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CAN DRIVING SIMULATION BE USED TO PREDICT CHANGES IN REAL-WORLD CRASH RISK?

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Abstract:

This report considers and answers the question of whether driving simulation can be used to reliably predict changes in real-world crash risk. Following a review of the main issues relating to simulator validity and fidelity, including advantages and disadvantages of using driving simulators compared to test-track, or on-road, instrumented vehicle research, descriptions of a number of popular simulated dependent measures are presented. These measures are discussed in terms of their validity as the potential bases for conclusions regarding real world crash risk estimations. Some of the more common psychological and/or behavioural concepts targeted by simulated driving research are then defined and discussed, also in terms of their suitability for use in predicting actual on-road driver behaviour. Finally, it is concluded that, as long as policy makers and road safety administrators are aware of the limitations of simulator research, especially its inability to allow for the calculation of precise predictions of actual numbers of collisions, driving simulation offers a safe, relatively low cost, alternative to on-road instrumented vehicle or naturalistic research. The use of simulation is particularly recommended as a first step in the evaluation of novel road safety interventions.

Key Words:
Road safety; driving simulator; validity; fidelity

Disclaimer

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Preface

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CMR-B researched and wrote the report.

MGL provided guidance regarding the direction of the report.

AW collected literature relating to the report and wrote some of the descriptions of the dependent measures.

Ethics Statement

Ethics approval was not required for this project.

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1. INTRODUCTION

The risk of a driver being involved in a crash depends on many factors. These include, but are not necessarily limited to, the following: roadway type (e.g., urban *vs.* rural), environmental features, vehicle characteristics, weather, road conditions, traffic density and flow, the behaviour of the driver, his or her passenger(s) and other road users, as well as their respective state and trait (personality) variables, and finally, opportunity. ‘Crash risk’ is the technical expression that describes the probability of being involved in a collision given one’s interaction with the road transport system. The crash risk associated with any one of the above elements is usually calculated by statistical analysis of frequencies of observed road crashes; in particular, through the application of statistical modelling approaches such as factor analysis and logistical regression to databases of police-reported crash statistics.

While it is not feasible or realistic for road safety authorities to legislate many of the above-listed factors, it *is* possible to manipulate those factors that are of a physical, or static, nature. Accordingly, the contribution of physical, environmental and roadway factors to crash risk is the focus of the broader Baseline project that prompted the development of the present chapter (Edquist, Rudin-Brown, & Lenné, 2009).

A scan of the relevant literature reveals a wide variety of environmental and roadway factors that have been found to influence crash risk (see Table 1). A first step in identifying how and to what degree manipulation of these factors could be used to reduce crash risk in a systematic way by road safety authorities would be to test their effects in a simulated environment. A summary of the crash analysis data from studies presented in Table 1 reveals that the following factors are reliably associated with increased crash risk on rural roads: number of minor junctions within a given road segment (Taylor, Baruya, & Kennedy, 2002), narrow road width (Transportation Research Board, 1987; Milton & Mannering, 1998; Taylor et al., 2002; Gross, Jovanis, & Eccles, 2009), poor quality street lighting (Beyer & Ker, 2009), deteriorated road surfaces (Transportation Research Board, 1987; Baldock, Kloeden, & McLean, 2008), small curve radii (Transportation Research Board, 1987; Milton & Mannering, 1998; Anderson, Bauer, Harwood, & Fitzpatrick, 1999), and density of sharp bends (Taylor et al., 2002). Similarly, increased crash risk on urban roads is associated with: number of lanes (Sawalha & Sayed, 2001), number of minor junctions (Taylor, Lynam, & Baruya, 2000; Sawalha & Sayed, 2001), density of driveways (Sawalha & Sayed, 2001) and density of pedestrian crosswalks (Sawalha & Sayed, 2001).

Table 1. Environmental roadway factors that influence crash risk.

Road environment	Factor	Reference
Rural	• Road width (narrow > wide) • Number of minor junctions	(Taylor et al., 2000)
Rural	• Density of sharp bends • Density of minor junctions	(Taylor et al., 2002)
Rural	• Lane width	(Gross et al., 2009)
Rural	• Quality of street lighting	(Beyer & Ker, 2009)
Rural	• Road surface quality	(Baldock et al., 2008)
Rural	• Curve radii • Road width • Road surface quality	(Transportation Research Board, 1987)
Rural	• Shoulder width • Curve radii	(Milton & Mannering, 1998)
Rural	• Curve radii	(Anderson et al., 1999)
Urban	• Number of lanes • Number of minor junctions • Driveway density • Pedestrian crosswalk density	(Sawalha & Sayed, 2001)
Urban	• Number of minor junctions	(Taylor et al., 2000)

The use of simulation to train operators and to conduct research on operator behaviour has been an accepted practice within the air transport industry since the early days of flight history (Allen & Jex, 1980; Moroney & Lilienthal, 2009). While the use of simulation to train pilots can be easily justified on the basis of the very high cost of real world flight operations, it is more difficult to justify the use of simulation for driver training and research based on cost alone. However, in both cases, the use of simulation offers a number of advantages unrelated to cost, the most salient being safety.

Driving simulation has been around since at least the 1960s (Allen & Jex, 1980) and, since then, has undergone many advances in terms of computing, visual display, and vehicle dynamics, capabilities. Today, many (if not all) universities and organisations involved in road safety research are proud to include a driving simulator amongst their array of research tools. Although driving simulators are popular for a variety of reasons among students and researchers, the validity of using driving simulation to measure behaviours predictive of actual crash risk is a critical issue that is commonly not considered (Godley, Triggs, & Fildes, 2002). What is needed is a thorough review of the relevant issues. In this way, road safety policy makers and administrators can be confident that the results of research studies using driving simulation are as relevant and applicable to real-world road safety policy as results that are based on crash statistics and on-road naturalistic driving studies. Any review would also simultaneously provide road safety administrators with confidence in the ability of driving simulation to adequately and effectively train new drivers.

The objective of the present review chapter is to determine whether driving simulation can, and should, be used to reliably predict changes in actual crash risk. An overview of the validity issues pertaining to driving simulators is first presented, followed by a discussion of the most common reasons for using driving simulation as an alternative to on-road driving in both training, and research, situations. The various dependent measures that are used in simulation research are introduced and described, as are some of the better-known psychological, or behavioural, concepts that have been demonstrated to affect both simulated, and actual, driving performance. So-called "surrogate" measures of actual crash risk are also presented, and a conclusion drawn.

2. SIMULATOR VALIDITY

In essence, the term 'validity', when used in the context of behavioural research, refers to how well a study, a procedure, or a measure does what it is supposed to do (Graziano & Raulin, 1989). The validity of a driving simulator, when used as a training tool or for research, is obviously of great importance to driver trainers, researchers, and policy makers alike. Although important, it is possible (and common) for simulation enthusiasts to get caught up at times in the technical details and similarities between a simulator and how well it represents reality. Experienced researchers and experts in human behaviour will often remind novices in the field, however, that it is not necessary for *all* elements of a driving simulator to be identical to those associated with a real vehicle. Instead, the choice of whether to use a driving simulator should be based on whether the simulator is sufficiently valid for the specific task or behaviour that is under investigation. As long as the set of cues that is important to whatever aspect of driving is the subject of investigation or training is valid, then that simulator may be as valid as a field experiment (Kaptein, Theeuwes, & van der Horst, 1996).

The validity of a driving simulator, in terms of its ability to reliably measure a given aspect of driving performance, depends on a number of factors. Two types of validity that are often discussed in the simulation literature are *physical validity* and *behavioural validity*. Depending on the underlying purpose(s) for using a simulator in a given situation, either of these types of validity can be more, or less, relevant.

2.1 Physical validity (fidelity)

Driving simulators come in many shapes and sizes. The physical correspondence of components, layout, and dynamics with those experienced in a real world setting is often referred to as simulator "fidelity", or physical validity (Godley et al., 2002; Liu, Macchiarella, & Vincenzi, 2009). The level of simulator fidelity that is ultimately selected by a given lab or research facility is almost always determined by one factor alone: cost (Liu et al., 2009). Low fidelity simulators, which are often based on personal computers or workstations with add-on steering wheel and pedal components originally designed for video games, provide no or limited kinaesthetic feedback to the driver (therefore they are known as being "fixed-base"), have limited visual graphic capabilities, and only rudimentary control of vehicle dynamics. Medium fidelity simulators typically demonstrate a greater degree of similarity between the simulated driving experience and reality by using more sophisticated and comprehensive graphics technology, and by providing dynamic feedback to the driver that is interpreted as more realistic. These simulators usually involve the added authenticity of participant drivers being seated within part or all of an actual vehicle cab. High fidelity, or ‘advanced’ simulators, like the one housed at MUARC (see Figure 1), offer an added level of concordance between the simulated stimuli and those which would be experienced on an actual roadway by employing even more sophisticated graphics packages. These ‘moving-base’ simulators, which always allow for some amount of physical / kinaesthetic movement correlated with the visual scene, typically provide at least a 180 degree field-of-view, and are commonly experienced by participants as very closely reproducing the experience real driving.

Figure 1. MUARC's advanced driving simulator.

Finally, ‘very high’ fidelity simulators provide drivers with close to a 360 degree field-of-view involving sophisticated and realistic visual graphics, and an extensive moving base capable of accurately simulating physical (g) forces equivalent to moderate levels of acceleration and deceleration. An example of a very high fidelity simulator is the multi-million dollar National Advanced Driving Simulator (NADS) housed at the University of Iowa. The NADS, developed by the U.S. National Highway Traffic Safety Administration (NHTSA) over a 5-year period, consists of a dome that contains a vehicle cab, which is attached to a motorized turntable allowing it to rotate and simulate a variety of different driving conditions (see Figure 2). According to its web site, the NADS is currently “the most advanced ground vehicle simulator in the world” (NADS, 2009).

Figure 2. The National Advanced Driving Simulator (NADS) at the University of Iowa.

2.2 Behavioural / predictive validity

Another type of simulator validity relates to the comparison of operators' performance in the simulator *vs.* that which occurs in the real world. Known as a simulator's 'behavioural' or 'predictive' validity, it is often presumed to be closely correlated with a simulator's fidelity; however, this is not necessarily the case (Godley et al., 2002). It is possible, for example, for a high fidelity driving simulator to have the same behavioural validity as a much less expensive one, allowing the same conclusions to be drawn from research conducted using both models. At the same time, there may be advantages other than cost that are associated with a lower fidelity model, such as the ease with which it can be programmed and with which data can be extracted. There may, in fact, be a specific, yet to-be-determined, level of simulator fidelity required in order to obtain an acceptable level of behavioural validity in terms of most human factors research.

Unfortunately, it is the physical, and not the behavioural, validity of a simulator that is most often reported. A researcher or research organisation considering the purchase of a driving simulator must, therefore, be careful to consider trade-offs that are associated with behavioural *vs.* physical validity as, oftentimes, too much importance is placed on the latter (Godley et al., 2002; Liu et al., 2009).

If results from driving simulation research are to be used as the basis for informing real world road safety policy, it is important that a simulator's behavioural validity be assessed and demonstrated to lie within an acceptable range. The most effective way to accomplish this is to compare driving performance in a real vehicle to that observed in a driving simulator, using tasks that are as similar as possible to one another in both environments (Blaauw, 1982). This comparison will generate two subsets, or categories, of simulator behavioural validity that are argued to have opposing levels of importance for effective human factors research (Törnros, 1998). The degree to which a simulator generates the same numerical values of driving performance that are observed in the real world is called its *absolute validity*. On the other hand, the degree to which any changes in those measures of driving performance are in the same direction, and have a similar magnitude, as those in the real world is known as a simulator's *relative validity*. Some researchers have put forth the notion that it is a simulator's relative validity that is of greatest import in human factors research, as research questions in this discipline usually deal with matters relating to the effects of treatment *vs.* control levels of independent variable(s), rather than absolute numerical measurements of driving performance. It is plausible that, while relative validity may be more important for human factors research, absolute validity is more important for certain kinds of engineering research (Moroney & Lilienthal, 2009). For example, this would explain why a simulator study looking at the effects of specific engine component design changes on engine noise level would require a higher degree of absolute validity than a study examining the effects of road engineering interventions on driver's speed maintenance behaviour.

