Effects of fatigue on driver performance on slippery roads

Andres Levitski
Master’s Thesis
Psychology
Faculty of Medicine
July 2020
Supervisor: Igor Radun

Tiedekunta – Fakultet – Faculty
Faculty of Medicine
Koulutusohjelma – Utbildingsprogram – Degree Programme
Master of Arts (Psychology)
Tekijä – Författare – Author
Andres Levitski
Työn nimi – Arbetets titel – Title
Effects of fatigue on driver performance on slippery roads
Oppiaine/Opintosuunta – Läroämne/Studieinriktning – Subject/Study track
Psychology

Työn laji – Arbetets art – Level	Aika – Datum – Month and year	Sivumäärä – Sidoantal – Number of pages
Master's thesis	July 2020	37

Tiivistelmä – Referat – Abstract

Objectives

Fatigue is a major factor affecting driving performance and traffic accident risk. Driving conditions influence how people experience fatigue while driving. Driving in demanding conditions may increase vigilance in tired drivers; however, it may also increase cognitive load and become an additional source of fatigue. The current study investigated how driving on a slippery road interacts with fatigue caused by sleep deprivation and how it influences driving performance.

Methods

Twelve male participants (aged 19–21) drove 52.5 km in a driving simulator in four different conditions (day vs night and dry vs slippery road). Subjective sleep-related fatigue was measured with the Karolinska Sleepiness Scale and physiological fatigue in blink durations with electro-oculography. Three measures were used for driver performance: standard deviation of lateral position, mean steering wheel movement amplitude and mean steering wheel movement peak velocity. After each driving session, participants negotiated a cone track. The success rate for this task was analysed separately.

Results

Driving on slippery roads improved performance in all three performance metrics in sleep-deprived drivers. The three-way interaction between driver condition, road condition and time-on-task was significant for subjective sleep-related fatigue but not for performance. Sleep-deprived drivers became increasingly sleepy over time when driving in slippery conditions; however, this did not negatively affect their performance.

Conclusions

Driving in demanding weather conditions can increase the fatigue experienced by drivers; however, this change may not be initially detectable in performance. Large individual variability in response to both fatigue and driving conditions requires further research.

Avainsanat – Nyckelord – Keywords
Traffic psychology, fatigue, sleepiness, driving simulator
Ohjaaja tai ohjaajat – Handledare – Supervisor or supervisors
Igor Radun
Säilytyspaikka – Förvaringställe – Where deposited
E-thesis (HELDA), ethesis.helsinki.fi
Muita tietoja – Övriga uppgifter – Additional information

Tiedekunta – Fakultet – Faculty
Lääketieteellinen tiedekunta

Koulutusohjelma – Utbildingsprogram – Degree Programme
Psykologian maisteriohjelma

Tekijä – Författare – Author
Andres Levitski

Työn nimi – Arbetets titel – Title
Väsymyksen vaikutus ajosuoriutumiseen liukkaalla tiellä

Oppiaine/Opintosuunta – Läroämne/Studieinriktning – Subject/Study track
Psykologia

Työn laji – Arbetets art – Level	Aika – Datum – Month and year	Sivumäärä – Sidoantal – Number of pages
Pro gradu -tutkielma	Heinäkuu 2020	37

Tiivistelmä – Referat – Abstract

Tavoitteet
Kuljettajan väsymys vaikuttaa keskeisesti niin ajokykyyn kuin onnettomuusriskiinkin. Ajo-olosuhteet taas määrittävät sen miten kuljettajat kokevat väsymyksen ajon aikana. Haastavissa olosuhteissa ajaminen saattaa lisätä väsyneiden kuljettajien tarkkaavaisuutta ajotapahtumaa kohtaan, mutta tämä voi lisätä myös kognitiivista taakkaa ja aiheuttaa näin lisää väsymystä. Tämän tutkimuksen tavoitteena on selvittää miten liukkaalla tiellä ajaminen vaikuttaa yhdessä univajeesta johtuvan väsymyksen kanssa kuljettajan ajosuoriutumiseen.

Menetelmät
Kaksitoista miespuolista koehenkilöä (i’iltään 19–21) ajoivat ajosimulaattorissa 52.5 km matkan neljässä eri asetelmassa (päivä- ja yöaikaan sekä kuivalla ja liukkaalla tiellä). Subjektiivista uneliaisuutta mitattiin Karolinska Sleepiness Scalen avulla ja fysiologista väsymystä silmänräpäysten pituuden perusteella elektro-okulografiaa käyttäen. Kuljettajien ajosuoriutumista arvioitiin kolmella muuttujalla: auton sivuttaissijainnin keskipoikkeama ajoradalla, ohjausliikkeiden amplitudien keskiarvo ja ohjausliikkeiden huippunopeuden keskiarvo. Ajosession jälkeen koehenkilöt ajoivat liikennekartiopujottelutehtävän, jossa onnistumista arvioitiin erikseen.

