) as compared to cut-ins from the fast lane (Figure 5.15).
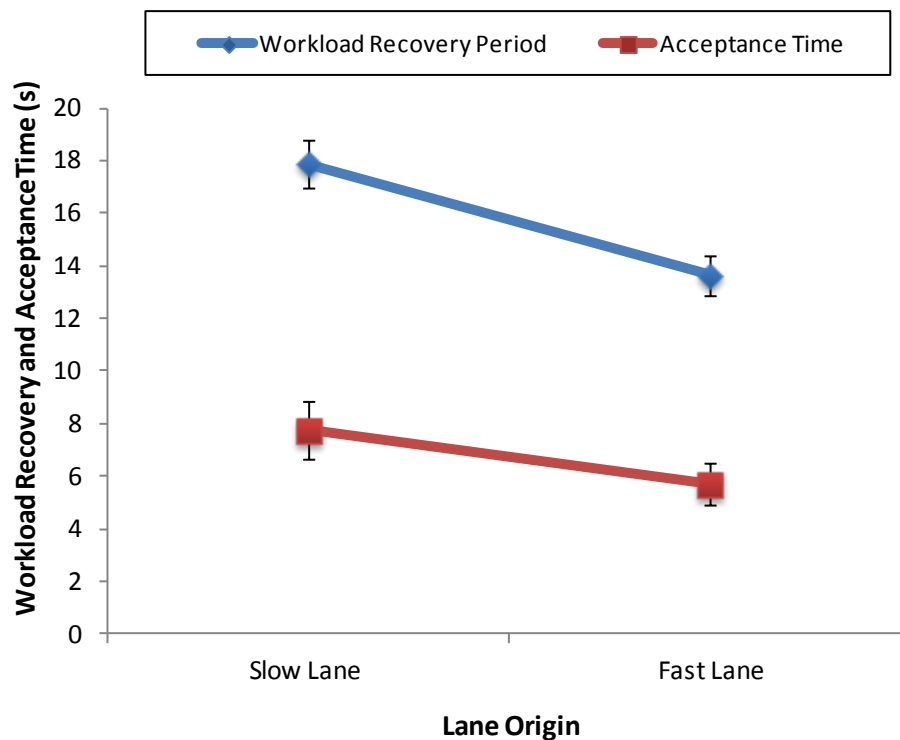
Figure 5.15: Workload Recovery Period (and std error) by Lane Origin

Comparison of the workload recovery period and the acceptance time (i.e delay) in responding to a task alert indicates that the drivers were sensitive to this demand manipulation as the average acceptance time of the secondary task not only increases with Lane Origin (as shown in Figure 5.15) but also with Lane Change Proximity. The average acceptance time ranged from 6 s in low demanding driving

conditions (Lane Change Proximity 30 m) to 10 s in highly demanding driving conditions (Lane Change Proximity 5 m).

Since this task was driver-controlled, this delay might be the result of a voluntary performance strategy which consist of the time taken to decide whether accepting the mobile phone call would unacceptably compromise driving performance. However, participants were still found to perform some errors in higher traffic difficulty conditions despite the implementation of delay in task initiation. In this study, this error was found to be highly associated with shorter Lane Change Proximity such as 5m and 10m.

With the use of the high-fidelity driving simulator and the scripted "naturalistic" traffic and driving scenario in this study, it is suggested that the effect is the realistic and valid outcome of traffic behaviour. Findings in this study shows that careful design of tests situations, measurements and analyses may help provide a strong basis for investigations of driving performance of drivers in unexpected driving situations which in return could be used to evaluate the benefit of a workload manager. The findings regarding workload recovery is particularly worthy of further exploration. For example whether performing a concurrent task within the recovery time is to be avoided completely and if so, how can this be monitored by the workload manager.

Furthermore, the task involved in this study were mainly simple arithmetic questions and may not fully load the driver since they were driver-controlled tasks. Therefore, a different type of distracting task involving system-initiated interface could be manipulated and evaluated for influence on driving performance. This is particularly important in critical conditions, specifically in avoidance of unexpected hazards. As such, the impacts of the lane changes on driver workload warrants further investigation and the management of workload in critical conditions will be considered in the following study.

Chapter 6

Effect of Information Scheduling on Driver Reaction Time and Secondary Task Performance

6.1 Study Aims

This chapter reports on the final of the three studies presented in this thesis. The first two studies have demonstrated the existence of a lane change effect on driver workload and the workload recovery period. The primary objective of this present study was to examine the benefit of using a workload manager to manage the presentation of system-controlled messages during safety-critical conditions. This involved the presentation of an in-vehicle task either prior or concurrently with a safety critical braking event.

A safety-critical braking event can be defined a sudden event requiring the driver to perform a braking response due to the very short reaction time available. One of the causes of these situations are due to the failure to detect changes in the environment complexity whether due to inattention, distraction or attentional tunnelling (Baddeley, 1972; Endsley, 1995; Endsley, 2006). With distraction taking place while driving, drivers may dedicate less attention to scanning the environment and maintaining accurate situation awareness. This is one of the reasons why rear-end collisions occur more frequently than other kinds of crash type in vehicle accidents as the driver did not expect any hazard and did not reduce speed earlier in response to a cutting-in vehicle or slowing lead vehicle (Najm et al., 1995). Thus in a situation where the driver needs to act abruptly, the driver has insufficient time to respond. Therefore in this study, the effect of occurrences of in-vehicle messages on driver performances was examined via braking time and the time taken to respond to a secondary task in various safety-critical situations involving a lane change performed by neighbouring vehicle.

The second objective was to assess the influence of age in responding to these safety-critical situations. The aim was not only to investigate which of the age

groups showed faster reaction times to the hazard, but also to understand how these two groups of drivers (younger drivers aged between 25 and 50 years old; older drivers aged between 60 and 75 years old) manage the in-vehicle task. Research has shown older drivers attempt to adopt more restrictive driving patterns (i.e. limiting exposure to demanding situations) to compensate for their deterioration in cognitive and motor capacities due to ageing (Lang, Parkes, and Fernández-Medina, 2013). But the practice of self-regulation may not be timely in the less predictable safety-critical situations and there is a lack of research in understanding how and when different age groups of drivers use this as a tool in modulating own workload and performance to ensure safe driving. Moreover, with the projected increase of older drivers on-road based on the UK National Travel Survey (i.e. due to ageing of existing license holder; Department for Transport, 2012), it becomes apparent to ensure that the development of support systems such as a workload manager considers not only the comfort and safety of younger drivers, but also the growing population of older drivers.

6.1.1   Study Rationale

A driver workload manager continuously estimates driving demand and manages the flow of information coming to drivers that could interfere with driving. Such a system might enhance highway safety by helping to reduce potential distractions during driving periods when the driver may not have sufficient spare attentional capacity to handle them. Several classes of factors may be used to estimate the difficulty of driving, including road characteristics (e.g., road curvature), dynamic traffic conditions (e.g., traffic density, range, range rate to obstacles ahead), and traffic behaviour of other road users. A number of studies have examined the effectiveness of workload managers in simulator, track, and on-road venues (Piechulla et al., 2003; Uchiyama et al., 2004; Donmez et al., 2006b; Wu et al., 2008; Tijerina et al., 2011). Research suggests that workload managers may provide some benefits to the driver, for example a locking strategy on an in-vehicle information system that deny access to initiate a task function was found to promote a consistently quick response in braking (Tijerina et al., 2011). However, Tijerina et al., (2011) suggested that implementation of a locking strategy on an in-vehicle task

that is already underway is to be avoided due to additional cognitive delay in interpreting the task interruption. This is particularly important in driving conditions which suddenly grow more intense, requiring drivers' attention on the driving task to maintain safe driving. Most of these studies investigating intervention strategies of in-vehicle tasks were focused on mobile phones and engaging navigation tasks which have a higher level of distraction due to the length of the tasks and the motivation level involved in the tasks. However less is known on how to manage system-controlled tasks of shorter distraction durations for example, visual warning messages such as 'FUEL LEVEL LOW'.

Research has suggest that secondary tasks introduced by driver assistance systems can affect driving performance, particularly in increasing drivers' reaction times in responding to unexpected events. For example, research on car-following indicates that when the lead vehicle suddenly decelerates, drivers performing a cognitive distraction task take longer to release the accelerator pedal (Hurwitz and Wheatley, 2001; Lee et al., 2002). Additionally, foot movement time and responses to braking events is influenced by the type of distracter task and the order of in-vehicle task presentation for example, leading to an improvement in braking performance when the braking task was presented after the in-vehicle task (Hibberd et al., 2013). Therefore, manipulation of distracter task modality may not be a completely effective method for the removal of an in-vehicle distraction effect (Vollrath and Totzke, 2005) but accurate timing of the secondary tasks is rather important to prevent the driver from being overloaded. Although traffic and vehicle safety information can be useful to the driver, there are possible negative side effects. One of these expected negative effects is that the extra information source in the car may lead to increased task demand and capacity overload in the driver (Pauzie and Alauzet, 1991; Verwey, 2000; Blanco et al., 2006), especially for older drivers, who are known to have decreased perceptual, motor and cognitive functioning due to normal ageing (Anstey et al., 2005). While driving is generally self-paced and compensating strategies can be executed to limit the interference of secondary tasks, a safety-critical question concerning system-initiated safety visual information arises. While discrete and system-paced messages are useful to the drivers, inappropriate timing of presentation of these messages could well result in driver overload.

The basic idea behind workload management (WM) functions is to prevent excessive workload and distraction by dynamically supporting the driver to manage the driving and nondriving- related tasks, in particular by controlling the information initiated by in-vehicle systems and by limiting the system functionality available to the driver in demanding, or potentially demanding, situations. This study is conducted as a continuation of the simulator study presented in Chapter 5 which found that driver workload is influenced by the presence of critical lane changes performed by neighbouring vehicles. It aims to explore these events further in dual-tasking conditions involving system-initiated messages which are not under the driver's control. Given that the criticality of lane changes can be measured via sensors installed within the vehicle, this study was designed to discover whether delaying incoming information in safety-critical situations involving a critical cut in (such as lane change proximity of 5 m and 10 m) would improve driver's braking performance and reduce subjective workload. This range was selected based on the Lane Change Proximity levels that produced a high workload effect in Study 2 (as measured by Relative Workload) and high error ratio (as measured by the ratio of percentage of error and acceptance delay) across the Lane Change Proximity range. The largest workload increase and percentage error was observed when the adjacent vehicle cut in at close proximity (<5 m). This increase in Relative Workload decreased monotonically with increasing Lane Change Proximity. Similarly the percentage error per acceptance delay decreased monotonically between 15m and 30m Lane Change Proximity. The highest mean percentage error was found when the adjacent vehicle cut in at a Lane Change Proximity of 10m. Additionally, the average time headways during cut-in (measured at the point when the cutting-in vehicle crosses the lane divider) for 5 m and 10 m Lane Change Proximity were critical as defined by Ohta (1993) whereby the following vehicle is within 0.6 s of a lead vehicle. Although the cut-ins for Lane Change Proximity 15 m and 20 m were at the boundaries of critical zone and danger zone (i.e. between 0.6s to 1.1.s headway), these lane change proximities were not explored in the present study as the focus of this study is to examine safety-critical events and therefore any lane change proximity which does not have at least 95% of the lane change trials occurring within 0.6s time headway were excluded. As such the lane change events of 5m and 10m cutting-in distances were manipulated as critical events in this study.

Table 6.1: Distribution of average relative workload, ratio of percentage error per acceptance delay and time headway of cut-in across Lane Change Proximity from Study 2

Lane Change Proximity	Average Relative Workload	Ratio of (Percentage Error/ Acceptance Delay)	Lane Change Time Headway Mean/SD *(95% CI)*
5m	5.741	3.504	0.193/0.081 *(0.168-0.219)*
10m	3.795	4.125	0.379/0.200 *(0.315-0.443)*
15m	2.994	2.531	0.549/0.308 *(0.450-0.647)*
20m	2.217	2.276	0.651/0.271 *(0.527-0.707)*
25m	1.939	2.029	0.748/0.074 *(0.598-0.899)*
30m	1.977	1.556	1.131/0.086 *(0.957-1.305)*

In the dual-tasking conditions examined in Study 2, drivers performed worse on a surrogate in-vehicle task as a result of the lane change effect. This means that a 10 seconds acceptance delay for the secondary task would not be sufficient to remove the "damage-workload increase" caused by the lane change effect for all drivers. This study thus utilises the measure of workload recovery period as used in the previous simulator study to assess the effects of a critical lane change on braking performance and to make subsequent recommendations about the in-vehicle delay timing.

The mean workload recovery period (i.e. defined as the time taken to achieve steady-state workload or baseline workload) both in the non-critical and critical lane-change situations in Study 2 were considered. In addition to utilising the minimum workload recovery of 12 s (as suggested in Study 2), the mean workload recovery period in critical lane-change situations of 21 s was chosen as the second delay parameter to be investigated. This value of 21 s is an over-estimation of the time to recover as drivers may have spare capacity to conduct other tasks within this recovery time, which has been shown in Study 2 whereby all drivers answered their "phone calls" within 10 seconds from the first ring in all circumstances relating to a cut-in performed by a neighbouring vehicle. Moreover the system-controlled in-vehicle messages investigated in this current study have higher relevance towards the driving task. Therefore the range of delays should not be so short that it would overload the driver and also not too long since the warning messages are relevant to the driving task. Hence these two values of 12 s and 21 s will be used to design the

system-controlled delay guidelines in this study as these delays would be sufficient to remove the "damage" caused by the lane change effect for all drivers.

This study represents the final effort of this thesis to explore the lane change effect on workload and to define the appropriate time delay of a system-controlled in-vehicle task in order to minimise driver distraction and maintain performance of the safety-critical aspects of the driving task - in this case a braking response to a critical cut in performed by neighbouring vehicle.

6.2 Methods

6.2.1 Apparatus

Similar to the apparatus used in the previous studies examined in this thesis, this present study was also conducted in the University of Leeds Driving Simulator (UoLDS) and also uses the manual data collection approach used in Study 2 to examine driver's vocal response time due to the time investment required to train voice recognition system (Pashler, 1990; Van Selst et al., 1999).

6.2.2 Participants

Drivers were recruited on the basis of a volunteer sample scheme, drawn from both an existing database, responses to University of Leeds' website and local poster advertisement seeking volunteers. To avoid the issue of older drivers driving less distance annually compared to younger driver (Rimmö and Hakamies-Blomqvist, 2002; Hu and Reuscher, 2004; Alvarez and Fiierro, 2008) due to the changes in lifestyle after retirement, all recruited participants were drivers who still use their vehicle more than four times a week with a reported minimum annual mileage of at least 5000 miles.

A total of fifty drivers, holders of a valid driving license for over five years were recruited. They all had normal or corrected-to-normal vision. Participants were screened for visual and auditory sensory deficits during the practice stage to ensure they would be able to detect the task stimuli to be presented in the experiment. Six participants did not complete the experiment; four participants due to simulator

sickness and technical complications, two older participants were excluded due to their large amount of errors in the driving task during the practice stage. Twenty six young drivers aged between 25 to 49 years (13 males and 13 females) and eighteen older drivers aged between 60 to 72 years old (10 males and 8 females) who successfully completed the experiment are reported in Table 6.2. All drivers were paid for their participation (£15).

Table 6.2: Statistics of participants' demographic details

Age	Gender	N	M_{age} (SD_{age})	$M_{driving\ experience}$	$M_{annual\ mileage}$
Young Drivers	Male	13	32.2 (7.4)	12.5	11775
	Female	13	33.3 (10.8)	13.7	7400
Older Drivers	Male	10	66.1 (3.6)	41.2	10700
	Female	8	65.7 (3.2)	40.5	6200

Note: N= number of participants, M_{age}= mean age, SD_{age}= standard deviation of age, $M_{annual\ mileage}$= mean annual mileage

6.2.3 Experimental Design

A mixed between and within subject design was used. The between subject variable was age (Younger or Older driver). There were two within subject variables, each with two levels. The first was Lane Origin (Slow Lane or Fast Lane) and the second was Workload Manager (On or Off).

6.2.3.1 Driving task

A three-lane motorway was simulated with occasional adjacent vehicles (either from the slow or the fast lane) pulling in front of the participants. Vehicles in the slow lane were programmed to maintain 60 mph while fast-lane vehicles travelled at 70 mph. The adjacent vehicle was programmed to pull in at a certain distance from the participant vehicle. The critical lane change distance was defined as approximately 5 m (+/- 2m) upon crossing the lane divider and a non-critical lane change was defined as a lane change beyond 20m from the participant vehicle. The participants were instructed to drive in the middle lane, maintain a speed of 65 mph and not pass the new 'lead vehicle'.

All participants were required to complete two drives (35 minutes each); a drive with Workload Manager Off (i.e. no delay of messages) during critical lane-

change situation and the other drive with Workload Manager On (i.e delay of 12 s or 21 s) following a critical lane change. Each drive contained twenty events involving a mix of critical and non-critical lane changes and non-lane change conditions as catch trials to avoid predictability of the event. The order of these drives was counterbalanced among the participants.