In summary, there are several different types of validity that can be applied to driving simulators. A standard design approach for many simulator developers and users is to incorporate the highest possible level of fidelity and hope for the best possible outcome with respect to transfer of training and/or research results to the real world. This approach is the direct result of the belief that high levels of physical validity, or fidelity, equate to high levels of behavioural validity, despite the fact that there is evidence that suggests this might not be true (Liu et al., 2009). It is important to focus on the specific goal of the research or training concerned, and carefully consider the trade-offs between fidelity and cost; it is quite possible, and even likely, that a lower-fidelity simulator will be entirely adequate for the underlying purpose of a research or training program. As Liu et al. (2009) point out, the answer to the question of how real does simulation need to be in order for the trainee to properly execute the skills learned in simulation (or to translate the effects of a road safety intervention) to the real world, is "it depends" (p.71). Most importantly, it will depend on the underlying purpose for choosing to use simulation in the first place.

3. WHY USE SIMULATION?

Driving simulation is typically used for either of two purposes: training and research. While there are many reasons that one might choose to use simulation for either of these objectives, the most salient are efficiency (cost) and safety (Nilsson, 1993; Kaptein et al., 1996; Godley et al., 2002; Bella, 2008; Moroney & Lilienthal, 2009). When used for research purposes, simulation offers a cost-effective alternative to real world naturalistic or test-track driving, in that it saves both time and money while, at the same time, achieving the desired goal(s) in terms of research (Moroney & Lilienthal, 2009). Independent variables related to engineering, educational and technical interventions can be systematically manipulated, and driver behaviour measured precisely, in a controlled, safe environment.

Other than cost efficiency and safety, advantages of using simulation to research driver behaviour include: experimental control (Nilsson, 1993; Kaptein et al., 1996; Godley et al., 2002; Bella, 2008; Moroney & Lilienthal, 2009), ease of data collection (Nilsson, 1993; Godley et al., 2002; Bella, 2008), availability of the simulator (Moroney & Lilienthal, 2009), environmental benefits (in terms of lack of fuel consumption and/or damage to roads) (Kaptein et al., 1996; Moroney & Lilienthal, 2009), the surrogate value of the simulator (e.g., the value of using simulation instead of actual vehicles, which, in turn, reduces mechanical wear and tear and other maintenance and road infrastructure costs) (Moroney & Lilienthal, 2009), the ability to investigate the effect of nonexistent road elements (Kaptein et al., 1996), the ability to repeatedly present events to participants that may occur only rarely in reality (Kaptein et al., 1996), and the collection of data that is not otherwise available in the real world, such as accurate measurement of a subject vehicle's proximity to other vehicles within the road scene (Moroney & Lilienthal, 2009).

Disadvantages of simulation also exist, and depend on the nature and scope of the problem under study. One of the most common disadvantages to using simulation, especially in research involving older or medically impaired participants, is simulator sickness (Godley et al., 2002; Stanney & Kennedy, 2009), whereby an operator experiences symptoms of motion sickness even after only a brief exposure to the driving simulator. Although the exact causes of simulator sickness are not well established, they are believed to result from a combination of system design, technological deficiencies of the simulation (e.g., distortions, limited sensorial cues) and an individual's susceptibility to motion sickness (Stanney & Kennedy, 2009). Other disadvantages of driving simulation include the lack, or incomplete replication, of physical sensations (Godley et al., 2002), costs related to purchasing the equipment and maintaining the facility (Moroney & Lilienthal, 2009), user acceptance (Moroney & Lilienthal, 2009) and validity (Godley et al., 2002; Moroney & Lilienthal, 2009).

There are typically a large number of contributory factors that are at play in the lead-up to a crash. Very often, it is road users' behaviour that plays a central role in crash causation (Shinar, 2007). Because, technically, it is not currently possible to have multiple, independent drivers interact in a common driving simulation platform in a way that is similar to that experienced in real traffic situations, it is therefore also not possible to measure simulated crash risk directly. Researchers can measure how often a subject vehicle 'crashes' with other simulated vehicles in the simulator; however, these vehicles, which are part of the simulated ambient traffic, are usually programmed to behave in a random or semi-random manner, and are not able (in most cases) to interact 'intelligently' with a subject vehicle. Instead, it is common and accepted practice amongst road safety researchers to measure changes in so-called "surrogate" measures of crash risk (Yan, Abdel-Aty, Radwan, Wang, & Chilakapati, 2008). Because there is an assumption that any behavioural changes seen in the simulator would translate in a similar way to the real world, they are also assumed to be representative of an analogous change in actual or real world crash risk.

4. DEPENDENT MEASURES OF SIMULATED DRIVING PERFORMANCE

Most simulators, even those of lower fidelity, are able to collect vast amounts of data, and this is one of the advantages of simulation over more naturalistic investigative methods (Moroney & Lilienthal, 2009). Driving simulators can be programmed to collect data at a rate of up to 240 Hz (NADS, 2008). It is more common, however, to collect data at a rate of between 10 and 60 Hz (Hoffman, Lee, Brown, & McGehee, 2002; Rudin-Brown & Noy, 2002), a fact that nevertheless requires the use of data reduction and conversion methods to provide output in a manageable format. The following are a selection of the most common dependent variables, or measures, of driving performance that are collected in driving simulation research. A short discussion relating to the relationship between the measure and crash risk accompanies each.

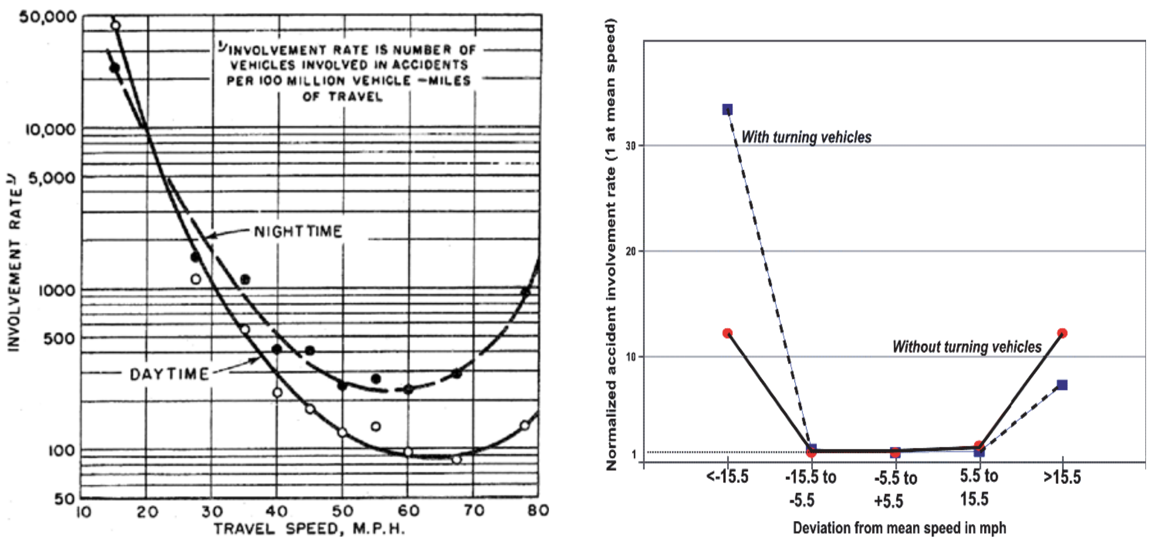
4.1 Speed

Simulated vehicle speed is the most common dependent variable measured in research studies using simulation. Most simulators can collect speed data in a variety of formats and/or units of measurement, including the more commonly used kilometres per hour (kph), but also including metres per second (m/s) and any number of other formats.

The relationship between speed and collision severity in the real world is well established. The laws of physics dictate that, given a situation in which all other factors are held constant, the faster the speed one is travelling, the more severe will be the damage sustained in the event of a collision (Hauer, 2009). Similarly, if one is travelling at a slower speed, damage and resultant injuries will be relatively less serious.

Although the relationship between speed and collision severity is well established and accepted amongst members of the road safety community, the same cannot be said for the relationship between travelling speed and the likelihood of being involved in a collision. Although a well-known study by Solomon (1964) found an inverted U-shape relationship to exist between speed and collision likelihood (see Figure 3, left panel) and variation from mean traffic flow speed and collision likelihood (Figure 3, right panel), later studies (e.g., Research Triangle Institute, 1970) demonstrated that this relationship, in fact, was not as robust as initially proposed, and basically disappeared (returned to chance levels) once collisions relating to turning vehicles (which would be predicted to have very low speeds compared to accompanying 'free-flowing' traffic) were removed from the analysis (Figure 3, right panel).

Figure 3. Relationship between speed and crash risk (Solomon, 1964; Research Triangle Institute, 1970).



Hauer (2009) suggests that, rather than because of vehicle speed, the mild U-shaped relationship that exists between speed differential and crash risk most likely results from individual differences among drivers in terms of their physical and personality traits. For example, collisions involving older drivers who tend to drive more slowly and are more fragile than younger drivers may make up most of the left side of the U curve, while younger, male drivers who tend to drive faster and have a higher accident involvement rate may make up the right side of the curve (Figure 3, right panel).

A more likely explanation for the relationship between speed and crash risk, like the one for speed and crash severity, derives from the laws of physics. These contend that, if all other variables are held constant, then a driver who is travelling in a vehicle at a higher speed will, in the event of a critical situation, have less time to react safely and, therefore, will be more likely to be involved in a crash than if the vehicle was travelling at a slower speed. Hauer (2009) cautions, though, that while it may be reasonable to believe that the longer it takes to stop a vehicle, the larger is the probability of accident involvement, things may not be so clear-cut in reality. He says that the 'tortuous' history of research on the subject of speed and crash risk reveals a tension between researchers' inability to show that the higher the speed the larger the chance of an accident and the pivotal role that stopping distance plays in highway geometric design.

4.2 Speed variability

Speed variability, or the standard deviation of speed, refers either to that which is calculated across sequential speed measurements within a single driver-vehicle pair, or to that which is observed among a population of drivers-vehicles who are using a given road segment at a given time of day. Speed variability data are, like speed data, usually represented using the same unit of measurement as that used to represent vehicle speed.

The relationship between speed variability and crash risk is not clear. Speed variability within a non-distracted, attentive driver who is travelling in 'free-flowing' conditions (unimpeded by other road users) on a given road segment with a consistent speed limit should not, theoretically, be large. Typically, though, if a driver begins to perform a secondary task (such as talking on a mobile phone or looking at an in-vehicle device) s/he will tend to reduce their speed in order to compensate for the increase in visual and/or cognitive workload required (Patten, Kircher, Östlund, & Nilsson, 2004; Engstrom, Johansson, & Ostlund, 2005; Jamson & Merat, 2005). If performance of the secondary task is intermittent, then the driver will consequently tend to speed up and slow down, depending on whether or not s/he is actively engaged in the task. Fuller (2005) refers to the tendency of drivers to regulate their vehicle speed in order to maintain task difficulty within selected boundaries the 'task capability interface' model of driver behaviour. He postulates that speed is the easiest, and the most common, vehicle control variable that drivers use, when required, to reduce mental workload associated with the driving task.

Compared to that which is measured within a single driver, speed variability in terms of a population of drivers/vehicles using a given road segment at a given time is quite a different measure. Analyses of observed crash data have conclusively found that the greater the average speed differential is among vehicles on a given road, the greater the crash risk associated with that road will be. For example, data from a multivariate regression modelling analysis of UK urban roads demonstrated that: a) the faster traffic moves on average, the more collisions there are, and b) the larger the spread of speeds around the average speed, the more collisions there are (Taylor et al., 2000).

4.3 Lane position and lane position variability

A driver's ability to maintain their vehicle's lateral position within the lane is often used as a measure of safe driving performance. Lane position is commonly represented by a unit of distance, such as metres (m), and is calculated from measuring the difference between the absolute centre of the vehicle and any point within the simulation scenario. Typically, this point will be the centre of the roadway. So, for example, a vehicle travelling at the exact centre of a lane with a width of 3.66 m will generate a lane position value of -1.83 m (for vehicles travelling in the left lane) or +1.83 m (if travelling in the right hand lane).