Tulokset
Liukkaalla tiellä ajaminen paransi univajeesta kärsivien kuljettajien ajosuoriutumista kaikilla kolmella muuttujalla mitattuna. Kolmisuuntainen yhdysvaikutus kuljettajan tilan, tieolosuhteiden ja ajan välillä oli merkitsevä vain subjektiivisen uneliaisuuden kohdalla. Univajeisten kuljettajien uneliaisuus lisääntyi nopeammin liukkaalla tiellä, mutta tämä ei vaikuttanut heidän ajosuoriutumiseensa.

Johtopäätökset
Haastavissa olosuhteissa ajaminen voi lisätä jo valmiiksi väsyneiden kuljettajien väsymystä, mutta muutokset suorituskyvyssä voivat näkyä vasta viipeellä. Suuret yksilölliset erot niin väsymys- kuin ajo-olosuhdevasteissa vaativat lisätutkimusta.

Avainsanat – Nyckelord – Keywords
Liikennepsykologia, väsymys, uneliaisuus, ajosimulaattori

Ohjaaja tai ohjaajat – Handledare – Supervisor or supervisors
Igor Radun

Säilytyspaikka – Förvaringställe – Where deposited
E-thesis (HELDA), ethesis.helsinki.fi

Muita tietoja – Övriga uppgifter – Additional information

Foreword

The data for the thesis were collected as part of a research project on the same topic led by my thesis supervisor, Igor Radun, PhD. The data collection was financed by the Swedish Transport Administration (Trafikverket) and SAFER - Vehicle and Traffic Safety Centre, Göteborg, Sweden. Several other people participated in the study design, data collection and data analysis phases before I was involved. When starting this thesis, I was provided with pre-collected datasets and an early draft article on the results. After conducting further analysis of the data and more research on the topic, the approach to the topic and, subsequently, the results were modified. The previous work was extremely useful in analysing the results and writing this thesis.

I am grateful to Mattias Wahde, PhD, Ola Benderius, PhD, and Jenni Radun, PhD, for their work on this project and preliminary analysis of the data and also to Göran Kecklund, PhD, and Michael Ingre, PhD, for their comments on the results presented in this thesis. I would like to thank my supervisor for his helpful comments and suggestions and for providing useful sources that served as a motivation for the original study design. Additionally, I thank Jari Lipsanen, MA, for his invaluable help with questions related to statistical analysis of the data.

Andres Levitski

Helsinki, 28th July 2020

Contents

1. Introduction 1

1.1 Definition of fatigue 2

1.2 Causes of fatigue 4

1.3 Measuring fatigue 7

1.4 Fatigue and driving performance 10

1.5 Driving environment and fatigue 12

1.6 Research question and hypotheses 14

2. Method 14

2.1 Simulator 15

2.2 Participants 15

2.3 Driving scenario 15

2.4 Protocol 16

2.5 Measurements and variables 17

2.6 Statistical analysis 18

3. Results 18

4. Discussion 24

4.1 Limitations of the current study 26

4.2 Conclusion and future considerations 27

References 29

1. Introduction

Driving is a multidomain goal-oriented task that requires attention and the successful cooperation of sensory, cognitive and motor processes (Fuller, 2011). Other road users, the road profile, roadside signs, road markings, weather conditions and gauges in the car all provide valuable information and compete for the driver's attention. Gathering this information requires alertness, time-sharing strategies and the ability to shift and share attention. Drivers use this information to accurately predict the environment and to plan and execute future actions. Even the basic task of lane-keeping requires attention and steering corrections on a second-to-second basis. Therefore, driving involves constant cognitive work and, like other types of work, causes fatigue.

Fatigue influences human performance in multiple ways. It has been linked to increases in both errors of commission and omission (Doran, Dongen, & Dinges, 2001). In traffic, these effects can manifest as unsafe steering actions or delayed or missing reactions to events. The performance loss due to sleepiness-related fatigue was shown to be comparable to that of drunk driving (Dawson & Reid, 1997; Arnedt, Wilde, Munt, & MacLean, 2001). It is also generally accepted that fatigue-related crashes are, on average, more deadly (Horne & Reyner, 1995). Drivers who have fallen asleep may not react to avoid a crash, or they may react too late to make a difference (Smith, Cook, Olson, Reading, & Dean, 2004).

It is difficult to evaluate the role of fatigue in traffic crashes, as no clear and widely accepted definition of the concept is available, and no standardised method for crash investigators to measure it exists. Fatal crashes usually warrant more comprehensive investigation and can provide more accurate information on all the factors contributing to them. International estimates of fatal crashes where falling asleep was the main cause range from a few percent to over 10% (Radun & Radun, 2008). Alternatively, estimates of fatal crashes where fatigue was in some way involved reach 30% (Partinen, 2004).