6.2.3.2 Simulated critical cut-in scenarios

To quantify the effects of the intervention on driver responses and driver workload, instantaneous parameters reflecting the conditions that the drivers faced at the moment of cut-in were measured, which included time-to-collision (in seconds), spaces i.e. gap measured in metres between the participant's vehicle and the adjacent vehicle and time separations i.e. time headway measured in seconds at cut-in. These instantaneous variables that the drivers faced at the moment of cut-in provide information on the criticality of the situation. These values of the instantaneous parameters were measured at the point where the adjacent vehicle started to cross the lane divider (i.e. the front wheel of the adjacent vehicle first touched the lane divider) and can be straightforwardly extracted. Apart from measures of instantaneous distance gap and time headway, time to collision which is a continuous measure of safety margin determining how long it will take for the two vehicles to collide at their current relative position, velocity and acceleration was computed. These measures are important as they help to define the severity of the situation. The description of the severity of the lane changes in this study is provided in Table 6.3. The critical cut-ins were measured at the point the adjacent vehicle crosses the lane divider.

Table 6.3: Statistical description of the critical lane changes in this study

Lane Change Characteristics	Slow Lane Mean/SD *(95% CI)*	Fast Lane Mean/SD *(95% CI)*
Distance gap (m)	3.678 / 2.191 *(2.622-4.734)*	4.234 / 3.139 *(2.765-5.704)*
Time headway (s)	0.171 / 0.089 *(0.128-0.214)*	0.186 / 0.125 *(0.128-0.244)*
Time-to-collision (s)	4.807 / 3.252 *(3.239-6.374)*	N/A*

Note: * No value for TTC as the cutting-in vehicle travelled at a higher speed than participant's vehicle

Therefore all the critical lane change events in this study would require the participant to brake to avoid a collision assuming the current speeds of their vehicle and the vehicle ahead did not change. However the severity of the cut-in may differ between drivers depending on whether the driver initiated braking before the adjacent vehicle crossing the lane divider.

6.2.3.3 Secondary Task

Periodically during each drive, messages were presented on the dashboard screen, situated below the tachometer as shown in Figure 6.1.

Figure 6.1: Location of the system-controlled messages

The system-controlled messages (Table 6.4) were obtained from a vehicle manufacturer and were investigated in two main dual-task conditions where the occurrence of these messages could possibly influence driver workload and performance. The messages were initiated in two cut-in conditions; message onset was either Before a critical lane change or Concurrent with a critical lane change. Messages were also presented during No-lane change conditions in each drive to reduce the predictability of a cut-in.

With each incoming message, an audible 'beep' was presented to alert the driver. Each message appeared for 2.5 seconds before being overwritten by the next message. The secondary task initiation was contingent on the development of the scenario to ensure that the task was performed at the critical moment, that is when the adjacent vehicle initiated a lane change.

Table 6.4: List of system-controlled messages to be displayed on dashboard. Vehicle system messages obtained from a vehicle manufacturer

Vehicle Systems Messages	Non-Vehicle System Messages
ACC SENSOR BLOCKED	WIND SPEED 5MPH
BONNET OPEN	TEMPERATURE 15C
BRAKE FLUID LOW	THREE LANE MOTORWAY
CHARGING SYSTEM FAULT	DRIVE IN MIDDLE LANE
ENGINE TEMP VERY HIGH	SLIPPERY WHEN WET
CAMERA SYSTEM FAULT	LOW BRIDGES
COOLANT LEVEL LOW	HEAVY TRAFFIC AHEAD
EDIPSTICK FAULT	TOW AWAY ZONE
ENGINE SYSTEMS FAULT YELLOW	WINDING ROAD AHEAD
GEARBOX OVERTEMP	TRAFFIC QUEUES LIKELY
OIL LEVEL LOW	SLOW VEHICLE BEHIND
BOOT OPEN	SLIPPERY ROAD
BRAKE PAD LOW	SPEED CAMERA AHEAD
FUEL LEVEL LOW	MAINTAIN SPEED AT 65MPH
KEY BATT LOW	SPEED LIMIT 70MPH
TPMS CHECK SPARE	STAY IN LANE
WASHER FLUID LOW	TUNNEL AHEAD
EDB FAULT	ICY ROAD AHEAD

In the drive with Workload Manager Off, no delays to the messages were implemented during the critical cut-in. When message onset commenced Before the cut-in, in total six messages were played and the lane change was initiated during the third message. Thus the driver had to respond to the cut-in during the fourth message as shown in Figure 6.2. Drivers' braking responses to the cut-in and responses to the secondary task (average response times of the fourth, fifth and sixth messages) following the cut-in were measured.

Figure 6.2: Timeline where message onset was Before a critical cut-in (Workload Manager Off)

Similarly for the Concurrent cut-in condition, in-vehicle messages were initiated to coincide with the critical lane change. The in-vehicle messages were initiated when the adjacent vehicle started a lane change (i.e. as soon as when the adjacent vehicle was triggered to move from own lane). The first of the three in-vehicle messages was triggered at the start of the lane change. Thus the first message coincided with the critical cut-in as the participants juggled between the two tasks; driving task and in-vehicle task, as shown in Figure 6.3. The interference effect of concurrent in-vehicle task on driving performance was measured for braking performance.
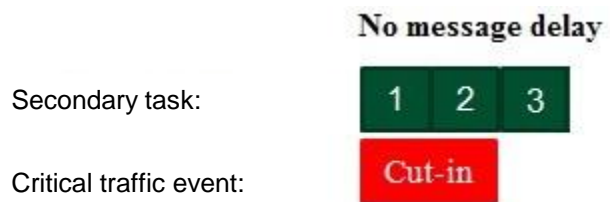
Figure 6.3: Timeline where message onset was Concurrent with a critical cut-in (Workload Manager Off)

In the drive with the Workload Manager On, the messages were managed by delaying them for a certain duration following a lane change. When message onset was Before the cut-in, the fourth to sixth messages were postponed for a duration of 12s to allow drivers to concentrate on the driving task as shown in Figure 6.4.
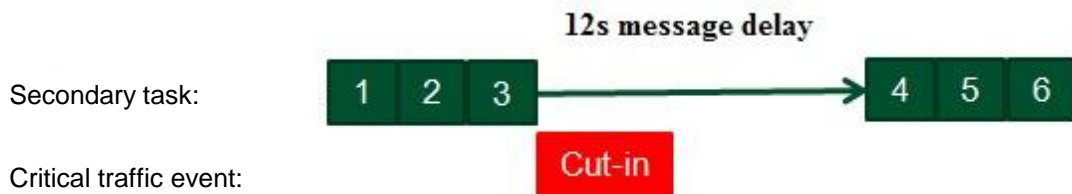
Figure 6.4: Timeline where message onset was Before a critical cut-in (Workload Manager On)

Since this constitutes a task interruption, a delay of 21 s was not used due to the assumption that a task which has been started should be allowed to resume as soon as possible.

Where the message onset was Concurrent with a cut-in, two delay timings were manipulated whereby incoming messages were delayed either for 12 s or 21 s, following a critical cut-in as shown in Figure 6.5. Justification of these chosen delay values can be found in Section 6.1.1.

Figure 6.5: Timeline where message onset was Concurrent with a critical cut-in (Workload Manager On)

6.2.3.4 Procedure

Upon arrival at the simulator, participants were given the participant briefing sheet and a consent form to complete. Participants then drove the simulator three times, one practice run (approximately 15 minutes) and two experimental runs (approximately 35 minutes) each.

Following the short briefing on the study, the participants conducted a short practice drive. The blocks of in-vehicle messages were presented eight times in the familiarisation drive to ensure that participants were familiar with the vehicle controls and the tasks to be conducted. After completing a 15 minutes practice drive involving a series of critical and non-critical lane changes as well as system-controlled messages, the participant then performed the first experimental drive with the secondary task and rating task.

For the in-vehicle task, the participant was required to provide a verbal answer 'Yes' to indicate if it was a vehicle system-related message such as 'BRAKE FLUID LOW' or 'No' to indicate if it was other types of message (i.e. non vehicle system-related such as traffic information). Examples of non vehicle system-related messages are 'TRAFFIC QUEUES LIKELY', 'WINDING ROAD AHEAD'.

For the rating task, participants were prompted with an audible 'PLEASE RATE' message to provide a rating between 1-10 to indicate their overall workload based on the task which they had recently completed and any events that had occurred since the last rating (approximately 30 seconds).

After completion of the first drive, participants filled out the RSME and NASA-RTLX questionnaires. This was repeated with the second drive. After the completion of the second drive, they were then debriefed and paid for their time.

6.2.4 Experimental Hypotheses

- The primary experimental hypothesis was that accelerator pedal release reaction time would improve with the Workload Manager On. This effect would be observed as a quicker release of accelerator pedal or brake response to increase the onset time between the critical cut-in and in-vehicle task. The principles of resource competition mean that the concurrent presentation of a secondary task during critical cut-in requiring control of accelerator pedal release should produce greater interference on the throttle control than when it was presented after the critical cut-in.

- A positive effect of the intervention of a workload manager would be expected for secondary task reaction times when presented during a critical cut-in. The predictions were derived from Multiple Resource Theory (Wickens, 1984; 2008). With a common visual stimulus between the two tasks (secondary task and critical cut-in requiring throttle control) was expected to slow the release of accelerator pedal response across all non-intervened conditions. The presentation of tasks that require simultaneous response processing demand with the throttle control tasks would be expected to enhance dual-tasking interference effects.

- Driver workload was expected be lower in conditions where a workload manager was used. The use of delay should avoid the need to share resources when driving conditions suddenly grow more intense. It also helps the driver to devote more visual attention to driving and focus on the driving task until the driving conditions calm down.

6.3   Data Collection

6.3.1   Driving performance

There were three variables used to estimate the safety benefit of the delay strategy, i.e. the braking response time, braking profile and the number of collisions. Braking response time focused largely on the speed of response to the critical cut-in event. It was decomposed into two specific measures; accelerator release reaction time and accelerator-to-brake transition time. *Accelerator release reaction time* was defined as the time from the onset of the cutting-in vehicle indicator light to the moment when the accelerator pedal was fully released, and *accelerator-to-brake transition time* defined as the time from accelerator release to initial brake pedal depression.

Additionally, the number of trials involving a collision with the cutting-in adjacent vehicle was also recorded.

6.3.2   Subjective workload measures

Two measures of subjective workload were elicited; o*verall workload (NASA-RTLX and RSME)* and *continuous subjective rating (CSR)*. The CSR rating scale consisted of a 1-10 point scale and was explained verbally to the participants as follows, "Please provide a rating on how easy or difficult to drive in the traffic. Low difficulty is between 1 to 3, medium difficulty is between 5 to 6 and high difficulty is between 8 to 10". Fluctuation of driver workload following the driving only or dual-tasking condition both with and without the Workload Manager, was measured at various points during the drive via the 10-point rating scale. RSME and NASA-RTLX were administered at the end of each drive.
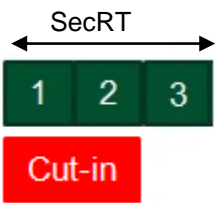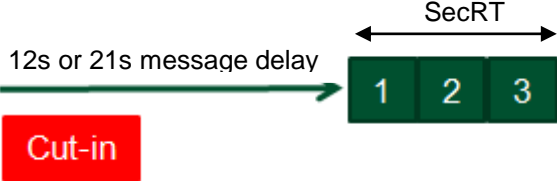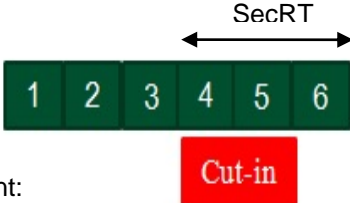
6.3.3 Secondary task performance

Participants' verbal responses were recorded on a digital recorder and processed manually using spectral analysis software ('Praat'). The software displayed both the waveform (amplitude vs time) and the spectogram (frequency vs time) of the sound recording. The following equation was used to measure vocal responses time:

Vocal Reaction Time = Vocal Response Onset (i.e start of the vocal response) - Auditory Stimulus Onset (i.e. beep alert)

Driver's response time to the Secondary Task (SecRT) was measured as the 90th percentile value of the average Vocal Reaction Time responses to exclude the cases of unusual response times. Table 6.5 shows how the responses were measured in all four scenarios.

Table 6.5: Measure of secondary task response times (SecRT)

Additionally, percentage error of secondary task (which includes the number of missed responses and wrong responses) was also measured.

6.4   Data Analysis and Results

Data from 44 participants were compiled to form a database of 1232 lane change events. Each variable was checked for normal distribution and homogeneity of variance using the Kolmogorov Smirnov test and Levene's tests respectively. All data were analysed using the two way repeated-measures ANOVA with the Lane Origin (Slow/Fast) and Workload Manager (On/Off) as within-subject factors and age as the between factor. These tests were applied to all analyses undertaken, and thus will not be described in detail for each.

6.4.1   Driving Performance

The braking response times were analysed separately depending on whether message onset was before or concurrent with a lane change.

6.4.1.1 Secondary task onset Before a critical cut-in

In these cut-in situations, the participants were presented with the in-vehicle task prior to a critical cut-in. The braking components and the total braking response were analysed to establish whether Lane Origin and the Workload Manager had any effect on any of the measures.

Accelerator release reaction time

There was a significant main effect of Lane Origin $F(1,42)=26.584$, $p<0.001$, $\eta^2=0.388$ whereby the accelerator pedal release reaction time was faster when the cutting-in vehicle originated from the slow lane (M=1.109s) compared to the fast lane (M=1.608s). A main effect of Workload Manager was also found ($F(1,42)=31.637$, $p<0.001$, $\eta^2=0.430$) whereby participant took an average 272ms longer to react when it was not in use (refer Figure 6.6). The main effect of age failed to reach significance (p=0.403).
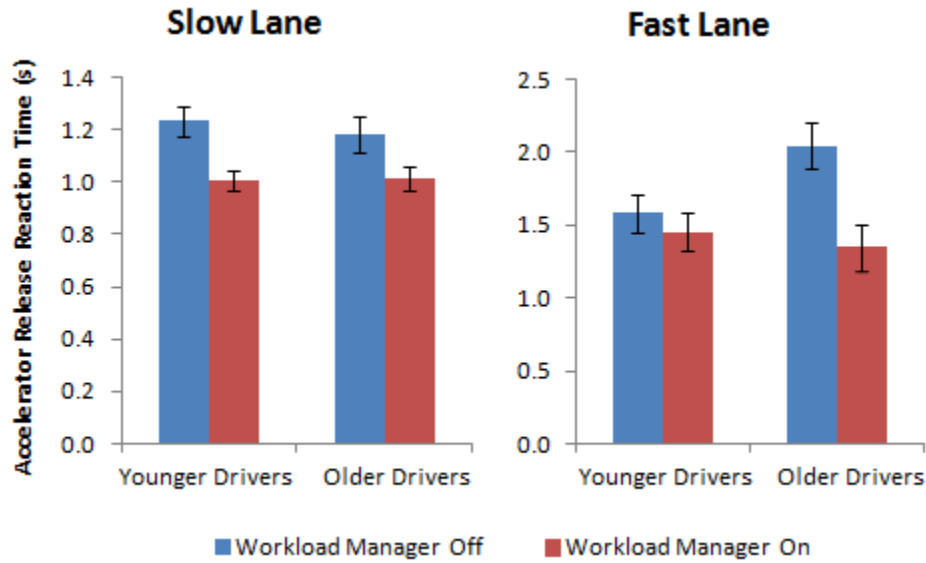
Figure 6.6: Accelerator release reaction times for secondary task onset Before a critical cut-in

The two-way interaction of Workload Manager x Age (F(1,42)=5.25, p=0.027, η^2=0.111) and a three-way interaction of Lane Origin x Workload Manager x Age (F(1,42)=8.47, p=0.006, η^2=0.168) on accelerator release reaction time were also significant. A simple analysis with a paired sample t-test was conducted for older and younger drivers to compare whether the accelerator release reaction time of distracted drivers improved with the use of a workload manager. The results are displayed below (Table 6.6).

Table 6.6: Paired sample t-test comparisons of Workload Manager On and Off accelerator release reaction time

Lane Origin x Age	Mean difference of accelerator release reaction time (s)	t	Sig.	Effect size (r)
Slow lane, younger	0.229	t(25)=3.557	**0.002**	0.579
Slow lane, older	0.167	t(17)=2.758	**0.013**	0.556
Fast lane, younger	0.133	t(25)=1.372	0.182	0.265
Fast lane, older	0.694	t(17)=3.680	**0.002**	0.666

Note: **BOLD** denotes significance < 0.05

The workload manager had a significant effect on the improvement of accelerator release reaction time for older drivers regardless of lane origin. For

younger drivers, this improvement on accelerator release reaction time was only found with a slow lane cut-in.