Lane position variability, or the standard deviation of lane position (SDLP), is often regarded as a more useful dependent measurement of safe driving, and measures the amount of a vehicle's lateral deviation within a lane over time. Driving simulators collect lane position data at the same rate as other vehicle performance data, usually between 10 and 60 Hz. Data that have been collected at a very high resolution such as this can, therefore, be inspected and analysed with respect to very precise timing of experimental manipulation(s). As this data is collected within the same intelligent environment that also produces the environmental (e.g., visual) stimuli presented to participant drivers, simulation allows for very precise measurements to be made of drivers' physical reactions to a variety of stimuli in the simulated environment, such as, for example, vehicles or other road users appearing suddenly within the vehicle path.

Use of mobile telephones, or performance of an in-vehicle secondary task, while driving has been shown to increase lane position variability in both simulated (Rudin-Brown & Noy, 2002; Engstrom et al., 2005; Jamson & Merat, 2005) and on-road (Rudin-Brown & Noy, 2002; Engstrom et al., 2005) driving environments. The common perception among road safety researchers is that, if a manipulation causes a driver to deviate more within the lane, and especially if the vehicle is seen to cross one or both of the lane boundaries, then the risk of a crash is also increased. This is a logical argument, and one that most researchers endorse. However, some have raised the possibility that, just because a driver allows the vehicle to deviate more within the lane does not, necessarily, mean that they are more likely to be involved in a crash. These authors posit that increased lane deviation and lane excursions will only increase crash risk if the road environment, including other drivers and road users, interacts with the subject vehicle to contribute to an increase in crash risk. In actual fact, an increase in lane deviation, as long as the surrounding conditions allow for it, may actually demonstrate that the driver is more relaxed, perceiving less of a risk of crashing and, hence, that s/he is able to allow the vehicle to deviate more within the lane. Of course, this would not be the case if lanes that were adjacent to the subject vehicle were filled with other vehicles.

4.4 Braking reaction time

The time it takes from the moment a stimuli (auditory or visual) reaches our retina or our ear drum until the time that we initiate a response is known as perception reaction time (PRT) (Shinar, 2007). In driving, braking reaction time (BRT) is the time that passes from the moment a stimulus (such as a brake light or stop light) appears until the driver presses the brake pedal (Shinar, 2007). Usually, the location of the foot at the beginning of this moment will have been on the accelerator pedal; however, it may vary if, for example, the driver had previously had the cruise control engaged, or if the driver's foot was 'hovering' between the accelerator and the brake pedals. It is a common practice, in both simulated and on-road research using instrumented vehicles, for researchers to position a video camera unobtrusively in the foot well above the control pedals, so as to confirm the position of the foot prior to the manipulation of interest (Rudin-Brown & Noy, 2002). This is one of the only ways to be absolutely certain that BRT is consistent across all 'events' and across participants. Using this method, a researcher can retrospectively review outliers and any other data anomalies by visually inspecting the recorded video data.

In real world driving, total stopping distance (or TSD) is made up of a number of variables, including the driver's PRT, the vehicle's speed, the grade of the pavement, and the coefficient of friction between the pavement and the vehicle's tires. The 'wild card' in the TSD calculation, if all else is held constant, is the PRT. This can be affected by many variables, including those relating to the vehicle (e.g., pedal position/height), the environment (e.g., poor visibility, visual clutter), and the driver (e.g., fatigue, distraction, intoxication). Hence, the slower the PRT and, consequently, the BRT, then the longer the stopping distance will be and the greater the risk of collision (Shinar, 2007).

Under laboratory conditions, PRT can be quite short (i.e., under 0.5 s) (Shinar, 2007). When driving, however, even under highly predictable conditions, as when the driver is instructed to "brake as quickly as possible when the brake lights (or a red light affixed to the bonnet of the subject vehicle) of the car in front come on", BRT can range from between 0.35 to 0.7 s (Warshawsky-Livne & Shinar, 2002; Boyle, Trick, Johnsen, Roach, & Rubens, 2008). 'Safe' BRT has been defined as braking within 2.0 s of stimulus onset when travelling at highway speeds (≅ 80 kph) (Taoka, 1989; Rudin-Brown & Parker, 2004); however, whether it is safe will obviously depend on other factors, such as the distance to the obstacle in question.

Like lane position and lane position variability, BRT can be measured extremely precisely within a simulated environment. This makes it an ideal dependent measure for most studies designed to evaluate the effects of environmental or secondary task manipulations on driver behaviour and response to threatening or potentially hazardous stimuli. In a simulator study looking at drivers' use of in-vehicle MP3 players (iPods), BRT was found to increase significantly by 26 percent, or by 0.42 s, when drivers were performing a 'difficult' iPod task compared to when performing an 'easy' task (Chisholm, Caird, & Lockhart, 2008). The authors interpreted this finding as indicating that iPod interactions impaired drivers' ability to respond to hazards on the roadway and to maintain safe vehicle control, as prolonged glances away from the road have been argued by many to pose an increased crash risk (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006; Green, 2007). Interestingly, BRT in this study was observed to improve (decrease) over subsequent sessions in the driving simulator, suggesting that practice on a secondary task can lessen related detrimental effects on driving performance. However, the authors stress that, despite practice on the iPod task improving the impaired (compared to baseline) BRT, even after prolonged experience drivers remained unable to improve their dual-task performance to a 'safe' (baseline) level (Chisholm et al., 2008).

4.5 Brake pressure / braking force

Measuring the amount of pressure or force that a driver applies to the brake pedal during a braking manoeuvre is an accepted method to investigate the criticality or urgency with which a driver experiences a situation. Results from simulation and on-road research appear to support this assumption.

Several simulator studies have included the measurement of either brake pressure or force. For example, in a study that evaluated driver responses to advanced warnings of emergency vehicles using an advanced driving simulator (Lenné, Triggs, Mulvihill, Regan, & Corben, 2008), brake pressure (measured in percentage actuation) was found to be highest, and associated with greater reductions in speed, in the advanced warning condition compared to a standard warning condition. Similarly, in a simulator study that evaluated the efficacy of rear-end collision warning systems, higher brake pressure (as measured using brake-to-maximum brake transition time) was observed in the warning condition compared to the no-warning condition (Lee, McGehee, Brown, & Reyes, 2002). A similar pattern of results was found in a simulator study that investigated the effectiveness of a heavy braking light (one that was programmed to flash under conditions of heavy deceleration). Participants braked harder (measured in maximum pressure and time-to-reach maximum pressure) in response to the heavy braking light compared to a standard centre mounted brake light (Regan, Triggs, Mitsopoulos-Rubens, Symmons, & Tomasevic, 2007).

Brake pressure has also been used to assess the effects of various forms of driver distraction. The relative impairment associated with conversing on a cell phone while driving compared to while drink driving was investigated in a driving simulator. Results showed that when conversing on either a hand-held or a hands-free cell phone, braking *reactions* were delayed. In contrast, when drivers were intoxicated they applied more force (measured in terms of maximum braking force) while braking, indicating a more aggressive driving style (Strayer, Drews, & Crouch, 2006). The impact of multiple in-vehicle information systems on driver behaviour was investigated in another simulator study, whereby increased brake pressure (and reduced headways) were observed in conditions that contained multiple secondary tasks compared to conditions made up of only single tasks and normal driving (Lansdown, Brook-Carter, & Kersloot, 2004). Furthermore, differences in hazard detection between trained and untrained young drivers showed differential braking behaviour (including difference in applied brake pressure) in several simulated driving scenarios (Fisher, Laurie, Glaser, Connerney, Pollatsek, Duffy, & Brock, 2002).

There is less evidence for the use of braking pressure and force as a dependent measure in on-road studies than in simulators. However, with the fairly recent development of vehicle systems such as adaptive cruise control (ACC) and anti-lock braking systems (ABS), which may be better suited for on-road evaluation, the use of braking pressure or force in on-road studies is becoming more apparent. For example, the effects of a post-license driver training program on brake performance in cars with ABS were recently assessed in an on-road study (Petersen, Barrett, & Morrison, 2006), with the post-training group using a smoother braking profile compared to a control group. Finally, in an earlier study looking at the potential for behavioural adaptation to ABS, drivers who were shown the increased control available with ABS drove faster in a curve-following task, and used higher brake pedal forces than those who had not been shown the benefits of ABS (Grant & Smiley, 1993).

4.6 Throttle position

Position of the throttle, or accelerator, pedal in terms of percentage of full throttle (ranging from 0 to 100 percent pedal depression) (Reed & Green, 1995) or in terms of acceleration and deceleration (expressed in g's) (Hatfield & Chamberlain, 2008), is another way to measure the driver's intention with respect to speed maintenance. Generally, however, depression of the accelerator pedal when a vehicle is travelling at average highway speeds is restricted to a limited range. For example, in a study designed to assess the validity of a low-cost, fixed base driving simulator with on-road driving of an instrumented vehicle, measured standard deviation of throttle position ranged from 2.8 percent during normal driving to 3.4 percent during driving while speaking on a mobile phone (Reed & Green, 1995). Similarly, when throttle, or accelerator, input is measured in terms of g's, its variability is also limited. A simulator study that examined the potential for driver distraction from neighbouring vehicles' entertainment displays (Hatfield & Chamberlain, 2008) found accelerator variability to range from 0.11 to 0.12 g, in baseline *vs.* distracted conditions, respectively.

4.7 Headway

Headway can be measured in units of distance and/or time. Headway *distance* (in metres) is defined as the distance from the front of the subject vehicle to the rear of the target (or lead) vehicle. This measurement by itself would not provide much in terms of valuable information if the speed of the two vehicles was not known. On the other hand, headway *time* is the time to impact (in seconds) for a following vehicle travelling at a given speed to strike a lead vehicle if it were to come to a sudden and complete stop. Another term used to describe headway time is *time-to-collision*, or TTC.

The measurement of headway in terms of time provides more complete and valuable information to researchers than its corollary measurement in distance. Typically, drivers will adapt their following behaviour by increasing or decreasing headway distance depending on the speed of a lead vehicle. This, in turn, has the effect of maintaining a given time headway at which the driver feels comfortable and safe. Most driver training guidelines recommend adopting at least a 2.0 s time headway, as this will allow the majority of drivers to react to any unexpected event(s) ahead in a safe time margin.

Studies have shown that time headway is a sensitive measure to manipulations that have the capacity to distract drivers. For example, in a driving simulator study, drivers conversing by either hand held or hands free mobile phones were found to increase their following distance to a vehicle ahead by over four percent (Strayer, Drews, & Crouch, 2004). The authors concluded that this increase in headway to a lead vehicle was adopted in order to compensate for drivers' increased reaction time, which was slowed by over eight percent compared to baseline. In addition, this slowed reaction time resulted in their being involved in significantly more rear-end collisions, when the leading "pace car" braked unexpectedly. Another simulator study found an opposite effect of secondary task involvement on headway. When drivers interacted with a variety of secondary in-vehicle tasks while driving, headway distance to a lead vehicle was found to increase significantly compared to a control condition (Lansdown et al., 2004). The authors speculate that distraction by the secondary task may have disrupted drivers' ability to control the vehicle, but that it may not have been perceived to be taxing enough to warrant a more cautious driving style by drivers.

4.8 Steering wheel angle

The angle, in terms of degrees, at which a driver positions the vehicle steering wheel is often used as a supplemental measure of lane position or, more precisely, of the driver's intention with respect to lane position and lane-keeping. Derived using an optical encoder within the steering wheel assembly, steering wheel angle can theoretically range from -360 degrees to +360 degrees, depending on the driving manoeuvre undertaken. When driving in free-flowing conditions on a straight segment of road, steering wheel angle should, theoretically, remain relatively constant, at around zero degrees.