Fatigue is not always included in the recorded causes of accidents and could go unnoticed if other plausible causes are found. If elimination is used to determine the main cause, other simultaneous factors could be overlooked (Rajaratnam & Jones, 2004). Weather and road conditions can influence accident risk independently but can also interact with the state of the driver. Therefore, in demanding conditions, an accident could be caused by the state of the driver, the state of the road or a combination of these. It is possible that driving in demanding conditions contributes to the accumulation of fatigue or that a performance decrease due to fatigue is more dangerous when driving becomes more challenging. Thus, recognising how fatigue and driving conditions interact and influence driver performance is important from a traffic safety perspective.

1.1 Definition of fatigue

The concept of fatigue is multidimensional and difficult to define consistently. Sleepiness, boredom, tiredness and exhaustion are all words that overlap with fatigue and can be used interchangeably to describe the same phenomenon or to reference a specific subcomponent of it (Johns, 1998; Shen, Barbera, & Shapiro, 2006). No commonly accepted and comprehensive definition of fatigue exists, and many competing and supplementary definitions add to the confusion. Generally, both symptoms and causes have been used as a basis for the definition.

The common symptoms of fatigue include subjective discomfort, reduced willingness to work, changes in physiological activation and performance deterioration (Grandjean, 1979; van der Linden, Frese, & Meijman, 2003; Shen et al., 2006). The symptomatic definitions of fatigue can be similarly classified based on the areas where change is observed: subjective experience, physiological change, performance-related decrement or a combination of these (Phillips, 2015). Those that emphasise subjective experience base their definition on feelings of discomfort, low energy and reduced inclination to work. Definitions based on physiology define fatigue through changes in biological functioning that manifest in muscle weakness and insufficient cellular capacity to maintain the original activity. Performance-related definitions highlight observable changes in key areas of functioning, including attention, perception and decision-making.

Symptomatic definitions are useful for operationalisation and measuring fatigue; however, they provide minimal information about causes and mechanisms. Including causes in the definition can provide insight into how fatigue is created and how it can be prevented. Causes of fatigue are also important in defining the relationship between the closely related concepts of fatigue and sleepiness.

Working leads to exhaustion, and rest is required to replenish depleted energy. However, sleepiness is a state mainly dependent on internal biological processes that regulate wake and sleep homeostasis, rather than work. It is counteracted not by rest but by sleep. Because fatigue is often accompanied by sleepiness, and because it is difficult to operationalise and measure fatigue without measuring sleepiness, these two concepts are often used interchangeably. However, views differ regarding whether both task-related and task-independent, state-related factors should be considered as causes of fatigue and in what way.

Philips (2015) argued that all fatigue is caused by exertion and that only the context and target of exertion varies. Homoeostatic and circadian sleep drives can provide a context for exertion; however, sleepiness due to these factors would not itself constitute fatigue unless there is active work to combat sleep onset. Grandjean (1979) separates fatigue into muscular and mental components. Continuous muscle activation depletes energy reserves and induces changes in chemical compositions that lead to acidification of the tissue, inducing muscle fatigue. Mental fatigue, conversely, is a functional state affected by multiple factors, including mental and physical work and circadian rhythm.

The value of a definition can also be evaluated by its practicality. May and Baldwin (2009) argued that traffic safety and fatigue countermeasure research ultimately focuses on the effects of fatigue on driving performance. Subjective experiences and changes in physiology can serve as good proxies for performance-related changes but are useful only if they can predict changes in driving ability. The requirements for traffic psychology are therefore considerably different from those in a clinical setting. Because both exertion and sleepiness influence driver performance, the authors have presented their three-pronged definition of fatigue that includes both task-related and driver state-related causes of performance changes (Figure 1). The three categories presented in the definition are passive task-related fatigue, active task-related fatigue and sleep-related fatigue. All three fatigue states impact driving performance separately; however, task-related fatigue can also worsen sleep-related fatigue. Therefore, the model provides a framework that can explain how cognitive underload (boredom), cognitive overload and sleepiness can all coexist independently and lead to the same outcome.