Accelerator-to-brake transition time

There was significant main effect of Lane Origin $F(1,42)=10.279$, $p=0.003$, $\eta^2=0.197$ on the accelerator-to-brake movement time whereby participants responded 131ms faster when the cut-ins originated from the slow lane as compared to cutting-in vehicle originating from fast lane. Although there was no main effect of Workload Manager ($p=0.191$), the interaction between the Lane Origin and Workload Manager was significant ($F(1,42)=10.566$, $p=0.002$, $\eta^2=0.201$) (refer Figure 6.7). In slow lane cut-in scenarios, participants reacted more quickly with Workload Manager On (M=375ms) as compared to Workload Manager Off (M=468ms). However in fast lane critical cut-in situations, participants waited for a longer duration of time to initiate braking when Workload Manager was On (M=642ms) as compared to Workload Manager Off (M=463ms). No main effect of age or other two way interaction was found.
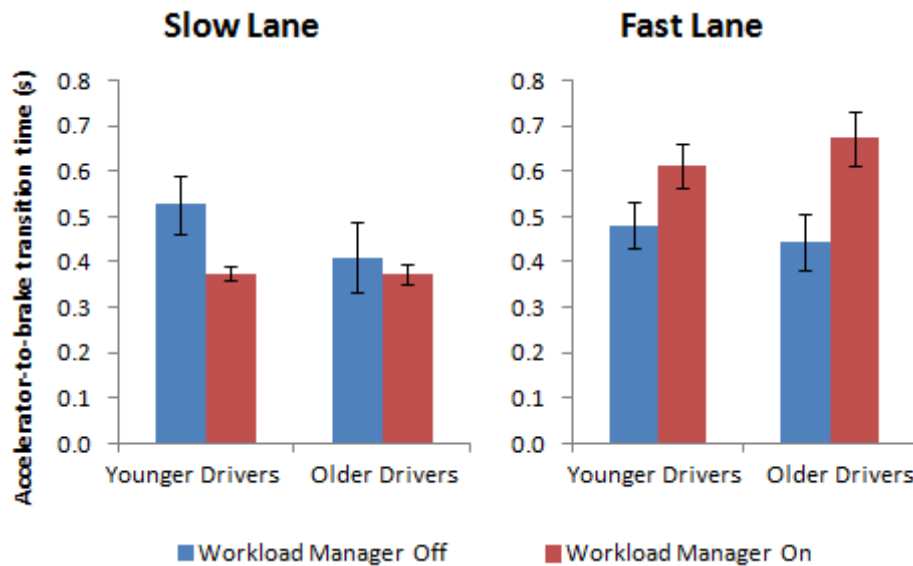
Figure 6.7*:* Accelerator-to-brake transition time for secondary task onset Before a critical cut-in

Brake Response Time

Brake response time is the summation of accelerator release time and accelerator-to-brake transition time. Overall, main effects of Lane Origin

F(1,42)=34.05, p<0.001, η^2=0.448 and Workload Manager F(1,42)=17.406, p<0.001, η^2=0.293 on brake response time were significant. With the Workload Manager On (M=1.714s), participants responded 263ms more quickly as compared to with Workload Manager Off (M=1.917s) (see Figure 6.8). The main effect of age was found to be non-significant (p=0.559).
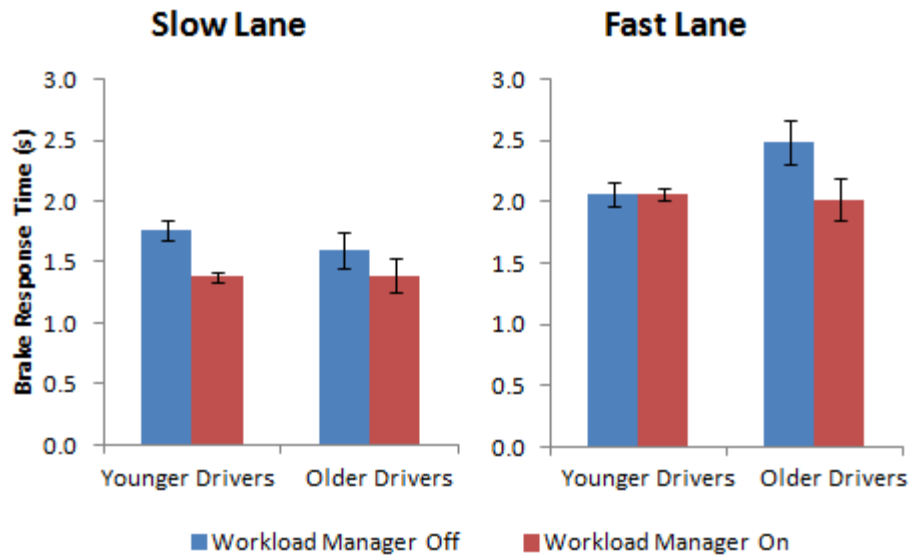
Figure 6.8: Brake response time for secondary task onset Before a critical cut-in

No two-way interaction was found to be significant. A significant three-way interaction of Lane Origin x Workload Manager x Age (F(1,42)=5.494, p=0.024, η^2=0.116) on brake response time was found. A simple analysis of paired sample t-test was conducted for older and younger drivers to compare whether the brake response time of distracted drivers improved with the use of the workload manager. The results are displayed below (Table 6.7).

Table 6.7: Paired sample t-test comparisons of Workload Manager On and Off brake response times

Lane Origin x Age	Mean difference of brake response time (s)	t	Sig.	Effect size (r)
Slow lane, younger	0.380	t(25)=3.749	**0.001**	0.560
Slow lane, older	0.203	t(17)=2.777	**0.013**	0.559
Fast lane, younger	0.002	t(25)=0.018	0.986	0.004
Fast lane, older	0.467	t(17)=2.142	**0.017**	0.461

Note: **BOLD** denotes significance < 0.05

Similar to the results found with accelerator release reaction time, the workload manager had a significant effect on the improvement of brake reaction time for older drivers regardless of lane origin. For younger drivers, these improvements in brake reaction time were only found in slow lane cut-ins. Figure 6.9 depicts the brake response time components, accelerator pedal release time and accelerator-to-brake transition time, for slow and fast lane cut-ins.

Figure 6.9: Braking components for secondary task onset Before a critical cut-in

Figure 6.9 shows that the response times for older drivers were relatively similar to younger drivers' response times when the Workload Manager was On. This means that both groups of distracted drivers (i.e.in-vehicle messages started before a critical cut-in) will benefit from the use of the delay strategy, but older drivers benefit more in fast-lane cut-ins.

6.4.1.2 Secondary task onset Concurrent with a critical cut-in

Accelerator Release Reaction Time

There was a significant main effect of Lane Origin $F(1,42)=76.62$, $p<0.001$, $\eta^2=0.646$ whereby the accelerator pedal release reaction time for cutting-in vehicle originating from the slow lane (M=0.969s) was shorter than from the fast lane (M=1.668s). A main effect of Workload Manager was also found ($F(1,42)=32.72$, $p<0.001$, $\eta^2=0.438$) whereby participants took an average 357ms longer to react when it was not in use (M=1.497s) as compared to when the workload manager was On (M=1.140s).

Generally, older drivers showed a slower response to throttle control, having an overall larger mean reaction time (1.446s) than the younger drivers (1.191s) ($F(1,42)=8.719$, $p=0.005$, $\eta^2=0.172$). The two way interaction of Lane Origin x Age ($F(1,42)=7.719$, $p=0.008$, $\eta^2=0.155$) and Workload Manager x Age ($F(1,42)=12.10$, $p=0.001$, $\eta^2=0.224$) on accelerator release reaction times was significant, indicating that the influence of Workload Manager was consistent in all lane origins for older drivers. However, in fast lane cut-in conditions, there was no influence of Workload Manager on younger drivers (Figure 6.10) as compared to older drivers' reaction time.
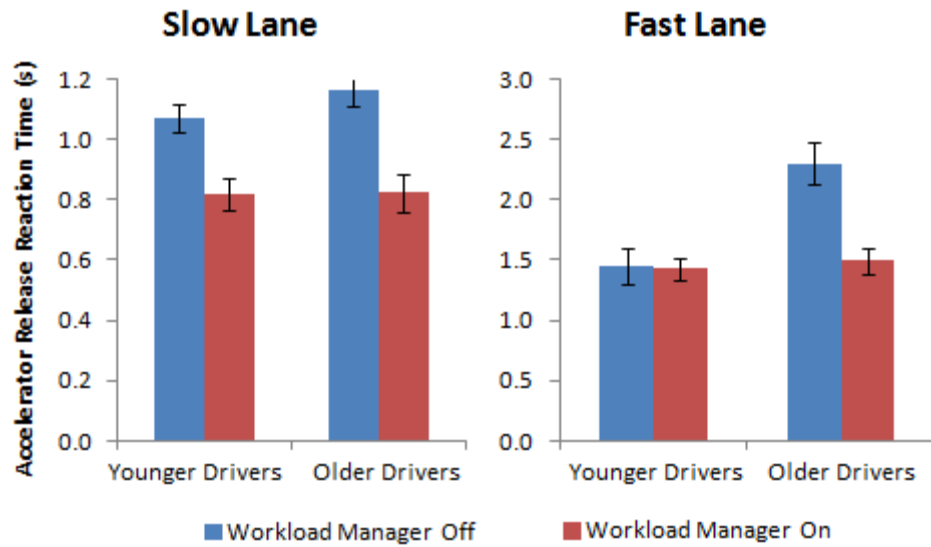
Figure 6.10: Accelerator release reaction time for secondary task onset Concurrent with a critical cut-in

Additionally, a three way interaction of Lane Origin x Workload Manager x Age was also found to be significant ($F_{(1,42)}=7.37$, p=0.01, $\eta^2=0.149$). A simple analysis with a paired sample t-test was conducted for older and younger drivers to compare whether the accelerator release reaction time performance improved with the use of the workload manager to delay in-vehicle messages which coincide with a critical cut-in. The results are displayed below (Table 6.8). Based on the effect size, older drivers benefited from the delay intervention more than younger drivers in all types of cut-in conditions (Slow Lane/Fast Lane).

Table 6.8: Paired sample t-test comparisons of Workload Manager On and Off accelerator release reaction time

Lane Origin x Age	Mean difference of accelerator release reaction time (s)	t	Sig.	Effect size (r)
Slow lane, younger	0.255	t(25)=5.674	**0.000**	0.750
Slow lane, older	0.342	t(17)=3.793	**0.001**	0.677
Fast lane, younger	0.025	t(25)=1.372	0.839	0.265
Fast lane, older	0.806	t(17)=3.655	**0.002**	0.663

Note: **BOLD** denotes significance < 0.05

Accelerator-to-brake transition time

There was a significant main effect of Lane Origin on accelerator-to-brake transition time ($F(1,42)=5.51$, $p=0.024$, $\eta^2=0.116$) whereby slower movements were associated with a cut-in from the fast lane (M=588ms) in comparison to cut-ins from a slow lane (M=471ms). Older drivers (M=428ms) reacted 183ms more quickly than younger drivers (M=621ms) ($F(1,42)=16.090$, $p<0.001$, $\eta^2=0.277$). A two way interaction of Workload Manager x Age ($F(1,42)=5.02$, $p=0.030$, $\eta^2=0.107$), indicated that older drivers reacted differently than younger drivers when the Workload Manager was in use. Older drivers generally moved more slowly by 89ms when Workload Manager was On while younger drivers moved more quickly by 128ms.

A significant three way interaction of Lane Origin x Workload Manager x Age ($F(1,42)=4.89$, $p=0.033$, $\eta^2=0.104$) was found. A simple analysis with a paired sample t-test was conducted for older and younger drivers to compare the accelerator-to-brake transition time in conditions where Workload Manager is On or Off. The results are displayed in Table 6.9.

Table 6.9: Paired sample t-test comparisons of Workload Manager On and Off accelerator-to-brake transition time

Lane Origin x Age	Mean difference of accelerator-to-brake transition time (s)	t	Sig.	Effect size (r)
Slow lane, younger	0.030	t(25)=0.329	0.745	0.203
Slow lane, older	-0.018	t(17)=-0.241	0.812	0.058
Fast lane, younger	0.225	t(25)=2.480	**0.020**	0.444
Fast lane, older	-0.161	t(17)=-2.625	**0.018**	0.537

Results in Table 6.9 indicate that these differences are only significant in fast lane cut-in scenarios. In slow lane conditions, the times taken for foot movement between accelerator and brake pedal were relatively equal, regardless of whether the workload manager was in use. In fast lane cut-in conditions with the Workload Manager Off, younger and older drivers behaved differently: older drivers had shorter movement time (M=388ms) compared to younger drivers (M=821ms). This suggests that in multiple task situations, older and younger drivers perceived the urgency to brake differently, whereby older drivers had prioritised braking over the

secondary task more than younger drivers. When the workload manager is in use, both age groups had similar accelerator-to-brake movement time: older drivers (M=548ms), younger drivers (M=595ms) (refer to Figure 6.11). The older drivers responded more slowly in the accelerator-to-brake movement times with Workload Manager On, suggesting that the older drivers had longer judgement time in anticipating the progression of the driving situation before deciding to depress the brake pedal.
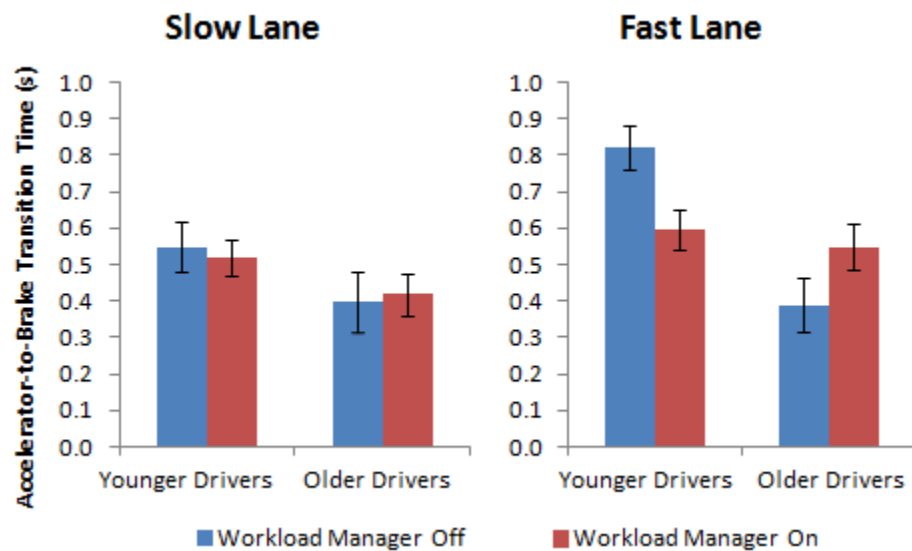
Figure 6.11: Accelerator-to-brake transition time for secondary task onset Concurrent with a critical cut-in

Brake Response Time

Overall, the main effects of Lane Origin , (F(1,42)=99.83, p<0.001,η^2=0.704) and Workload Manager, (F(1,42)=19.61, p<0.001, η^2=0.318) on brake response time were significant. While drivers in general responded more quickly when vehicles pulled in from the slow lane (M=1.441s) than for the fast lane (M=2.255s), there was also a significant reduction in brake response time when the workload manager was present (M=1.660s) compared to absent (M=2.036s). No main effects of Age were found on the brake reaction time indicating that older drivers performed equally well as the younger drivers in critical cut-ins. Figure 6.12 shows that the older drivers' brake responses in slow cut-in conditions were similar to the younger drivers suggesting that both age groups prioritised driving.
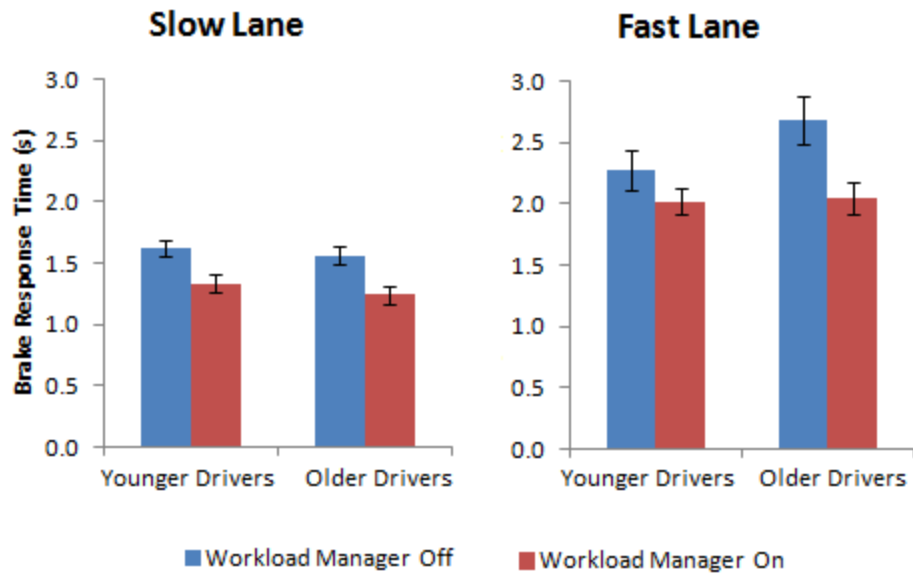
Figure 6.12: Brake response time for secondary task onset Concurrent with a critical cut-in

However there was also a marginally significant interaction of Lane Origin x Age (p=0.041) on brake response time. Visual inspection of the graph of the braking components and brake responses for both younger and older drivers in slow and fast lane critical cut-in indicated that both younger and older drivers responded equally fast in slow lane cut-in conditions. But the improvement in braking performance for older drivers in fast lane cut-in condition was inhibited by the increase in the accelerator-to-brake transition time (Figure 6.13). For younger drivers, the reduction in braking performance in fast-lane cut-ins with Workload Manager On is associated with the reduction on the accelerator-to-brake pedal transition time. Despite there being difference of Workload Manager effect on the accelerator-to-brake transition time between the two age groups, both age groups performed better in brake response times with Workload Manager On.