Standard deviation of steering wheel angle has been shown to increase when drivers perform difficult in-vehicle tasks, such as searching for music on an iPod MP3 player, while driving in a simulated environment (Chisholm et al., 2008). These results are especially interesting when viewed in the present context, as not only did steering wheel angle deviate significantly more when drivers were interacting with the devices, but the number of simulated collisions sustained also increased significantly. The methodology required that participants be exposed to a number of critical events on roadways while, at the same time, interacting with an iPod. Critical events included a pedestrian entering the roadway, a vehicle pulling out in front of the subject vehicle, and a lead vehicle braking. Because they were correlated with simulated crash risk, these results provide support for the view that measures of simulated driving performance (e.g., steering wheel angle) can be used to reliably predict changes in real world crash risk.

4.9 Subjective measures

Measures of participants' subjective state during simulated driving are often used to access and investigate variables that are not outwardly observable. Using paper and pencil or questionnaire format, these measures probe participants at various time points throughout a simulated drive or at selected time points during an experiment. An advantage to using subjective measures in a driving simulator (as compared to in vehicles on actual roadways) includes that the simulation can be stopped or paused on demand, without causing associated logistical or safety concerns that would be associated with stopping on-road.

Some of the more common subjective measures that are investigated in simulator studies include those that relate to the intrinsic state of the individual, where there is a concern that that state could have an associated detrimental effect on driving. The concern is that, if this underlying intrinsic state is not identified, then it may appear that the experimental manipulation is having an effect on driving when, in fact, it is not. One subjective questionnaire that is used throughout most simulator studies is the 'current well-being' questionnaire, which measures the degree to which a participant may be experiencing simulator sickness or discomfort. Another common variable of interest in longer-running simulator experiments is the Stanford sleepiness scale (Hoddes, Zarcone, Smythe, Phillips, & Dement, 1973), which, when administered at select points throughout a test session, will allow the experimenter to determine whether any effects on driver behaviour may have, in fact, been due to fatigue or lethargy on behalf of the participants. Another common subjective measure of interest in driving simulation studies is the amount of workload experienced by participants. The NASA-TLX (Task Load Index) (Hart & Staveland, 1987) is a subjective workload questionnaire that uses a 10-point Likert scale to explore various aspects of mental workload, such as task demand, participant's feelings of being rushed, and their feelings of discouragement.

4.10 Performance on secondary task(s)

Apart from being a focus of study in and of itself, performance on a secondary in-vehicle task is often used in simulation studies as a method to indirectly measure an independent variable's effect on driving performance. Baseline measures of secondary task performance are collected, first while the participant is not driving and again while driving, and subsequent performance on the secondary task (which is accompanied by varying levels of the independent variable of interest) is compared between the two. If performance on the secondary task worsens upon the introduction of the independent variable, the results are interpreted to suggest that actual crash risk, in similar driving conditions, would increase. For example, in studies where participants are required to interact with an in-vehicle information system, or IVIS, their driving performance in terms of dependent variables such as speed variability, lane position variability, and reaction time to visual stimuli is often found to deteriorate when they use the IVIS (Horrey & Wickens, 2006). If a road engineering intervention, such as adding pavement markings, were to cause driving performance under the secondary task conditions to deteriorate even further, then it would be concluded to have a deleterious effect on road safety. On the other hand, if the road engineering intervention improved driving performance under the secondary task condition, it would be concluded to improve overall road safety. Simulator studies have found that performance on the secondary task can be compromised in these situations (Tsimhoni & Green, 2003) and, in fact, depends on the demands of the driving task in question.

4.11 Eye glance behaviour

Depending on the degree of technical sophistication, automated eye-tracking systems are capable of measuring the target of driver eye glances, as well as the duration of any eye fixations. The associated software system can automatically calculate the percentage of time that is spent with the eyes focussed on various locations, or quadrants, within the visual field, and this data can be used for a variety of purposes. Most commonly, eye glance behaviour is used as a dependent measure of visual attention, the theory being that wherever the participants' eye glances fixate, that is also the place where they are looking.

The electro-oculogram (EOG) is a simple way of measuring eye movement activity using electrodes that are positioned around the eye which then pick up electrical activity. A number of other eye movement recording technologies are also available such as GazeTracker, JAZZ, Smart Eye and FaceLab, as well as video based techniques (Wilson & Eggemeier, 2001; Alfredson, Nählinder, & Castor, 2004). The relative simplicity and unobtrusiveness of both head mounted and video based eye tracking systems means that they can be used easily in both simulated and on-road settings.

Engström et al (2005) evaluated the effects of visual and cognitive load in real and simulated motorway driving. In the simulator, as well as in the field, the cognitive task resulted in significantly increased concentration of gazes towards the road centre. As part of the same EU project, HASTE, Victor, Harbluk and Engström (2005) investigated eye movements in more detail by comparing the sensitivity of a range of eye movement measures in both on-road and simulated settings. It was concluded that, as visual task difficulty increases, drivers look less at the road centre area ahead, and instead look at the display area more often, for longer periods and for more varied durations. On the other hand, increased auditory task complexity led to an increased gaze concentration to the road centre. It was noted that drivers in the on-road study were less susceptible to take their eyes off the road to do the in-vehicle tasks than were drivers in the simulated setting, possibly reflecting a difference in perceived risk between the settings; however, overall trends in eye movement measures were comparable between the two.

Harbluk et al (2007) performed an on-road assessment of cognitive distraction looking specifically at its impacts on drivers' visual behaviour and braking performance. When distracted, drivers spent more time looking centrally ahead and spent less time looking to areas in the periphery, including reduced visual monitoring of instruments and mirrors, and fewer inspection glances to traffic lights and scanning to the right at intersections. In another on-road study, Recarte and Nunes (2003) reported that targets were glanced at later, less frequently and inspected for less time while drivers were performing a mental task. A similar pattern of results was found in a simulator study by Strayer and Johnston (2001), who examined the effects on driving of conversing on a cellular telephone. Cell phone use resulted in a two-fold increase in the failure to detect simulated traffic signals and slower reaction times to those signals that were detected.

4.12 Physiological measures

The physiological measurement of driver status is commonly used to supplement driving performance and subjective data in both on-road and simulation studies. Such measures include heart rate and heart rate variability (HR/ HRV), galvanic skin response (GSR), electroencephalography (EEG), electromyography (EMG), blood pressure (BP), respiration rate, hormone levels and ocular measures such as pupil diameter, blink rate and eye movement. Depending on the psychological construct under study (i.e., workload, fatigue, stress, distraction), these measures have shown varying degrees of validity, sensitivity and reliability and can provide a valuable addition to the collection of other data.

Similar physiological results have been found both in simulation and on-road driving studies. For example, Engström, Johansson and Östlund (2005) observed the effects of visual and auditory secondary task performance while driving in a moving based driving simulator and in the field using an instrumented vehicle. In both settings, an increase in skin conductance (GSR) as well as skin conductance variation was found with increased visual task difficulty. Moreover, heart rate inter-beat intervals during more difficult task performance were significantly reduced in both driving environments, indicating increased driver workload.

Rakauskas et al (2005) measured EEG in a driving simulation study that investigated crash risk associated with cell phone use, alcohol intoxication and distraction while driving. Impairment (in terms of reduced mental processing) caused by alcohol intoxication and distractions was evidenced by changes in the mapping of brain activity as measured by EEG. Similarly, in an on-road driving experiment, Brookhuis and de Waard (1993) assessed driver status using EEG and showed the same pattern of changes in driver performance and brain activity when predicting the impairment caused by alcohol.

Many driving studies have used cardiac measures to estimate driver workload. For example, a simulator study (Backs, Lenneman, Wetzel, & Green, 2003) revealed driving performance, visual demand and cardiac measures (heart period, HR and HRV) to be affected by the radius of the curves the drivers negotiated. A number of studies have used cardiac measures to evaluate the increased workload imposed on drivers when using a mobile phone (Haigney, Taylor, & Westerman, 2000). Changes in HR were found to reflect the increase in cognitive demand experienced by drivers during a call, irrespective of phone type (hands-free versus hand held) in a driving simulator (Haigney et al., 2000). A similar pattern of results has been found on-road (Brookhuis, de Vries, & de Waard, 1991), in a study using HR and HRV to examine the effects of mobile phone telephone conversations on driving performance. A clear increase in HR and similar decrease in HRV was found with increased workload. Further, variations in HR have also been found according to road type (motorway *vs*. urban road) and traffic events such as overtaking and speeding (Liu & Lee, 2006). Finally, a simulator study was conducted that collected HR and HRV data (in conjunction with the NASA-TLX and the Peripheral Detection Task) to measure the workload demands of interacting with two route guidance systems while driving. HR and, to a lesser degree, HRV (due to high inter-individual variability) were sensitive to the workload manipulations in the driving study, with increased workload causing increases in HR (Jahn, Oehme, Krems, & Gelau, 2005).

5. PSYCHOLOGICAL CONCEPTS RELATED TO DRIVING PERFORMANCE

The preceding dependent measures that are commonly used in simulation studies are often employed in the investigation of broader psychological, or behavioural, concepts related to driving behaviour. In fact, many such psychological constructs have been put forward to better understand driver behaviour and its consequential effects on crash risk. Basically, the widespread belief exists that any factor affecting simulated driver behaviour or performance in a detrimental way will, in a similar way, have an exacerbating effect on crash risk in the real world, and both consequences can be explained in terms of the factor's effect(s) on an underlying concept. The following are some of the more commonly used, and better known, psychological constructs that are investigated in research on driver behaviour. Reference is made to the dependent measures (from Section 4, above) that are typically used to indirectly measure these larger concepts.

5.1 Driver workload

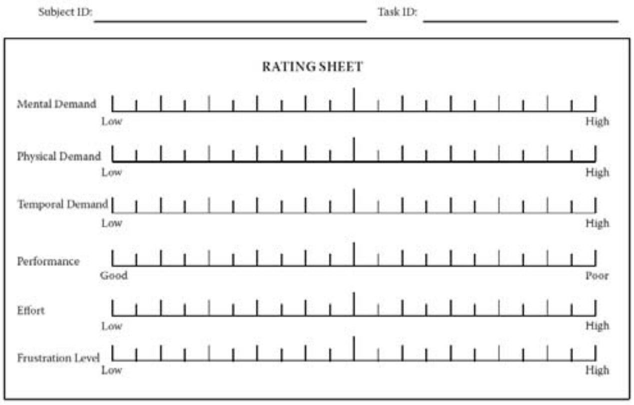
Driver workload refers to the amount of effort a driver devotes to the driving task. Others have defined workload in general as a set of task demands, as effort, and as activity or accomplishment (Gartner & Murphy, 1979), where the task demands are the goal to be achieved, including the time allowed to perform the task, and the performance level to which the task is to be completed (Gawron, 2008).

There are four methods that can be used to measure driver workload: stand-alone performance measures, secondary task performance, subjective estimates of workload, and physiological measures. An example of a stand-alone performance measure of the visual component of driver workload is driver eye glance behaviour (see Section 4.11). In particular, increased glance duration and greater frequency of glances to a particular area in a driver's visual field are generally accepted as measures of increased visual workload (Gawron, 2008).

Secondary task performance is one of the most commonly used measures of workload in driving research. This technique requires the driver to perform the primary task of driving while, at the same time, use any spare attention or capacity to perform the secondary task. The decrease in performance in the secondary task between different driving conditions is considered to indicate the amount of workload generated by each (Gawron, 2008). One commonly used secondary task is the peripheral detection task, or PDT, wherein a participant driver must press a button, for example, every time a light or other stimulus is presented in the driver's peripheral field of vision. Driver performance on the PDT has been found to deteriorate when drivers are engaged in mobile phone use both in simulated (Nilsson, Tornros, & Ceci, 2005) and on-road field studies (Patten et al., 2004).