Figure 6.13: Braking components for secondary task onset Concurrent with a critical cut-in

6.4.1.3 Number of collisions

The occurrence of a collision with the new cutting-in vehicle was recorded. A collision was identified if the time headway was less than 40ms or if the time to collision was between 0 and 70ms. For the total number of crashes, only descriptive data are presented since the number of collisions across the entire experiment was not sufficient to perform statistical analysis. Nevertheless, as Table 6.10 demonstrates, there was an indication that more crashes occurred when the

Workload Manager was Off (41 out of 440) compared to when Workload Manager was On (3 out of 528).

Table 6.10: Number of collisions per scenario

Workload Manager	Secondary task onset Before a critical cut-in		Secondary task onset Concurrent with a critical cut-in	
	Number of collisions recorded	**% Events with collision**	**Number of collisions recorded**	**% Events with collision**
Workload Manager Off	26	14.77	15	8.52
Workload Manager On	2	0.01	0	0.00

When the Workload Manager was Off, the collisions were evenly split between situations where message onset was either before or concurrent with a critical cut-in event. However, when the Workload Manager was On, the percentage of collisions reduced in both situations.

Further analysis of the number of collisions in Workload Manager Off condition showed that these could be attributed to younger drivers. The percentage of younger drivers (65.4%) involved in collisions with the Workload Manager Off was higher than for older drivers (16.7%) (Table 6.11).

Table 6.11: Number and percentage of drivers involved in collision by Age and Workload Manager

Age	Workload Manager Off		Workload Manager On	
	Number of participants	**% Involved in collisions**	**Number of participants**	**% Involved in collisions**
Younger Drivers	17	65.4	1	3.8
Older Drivers	3	16.7	0	0.0

Comparisons of the percentage of drivers involved in a collision indicate that younger drivers were more likely to be involved in collision as compared to older drivers.

6.4.1.4 Summary of driving performance

Statistical analysis and visual inspection of the graphs indicated that driver response time was slower when distracted by an in-vehicle task regardless of whether the driver was distracted prior to a cut-in or when the in-vehicle task coincided with the critical lane change. When a workload manager with a 12s delay was used to postpone any incoming messages that coincided with a critical lane change or to interrupt by delaying any subsequent in-vehicle messages following a lane change, there was an improvement in the response time. Table 6.12 shows that the effect of this intervention is significant for the braking response time in both conditions.

Table 6.12: Summary of main effects and interactions
(Workload Manager x Age) on driving performance

Scenario	Workload Manager	Age	Workload Manager x Age
In-vehicle task before critical cut-in			
Accelerator release time	✓	✗	✓
Acc-to-brake transition time	✗	✗	✗
Braking response	✓	✗	✗
Coincident in-vehicle task with critical cut-in			
Accelerator release time	✓	✓	✓
Acc-to-brake transition time	✗	✓	✓
Braking response	✓	✗	✗

Overall, older drivers were found to be capable of responding well to the critical lane changes in situations where secondary task onset was Before a critical cut-in, in comparison to younger drivers. This may suggest that these drivers were capable of managing own their workload. However in situations requiring simultaneous response to an in-vehicle task and throttle control, older drivers were found to respond slower in releasing the accelerator pedal in critical lane changes. While this could be due to the switching cost between two tasks that requires the same visual resources, older drivers were found to prioritise driving better than younger drivers. This is because older drivers were less involved in collisions (as shown in Table 6.11) despite slow response in braking. In sum, although the difference between the age groups was not significant in braking response, both age

groups performed worse in the driving task when an in-vehicle task was present simultaneously in situations requiring a quick response from the driver (i.e. critical cut-in). To confirm the findings regarding driver responses, analysis of driver's rating of effort and workload are examined in the following section.

6.4.2 Subjective workload measures

Two measures of driver workload were collected: the overall workload (measured at the end of each of the two drives: one with Workload Manager On, the other with Workload Manager Off) and momentary workload (measured at the end of each event using the rating scale between 1 and 10).

6.4.2.1 Overall workload

Paired-sample t-tests with α of 0.05 were carried out to compare the differences in workload between the two drives (drive with Workload Manager Off, drive with Workload Manager On) for each of the six dimensions of NASA-RTLX including the Overall NASA and also RSME as shown in Table 6.13. Results showed that the use of a Workload Manager (WLM On) significantly reduced workload.

Table 6.13: Descriptive statistics and t-test results of subjective workload

Statistics		Mean (SD)		Sig.	Effect size, (r)
		WLM Off	WLM On		
NASA-RTLX Dimensions	Mental Demand	64.46(17.20)	45.66(21.43)	$p < 0.001$	0.611
	Physical Demand	48.28(23.26)	31.70(22.63)	$p < 0.01$	0.499
	Time Pressure	54.03(25.24)	34.45(21.82)	$p < 0.01$	0.482
	Own Performance	53.45(18.76)	40.83(22.47)	$p < 0.05$	0.382
	Effort	56.88(21.68)	37.90(22.49)	$p < 0.001$	0.520
	Frustration	52.76(25.80)	33.90(22.95)	$p < 0.01$	0.486
Overall NASA-RTLX		54.98(17.18)	37.41(17.94)	$p < 0.001$	0.581
RSME		61.40(19.39)	48.51(18.11)	$p < 0.001$	0.810

The effect size for each significant results in Table 6.13 were calculated using Equation 4.1 (Fields, 2005). Results showed effect of substantial reduction in Overall NASA-RTLX (Figure 6.14) with the use of a workload manager. All the six

effects of NASA-RTLX dimensions were moderate to strong, accounting for at least 15% to 38% the variances in the data. Similarly for the RSME questionnaire, participants provided a higher rating of effort (M=61.4, with the label 'Rather much effort') for the drive with Workload Manager Off. This was significantly higher than the level of effort required to complete a drive with Workload Manager On (M=48.5).
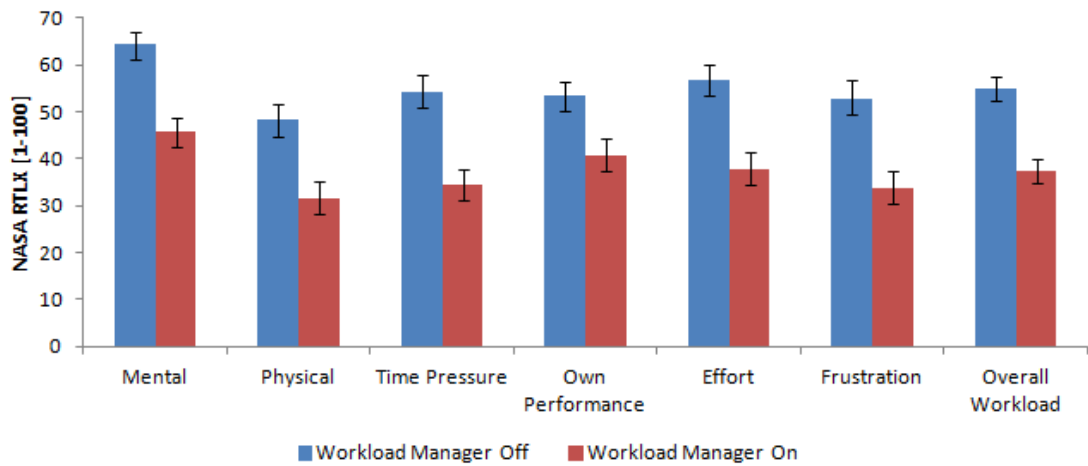
Figure 6.14: Workload Manager effect on ratings of NASA-RTLX dimensions

Additionally, both age groups of drivers were found to benefit from the use of a workload manager. As show in Figure 6.15, both age group of drivers reported lower workload (as measured by NASA-RTLX and RSME) when the Workload Manager was On.
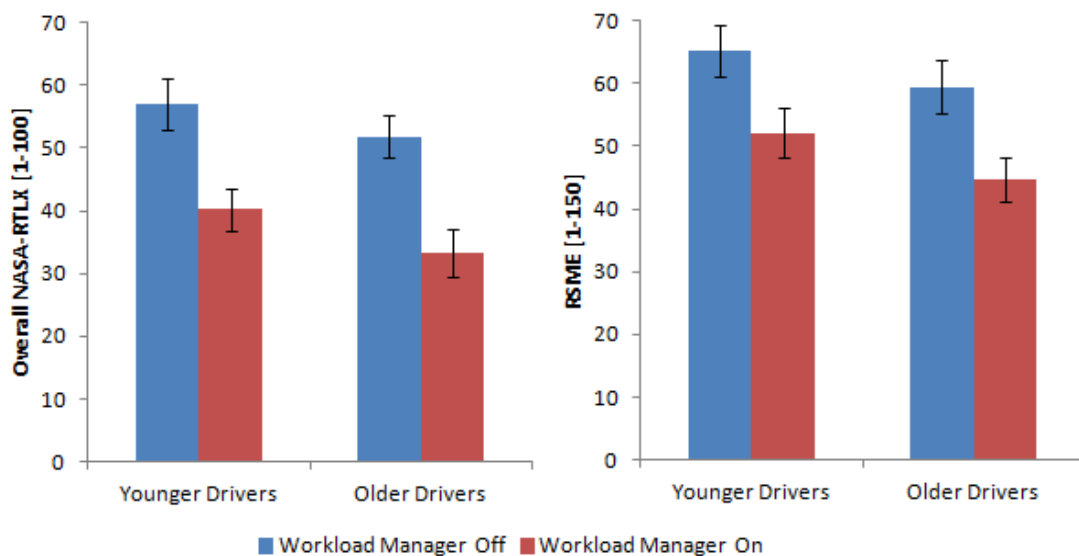
**Figure 6.15: Workload Manager effect on overall workload
(overall NASA-RTLX and RSME)**

Although older drivers, in general, were found to provide a lower rating of workload and effort, in comparison to the younger drivers in all conditions, the average reduction in workload and effort with Workload Manager On were consistent across the age groups. Paired-sample t-test indicated that both age groups experienced significant reduction in effort with Workload Manager On; whereby younger and older drivers experienced average reduction of 13.07 (95% CI - 8.51 to 17.64) and 14.49 (95% CI - 10.49 to 18.88) in effort, respectively.

6.4.2.2 Momentary workload

To examine whether the effects of Workload Manager and Age were found with the driver's momentary workload during the drive, further analysis was conducted on the continuous workload rating data (collected using the 1-10 point rating scale) which was measured at the end of each cut-in event within a drive. This was carried out to investigate whether the workload manager is capable of managing drivers' temporal workload in safety-critical situations

A three way repeated-measures ANOVA with the Lane Origin (Slow/Fast) and Workload Manager (Off/On) as within-subject factors and Age as the between effect was carried out. Data analysis were conducted separately to examine the effect of Workload Manager on each of the dual-task conditions (i.e. secondary task onset Before a critical cut-in, secondary task onset Concurrent with a critical cut-in).

Secondary task onset Before a critical cut-in

There was a main effect of Lane Origin, $F(1,42)=47.72$, $p<0.001$, $\eta^2=0.532$ on momentary workload. Drivers' momentary workload in slow-lane cut-in situations (M=5.949) were higher than fast-lane cut-ins (M=4.778) in all dual-task conditions.

A reported significant main effect of Workload Manager ($F(1,42)=38.22$, $p<0.001$, $\eta^2=0.476$) suggest that driver workload was lower when the Workload Manager was On. Pairwise comparisons showed that participants rated the in-vehicle task before critical cut-in conditions with a significantly lower workload rating in

scenarios with Workload Manager On (M=4.686) than the scenarios with Workload Manager Off (M=5.861, mean difference=1.172, SE=0.190, p<0.001) (Figure 6.16).
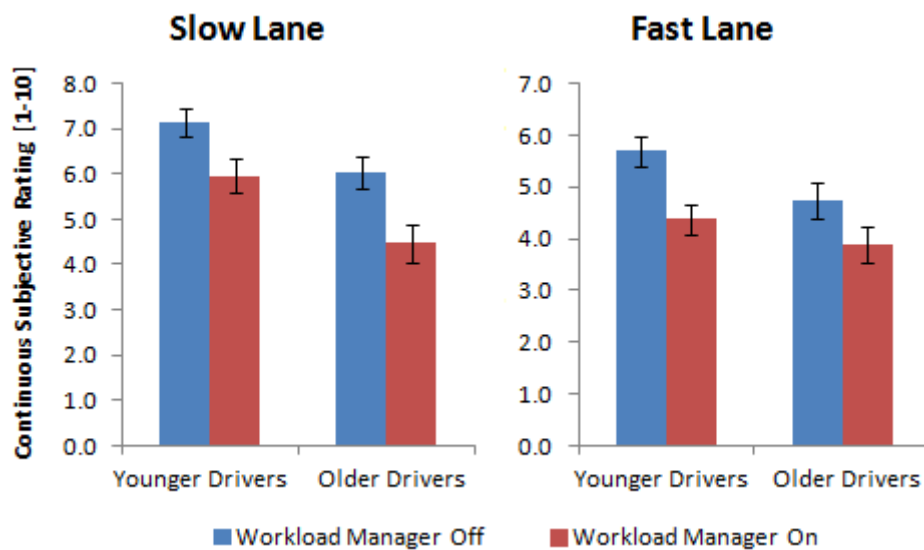
Figure 6.16: Momentary workload for secondary task onset Before a critical cut-in

A significant main effect of Age on workload ratings was also found, $F(1,42)=7.107$, $p=0.011$, $\eta^2=0.145$. Younger drivers (M=5.769) in general rated workload higher than the older drivers (M=4.778, mean difference=0.991, SE=0.372, p=0.011) (Figure 6.16). No two way or three way interactions were found.

Secondary task onset Concurrent with a critical cut-in

A three way ANOVA with Lane Origin (two levels) and Workload Manager (three levels: Workload Manager Off with no delay, Workload Manager On with 12s delay and Workload Manager On with 21s delay) as within subject factors and Age as between subject factor was conducted. There were main effects of Lane Origin, $F(1,42)=33.915$, $p<0.001$, $\eta^2=0.393$ and Workload Manager, $F(2,84)=36.927$, $p<0.001$, $\eta^2=0.468$. Workload ratings were higher when secondary task was performed concurrently with a slow-lane critical cut-in (M=5.442) as compared to fast-lane critical cut-in (M=3.918). With Workload Manager On, workload reduces with the increasing delay duration (Mean for 0s=5.726, Mean for 12s=4.403, Mean for 21s=3.911) with Workload Manager On.

Similar to the findings in the previous section on overall workload, older drivers (M=4.316) provided a lower rating than younger drivers (M=5.045, Mean difference=0.729, SE=0.140, p<0.001) for all critical cut-in situations (Figure 6.17).
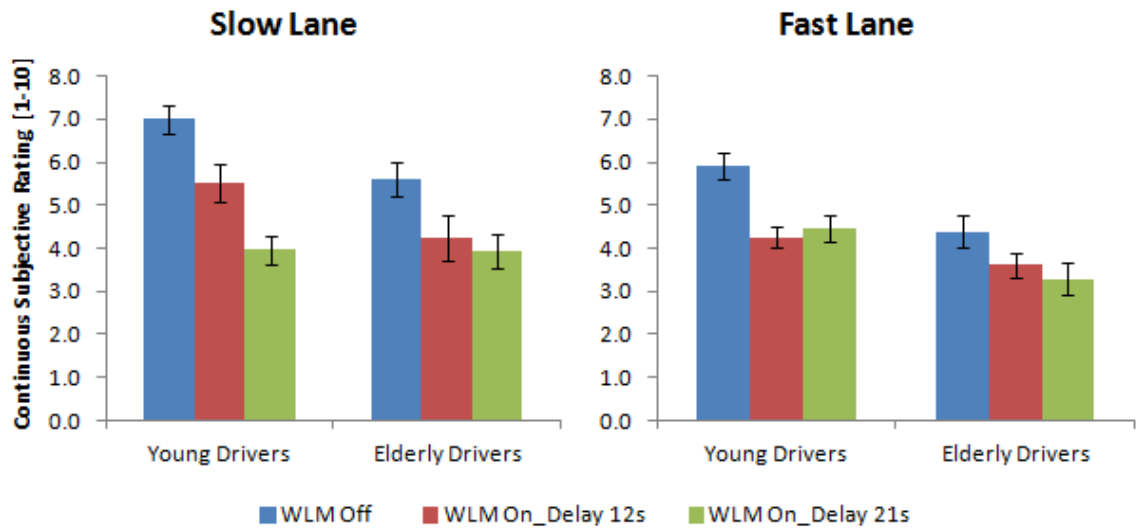
Figure 6.17: Momentary workload for secondary task onset Concurrent with a critical cut-in

An interaction of Lane Origin x Workload Manager on workload rating was found to be significant, $F(2,84)=4.292$, $p=0.017$, $\eta^2=0.093$. Simple analysis of one way ANOVA was computed for each lane origin (Slow/Fast). Results of the ANOVA analysis are provided in Table 6.14 below.

Table 6.14: Workload Manager effect on momentary workload (per Lane Origin)

Lane Origin	F (2,86)	Sig.	Effect size (μ^2)	Pairwise Comparison
Slow lane	24.05	<0.001	0.364	Delay 0s > Delay 12s, Delay 12s =Delay 21s
Fast lane	19.173	<0.001	0.313	Delay 0s > Delay 12s, Delay 12s =Delay 21s

From the pairwise comparisons results in Table 6.14, it can be concluded that the workload ratings were independent of the delay duration (12s vs 21s). Thus, participants did not experience a significant reduction in workload when delay was increased from 12s to 21s.

6.4.3 In-Vehicle Task Performance

6.4.3.1 Secondary Task Response Times

Participants verbal responses to the secondary task were measured at 90th percentile to exclude the cases of unusually long response times. The response times were compiled and analysed with two main aims: i) to examine whether drivers' response times increase when the critical cut-in event happens and ii) to investigate the benefit of delays on secondary task response times.

i) Do drivers slow down on response to secondary task when the critical cut-in event happens?

To investigate this, drivers' response times to the secondary task initiated before a critical cut-in were examined. The secondary task response times prior to a critical cut-in was defined as the baseline, which was then compared with the secondary task response times following a critical cut-in conditions by Workload Manager (Workload Manager Off, Workload Manager On). With the Workload Manager Off, the secondary task overlaps with the critical cut-in and thus the secondary task response times is defined as WLM Off, while with Workload Manager On, the secondary task which occurs 12s later following a critical cut-in is measured as WLM On (refer Figure 6.18). By examining the secondary task response times, the benefits of employing a 12s delay during a slow or fast lane critical cut-in can be examined and compared.

a) Secondary task onset Before a critical cut-in with WLM Off
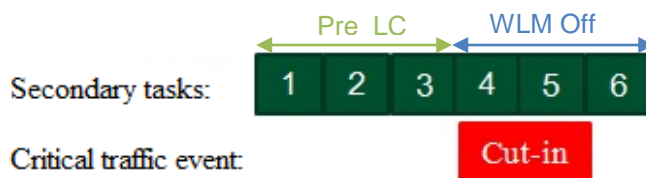
b) Secondary task onset Before a critical cut-in with WLM On
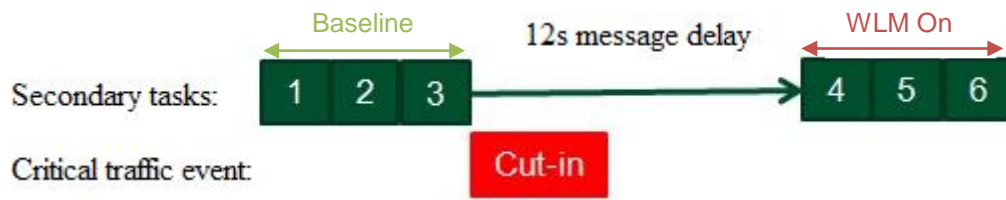
Figure 6.18: Definition of the secondary response times measures

Each variable was checked for normality and homogeneity of variance using the Kolmogorov Smirnov test and Levene's tests respectively. The data were also tested for sphericity using the Mauchly's test. In case of violation of sphericity, the Greenhouse Geisser correction was used. A three-way repeated-measures ANOVA with Workload Manager (Baseline, WLM Off, WLM On) and Lane Origin (Slow Lane, Fast Lane) as within-subject factors and Age (Younger, Older) as the between factor was carried out on the participants' verbal responses.

When the secondary task was performed in non-critical driving situations, older drivers performed slower as compared to the younger drivers (M= 1424 ms, 1283 ms, respectively, p<0.001). Critical cut-in events were found to cause an increase in secondary task response time for both age groups (F(2,84)=123.66, p<0.001, η^2=0.746), and when examining the effect of the Workload Manager on secondary task performance, post hoc pairwise comparisons showed this effect was highest with the Workload Manager Off (M_{older}= 2143ms, $M_{younger}$= 1675ms) and then followed by Workload Manager On (M_{older}= 1759ms, $M_{younger}$= 1377ms). Additionally, there was also main effect of Lane Origin whereby drivers were also found to respond slower to the secondary task when the cut-in events originated from the slow lane as compared to fast lane (F(1,42)=122.16, p<0.001, η^2=0.744). Compared to younger drivers, older drivers were found to respond slower to secondary task in all dual-task conditions. A significant interaction between Age group and Workload Manager revealed that the effect of critical cut-in on secondary task response times was particularly strong in older drivers (F(2,84)=10.75, p<0.001, η^2=0.204) as shown by the large increase in response times with WLM Off, in Figure 6.19.
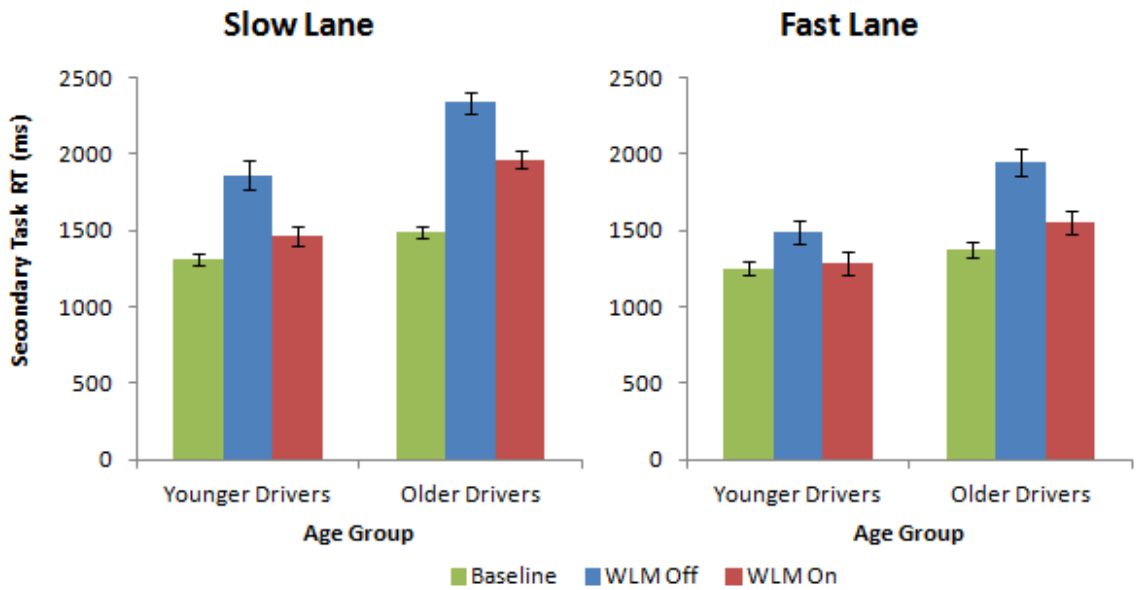
Figure 6.19: Secondary task RTs of secondary task onset Before a critical cut-in

In sum, both age groups performed slower on responding to secondary tasks in the event of critical cut-in, regardless whether the cutting-in vehicle originated from slow or fast lane. With respect to Workload Manager, all drivers in general, benefited from the delay of 12s with WLM On.

ii) Do drivers benefit from a longer delay on the secondary task onset?

Reaction times for the secondary tasks initiated concurrently with a critical lane change were examined to investigate the benefits of employing a longer delay on a system-controlled task. The 528 datapoints (from 44 participants) involving an secondary task which coincided with a cut-in were compiled and analysed. The tests for normality and homogeneity of variance were conducted on the data. In case of violation of sphericity, the Greenhouse Geisser correction was used.

A three way repeated-measures ANOVA with the Lane Origin (Slow/Fast, Workload Manager (WLM Off with 0s, WLM On with 12s, WLM On with 21s) as within-subject factors and Age (Younger/Older) as the between factor was carried out on the participants vocal responses (measured at 90th percentile to exclude the cases of unusually long response time).

The reaction times of the correct trials on the visual task showed that there was a significant main effect of Lane Origin $(F(1,42)=112.85, p<0.001, \eta^2=731)$.

Response time to the secondary task in slow-lane critical cut-in situations (M=1975ms) was 548ms longer than fast-lane critical cut-in situations (M=1427ms) (Figure 6.20).
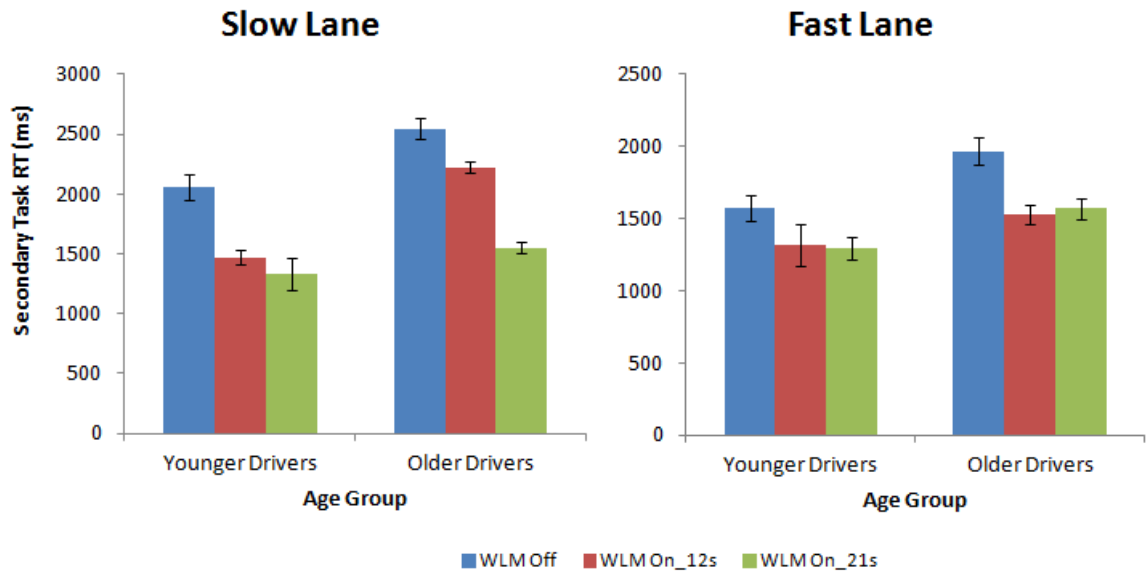
Figure 6.20: Secondary task RTs for secondary task onset Concurrent with a critical cut-in

There was a significant main effect of Workload Manager ($F(2,84)=19.007$, $p<0.001$, $\eta^2=312$) whereby participants' secondary task response time reduced systematically with the increase in delay on the secondary task onset (Figure 6.20), On average, participants were more than 0.2s faster when responding to a secondary task with Workload Manager On with a delay of 12s (M=1635ms) and 21s (M=1609m s) than when Workload Manager was Off (M=1858ms). When no delay was implemented (i.e. WLM Off), participants' performance on the secondary task was the worst as participants had to juggle between the secondary task while simultaneously dealing with throttle control to manoeuvre the vehicle safely. Additionally, there was also a main effect of Age whereby older participants on average responded more slowly by 397ms than younger participants ($F(1,42)=27.253$, $p<0.001$, $\eta^2=0.394$).

Lane Origin was found to interact significantly with Workload Manager $F(2,84)=23.53$, $p<0.001$, $\eta^2=0.359$). To examine the simple effects of the interaction of Lane Origin x Workload Manager, one way ANOVA was conducted on each Lane Origin trials. Results showed that there was a significant benefit of longer delay onset only in slow-lane critical cut-ins. Although participants' response time

for secondary task was the highest when no delay was implemented and the response times reduce with increasing delay, the benefit of longer delay onset of 21s was not found in fast-lane critical cut-ins (refer Table 6.15). In fast-lane cut-in conditions, pairwise comparison showed that the response times for 12s and 21s delay were not significantly different.

Table 6.15: Workload Manager effect on secondary task response times (per Lane Origin)

Lane Origin	F (2,86)	Sig.	Effect size (μ^2)	Pairwise Comparison
Slow lane	52.17	<0.001	0.548	Delay 0s > Delay 12s, Delay 12s > Delay 21s
Fast lane	23.69	<0.001	0.355	Delay 0s > Delay 12s, Delay 12s = Delay 21s

No other two-way or three-way interaction was found. In sum, these findings showed that although both age groups benefited from the Workload Manager On with 12s delay in all critical cut-in conditions, there is an additional benefit of a longer delay of 21s on secondary task onset concurrent with slow-lane critical cut-ins.

6.4.3.2 Percentage of Error

Secondary task onset Before a critical cut-in

A three way ANOVA with Lane Origin (Slow/Fast) and Workload Manager (On/Off) as within-subject factors and Age as between-subject factors was carried on the participants percentage of error. There was a significant main effect of Lane Origin ($F(1,42)=73.837$, $p<0.001$, $\eta^2=0.637$) whereby participants on overall performed more poorly in secondary task during slow-lane critical cut-ins (M=13.00%) as compared to fast-lane cut-ins (M=4.97%). Significant main effects of Workload Manager $F(1,42)=146.89$, $p<0.001$, $\eta^2=0.780$) indicates that participants performs more error when Workload Manager is Off (M=16.40%) than when Workload Manager is On (M=1.57%). A significant main effect of Age $F(1,42)=7.14$, $p=0.011$, $\eta^2=0.145$ showed that the older driver (M=11.00%) in general performed more errors than younger drivers (6.97%). Age effect interacted

significantly with Workload Manager ($F_{(1,42)}=9.208$, $p=0.004$, $\eta^2=0.180$) suggesting that both age groups although performed poorly with Workload Manager Off, but a large percentage of these errors when Workload Manager was Off was attributed to older drivers ($M=20.62\%$).

Secondary task onset Concurrent with a critical cut-in

With Workload Manager Off, participants made significantly more errors ($M=21.50\%$; $F_{(2,84)}=85.57$, $p<0.001$, $\eta^2=0.671$) compared to when Workload Manager was On ($M=1.71\%$ for 12s and $M=0.58\%$ for 21s). Additionally, drivers were found to perform more errors in slow-lane cut-ins ($M=10.17\%$) than in fast-lane cut-ins ($M=5.69\%$; $F_{(1,42)}=21.773$, $p<0.001$, $\eta^2=0.341$). Similar to other dual task conditions, an age effect ($F_{(1,42)}=6.50$, $p=0.017$, $\eta^2=0.128$) on error rate was found, whereby older drivers on average performed 4.21% of errors more than younger drivers. Table 6.16 shows a summary of the number of misses and the contribution of these misses in percentage, by age group. There is an indication that the overall increase of errors in dual-tasking for older drivers is due to older participants performing more misses than younger drivers when simultaneously performing the driving task and the secondary task (Table 6.16).

Table 6.16: Mean (and standard error) of number of misses and the contribution of missed responses in percentage error

Secondary Task Performance	Slow Lane		Fast Lane	
	Younger Drivers	Older Drivers	Younger Drivers	Older Drivers
Misses (count)	15.4 (2.7)	41.1 (6.5)	5.1 (0.8)	12.1 (2.1)
Contribution of missed responses in percentage error (%)	5.3 (1.7)	10.5 (2.9)	2.6 (1.3)	7.6 (1.9)

Lane Origin was found to interact significantly with Workload Manager ($F_{(2,84)}=15.173$, $p<0.001$, $\eta^2=0.265$). One-way ANOVA was conducted on each of the Lane Origin to examine whether there was a benefit of longer delays on secondary task onset. Results in Table 6.17 indicate that while there was an extra benefit of longer delay of up to 21s in slow-critical cut-ins, this was however not found with fast-lane critical cut-ins ($p>0.05$).