Subjective estimates of driver workload are usually comprised of one or more questions presented in a questionnaire format that are designed to probe a driver's experience of workload. One of the most commonly used subjective workload questionnaire used in driving research is the NASA task load index, or TLX (Hart & Staveland, 1987) (see also Section 4.9). The NASA TLX is a multidimensional rating instrument that assesses six dimensions of subjective workload: mental demand, physical demand, temporal demand, performance, effort, and frustration level. Participants are required to indicate their subjective experience of workload in each of these six categories by indicating a point on a graded scale. There are also subjective workload measurement scales that have been specifically designed to assess driver workload. For example, the Driving Activity Load Index (DALI) is a modified version of the NASA TLX that has been specifically tailored to the assessment of in-vehicle systems and tasks in the automotive environment (Pauzié, Manzan, & Dapzol, 2007). An example of the NASA TLX rating sheet and descriptions of the rating scales are shown in Figure 4.

Figure 4. The NASA Task Load Index (TLX) (Gawron, 2008)


Subject ID:
Task ID:

RATING SHEET

Mental Demand — Low / High

Physical Demand — Low / High

Temporal Demand — Low / High

Performance — Good / Poor

Effort — Low / High

Frustration Level — Low / High

NASA TLX Rating Scale Descriptions

Title	Endpoints	Descriptions
Mental demand	Low, High	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical demand	Low, High	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal demand	Low, High	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
Performance	Good, Poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Effort	Low, High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration level	Low, High	How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during the task? (NASA Task Load Index, p. 13)

Finally, physiological measures are also used in driving research to assess mental workload. For example, cardiac activity (heart period, HR and, to a lesser degree, HRV) has been found to be related to the amount of workload experienced by a driver (refer to Section 4.12, above).

5.2 Speed estimation

Processes by which drivers select, and are able to accurately perceive or estimate, travel speed are central to the understanding of driver speed behaviour. Speed estimation in drivers is influenced by a number of sensory elements including visual, auditory, kinaesthetic/ vestibular and, most predominantly, optic flow (Rudin-Brown, 2006). The associated choice of speed has been shown to be one of the most important predictors of road accident involvement (Horswill & McKenna, 1999).

A comparative study of speed perception in a driving simulator environment and in the field was conducted to evaluate the application of simulation in speed-related research. Results indicated that drivers tend to underestimate their travel speeds in both environments as well as there being a consistency in the trends associated with both the speeds selected and perceived. This preliminary comparative study lends support for the use of simulation to investigate speed-related behaviour, including that of speed estimation (Hurwitz & Knodler, 2007). Two separate simulator studies that used the same methodology assessed the effect of driver eye height on speed choice, lane keeping and car following behaviour. When viewing the road from a high seated eye height, and without the aid of a speedometer, drivers drove faster, with more variability and were less able to maintain a consistent position within the lane than when viewing the road from a low eye height. These results demonstrate the perceptual difference in drivers of different-sized vehicles and point to the need to educate drivers of this phenomenon (Rudin-Brown, 2006).

Speed estimation and the associated choice of speed are implicated in the understanding of driver risk-taking behaviour. In a study that aimed to develop, validate and apply a measure of drivers' speed choice, a video simulation measure was found to relate to speed-related accident involvement, implying a degree of external validity. The effects of auditory feedback on speed choice were also investigated, and results showed that increasing the level of internal car noise decreased the drivers' preferred speeds, likely due to the perceptual effects on speed estimation (Horswill & McKenna, 1999). In another simulator study that focused on the role of noise (and also discussed in terms of risk-taking), the effects of music tempo on driving were evaluated. Results showed that as the tempo of the music increased, so too did simulated driving speed and speed estimation (Brodsky, 2002).

The role of sight and hearing in the estimation of speed has also been investigated in an on-road study. Passengers' speed estimation was assessed while travelling in a vehicle with a hidden speedometer. Four sensory conditions were evaluated: baseline, travelling while unable to see, travelling while unable to hear, and travelling while unable to both see and hear. Under all conditions, slow speeds (25 mph or less) were underestimated by passengers. For the two conditions associated with diminished hearing capacity, the mean estimates of speed were always lower than the set speeds, indicating that the sense of hearing is of great importance in the task of speed estimation (Evans, 1970). Another on-road study investigated the speed perception of drivers in road curves. Results showed that drivers underestimated their vehicle speed in the central part of a small-radius curve, and this inaccurate estimation (similar to that found more generally when drivers travel at low speeds) may be related to increased risk-taking behaviour. The importance of appropriate advisory signs for drivers approaching curves was, therefore, emphasised (Milosevic & Milic, 1990).

5.3 Risk perception

Because there is no human action with total certainty in terms of its outcome, all behaviour can, in some way, be viewed as risk-taking behaviour. It is therefore of interest to identify the factors and mechanisms that determine people's perception of risk, their acceptance of it, and the actions they take to minimise it (Wilde, Hennessy, & Wiesenthal, 2005). Accident countermeasures and road safety strategies are often discussed in terms of theories of how people behave in the face of danger. For example, risk homeostasis theory, or RHT, predicts that, as safety features are added to vehicles and roads, drivers will tend to increase their exposure to collision risk because they feel better protected (Wilde, Robertson, & Pless, 2002). The nature of these perceptions of safety clearly holds importance in terms of the implementation of initiatives, technologies, training and design features.

Risk perception is often discussed in the young driver literature as being a higher-order perceptual skill that takes much longer to develop than the motor skills of controlling a vehicle (Deery, 1999). Research indicates that young drivers underestimate the crash risk of a variety of hazardous situations, while at the same time overestimating their own driving skill (Deery, 1999). It is also argued that young drivers are more willing to accept risk while driving than experienced drivers.

Typically measured via the use of surveys and questionnaires, the risk perception associated with various driving activities has been investigated in several studies. For example, the frequency of night time driving has been correlated with the risk perception of driving at night. One study revealed that the perceived likelihood of having a sleep-related car crash and the worries related to it are lower for those who report driving at night more frequently (Lucidi, Russo, Mallia, Devoto, Lauriola, & Violani, 2006). The relationship between genre of television viewing (action movies, news and music videos) and adolescents' intentions to take risks in traffic has also been investigated. Interestingly, high levels of news viewing was associated with a higher perceived risk of drunk driving and speeding (compared to those who watched less news), while music video viewing was negatively associated with the assessment of the dangers of speeding and driving under the influence of alcohol (Beullens & Van den Bulck, 2008). Personality characteristics have also been linked to risk perceptions and driving behaviour. One study, for example, showed that 39% of the variance in young drivers' speeding behaviour was accounted for by excitement-seeking, altruism and their aversion to risk taking (Machin & Sankey, 2008). Others studies have investigated the risk perception associated with a number of driving related activities. Results of a study designed to assess the risk perception of cell phone use while driving suggest that, even though people believe that talking on a cell phone is dangerous, they will initiate a cell phone conversation if they believe that the phone call is important enough (Nelson, Atchley, & Little, 2009). Another study investigated the perceptions of level of intoxication and risk related to drinking and driving. Individuals in this study were found to be more likely to drink and drive, felt an intervention effort by another would be less likely, and would be less receptive to an intervention effort, when asked to assume they had a short distance to travel versus a long distance (Gustin & Simons, 2008).

Simulation is an appropriate data collection method for the assessment of risk perception in drivers, in terms of linking driving performance and risk taking behaviours with measures of drivers' perceived risk. For example, a simulator study that used an eye-tracking device to measure visual scanning behaviour found significant age-related differences in driver scanning patterns, consistent with the hypothesis that novice drivers' narrower scanning patterns reflect their failure to acquire information about potential risk. These results were discussed in relation to an already developed PC-based risk awareness training program. Results from an evaluation of this program showed that those trained were almost twice as likely to recognise a risk as an untrained control group (Pradhan, Hammel, DeRamus, Pollatsek, Noyce, & Fisher, 2005). Driver training programs may therefore benefit from the inclusion of a risk perception/awareness training component.

5.4 Behavioural adaptation

The expression “behavioural adaptation”, when used in the context of transportation psychology, describes the changes in behaviour(s) that occur following a change to the road traffic system (OECD, 1990). Typically, researchers are most interested in those adaptations that negatively impact aggregate road safety. Despite a poor understanding of the mechanisms underlying it, BA is often cited as an explanation for the observed discrepancies between engineering estimates of the safety benefits of collision countermeasures and actual experience.

Driving simulators have been used to assess whether drivers demonstrate behavioural adaptation to in-vehicle advanced driver assistance systems (ADAS), such as those that provide lane departure warnings (Rudin-Brown & Noy, 2002). Drivers were exposed to one of two different lane departure warning systems. One was programmed to produce very reliable warnings, each and every time the simulated vehicle crossed the simulated lane boundaries, while the other was programmed to give accurate warnings, plus a false positive every four warnings, on average, plus one false negative every four warnings, on average. Compared to baseline driving (without any warnings), accurate lane departure warnings were found to result in an improvement in participants’ lane-keeping performance, as measured by a decrease in lane departures, and smaller lane position variability. The inaccurately programmed lane departure warning system also resulted in improved lane-keeping performance; however, not to the same extent as the accurate system. Although the system was inaccurate, and the participants could tell it was inaccurate, as measured by less overall rated trust in the device, only the drivers who reported trusting the inaccurate device made complete (i.e., both front wheels exceeded the lane boundary) lane departures. It is interesting to note that these simulated results were replicated in an actual on-road test track study that used the same study design (Rudin-Brown & Noy, 2002), a fact which allowed the researchers to confirm the relative validity of the driving simulator used.

Another in-vehicle technology that has been shown, in simulator studies, to induce behavioural adaptation in drivers is adaptive cruise control (ACC). An enhanced version of conventional cruise control, ACC allows a vehicle to follow another at an appropriate speed and distance by controlling the engine and/or brake. A vehicle equipped with ACC will thus reduce speed automatically, within limits, to match the speed of a slower vehicle that it is following. By deliberately limiting braking capacity so that it is sufficient to maintain headway distance under most driving conditions but not sufficient to bring the vehicle to a complete stop without driver intervention, manufacturers have marketed ACC as a driver convenience, rather than a safety system. ACC automates two components of the driving task: operational control of headway and speed. When used correctly, it is predicted that ACC use may reduce tailgating and, as a consequence, reduce the number and severity of rear-end accidents; however, this has not yet been demonstrated empirically.

Despite the potential benefits of ACC, negative BA does occur with its use. Drivers rate simulated driving with ACC as less effortful than driving without ACC (Hoedemaker & Brookhuis, 1998). When using ACC, drivers are more likely to perform in-vehicle tasks that they would not normally do (Rudin-Brown & Parker, 2004), and their performance on a secondary task improves (Stanton, Young, & McCaulder, 1997). The visual demand of driving decreases when drivers use ACC, allowing them to monitor the road ahead less (Hoedemaker & Kopf, 2001). Finally, driving performance can deteriorate when using ACC; lane position variability has been shown to increase (Ward, Fairclough, &

Humphreys, 1995; Hoedemaker & Brookhuis, 1998), and drivers tend to brake harder (Hoedemaker & Kopf, 2001) than necessary.

5.5 Task-sharing (task difficulty)

The level of difficulty of the driving task is assumed, by some theories of driving behaviour, to be the central determinant of the way in which an individual drives. Risk Allostasis Theory or Task Difficulty Theory (Fuller, 2005), for example, posits that driving is basically an interaction between the demands of the environment in which the behaviour is being produced and the capability of the individual producing the behaviour. This interaction produces the difficulty of the task being performed, which is then perceived by drivers. If the task difficulty becomes too great, then loss of control occurs.

Sharing, or partitioning, between the primary task of driving and engagement in a secondary task is often used in simulator studies as a measure of a driver's available mental resources. If the resources are scarce, either because the majority of resources is being used to control the vehicle, or because the secondary task, in and of itself, is excessively demanding, then performance on that secondary task will be impaired. For example, in a simulator study that assessed the elements that affect whether a visual in-vehicle secondary task can be successfully partitioned while driving, Tsimhoni and Green (2003) found that total task time on an in-vehicle navigation system increased in a dose-dependent manner from 11 s while parked, to 15.5 s on a straight road, to 16.5 and 19.3 s on a moderate and sharp curve, respectively. Thus, road curvature was revealed to add a significant amount of difficulty to the secondary task of interacting with the navigation display, which ultimately led to an increase in total task time. At the same time, single glance duration *decreased* with decreasing (more severe) road curvature, suggesting that participants changed their time-sharing strategies, namely by making shorter glances when driving was more demanding, and making longer glances when the cost of looking away from the task was higher.