Table 6.17: Workload Manager effect on secondary task percentage error (per Lane Origin)

Lane Origin	F (2,86)	Sig.	Effect size (μ^2)	Pairwise Comparison
Slow lane	74.774	<0.001	0.635	Delay 0s > Delay 12s, Delay 12s > Delay 21s
Fast lane	23.507	<0.001	0.348	Delay 0s > Delay 12s, Delay 12s = Delay 21s

6.4.3.3 Summary of secondary task performance

In sum, both age groups of drivers benefited with the Workload Manager On that implements a delay of 12s during critical cut-in conditions. Drivers were found that longer delays of up to 21s have significant impact on improving drivers' secondary task performance, particularly in slow critical cut-in conditions. Considering that older drivers performed poorer than younger drivers in secondary task, older drivers may actually benefit more than younger drivers with the implementation of longer delays. A summary of secondary task response times and error rates for younger and older drivers in all dual-task conditions is shown in Figure 6.21.
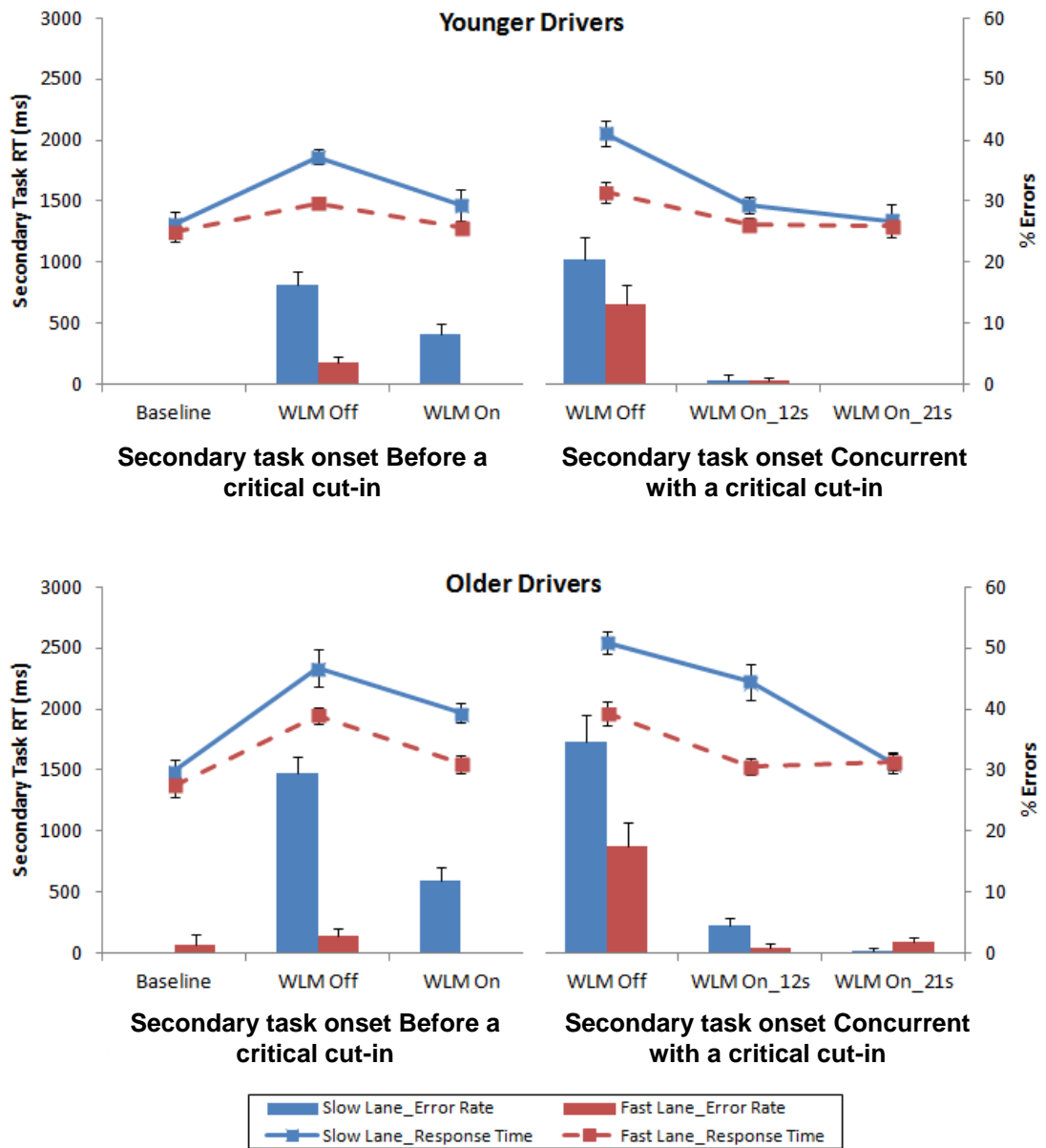
Figure 6.21: Mean secondary task response times (with standard errors) with mean percentage error (with standard errors)

6.5 Discussion

Results from the present study are consistent with Study 2 in that a vehicle cutting in from the slow lane increases driver workload and is considered more urgent than a vehicle cutting-in from the fast lane. While participants in study 2 had expressed their concern that the cutting-in vehicle from the slow lane may not cope with the average speed on the middle lane and is perceived as more urgent than fast lane cut-in thus increasing the driver workload, the present study indicates that the presence of a secondary task during these events has a consistent additive effect on response performance and driver workload across all lane change condition (as shown in Table 6.18). For conditions where secondary task was initiated before a critical cut-in, drivers were distracted during the cut-in situation. Results from Table 6.18 indicate that on average, there is a reduction of 16% (at a minimum) in accelerator release time for both slow lane cut-ins and an average reduction of 19.2% for fast lane cut-ins with the use of the intervention system. Driver workload was also reduced by 20% in both critical cut-in situation (both from slow and fast lane). These findings will be discussed further in Section 6.5.1.

The accelerator-to-brake transition time however differs with lane origin. In slow lane cut-in situations, the movement time reduced significantly for distracted conditions (i.e. secondary task onset Before a critical cut-in). For in-vehicle messages that were initiated at the time of critical cut-in, this improvement was minimal. While this measure improves with delay in the slow lane situation, this was however not found in the fast lane conditions and will be discussed in Section 6.5.2.

Table 6.18: Workload Manager (WLM) effect on driving performance and workload (per Lane Origin)

Measures	Slow Lane		Fast Lane	
	WLM Off Mean(SD)	WLM On Mean(SD)	WLM Off Mean(SD)	WLM On Mean(SD)
Secondary task onset Before a critical cut-in				
Accelerator release time (s)	1.213 (0.285)	1.009 (0.192)	1.773 (0.702)	1.410 (0.665)
% Improvement in accelerator release time	16.82%		20.47%	
Accelerator-to-brake time (s)	0.478 (0.356)	0.375 (0.086)	0.466 (0.258)	0.637 (0.245)
% Improvement in accelerator-to-brake time	21.55%		-36.70%	
Driver workload	6.67 (1.56)	5.32 (1.93)	5.27 (1.55)	4.17 (1.48)
% Reduction in driver workload	20.24%		20.87%	
Secondary task onset Concurrent with a critical cut-in				
Accelerator release time (s)	1.110 (0.244)	0.819 (0.268)	1.798 (0.853)	1.453 (0.475)
% Improvement in accelerator release time	26.22%		19.19%	
Accelerator-to-brake time (s)	0.488 (0.354)	0.478 (0.245)	0.643 (0.378)	0.576 (0.272)
% Improvement in accelerator-to-brake time	2.05%		10.42%	
Driver workload	6.40 (1.80)	4.94 (2.32)	5.27 (1.82)	3.96 (1.30)
% Reduction in driver workload	22.81%		24.86%	

6.5.1   Benefit of a Workload Manager During Safety-Critical Situations

In this experiment, the effectiveness of strategies to interrupt a task during critical cut-in situations was investigated. Investigation of the braking responses indicates that during lane changes with Workload Manager On, drivers responded quicker to the lane change events as compared to Workload Manager Off. This was applicable to all cut-in situations regardless of whether the adjacent vehicle originated from the slow lane or the fast lane.

Thorough investigation of the braking responses showed that participants undertaking an in-vehicle task prior to a critical cut-in event, responded more slowly in braking in the event of a critical cut-in. The accelerator release time and the accelerator-to-brake movement time improved with Workload Manager On during critical condition. However this additive effect of load was not found with accelerator-to-brake movement time in fast lane critical events. The accelerator-to-brake-time improves with delay at greater urgency situations (i.e. slow lane critical cut-in) but then paradoxically becomes longer for older drivers with message delay in less urgent situations (i.e. fast lane critical cut-in).

For messages that were presented concurrently, improvement on accelerator-to-brake reaction time was minimal. However improvement of accelerator release time with the Workload Manager On was in-line with the improvement in driver workload, thus indicating that accelerator release time is a good indicator of workload when evaluating the benefits of a workload manager. Moreover, the degree to which drivers rely on the different visual cues depends on their relative effectiveness (DeLucia and Tharanathan, 2009). In this situation where lane changes occur at very close distances (less than 10m headway) with the cutting-in vehicle originating from slow lane, the looming cues will be strong which may cause the drivers to perceive a slow lane cut-in as more threatening than a fast lane vehicle cutting-in at the same distance. On this occasion, the drivers' perception of the criticality of the situation would influence driver workload and thus driver's action to respond differently, which has been described earlier as the theory of perception-action coupling (Gibson, 1979).

On the occasions of successfully avoiding a collision, the response time in general was longer when the secondary task was initiated during the cut-in as

compared to non-overlapping secondary and driving task. The distracted drivers who were engaged in the visual task were less aware of the surrounding due to drivers looking away from the forward view at the moment when the lane change event was initiated. Thus in the intervened conditions, the cut-in events both from the slow lane and fast lane showed consistent improvement in braking response. However there were a number of distracted participants who did not respond fast enough, or possibly did not sufficiently prioritise the driving task and this resulted in collisions. This suggests that although people are fairly good at performing multiple tasks at the same time, both age groups were unable to continue to perform the driving task adequately in dual-task conditions requiring drivers to brake and process in-vehicle information simultaneously. Therefore, the implementation of a 12 seconds delay or more to minimise the distraction and thus to avoid overload may have merit for both age groups.

6.5.2   Age Effects

In general, older participants were more affected by dual task performance as they showed longer response times and worse performance (i.e. higher error rate) on the secondary task in comparison to the younger drivers. This could be attributed to the reason that older drivers needed more time to inspect the visual messages on the dashboard or that they have partly given up the secondary task and focus on the driving task. Similarly, the performance of older drivers was also poorer in situations relating to concurrent in-vehicle messages during critical lane-change. For example, in the fast lane critical cut-in situation, older drivers responded more slowly in releasing the accelerator pedal when the Workload Manager was Off. Older drivers experience a greater delay in braking more as the concurrent tasks requires simultaneous responses (as shown in Figure 6.22). With Workload Manager On however, older drivers were able to release the accelerator pedal and thus braking more quickly. Although Workload Manager has a varying effect on the two age groups, whereby improving the accelerator-to-brake transition times for the younger drivers, both groups of drivers performed better in braking response times with Workload Manager On.

Fast Lane Critical Cut-In
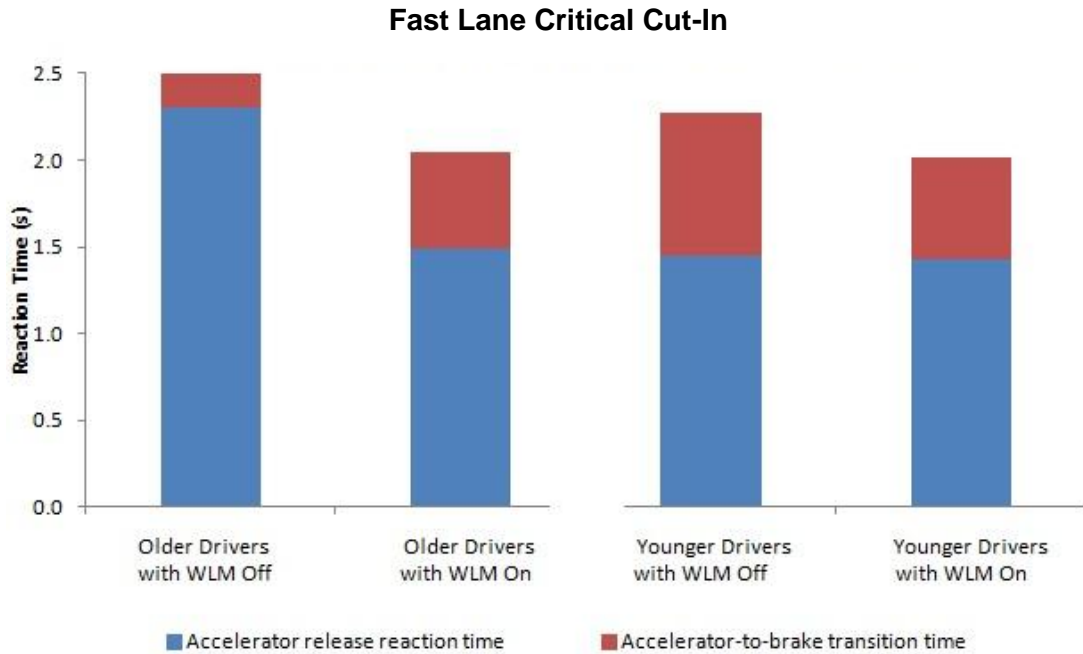
Figure 6.22: Braking components reaction time for secondary task initiated concurrently with a fast-lane critical cut-in

Despite the driving performance data showing that older drivers performed the braking task slower than younger drivers, the percentage of participants involved in a collision was comparatively lower for older drivers as compared to younger drivers. A likely explanation is that older drivers were more cautious in driving.

With regard to subjective workload, older drivers in general provided lower ratings as compared to the younger drivers. This indicates that older drivers were less influenced by the dual-tasking demand as older drivers were found to prioritise driving more (i.e. fewer collisions). Despite slower reaction times in comparison to younger drivers in conducting secondary tasks, older drivers were good or perhaps better drivers than younger drivers who were more prone or interested in dual-tasking. Thus when both age groups have similar annual high mileage, the older drivers perform driving as well as the younger ones, possible due to their higher capability of regulating own-driving which may be attributed to their higher number of years of driving experience than the younger drivers.

Overall, Table 6.19 shows that participants of both age groups in general benefited from the use of Workload Manager in all critical cut-in situations. With Workload Manager On, there is a consistent trend of improved driving and

secondary task performances which suggests that a workload manager that uses this strategy may be of benefit for some otherwise distracted drivers.

Table 6.19: Percentage improvement in brake reaction time following the use a Workload Manager

Age	Before a critical cut-in conditions		Concurrently with a critical cut-in conditions	
	Slow	**Fast**	**Slow**	**Fast**
Younger Drivers	21.65%	0.10%	17.56%	11.06%
Older Drivers	12.74%	18.78%	20.71%	24.00%

6.5.3 Influence of the Lane Origin of the Other Vehicle

The effect of the lane origin of the cutting-in vehicle on braking performance and subjective workload suggests a possible influence of looming effect. Loom is a psychological term widely used in the study of perception which refers to the "rapid expansion in the size of any given image so that it fills the retina and is perceived as an approaching object" (Schiff et al., 1962). In driving, whenever a person is on a collision course with an object, the apparent size of the visual image generated by the object on the observer's retina grows at an accelerated rate. If the lead vehicle travels in the same direction and at the same speed or higher to the driver, the lead vehicle image size will either be constant or contracting. On the other hand, if the lead vehicle is slower, the image of the vehicle expands. Such optical looming during approaching is an important cue for perception which provides approximate information about collision such as relative movement direction (approaching towards and departing from) and relative movement speed (fast or slow). Additionally, it also quantifies the time remaining before collision. According to Lee (1976), the time-to-collision is directly specified through Tau (defined as the inverse of the relative expansion rate of the retinal image), is used for judging when to start braking and how to control a vehicle during braking.

As previously shown in Table 6.3, the time-to-collision of the critical cut-in originating from the fast lane simulated in this study is negative in value due to the cutting-in vehicle travelling at a higher speed when crossing the lane divider. On the other hand, the time-to-collision for cut-ins from the slow lane is positive in value and these critical cut-ins have been found to be subjectively more demanding than

fast lane critical cut-ins. As such, the looming effect may offer an explanation from the psychological perspective on the differences in driver responses to the lane origin of the overtaking vehicle.

6.6 Conclusion

The results found in the current experiment indicated that older drivers had more errors on the secondary task and slower braking response times. These differences suggest that older drivers (a) prioritise driving thus making more errors and (b) experienced greater delayed response when switching between tasks (Monk et al., 2004)

This study also showed that delaying an in-vehicle task by 12 seconds or more during critical cut-in situations may have merit. This is because in circumstances of when distractions are system-controlled (i.e. out of driver's control), drivers may pay less attention to the driving situation. This could possibly due to driver's misinterpretation of a traffic situation or perhaps being unaware of his or her own limits of driving capabilities. Drivers who failed to timeshare the in-vehicle interactions and neglect potential collisions situations may cause a hazardous situation to arise. This is proven through statistical significant differences on driver responses (typically the brake response times) when the Workload Manager is present or absent. Additionally mental demand and effort was also found to improve with Workload Manager On, thus indicating reduction in driver workload (i.e. higher spare capacity following the implementation of information-scheduling strategy). Whilst this study is not focused on offering advice in regards to a particular delay duration to be implemented in critical cut-in situations, it does however clearly indicate the general detrimental effects on attention and performance which thus warrant caution to be exercised when allowing such in-vehicle messages.

In addition, drivers could also benefit from a notification system that provide warnings that alert them to an impending collision. Recent studies have indicated the potential benefits of warnings that alert the driver of a braking vehicle ahead (rear-end collision warning) and those that alert the driver when the vehicle begins to drift towards the edge of the road or out of its lane (road departure warnings). Fiat, for example has introduced a collision avoidance system that utilised radar or camera

sensors to detect an imminent crash. This safety system provides visual and audible warning to prompt drivers to take preventive action and also initiates braking and seat-belt retraction (i.e. increase of seatbelt tension) to hold the driver more securely, in the event that a collision is unavoidable. In relation to the findings obtained from the current study in regards to the managing driver workload during critical cut-in situations, implementing warnings that can alert drivers of dangerous neighbouring driver, such as Fiat's seat-belt retraction or possibly, haptic steering are potential alerts which can help steer driver's attention to the source of conflict, may have merit. Such alerts could be provided as additional support of a workload manager to warn drivers, particularly those who were busy dual-tasking in the event of a critical cut-in.

Chapter 7

Thesis Conclusions and Recommendations

7.1 Overview

The central aim of this thesis was to examine how the surrounding traffic influenced momentary driver workload, and to attempt to measure these workload fluctuations via comparison of systematically manipulated traffic conditions in within-subject experiments (De Waard, 1996; Lewis-Evans, 2012). The three simulator studies in this thesis provide a thorough investigation of how momentary driver workload can be measured and an evaluation of how the findings can be useful and relevant to traffic safety, with particular reference to workload managers.

The issue of workload measurement, in terms of its dynamic, evolving and multi-faceted nature, was highlighted and examined in the first study. Since workload is a construct with a variety of components (Meshkati, 1988) which can vary substantially over time, a range of subjective and objective measures were employed in the study to investigate the effect of traffic complexity on driver workload. The study provided findings on the sensitivity of measures in tapping into the fluctuations of the primary task demand manipulated in the study (i.e. traffic complexity), as well as highlighting a particular traffic behaviour that has an effect on driver momentary workload, namely the lane changes performed by a neighbouring vehicle. Among the measures examined, subjective measures were found not only to be sensitive to the overall changes in traffic complexity but was also more superior than other types of measures in capturing fluctuations in workload (Carsten, 2014). In addition to the low cost involved and ease of the administration, a subjective measure was used as the main workload measure in the latter two experiments presented in this thesis, which investigated the effect of lane changes.