In-vehicle eye movements have been used as an indicator of in-vehicle task difficulty, both in on-road instrumented vehicle studies, and in different fixed-base simulators (Victor et al., 2005). Both auditory and visual in-vehicle tasks of increasing difficulty were related to changes in gaze concentration as measured using a head-mounted eye-tracking system, in both simulated, and on-road, environments. The auditory task caused drivers to shift the focus of their gaze towards the centre of the roadway, while increasingly difficult visual tasks presented on an in-vehicle display caused drivers to look less at the road ahead and more often, for longer periods, and for more varied duration, at the in-vehicle display.

Similar results in secondary task effects on driving performance have been found in driving simulators and in the field (Santos, Merat, Mouta, Brookhuis, & Waard, 2005). In both research settings, clear differences were found between baseline and secondary task conditions in terms of adoption of lower speed, smaller distance to the road shoulder, and a longer time margin (or headway) to the vehicle in front, when interacting with a secondary in-vehicle task.

5.6 Situation awareness

Situation awareness can be defined as awareness of what is happening around you, and understanding what that information means to you now and in the future (Endsley, Bolté, & Jones, 2003). In terms of driving behaviour, situation awareness refers to how attuned a driver is to his or her current roadway surroundings, and how well he or she understands what is about to happen on-road in the near, and less near, future. Situation awareness in a driving context involves spatial, temporal, goal, and system awareness (Matthews, Bryant, Webb, & Harbluk, 2001).

The term 'situation awareness' (SA) is usually applied to operational situations where an operator must have a good understanding of what is happening in order to carry out a specific task or role. The formal definition of SA is "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" (Endsley, 1988).

The relationship between SA and crash risk is such that, as a driver's level of SA decreases, his or her risk of being involved in a collision increases. If a driver's attention is not focused on the driving task at hand, she or he may still be able to adequately control the vehicle under normal driving conditions; however, it is when unexpected events occur that the likelihood of collision increases. One of the most common ways for drivers' SA to decrease is to become distracted. In fact, the cognitive load involved with talking on a mobile phone while driving, whether it be in hand held or hands free mode, has been demonstrated to decrease drivers' SA when driving (Stanley, Kelly, & Lassacher, 2005; Kass, Cole, & Stanny, 2007). Authors have concluded that mobile phone conversations compete for limited mental resources of drivers, which leads to less attention to, and inaccurate knowledge of, the driving situation (Kass et al., 2007). Interestingly, the same increased risk of collision as driving while using a mobile phone was found in a simulator study when drivers engaged in conversation with an 'inconsiderate' passenger (i.e. one that did not pause during the occurrence of unexpected events in the driving scene) (Merat & Jamson, 2005).

One concept that is significant in terms of its relevance to driving-related SA is *automaticity*. Automaticity occurs when a person's behaviour and reactions become somewhat automatic, through experience with a routine task. It can have a positive effect on SA; for example, when it frees up mental effort for more demanding tasks, such as when experienced drivers are not aware of where their feet are positioned, and can instead concentrate on where they are steering. However, it can also have negative consequences on SA, as when information outside the scope of the 'routinised' sequence might not be attended to; for example, when a new stop sign is erected on a well-travelled route home, and many drivers drive right past it, not even noticing this new and significant piece of information. In other, similar, domains to driving such as aviation, the shortcomings associated with processes like automaticity are safeguarded against by the use of checklists; however, this is not the case for road transport.

The construct of SA has often been investigated through the use of driving simulators. Using a query method in which experimenters stopped the simulator at given time points and asked participants relevant questions about the current driving scene and a direction-following task, Kass et al. (2007) found that engagement in mobile phone conversations while driving decreased participants' scores on both SA measures. The authors concluded that, when participants talked on the mobile phone, they were unable to maintain the same level of SA as other drivers. These effects were observed in both novice and experienced drivers, although novice drivers demonstrated lower levels of SA than experienced drivers when not engaging in mobile phone use. Interestingly, in the simulated drive, novices using mobile phones were involved in more simulated collisions, drove through more stop signs, and crossed the centreline more often than more experienced drivers using mobile phones, a finding that mirrors on-road crash statistics (TAC, 2009).

Models of SA have been developed in the context of driving and, in particular, to the potential effects of new generations of intelligent transportation systems (ITS) on driver performance (Matthews et al., 2001). SA has been evaluated more systematically in driving tasks involving the use of as adaptive cruise control (ACC) and mobile phones (Ma & Kaber, 2005). Using a simulation 'freeze' technique and SA queries regarding the present driving situation, mobile phone engagement was found to cause deleterious effects on driving SA and increased driver mental workload.

Driver SA has also been found to suffer as a result of interaction with mobile phone-enabled travel information systems (Stanley et al., 2005). Drivers using mobile phones to access the U.S. 511 travel information system in a simulated driving environment were found to have a larger number of collisions and lower levels of SA (as measured by a SA questionnaire in which they were asked a series of questions regarding objects they remembered seeing while driving) than drivers who did not use mobile phones.

Finally, the use of driving simulators with older adult drivers has been found to result in an improvement in SA with subsequent one-on-one advisement (Romoser, Fisher, Mourant, Wachtel, & Sizov, 2005), demonstrating that post-simulation drive feedback can be used as an effective means of increasing older drivers' overall SA. The authors note that most of the feedback provided involved taking more primary and secondary looks toward oncoming traffic when in an intersection, which subsequently can allow the older driver to collect more information about their environment, and make it more likely that they will achieve accurate level 3A (projection) SA.

Because of the ease with which a simulated driving scenario can be stopped, or 'frozen', at any time point within a test drive, simulation is an apt platform through which to study SA. Although it can also be studied in on-road or test track studies by using retrospective recollection techniques or by an accompanying experimenter asking the driver probe questions while driving, the precise control over conditions and subjects makes driving simulation the ideal methodology for SA.

5.7 Attention

Broadly speaking, attention is used to describe that which directs our receptors to certain stimuli in the environment. Attention can enhance perception of the stimuli to which we are attending, and decrease our awareness of stimuli we are ignoring (Goldstein, 2002). Clearly, the role of attention is of great significance in driving and has been the subject of extensive research, both on-road and in the simulator. The research to-date establishes that eye movement data reflect moment-to-moment cognitive processes and that eye movements are closely linked to attention (Shinar, 2008).

Attention is described as being made up of four stages. Firstly, the process of selective attention determines to what we attend and what we ignore. This decision is governed by a combination of external cues as well as by our expectations. It is then thought that we make some decisions as to the meaning of the stimuli to which we attend; in other words, how valuable we consider the information. How to react to the information follows these decisions. The final stage of the process is the performance of an overt action: once we act the situation changes and the process starts over (Shinar, 2007).

Driver attention and inattention are intertwined with the related concepts of distraction, cognitive and visual workload and driver state (i.e. fatigue), and have therefore been the subject of much investigation. Several simulator studies have been conducted to evaluate the effects of attention in a safe and controlled environment. For example, the implications of roadside advertising for driver attention were investigated in a simulator study that tested the effects of billboards on driver attention, mental workload and driver performance. Results showed that roadside advertising has clear adverse effects on lateral vehicle control and driver attention, emphasising the need to carefully consider the authorisation and placement of billboards (Young, Mahfoud, Stanton, Salmon, Jenkins, & Walker, 2009). The effect of mobile phone use on driver attention has also received a lot of attention. In one simulator study, the deleterious effects of driving while using a mobile phone were viewed in terms of the proportion of situations to which subjects failed to respond (i.e. a pedestrian walking out onto the street) (McKnight & McKnight, 1993).

The advancement of in-vehicle technologies has also warranted a substantial amount of research into their effects on driver attention and inattention. For example, the effect of speech-based e-mail on drivers' attention to the road way was investigated in a simulator study. Results showed a 30% increase in reaction time to objects in the driving scenario when the speech-based system was used compared to a baseline condition (Lee, Caven, Haake, & Brown, 2001).

Cognitive distraction, in terms of the impact on drivers' visual behaviour and braking performance, has been assessed in on-road studies. Compared to when not conducting an additional task, performing a cognitive task had negative impacts on driving behaviour in terms of where the driver looked outside the vehicle and visual monitoring of mirrors and other instruments. Results highlight the distraction effects of the hands-free mode for telematics devices (Harbluk et al., 2007). Similarly, an on-road motorway driving study showed that when conversing on a mobile phone (both hands-free and hands-held), reaction times increased significantly. Furthermore, the greater the difficulty or complexity of the conversation, the greater the possible negative effect on driver distraction (Patten et al., 2004).

In-car warning signals for collision avoidance have also been the subject of research, in terms of how effectively they capture driver attention in demanding situations. For example, one on-road study showed that participants initiated their braking responses significantly more rapidly following presentation of audio-tactile warning signals than following the presentation of either uni-modal auditory or uni-modal vibro-tactile warning signals, suggesting that multi-sensory signals offer the most effective option (Ho, Reed, & Spence, 2007).

5.8 Decision-making

Driving is a dynamic process in which the driver must make both absolute and relative estimates and estimations (Morgan & Hancock, 2009). These estimations can include those that are based primarily on a single element or property of the driving scene, as well as those that are based on the comparative evaluation of multiple stimuli.

Several examples of driver decision-making behaviour have been evaluated using driving simulators. One study compared drivers' 'stop/go' decisions at a simulated signalised intersection with crash risk at the real intersection on which the simulated version was based (Abdel-Aty, Yan, Radwan, & Wang, 2009). Results showed that variability in drivers' stop/go decisions at the simulated higher crash risk location was greater than that at a lower simulated crash risk location. Further, it was found that the rear-end crash tendency at both locations as evidenced by drivers' stop/go behaviour in the driving simulator was consistent with findings from the real intersection's crash history. The authors conclude that simulators can be used to assess rear-end crash risk at signalised intersections in order to find effective engineering countermeasures for real-world high-risk locations.

Another form of decision-making performed by drivers is route choice. Route choice is often made according to personal driver preferences, as well as knowledge of the road transport system, including distance to destination, road conditions, and expected travel times. A simulator study assessing drivers' use of in-vehicle advanced traveller information systems (ATIS) found that drivers do not require perfect data in order to make decisions based on ATIS-provided information; however, there is an accuracy 'threshold' that exists, wherein drivers will not use a system if it does not provide a certain level of accuracy (Chang, 2009).

Gap acceptance is another type of decision made by drivers that is often studied in driving behaviour research. The probability that a driver will experience a crash with another vehicle or a near-miss when turning right (in Australia) across a stream of traffic at an unsignalised intersection depends on both the size of the gap that a driver will accept in an oncoming stream of traffic, and the time taken to cross the intersection once the gap has been accepted (Alexander, Barham, & Black, 2002). Gap acceptance timings observed in driving simulators have been found to closely approximate those typically observed at real intersections with similar characteristics (Alexander et al., 2002). As with other constructs discussed, driving simulators offer an ideal environment in which to evaluate drivers' gap acceptance, as they allow for the tight control of experimental manipulations and behaviour of oncoming and ambient traffic.

5.9 Hazard perception

A driver skill that has been found to reliably correlate with crash risk is hazard perception ability (Smith, Horswill, Chambers, & Wetton, 2009). In fact, the relation is so well established that many driver licensing systems, including that in Victoria, require license applicants to successfully complete a hazard perception test, or HPT, before they can be awarded licensure (VicRoads, 2009).

Hazard perception ability can be successfully evaluated using driving simulation. For example, driver conditions that have been found to affect hazard perception ability in driving simulation studies include sleepiness or drowsiness (Rogé, Pébayle, Kiehn, & Muzet, 2002; Smith et al., 2009), driver experience (Leung & Starmer, 2005; Lee, Klauer, Olsen, Simons-Morton, Dingus, Ramsey, & Ouimet, 2008; Liu, Hosking, & Lenné, 2009), and interaction with in-vehicle entertainment systems (Chisholm et al., 2008).

Other than benefits in terms of safety, simulation offers advantages over on-road methods in evaluating hazard perception. For example, the level of control over critical event presentation available to the experimenter is much greater in simulator studies than on-road, and it also allows for greater control over data collection. Further, precise hazard perception measurements such as drivers' 'useful field of view' can be measured more easily in driving simulators than in actual vehicles (Rogé et al., 2002). Previously validated hazard perception tasks, such as the brake light detection task, can be easily implemented in the driving simulator to test the effects of various road design, engineering and infrastructure-based interventions on road safety.

6. CONCLUSIONS

The question of whether results from driving simulator studies can and should be extended to allow for predictions regarding real world on-road crash risk was considered. Issues surrounding simulator validity, or fidelity, and the appropriateness of using simulator results to make predictions regarding real world collision risk were presented and discussed.

Although a simulator’s physical validity, or fidelity, is important insofar as ensuring that the simulator provides a driving environment that is reasonably representative of the real demands of driving, results from behavioural and other research that has considered the validity issues of simulators have concluded that it is a simulator’s relative, or behavioural, validity that is most important with respect to the validity of results and their application to the real world. Simulation offers a safe, cost-effective, efficient, and systematic method of systematically evaluating the effects of road design, engineering and infrastructure-based changes to the road environment on driving performance. In particular, it represents an important, and essential, first step in evaluating interventions that are previously untested.

7. REFERENCES

Abdel-Aty, M., Yan, X., Radwan, E. and Wang, X. (2009). "Using drivers' stop/go decisions in driving simulator to assess rear-end crash risk at signalized intersections." Journal of Transportation Safety & Security *1(85-100)*.

Alexander, J., Barham, P. and Black, I. (2002). "Factors influencing the probability of an incident at a junction: results from an interactive driving simulator." Accident Analysis & Prevention *34*: 779-792.

Alfredson, J., Nählinder, S. and Castor, M. (2004). Eye movements in applied psychological research- five different techniques- five different approaches, Swedish Defence Research Agency Linköping *1406*.

Allen, R. W. and Jex, H. R. (1980). "Driving simulation - Requirements, mechanization and application." SAE Technical Paper Series *Paper number 800448*: 1-12.

Anderson, I. B., Bauer, K. M., Harwood, D. W. and Fitzpatrick, K. (1999). "Relationship to safety of geometric design consistency measures for rural two-lane highways." Transportation Research Record *1658*.

Backs, R. W., Lenneman, J. K., Wetzel, J. M. and Green, P. (2003). "Cardiac measures of driver workload during simulated driving with and without visual occlusion." *Human Factors(4)*: 525-538.

Baldock, M. R. J., Kloeden, C. N. and McLean, A. J. (2008). In-depth research into rural road crashes, Centre for Automotive Safety Research: *057*.

Bella, F. (2008). "Driving simulator for speed research on two-lane rural roads." Accident Analysis and Prevention *40*: 1078-1087.

Beullens, K. and Van den Bulck, J. (2008). "News, music videos and action movie exposure and adolescents' intentions to take risks in traffic." *Accident Analysis and Prevention*: 349-356.

Beyer, F. R. and Ker, K. (2009). "Street lighting for preventing road traffic injuries (Review)." The Cochrane Library *2009(2)*.

Blaauw, G. J. (1982). "Driving experience and task demands in simulator and instrumented car: a validation study." Human Factors *24(4)*: 473-486.

Boyle, J., Trick, L., Johnsen, S., Roach, J. and Rubens, R. (2008). "Next-day cognition, psychomotor function, and driving-related skills following nighttime administration of eszopiclone." Human Psychopharmacology *23*: 385-397.

Brodsky, W. (2002). "The effects of music tempo on simulated driving performance and vehicular control." *Transportation Research Part F*: 219-241.

Brookhuis, K. A., de Vries, G. and de Waard, D. (1991). "The effects of mobile telephoning on driving performance." *Accident Analysis and Prevention(4)*: 309-316.

Brookhuis, K. A. and de Waard, D. (1993). "The use of psychophysiology to assess driver status." *Ergonomics(9)*: 1099-1110.

Chang, H.-L. (2009). Impact of uncertain travel information on drivers' route choice behavior. Proceedings of the Transportation Research Board 88th Annual Meeting. Washington, DC. 15.

Chisholm, S. L., Caird, J. K. and Lockhart, J. (2008). "The effects of practice with MP3 players on driving performance." Accident Analysis and Prevention *40*: 704-713.

Deery, H. (1999). "Hazard and Risk Perception among Young Novice Drivers." Journal of Safety Research *30(4)*: 225-236.

Edquist, J., Rudin-Brown, C. and Lenné, M. G. (2009). Road design factors and their interactions with speed and speed limits, Monash University Accident Research Centre:

Endsley, M. R. (1988). Design and evluation for situation awareness enhancement. Proceedings of the Human Factors Society 32nd Annual Meeting. Santa Monica, CA. 97-101.
Endsley, M. R., Bolté, B. and Jones, D. G. (2003). What is situation awareness? In: M. R. Endsley, B. Bolté and D. G. Jones, Designing for Situation Awareness. New York: Taylor & Francis, 13-30.
Engstrom, J., Johansson, E. and Ostlund, J. (2005). "Effects of visual and cognitive load in real and simulated motorway driving." *Transportation Research Part F*: 97-120.
Engström, J., Johansson, E. and Östlund, J. (2005). "Effects of visual and cognitive load in real and simulated motorway driving." Transportation Research Part F *8*: 97-120.
Evans, L. (1970). "Speed estimation from a moving automobile." *Ergonomics(2)*: 219-230.
Fisher, D. L., Laurie, N. E., Glaser, R., Connerney, K., Pollatsek, A., Duffy, S. A. and Brock, J. (2002). "Use of a fixed-base driving simulator to evaluate the effects of experience and PC-based risk awareness training on drivers' decisions." *Human Factors(2)*: 287-302.
Fuller, R. (2005). "Towards a general theory of driver behaviour." Accident Analysis and Prevention *37*: 461-472.
Gartner, W. B. and Murphy, M. R. (1979). Concepts of workload. In: B. O. Hartman and R. E. McKenzie, Survey of methods to assess workload: AGARD-AG-246.
Gawron, V. J. (2008). Human workload. In: V. J. Gawron, Human Perfromance, Workload, and Situational Awareness Measures Handbook. Boca Raton: Taylor & Francis. *2nd edition*, 87-230.
Godley, S. T., Triggs, T. J. and Fildes, B. N. (2002). "Driving simulation validation for speed research." Accident Analysis and Prevention *34*: 589-600.
Goldstein, E. B. (2002). Sensation and Perception. CA, Wadsworth Group
Grant, B. A. and Smiley, A. (1993). Driver response to antilock brakes: A demonstration of behavioural adaptation. Proceedings of the Canadian Multidisciplinary Road Safety Conference. Saskatoon, SK. June 14-16, 211-220.
Graziano, A. M. and Raulin, M. L. (1989). Research Methods: A Process of Inquiry. New York, Harper & Row.
Green, P. (2007). Where do drivers look while driving (and for how long)? In: R. E. Dewar and R. Olson, Human Factors in Traffic Safety, 2nd ed. Tucson, AZ: Lawyers & Judges Publishing, 57-82.
Gross, F., Jovanis, P. P. and Eccles, K. (2009). "Safety effectiveness of lane and shoulder width combinations on rural, two-lane, undivided roads." Transportation Research Record *2103*: 42-49.
Gustin, J. L. and Simons, J. S. (2008). "Perceptions of level of intoxication and risk related to drinking and driving." *Addictive Behaviors*: 605-615.
Haigney, D. E., Taylor, R. G. and Westerman, S. J. (2000). "Concurrent mobile (cellular) phone use and driving performance: task demand characteristics and compensatory processes." *Transportation Research Part F* 113-121.
Harbluk, J. L., Noy, Y. I., Trbovich, P. L. and Eizenman, M. (2007). "An on-road assessment of cognitive distraction: Impacts on drivers' visual behavior and braking performance." *Accident Analysis and Prevention*: 372-379.
Hart, S. G. and Staveland, L. E. (1987). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In: P. A. Hancock and N. Meshkati, Human mental workload. Amsterdam, North Holland: Elsevier.
Hatfield, J. and Chamberlain, T. (2008). "The impact of in-car displays on drivers in neighbouring cars: Survey and driving simulator experiment." Transportation Research Part F *11*: 137-146.

Hauer, E. (2009). "Speed and safety." Transportation Research Record *2103*: 10-17.

Ho, C., Reed, N. and Spence, C. (2007). "Multisensory in-car warning signals for collision avoidance." *Human Factors(6)*: 1107-1114.

Hoddes, E., Zarcone, V., Smythe, H., Phillips, R. and Dement, W. C. (1973). "Quantification of sleepiness: A new approach." Psychophysiology *10*: 431-436.

Hoedemaker, M. and Brookhuis, K. A. (1998). "Behavioural adaptation to driving with an adaptive cruise control (ACC)." Transportation Research Part F *1*: 95-106.

Hoedemaker, M. and Kopf, M. (2001). Visual sampling behaviour when driving with adaptive cruise control. Proceedings of the Ninth International Conference on Vision in Vehicles. Australia. August 19-22,

Hoffman, J. D., Lee, J. D., Brown, T. L. and McGehee, D. V. (2002). "Comparison of driver braking responses in a high-fidelity simulator and on a test track." Transportation Research Record *1803*: 59-65.

Horrey, W. J. and Wickens, C. D. (2006). "Examining the impact of cell p hone conversations on driving using meta-analytic techniques." Human Factors *48*: 196-205.

Horswill, M. S. and McKenna, F. (1999). "The development, validation and application of a video-based technique for measuring an everyday risk taking behavior: drivers' speed choice." *Journal of Applied Psychology(6)*: 977-985.

Hurwitz, D. S. and Knodler, M. A. (2007). Static and dynamic evaluation of the driver speed perception and selection process. Fourth Driver Assessment Conference. Stevenson, Washington D.C.

Jahn, G., Oehme, A., Krems, J. F. and Gelau, C. (2005). "Peripheral detection as a workload measure in driving: effects of traffic complexity and route guidance system use in a driving study." *Transportation Research Part F*: 255-275.

Jamson, A. H. and Merat, N. (2005). "Surrogate in-vehicle information systems and driver behaviour: Effects of visual and cognitive load in simulated rural driving." Transportation Research Part F *8*: 79-96.

Kaptein, N. A., Theeuwes, J. and van der Horst, R. (1996). "Driving simulator validity: Some considerations." Transportation Research Record *1550*: 30-36.

Kass, S. J., Cole, K. S. and Stanny, C. J. (2007). "Effects of distraction and experience on situation awareness and simulated driving." Transportation Research Part F *10*: 321-329.

Klauer, S. G., Dingus, D. R., Neale, T. A., Sudweeks, J. and Ramsey, D. J. (2006). The impact of driver inattention on near-crash/crash risk: an analysis using the 100-car naturalistic study data, National Highway Traffic Safety Administration: Washington, DC

Lansdown, T. C., Brook-Carter, N. and Kersloot, T. (2004). "Distraction from multiple in-vehicle secondary tasks: vehicle performance and mental workload implications." Ergonomics *47*: 91-104.

Lee, J. D., Caven, B., Haake, S. and Brown, T. L. (2001). "Speech based interaction with in-vehicle computers: the effects of speech based e-mail on drivers' attention to the roadway." *Human Factors(4)*: 631-640.

Lee, J. D., McGehee, D. V., Brown, T. L. and Reyes, M. L. (2002). "Collision warning timing, driver distraction, and driver response to imminent rear-end collisions in a high-fidelity driving simulator." *Human Factors(2)*: 314-334.

Lee, S. E., Klauer, S. G., Olsen, E. C. B., Simons-Morton, B. G., Dingus, T. A., Ramsey, D. J. and Ouimet, M. C. (2008). "Detection of road hazards by novice teen and experienced adult drivers." Transportation Research Record *2078*: 26-32.