In the second study, the characteristics of a lane change were explored and the workload recovery associated with each level of driving demand manipulated was examined. To investigate driver workload in dual-task conditions, a surrogate

mobile phone task (i.e. a driver-paced task), was introduced to evaluate the effect of a distracter task by measuring driver response times to secondary task alerts. This study highlighted the dynamics of changing task demand and the evolution of workload which would not be possible with the most common subjective workload measurement tools such as NASA-TLX or its derivative, DALI (Pauzié, 2008).

In the third, and final study presented in this thesis, driver workload and performance were evaluated in varying safety-critical dual-task conditions. The benefits of using a workload manager to reduce driver workload and improve performance in potentially safety-critical situations involving a critical lane change performed by a neighbouring vehicle were highlighted. Drivers' ability to manage own workload in demanding conditions were evaluated via primary and secondary task performances and comparisons were made between two age group of drivers (i.e. younger, older).

This thesis concludes with a summary of the potential contributions that these driving simulator studies make to our understanding of managing driver workload and reducing in-vehicle distraction during a critical-cut in.

7.1.1 Which workload measures are sensitive to changes in traffic complexity?

Multiple methods and metrics were used in the first study, serving as a screening to determine which of the workload measures are capable of classifying different levels of traffic complexity (i.e. sensitive to the primary task demand). The subjective measure of workload (CSR) was found to be more accurate than the objective (TDT) reaction times in distinguishing levels of demand; CSR significantly correlated with the two highly validated workload measures of RSME and NASA-RTLX. Additionally, CSR was found to respond to increasing traffic complexity, for example, increasing from LOS A (low traffic flow) to E (high traffic flow) and also to increase with the presence of lane changes. TDT reaction-time on the other hand only tapped into the lower primary task demand manipulated (LOS A to B) and was not found to vary with the presence of lane changes.

The workload construct associated with traffic complexity was demonstrated via correlations between objective and subjective measures. Despite there being studies that have shown workload to increase with increased task demand, the physiological measures examined in this study, such as pupil diameter, blink frequency and blink duration were not found to vary significantly with increasing traffic complexity. Additionally, no correlations between the eye behaviour measures and the workload measures were found. The non-significant results only suggest that different types of effort will have different physiological signatures and in this study, it was found that subjective appraisal of workload was the most sensitive measure associated with traffic complexity.

Although subjective measures may have their own drawbacks of response-bias with participants' scores clustering around multiples of 5 (refer to Section 4.3.1), if care is taken in the design stage, adequate piloting will ensure that an appropriate scale is being used and the scale is sensitive to gauging subjective workload. Since workload ratings should only be used to compare between different conditions in within-subject designs, it is perfectly acceptable that subjective tools are the best available technique to compare the different traffic complexities investigated in this thesis. Moreover, it is worth noting that drivers are active operators, who employ varying strategies to maintain their own driving performance. Therefore, the level of effort employed by participants to maintain safe driving can differ, and a simple and yet diagnostic measure is required to tap into these momentary changes in effort. Thus the CSR measure is not only much easier to implement as compared to the multidimensional NASA-RTLX questionnaire, but also a more viable method of measuring momentary workload as compared to the wider uni-dimensional RSME scale of 1 to 150. As such, the CSR was utilised in the subsequent studies that explored more specific criteria of the traffic behaviours. The continued use of this measure throughout this thesis provides an understanding of how driver workload evolves across different traffic scenarios and with the use of a workload manager. From this point on this thesis, the driver workload discussed refers to this CSR measure.

7.1.2 What traffic complexity characteristics influence driver workload?

In the first study, driver workload was found to increase with increasing traffic flow and also with the presence of lane changes undertaken by an adjacent vehicle. To encourage participants' interaction with the traffic environment, they were told that they were late for a meeting which added an element of urgency to driving task. Under this urgency, drivers would consider the surrounding traffic more than usual. And being in a hurry, they may be opportunistic, whereby finding a gap to overtake another vehicle in order to maintain their speed. For instance, drivers would constantly assess their own driving and the surrounding traffic for possible gaps and also to determine whether a gap is sufficient to stay in lane or even to initiate a lane change. Drivers may utilise simple cues and features inherent in the situation such as the safety-margin involved (Näätänen and Summala, 1976; Summala, 1985) to avoid hazards with other traffic users. Some on-road studies (Sultan et al., 2002; Lee, Olsen and Wierwille, 2004) have attempted to examine the cause and effect of traffic complexity based on driving performance, but investigating such connection by incorporating real-time driver workload as investigated in this thesis would be the first.

In the first experimental study, it was found that the increase in traffic complexity influences both driver workload and driving performance to a certain extent. Driver workload for example increases with the increasing flow between Traffic Flow A (i.e. free-flow) and D (i.e. approaching unstable flow). Beyond Traffic Flow D, the increase of traffic flow has a negligible effect on driver workload, possibly due to the restricted changes within the traffic environment. For example, participants cruised less due to reduced flexibility within the traffic. Within Traffic Flow A to D, the effect of adjacent vehicles pulling-in at close proximity has an effect on driver workload. Analysis of the lane change events suggests that driver workload was affected when an adjacent vehicle pulled into the gap between the participant vehicle and lead vehicle. Within this vicinity, adjacent vehicles pulling-in or a lead vehicle pulling-out had similar effects on driver workload. This shows that driver workload is influenced to some degree by the behaviours of adjacent vehicles on the roads. This highlights driving from a social perspective whereby driver workload changes under the influence of adjacent vehicle behaviours.

7.1.3 Does the Lane Change effect exist?

The differing effect of the presence of lane change on driver workload across the three studies reported suggests that there is a significant likelihood of observing the lane change effect across single- and dual-task conditions. The first study asked participants to rate subjectively 'How easy or difficult to drive in the traffic?'. Within this study, there were no constraints placed on the driver such that participants interacted with the surrounding traffic (for example, they could change lane as they wish). The driving situations examined were naturalistic and the subjective workload measured for the road sections involving lane changes had an effect size of 0.574 (refer to Section 4.5.1.1).

The second study focused on manipulating the lane change characteristics. In this study, the lane change proximity and the lane origin were found to be influencing factors on driver workload. This finding further verifies the importance of social interaction patterns in driver workload, as highlighted by Wilde (1976); the presence of other drivers increased anxiety and attention when driving in heavy traffic and the sense of invasion of one's personal space when other drivers come to close (i.e within close proximity). Although participants in this study were instructed to drive in the middle lane of a three lane motorway, the effect of a lane change was higher than the effect size of lane change found in the first experimental study; lane change proximity's effect size was 0.794 whilst lane origin's effect size stood at 0.873. (see Section 5.3.4.1). With a greater flexibility to manipulate the lane change characteristics systematically, the effect of a lane change on drivers can be measured more accurately, reflected in the larger effect size as compared to the first study. Results showed that the presence of a cut-in within 20m or less significantly affected driver workload. Furthermore, relative workload (i.e. workload increase) was the highest when the cut-in occurred within 10m or less. Additionally, participants experienced a higher increment in workload when the cutting-in vehicle originated from the slow lane as compared to the fast lane, suggesting that slow lane cut-ins were more demanding or perhaps more threatening than fast-lane cut-in.

Additionally, this thesis also shows that the presence of lane changes in dual-task conditions can negatively affect driver workload. In the third study, drivers were found not only to brake more slowly due to the distraction of a secondary task

presented prior to or concurrently with a critical cut-in, but they were also found to experience higher workload in these situations. The results indicated that, when a delay was presented to avoid the overlapping of the secondary and driving task, driver workload was lower. This suggests that the lane change effect on driver workload was not only being observed in driving-only conditions, but also in dual-task conditions. Thus, the presence of these lane changes can be potentially hazardous to drivers in real-world driving scenarios, especially involving dual tasking during critical cut-in conditions.

7.1.4 Do drivers delay the start of an interrupting task?

Drivers are not passive recipients of distracting activities but rather they play an active role in initiating and managing these activities (Lee and Strayer, 2004). Studies have shown that drivers may moderate in-vehicle activities based on the traffic conditions (e.g. Stutts et al., 2005; Lerner and Boyd, 2005; Pöysti et al., 2005; Esbjörnsson, Juhlin and Weilenmann, 2007), whereby they have a strong inclination to engage in in-vehicle activities so long as the driving conditions allow. Horrey and Lesch (2009), for example, conducted a study to investigate drivers' strategic coordination of in-vehicle activities while driving around a closed track of varying demand and difficulty (e.g. narrow road sections requiring precise handling; easy straight road sections). In this study, participants were asked to perform one of the four in-vehicle tasks (e.g. phone conversation, read a text message, find an address and pick up object on the floor) and were given the opportunity to decide when to initiate these tasks within a set of time. Horrey and Lesch (2009) found that, despite participants being fully aware of the relative demands of the road (as measured by the NASA-TLX), they did not strategically postpone the initiation of the in-vehicle tasks. Participants were found to have initiated tasks even in high workload conditions. However there are two main criticisms to this study: firstly, the NASA-TLX questionnaire was used to evaluate the demand of the driving condition. Due to the fact that the questionnaire was administered post-study, workload was not measured in real-time. This technique does not accurately embrace the dynamic nature of workload. Secondly, it is possible that the driver may engage in some form of adaptation by delaying their response times to initiate the task (i.e. to take place at

a less busy time), but this delay could be relatively small (i.e. within the time scale of seconds).

In contrast to Horrey and Lesch's (2009) findings that drivers did not delay initiation of a secondary task despite being aware of the increasing driving demand, the second study in this thesis has proven otherwise, whereby the participants were found to delay the secondary task, but the delay duration was insufficient. For example, the workload recovery measured in the study has shown that the presence of lane change has an effect on driver workload recovery with an average minimum recovery period of 12s (for 30m lane change proximity). When a distracter task alert was given concurrently with the lane change event, drivers were found to delay initiating the task, by 10s on average, from the start of the alert in all driving conditions.

Although the second study has shown that drivers do delay their response to an interrupting task, the duration of delay (i.e. 10s) was lower than workload recovery time (i.e. 12s). This can be attributed to the varying motivations for undertaking concurrent in-vehicle activities (Lerner and Boyd, 2005; Hancock et al, 2009). For example, drivers may find difficulty to resist reading or even responding to an alert of an incoming text message (Lansdown, 2012). Coupled with drivers' nature to be overly optimistic about their ability to perform in-vehicle activities (Horrey, Lesch, and Gabaret, 2008; Wogalter and Mayhorn, 2005), drivers may not be effective at gauging the appropriate times to perform in-vehicle tasks. Therefore, there will be obvious instances where it would be expected to break-down (Hancock et al., 2003), despite drivers perceiving that they could partition the in-vehicle task into more manageable chunks (e.g. Wierwille, 1993). This study has thus shown that despite drivers being aware of the changes in the primary task demand and employing a delay in initiating the secondary task in all cut-in situations, there is an indication that the duration of delay may be insufficient. This also highlighted the superiority of CSR as a real-time workload measure, as drivers' adaptation to the fluctuations in driving demand can now be measured and analysed as to whether such delay (also known as interruption lag; Altmann and Trafton, 2002; Trafton, 2003) is sufficient to minimise the disruptive effects of the secondary task (i.e. interrupting task) in dual-task conditions.

7.1.5   Is a workload manager beneficial during safety-critical situations involving critical cut-ins?

Various automobile companies are focusing on developing more advanced workload managers which monitor driving performance in real time, for example, the 'Do Not Disturb' option feature developed by the Ford Research Company which helps driver to stay focused on the road during high-demand situation. Although workload managers to monitor driving performance in real-time have been proposed, it is also important that these systems are consistent with the moment to moment coordination of multiple tasks with the fluctuating demands of the driving. Workload managers that manage interruptions based on a particular driving demand and in-vehicle distraction may have merit.

Therefore, the use of a workload manager during safety-critical situations was explored in the third study of this thesis. In this study, the distracter task alert was given either before a lane change or concurrently with the lane change. Thus, workload arises not only from each task but also from task switching itself (Pashler, 2000). In the dual task situation, a driver will have to make an evaluation of the effort required for the secondary task as compared to the effort required for the primary task in order to decide whether to surrender the secondary task. Results from the study showed that drivers' brake response times were impaired by the secondary task, as distracted drivers allocated less attention to the surroundings and were less aware of the driving situation. Braking responses times were longer when the drivers were distracted with a secondary task before a lane change.

However, when a workload manager was in use (i.e. an implementation of 12s delay on the secondary task), there was an improvement in braking reaction time in both dual-task conditions. With the use of a workload manager, the requirement to respond to both tasks simultaneously can be avoided; with this assistance support, there was also a reduction in driver workload suggesting that the use of system intervention improves both driver workload and performance. Additionally, drivers were involved in lower collisions as they could now allocate more attention to the primary task driving. This also suggests greater awareness of the surrounding traffic. As such, a delay of 12 seconds in the secondary task was found to be useful in reducing driver workload and improving driver performance.

7.1.6   Which age group of drivers benefited from the workload manager?

When comparing the brake reaction times for two different age groups in dual-task conditions, older drivers performed slower in both driving and secondary tasks, as compared to the younger drivers. Older participants were more affected by dual task performance, showing longer response times and poorer performance (i.e. higher error rate) on the secondary task in comparison to the younger drivers. This could be attributed to the fact that older drivers need more time to inspect the visual messages on the dashboard or that older drivers have partly given up the secondary task and focused on the driving task.

It is interesting to note that older drivers did manage the dual-task situations to some extent. In this study, older drivers (aged 60-72) appeared to surrender performance on the secondary task at high workload level as indicated by a high percentage of missed signals on the secondary task as compared to younger drivers. Although this suggests that older drivers may have insufficient resources for task switching, it also indicates that they were more cautious in driving. Despite slower reaction times, older drivers were also involved in fewer collisions as compared to the younger participants. This is possibly due to the higher number of years of driving among older drivers despite the fact that both age groups had similar annual mileage. With greater driving experience and perhaps due to older drivers choosing to surrender the secondary task, they experienced lower levels of effort in completing the driving task (i.e. lower rating in RSME, NASA-RTLX and CSR) in comparison to younger drivers who chose not to surrender the secondary task.

In general, participants of both age groups benefited from the use of a workload manager (i.e. delay of the in-vehicle task) in all critical cut-in situations. With this support system, there is an improvement across all age groups in driver workload and driving performance. Additionally the percentage of collisions among the younger drivers was also reduced, which suggests that the use of a workload manager in these dual-task situations may have merit not only for the benefit of older drivers but also for the younger drivers, who may otherwise be overwhelmed by the workload arising from the two tasks.

7.1.7 Can these results be generalised to the real-world driving scenarios?

There are many reasons as to why an accident may occur, ranging from lack of driver skills to unexpected events that drivers might not be adequately prepared for. Based on an analysis of distraction-related crashes from the US national crash databases, Tijerina et al., (2003) suggests two main converging findings regarding drivers' engagement in secondary activities. Firstly, drivers tend to engage in discretionary in-vehicle activities under conditions where they expect no trouble. Examples of these no-trouble conditions highlighted were driving in daylight on straight roadway sections, driving on dry pavement in clear weather, or driving with speed between 45 mph and 55 mph (varying up to 65 mph). Secondly, it was found that when these expectations of the traffic conditions were violated due to some random, unpredictable events occurring on the road, crashes may ensue. Often, these crashes occur due to excessively high demands at a point in time when a hazardous event on the road had also occurs, whereby both the driving and secondary tasks require the attention and a response from the driver. It is this co-occurrence which disrupts the human's capacity for multitasking performance. This thesis has highlighted traffic events which could be potentially hazardous to drivers, under conditions where drivers would expect no trouble (i.e. on dry pavement in clear weather). A thorough investigation of this traffic event (i.e. a lane change performed by neighbouring vehicle), measuring drivers' effort in performing the driving task as well as the interruption of secondary tasks were attempted. This was to provide an overall view of how driver workload would evolve with the unpredictability of these lane changes and also, to investigate how drivers would respond to such lane changes under dual-task conditions.

To ensure that the findings can be generalised to real-world driving, contributing both to the knowledge of traffic behaviour research and the design of a workload manager, this thesis focuses on a distracting task that is relevant to drivers. For example, a surrogate mobile phone task was used as the distracting task in the second study to examine driver's task prioritisation. Following the identification of high workload conditions associated with specific characteristics of traffic behaviours in the second study, for example lane changes at 10m of less, these critical cut-in conditions were explored further in the subsequent study. In the third

study, the effect of a short duration in-vehicle task was examined. The list of warning messages was obtained from a vehicle manufacturer to ensure that the messages used were valid messages utilised in the real-world. The intention of this work was to demonstrate the distraction potential of low demand tasks, so as to highlight the fundamental human performance limitations that should be considered in the design and presentation of in-vehicle tasks. The understanding of driver momentary workload suggested that suppressing the in-vehicle messages during critical cut-in situations should be included as part of a workload manager function. Moreover, on-going in-vehicle messages should be interrupted or modulated to reduce their influence on driver workload and braking response.