Lenné, M., Triggs, T., Mulvihill, C. M., Regan, M. A. and Corben, B. F. (2008). "Detection of emergency vehicles: driver resonses to advance warning in a driving simulator." *Human Factors(1)*: 135-144.
Leung, S. and Starmer, G. (2005). "Gap acceptance and risk-taking by young and mature drivers, both sober and alcohol-intoxicated, in a simulated driving task." Accident Analysis & Prevention *37*: 1056-1065.
Liu, B.-S. and Lee, Y.-H. (2006). "In-vehicle workload assessment: effects of traffic situations and cellular telephone use." Journal of Safety Research *37*: 99-105.
Liu, C. C., Hosking, S. G. and Lenné, M. G. (2009). "Hazard perception abilities of experienced and novice motorcyclists: An interactive simulator experiement." Transportation Research Part F *12*: 325-334.
Liu, D., Macchiarella, N. D. and Vincenzi, D. A. (2009). Simulation fidelity. In: P. A. Hancock, D. Vincenzi, J. Wise and M. Mouloua, Human Factors in Simulation and Training. Boca Raton: Taylor & Francis, LLC, 61-73.
Lucidi, F., Russo, P., Mallia, L., Devoto, A., Lauriola, M. and Violani, C. (2006). "Sleep related car crashes: risk perception and decision making processes in young drivers." *Accident Analysis and Prevention*: 302-309.
Ma, R. and Kaber, D. B. (2005). "Situation awareness and workload in driving while using adaptive cruise control and a cell phone." International Journal of Industrial Ergonomics *35*: 939-953.
Machin, M. A. and Sankey, K. S. (2008). "Relationships between young drivers' personality characteristics, risk perceptions, and driving behaviour." *Accident Analysis and Prevention*: 541-547.
Matthews, M. L., Bryant, D. J., Webb, R. D. G. and Harbluk, J. L. (2001). "Model for situation awareness and driving: Application to analysis and research for intelligent transportation systems." Transporation Research Record *1779*: 26-32.
McKnight, J. and McKnight, S. (1993). "The effect of cellular phone use upon driver attention " *Accident Analysis and Prevention(3)*: 259-265.
Merat, N. and Jamson, A. H. (2005). Shut up I'm driving! Is talking to an inconsiderate passenger the same as talking on a mobile telephone? Proceedings of the Third International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design. 426-432.
Milosevic, S. and Milic, J. (1990). "Speed perception in road curves." *Journal of Safety Research*: 19-23.
Milton, J. and Mannering, F. (1998). "The relationship among highway geometrics, traffic-related elements and motor-vehicle accident frequencies." Transportation *25*: 395-413.
Morgan, J. F. and Hancock, P. A. (2009). Estimations in driving. In: C. Castro, Human Factors of Visual and Cognitive Performance in Driving. Boca Raton: Taylor & Francis, 51-62.
Moroney, W. F. and Lilienthal, M. G. (2009). Human factors in simulation and training: An overview. In: P. Hancock, D. Vincenzi, J. Wise and M. Mouloua, Human Factors in Simulation and Training. Boca Raton: Taylor & Francis Group, LLC, 3-38.
NADS (2008). National Advanced Driving Simulator Overview, University of Iowa: Iowa City
NADS. (2009). "The National Advanced Driving Simulator at the University of Iowa." Retrieved 22 October 2009, from www.nads-sc.uiowa.edu.
Nelson, E., Atchley, P. and Little, T. D. (2009). "The effects of perception of risk and the importance of answering and initiating a cellular phone call while driving." *Accident Analysis and Prevention*: 438-444.

Nilsson, L. (1993). Behavioural research in an advanced driving simulator - experiences of the VTI system. Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting. Seattle, Washington. October 11-15, 612-616.

Nilsson, L., Tornros, J. and Ceci, R. (2005). Using the mobile phone while driving: How much load does it impose on the driver? Proceedings of the Road Safety on Four Continents: 13th International Conference.

OECD, O. f. E. C. a. D. (1990). Behavioural adaptations to changes in the road transport system, OECD Road Research Group: Paris

Patten, C. J. D., Kircher, A., Östlund, J. and Nilsson, L. (2004). "Using mobile telephones: cognitive workload and attention resource allocation." Accident Analysis and Prevention *36*: 341-350.

Pauzié, A., Manzan, J. and Dapzol, N. (2007). Driver's behavior and workload assessment for new in-vehicle technologies design. Proceedings of the 4th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design. Stevenson, Washington.

Petersen, A., Barrett, R. and Morrison, S. (2006). "Driver training and emergency brake performance in cars with antilock braking systems." *Safety Science*: 905-917.

Pradhan, A. K., Hammel, K. R., DeRamus, R., Pollatsek, A., Noyce, D. A. and Fisher, D. L. (2005). "Using eye movements to evaluate effects of driver age on risk perception in a driving simulator." *Human Factors(4)*: 840-852.

Rakauskas, M. E., Ward, N. J., Bernat, E., Cadwallader, M., Patrick, C. and de Waard, D. (2005). Psychophysiological measures of driver distraction and workload while intoxicated. 3rd International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design.

Recarte, M. A. and Nunes, L. M. (2003). "Mental workload while driving: effects on visual search, discrimination, and decision making." *Journal of Experimental Psychology: Applied(2)*: 119-137.

Reed, M. P. and Green, P. A. (1995). Validation of a low-cost driving simulator using a telephone dialing task, University of Michigan Transportation Research Institute: Ann Arbor *UMTRI-95-19.*

Regan, M. A., Triggs, T., Mitsopoulos-Rubens, E., Symmons, M. and Tomasevic, N. (2007). Driving simulator evaluation of a vehicle rear-mounted heavy braking light with and without distraction. 4th Driver Assessment Conference. Stevenson, Washington D.C.

Research Triangle Institute (1970). Speed and accidents, *RTI Project SU-409.*

Rogé, J., Pébayle, T., Kiehn, L. and Muzet, A. (2002). "Alteration of the useful field as a function of state of vigilance in simulated car driving." Transportation Research Part F *5*: 189-200.

Romoser, M. R. E., Fisher, D. L., Mourant, R., Wachtel, J. and Sizov, K. (2005). The use of a driving simulator to assess senior driver performance: Increasing situational awareness through post-drive one-on-one advisement. Proceedings of the Third International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design. 456-463.

Rudin-Brown, C. (2006). "The effect of driver eye height on speed choice, lane-keeping, and car-following behavior: results of two driving simulator studies." Traffic Injury Prevention *7*: 365-372.

Rudin-Brown, C. M. and Noy, Y. I. (2002). "Investigation of behavioural adaptation to lane departure warnings." Transportation Research Record *1803*: 30-37.

Rudin-Brown, C. M. and Parker, H. A. (2004). "Behavioural adaptation to adaptive cruise control (ACC): implications for preventative strategies." Transportation Research Part F *7*: 59-76.

Rudin-Brown, C. M. and Parker, H. A. (2004). "Behavioural adaptation to adaptive cruise control (ACC): implications for preventive strategies." Transportation Research Part F *7*: 59-76.
Santos, J., Merat, N., Mouta, S., Brookhuis, K. and Waard, D. d. (2005). "The interaction between driving and in-vehicle informaton systems: Comparison of results from laboratory, simulator and real-world studies." Transportation Research Part F *8*: 135-146.
Sawalha, Z. and Sayed, T. (2001). "Evaluating safety of urban arterial roadways." Journal of Transportation Engineering *127(2)*: 151-158.
Shinar, D. (2007). Driver information processing: attention, perception, reaction time and comprehension. In, Traffic Safety and Human Behaviour. Burlington: Emerald Group Publishing.
Shinar, D. (2007). Traffic Safety and Human Behavior. Amsterdam, Elsevier.
Shinar, D. (2008). "Looks are (almost) everything: where drivers look to get information." *Human Factors(3)*: 380-384.
Smith, S. S., Horswill, M. S., Chambers, B. and Wetton, M. (2009). "Hazard perception in novice and experienced drivers: The effects of sleepiness." Accident Analysis & Prevention *41*: 729-733.
Solomon, D. (1964). Accidents on main rural highways related to speed, driver, and vehicle,
Stanley, L. M., Kelly, M. J. and Lassacher, S. (2005). Driver perfromance while interacting with the 511 travel information system in urban and rural traffic. Proceedings of the Third International Driving Symposium on Human Factors in Driving Assessment, Training and Vehicle Design. 486-492.
Stanney, K. M. and Kennedy, R. S. (2009). Simulation sickness. In: P. A. Hancock, D. Vincenzi, J. Wise and M. Mouloua, Human Factors in Simulation and Training. Boca Raton: Taylor & Francis LLC, 117-127.
Stanton, N. A., Young, M. and McCaulder, B. (1997). "Drive-by-wire: the case of driver workload and reclaiming control with adaptive cruise control." Safety Science *27*: 149-159.
Strayer, D. L., Drews, F. A. and Crouch, D. J. (2004). Fatal distraction? A comparison of the cell-phone driver and the drunk driver. Proceedings of the Second International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design. 25-30.
Strayer, D. L., Drews, F. A. and Crouch, D. J. (2006). "A comparison of the cell phone driver and the drunk driver." *Human Factors(2)*: 381-391.
Strayer, D. L. and Johnston, W. A. (2001). "Driven to distraction: dual task studies of simulated driving and conversing on a cellular telephone." *Psychological Science*: 462-466.
TAC. (2009). "Young driver statistics." 2009, from www.tacsafety.com.au.
Taoka, G. T. (1989). "Brake reaction times of unalerted drivers." ITE Journal *March*.
Taylor, M. C., Baruya, A. and Kennedy, J. V. (2002). The relationship between speed and accidents on rural single-carriageway roads, Transportation Research Library: *TRL511*.
Taylor, M. C., Lynam, D. A. and Baruya, A. (2000). The effects of drivers' speed on the frequency of road accidents, Transport Research Laboratory: *TRL Report 421*.
Törnros, J. (1998). "Driving behaviour in a real and a simulated roadtunnel--a validation study." Accident Analysis and Prevention *30(4)*: 497-503.
Transportation Research Board (1987). Designing safer roads: Practices for resurfacing, restoration, and rehabilitation, National Research Council: *Special Report 214*.

Tsimhoni, O. and Green, P. (2003). Time-sharing of a visual in-vehicle task while driving: The effects of four key constructs. Proceedings of the Second International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design. Park City, Utah. July 21-24, 113-118.

VicRoads. (2009). "Hazard perception test." 2009, from www.vicroads.vic.gov.au/Home/Licensing/GettingYourPs/HazardPerceptionTest.htm.

Victor, T. W., Harbluk, J. L. and Engström, J. A. (2005). "Sensitivity of eye-movement measures to in-vehicle task difficulty." *Transportation Research Part F*: 167-190.

Ward, N. J., Fairclough, S. and Humphreys, M. (1995). The effect of task automatisation in the automotive context: A field study of an Autonomous Intelligent Cruise Control system. Proceedings of the International Confeence on Experimental analysis and Measurement of Situation Awareness. Daytona Beach, FL. November 1-3,

Warshawsky-Livne, L. and Shinar, D. (2002). "Effects of uncertainty, transmission type, and driver age and gender on brake reaction and movement time." Journal of Safety Research *33*: 117-128.

Wilde, G. J. S., Hennessy, D. A. and Wiesenthal, D. L. (2005). Contemporary issues in road user behavior and traffic safety. Hauppauge, Nova Science Publishers.

Wilde, G. J. S., Robertson, L. S. and Pless, I. B. (2002). "For and against: does risk homeostasis theory have implications for road safety." *British Medical Journal*: 1149-1152.

Wilson, G. F. and Eggemeier, F. T. (2001). Mental workload measurement. In, International Encyclopaedia of Ergonomics and Human Factors. London: Taylor & Francis. *1*, 504-506.

Yan, X., Abdel-Aty, M., Radwan, E., Wang, X. and Chilakapati, P. (2008). "Validating a driving simulator using surrogate safety measures." Accident Analysis and Prevention *40*: 274-288.

Young, M. S., Mahfoud, J. M., Stanton, N. A., Salmon, P. M., Jenkins, D. P. and Walker, G. H. (2009). "Conflicts of interest: the implications of roadside advertising for driver attention." *Transportation Research Part F*: 381-388.