Additionally, all three experimental studies were conducted using a high fidelity driving simulator. The differences in the safety cost of a failed braking response and in driver priorities relative to on-road driving suggest that testing is required in a real-world driving scenario before these results can be fully generalised to everyday driving situations.

7.2 Thesis Contribution

This thesis is presented in chronological order beginning with a study (Chapter 4) that examined multiple workload measures under varying traffic complexity. Based on the selected workload measure (i.e. CSR) and traffic event (i.e. lane change) highlighted in the first study as being worthwhile constructs, these findings were explored further in single- and dual-task conditions in Chapter 5. The thesis then concluded by investigating dual-task conditions relating to the use of a workload manager (in Chapter 6). Throughout the thesis, the focus was on the application of the findings on reducing driver workload and improving driving performance, with following three major contributions by: 1) developing and validating a robust method for measuring real-time driver workload 2) applying that method to assess the effect of traffic on driver workload and showing that traffic behaviour was more important than traffic density in causing high workload, and 3) showing that a workload manager could provide useful assistance in limiting excess workload during safety-critical situations caused by cut-ins of other vehicles in dense traffic. Following this, the main key findings were:

- Subjective measures of workload were found to be a more sensitive measure than objective measures within the scope of traffic complexity explored in this thesis.

- Driver workload is influenced by traffic complexity, particularly by traffic behaviour. In this study, this refers to the presence of a lane change performed by neighbouring vehicle.

- Traffic behaviours such as Lane Change Proximity and Lane Origin affect driver momentary workload. While driver momentary workload increases with increasing Lane Change Proximity, a lane change performed by a cutting-in vehicle that originated from the slower lane has a stronger effect on driver workload than if the pulling-in vehicle originated from the faster lane.

- Drivers' delay to initiating secondary tasks were found to be insufficient during cut-ins at a lane change proximity of less than 10m. As such, these lane change conditions were considered as critical cut-ins.

- Dual-tasking increases driver workload. Secondary tasks which are initiated before or concurrently with a critical cut-in can increase driver workload and impair performance.

- There is a potential benefit of the use of a workload manager in managing driver workload during safety-critical situations involving a critical lane change. A message delay of 12 s or more during critical cut-in situations was found to have a positive benefit on both age groups of drivers (younger and older), in reducing driver workload and improving driving performance.

There are however limitations in the study with respect to balancing the amount of lane changes that occur and the duration of the drive. Although this study attempted to create scenarios which are naturalistic, this method has several limitations. For example, the exact location and timing of the lane changes could not be pre-determined beforehand. Therefore this runs into the problem of variability in the duration of the run as the triggering of the lane change events would depend on meeting the criteria of availability of space ahead of the participant's vehicle and relative well-controlled speed from the driver. Although this provided the benefit of increasing the unpredictability of lane changes, it does however, come with the disadvantages of slightly longer runs than expected- on average, an increase of up to 5 minutes- as they had to drive until a certain number of lane changes had occurred. Though this may increase the risk of fatigue, participants were given rest time between each experimental drives and were allowed longer if required to ensure that fatigue was kept to a minimum.

Additionally, the lack of face validity of a driving simulator in terms of its ability to replicate the cutting-in characteristics may account for some of the differences found between the simulator and on-road studies (Sultan et al., 2002; Lee, Olsen and Wierwille, 2004). In the second and third study examined in this thesis, the cutting-in vehicles were scripted to stay in front of the participant's vehicle for 10 s after pulling-in and then sped up to create a gap ahead of the participant's vehicle for the preparation of the next lane change to occur. It is possible that for lane changes experienced on-road, these cutting-in vehicles may continue to be the participant's lead vehicle for a duration longer than 10 s and thus may have a greater influence on driver workload. Therefore further work can be

carried out, whereby participants can interact with a cutting-in vehicle for a much longer period of time than was examined in this research. Longer interactions with the surrounding traffic may have bigger impacts on driver workload.

In terms of the workload measure, temporal workload was measured every 7s, which was initially determined by the size of the tiles used in the simulator road layout (i.e. 252 m) in the first study. Since this thesis has proven that CSR (i.e. rating scale of 1 to 10) is a sensitive measure of momentary workload, it is possible that workload ratings can be collected at a smaller time interval for more accurate measurement of temporal workload.

The secondary task employed could be criticised for the lack of realism (i.e. due to the nature of a simulator study whereby a participant encounters numerous events within a short drive as opposed to one or few surprising events within a long drive). This imperfect construct of a simulator study is however the best available technique to investigate these high-workload driving task in a safe environment. After all, the goal of this research is to improve driver safety by addressing traffic behaviour factors attributed to driver error and crashes.

This thesis, overall, aims to add knowledge into the research of traffic safety and to enable knowledge transfer into the automotive industry (i.e. knowledge application) by constructing the studies using the current workload manager and sensor functions. To ensure the findings were useful to the automotive industry, the studies in this thesis were designed and constructed with inputs and advice from an international automobile company.

7.3 Recommendations for Future Work

A driver workload toolkit with several measures and stages of assessment is needed. Firstly, workload metrics must come with a detailed standard methodology that specifies standard test equipment, procedures, participants, data treatment, analysis procedures, criteria and decision rules. The lack of a standardised workload test that can provide the necessary measures of safety and the small number of studies which explore driver workload comprehensively leads to the difficulty of cross-referencing for experimental design. In this thesis, a specific measure of workload (i.e. subjective ratings) and a specific test environment (i.e. high validity driving simulator) were utilised throughout the study to ensure consistency of methodology and to allow comparison of workload in different situations. As CSR is utilised in a very similar nature of experimental design (i.e. lane change scenarios on a motorway based in virtual environment) across the three studies in this thesis, CSR can also be utilised in different experimental environments involving other demanding driving scenarios such as pedestrian crossing or roundabout. This may provide insight of the effort invested and highlight problematic traffic situations which can be considered for improving workload manager functionalities. Additionally, CSR can also be administered to analyse drivers' momentary workload when ADAS or satellite navigation systems are in-use in varying traffic situations.

Following the findings in this thesis that a lane change performed by a neighbouring vehicle can influence driver workload and performance, it is possible that the use of an alert to attract drivers' attention during these distracted safety critical situation may have merit. For example, a haptic alert via steering or brake pedal could be useful. Previous research by Donmez et al, (2006a) demonstrated that drivers trust visual feedback the most due to their reliance on sight throughout their daily lives. Visual feedback requires a high level of driver attention and is most effective in vehicles when combined with another form of feedback (Dingus et al., 1997). Auditory feedback can also produce excellent results when used as a driver warning feedback method (Jensen et al., 2007) and was found to reduce crash rate especially for older drivers (warning tone of 1000Hz; May et al., 2006). Some studies however have shown auditory warnings to lengthen reaction times and to be the cause of confusion when combined with auditory disturbances such as road noise

(Wiese and Lee, 2004). To direct a person's attention to a particular location, studies have shown have indicated a crossmodal connection in spatial attention between vision and touch (Butter, Buchtel and Santucci, 1989; Spence and Driver, 2004). This can be taken as a strength of tactile signals as vibrotactile warning signals not only can direct driver's attention to the spatial direction, but also can trigger a driver to respond appropriately (such as a braking response). Ho, Reed and Spence (2006) demonstrated that incorporating vibrotactile feedback (with vibrotactile frequency of 290Hz) through tactors fastened to the driver's stomach and back, decreased braking response times and directed visual attention to the appropriate location, thus helping to prevent front and rear-end collision.

Incorporating haptic feedback into the steering wheel of a vehicle proved to be effective in reducing reaction times for lane departure (Suzuki and Jansson, 2003) and improvement in avoiding hitting obstacles when introduced as supplemental feedback to the driver. Furthermore, the Forward Collision Warning (FCW) system is currently limited to operational millimeter wave radar and laser radar systems with horizontal field of view (FOV) of up to ±15° while horizontal FOV for a vision-based system might be ±30° to ±40°. When an obstacle suddenly appears in the participant's vehicle path, such as critical scenarios involving lane changes performed by a neighbouring vehicle, the FCW system may not have adequate time to detect the obstacle and provide a warning to the driver as the sensor performance has been exceeded. Direct feedback such as a directional vibrating steering wheel may be an effective way to attract driver attention to the road when the adjacent vehicles cross the lane divider within close proximity (i.e. critical lane change distance of less than 10m). Therefore in the presence of critical lane changes, there may be benefits in providing a vibrotactile cue (i.e. when the vehicle crosses the lane divider) to alert the driver of the potential danger and to provide time-critical directional information. Additionally, seat-belt retraction which increases the seatbelt tension to prompt drivers to take preventive action could also potentially be an example of notifications to the drivers. With such alerts, drivers' reaction time to braking may perhaps improve further with the use of these alerts.

Additionally, there are other driver characteristics which have not been examined in this thesis but could be considered in future studies. The influence of personality factors such as neuroticism or sensation seeking, on driver workload

could be explored. For example, in a study of measuring the perceived workload of a vigilance task measured using the NASA-TLX questionnaire, Rose et al. (2002) found that neuroticism was related to perceived frustration. In some other studies of examining the benefit of driver support system such as the impact of ACC system on their driving, general personality trait such as sensation seeking, was taken into account and was found to influence drivers' subjective assessment of the impact of the system on their driving (Ward et al., 1995; Rudin-Brown and Parker, 2004). Their results indicate that the higher sensation seekers reported lower level of arousal and effort when driving with ACC than the low sensation seekers. As such, understanding of individual differences may help contribute in improving the workload manager functionality as the workload manager can be personalised to the driver's personality.

Overall, it is hoped that this thesis offers potential methods for understanding the effect of traffic behaviour on driver workload and the management of driver workload and driving performance, specifically in safety-critical situations where the driver is required to prioritise the driving task. In addition, it is anticipated that the suggestions for future research will encourage further investigations and refinements of these workload measures and an exploration of more traffic events, which could also improve the functionality of a workload manager.

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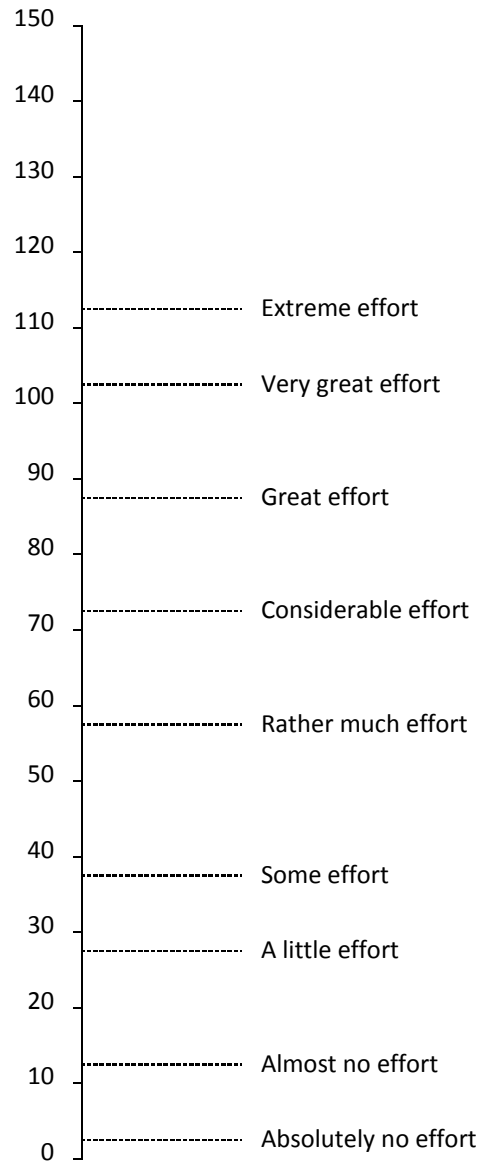
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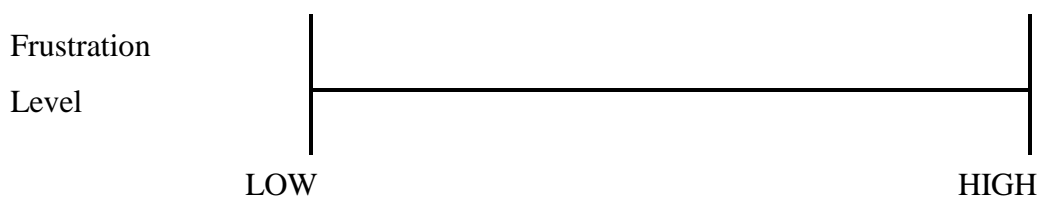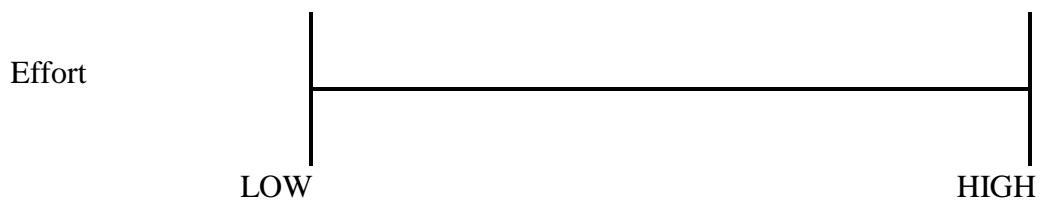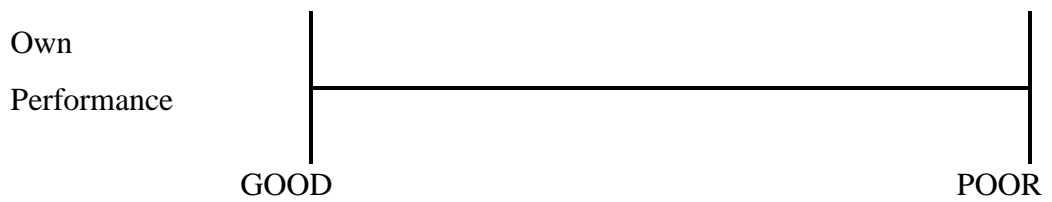
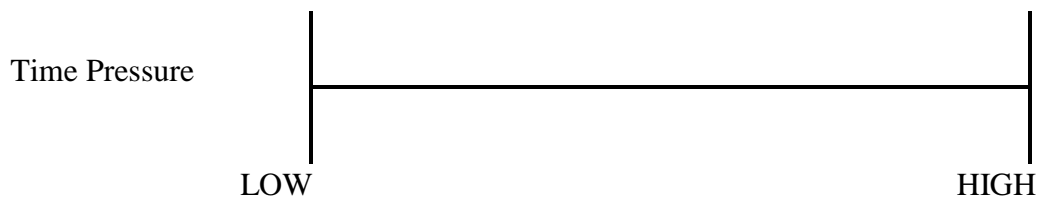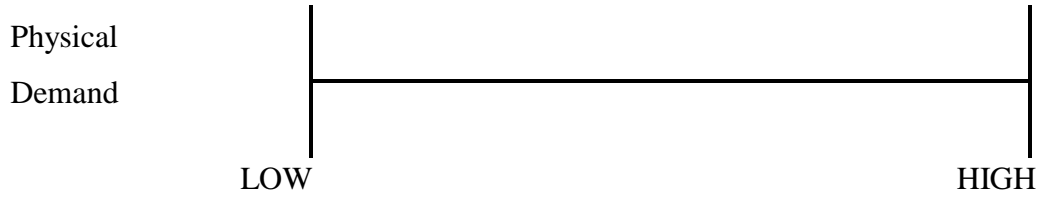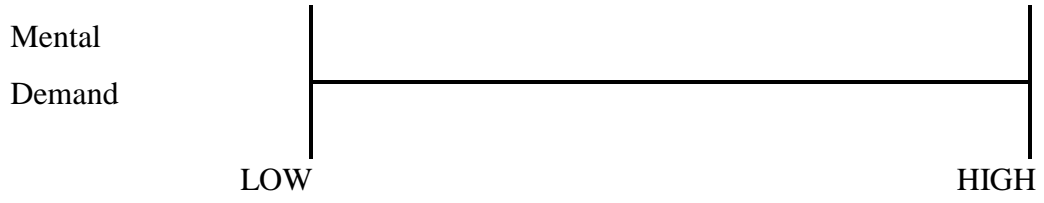Zhang, H., Smith, M. and Witt, G. (2009). Driving Task Demand-Based Distraction Mitigation. In M.A. Regan, J.D. Lee and K.L. Young (Eds.). *Driver Distraction: Theory, effects and mitigation* (pp. 485-500). London: Boca Raton.

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Appendix I: Rating Scale of Mental Effort

150	
140	
130	
120	
110	Extreme effort
100	Very great effort
90	Great effort
80	
70	Considerable effort
60	Rather much effort
50	
40	Some effort
30	A little effort
20	
10	Almost no effort
0	Absolutely no effort

Appendix II: NASA-RTLX

Mental
Demand

LOW   HIGH

Physical
Demand

LOW   HIGH

Time Pressure

LOW   HIGH

Own
Performance

GOOD   POOR

Effort

LOW   HIGH

Frustration
Level

LOW   HIGH

Appendix III: Study 1 Post Study Questionnaire

1. What factors affects how you give your rating?

2. Would you prefer a smaller rating scale?

3. Please rank the factors below in terms of influencing your driving task difficulty.

   a) Lead vehicle braking

   b) The adjacent vehicle pulling into your lane

   c) The number of vehicles in front of you

4. Is the TDT task stimuli too long or of the correct length?

5. Any other comments:

   _____

   _____

6. Observations by experimenter