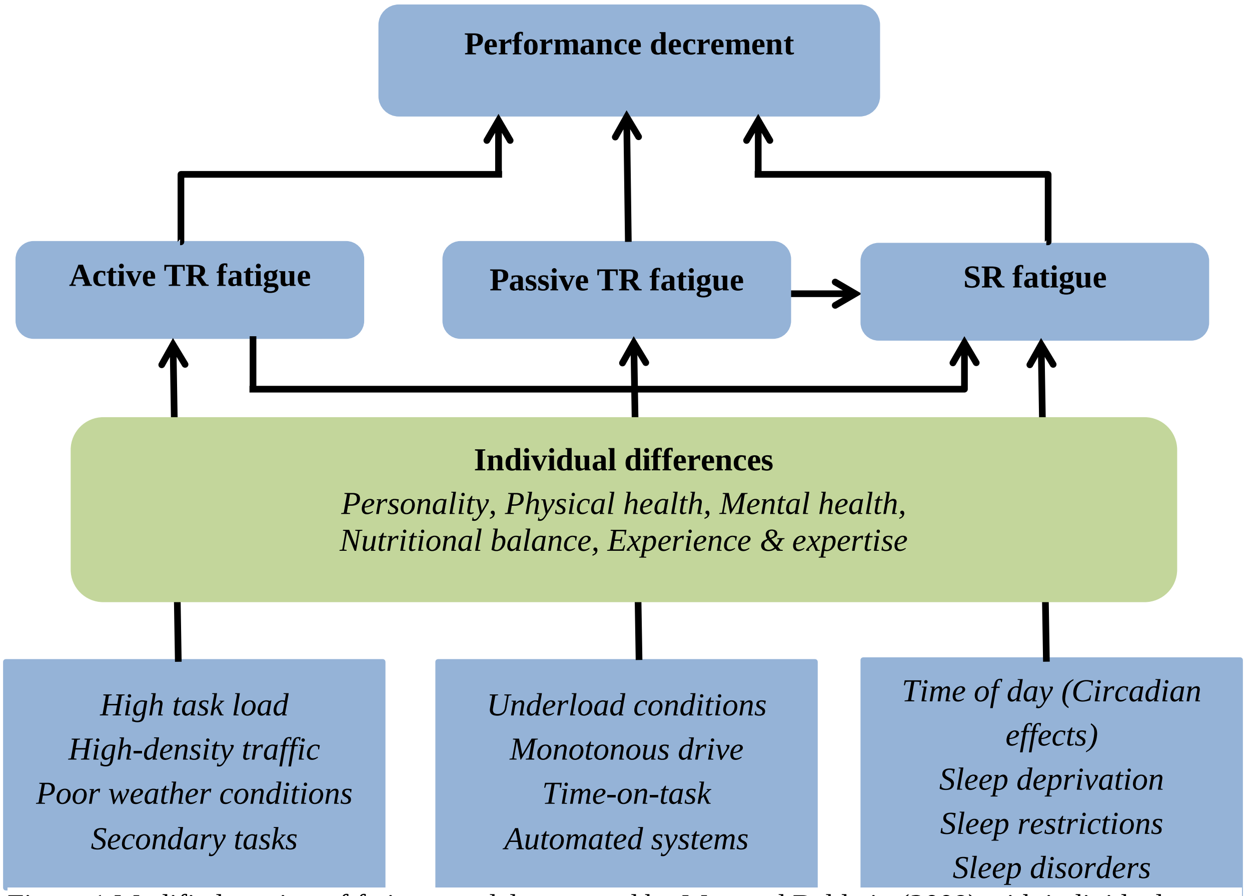

Figure 1 Modified version of fatigue model presented by May and Baldwin (2009) with individual differences added as moderators of causes of task-related (TR) and sleep-related (SR) fatigue.

In the current study, the framework proposed by May and Baldwin was used as a basis for defining and categorising fatigue. Both task-related and sleep-related factors are included in the definition. Fatigue itself serves as an umbrella term and refers to both task-related and sleep-related fatigue (sleepiness).

1.2 Causes of fatigue

Both the requirements of the driving task and the state of the driver can be sources of fatigue during driving. Additionally, individual differences between people determine their vulnerability to these effects and the effect on their driving ability.

Task-related effects cause fatigue through exertion. Physical or mental work, if too prolonged, eventually leads to fatigue symptoms and exhaustion (Okogbaa, Shell, & Filipusic, 1994). The demands of driving tasks can vary; however, at the minimum, driving requires constant vigilance, which involves mental work. Thus, driving time is an important factor in the accumulation of fatigue (Nilsson, Nelson, & Carlson, 1997). How this time-on-task effect causes fatigue can vary and depends largely on the driving environment and the challenges of the task.

Demanding weather conditions or complex interactions with other traffic increase mental load (Barr, Yang, Hanowski, & Olson, 2005). Multiple secondary tasks or distractions can compete for the attention of drivers, forcing them to multitask and prioritise tasks. If continued for too long, this increases active task-related fatigue. Distracting sensory stimuli such as noise, heat and vibration were also linked to fatigue (Lal & Craig, 2001a).

Task monotony was also associated with increased fatigue-related symptoms (Mascord & Heath, 1992). Underload (or boredom) is closely related to mental fatigue as it is characterised by both lower cerebral activation and reduced vigilance (Grandjean, 1979). Most driving tasks comprise repetitive and monotonous subtasks. Monitoring the largely unchanging environment and applying corrective steering wheel movements to keep the car in the correct lane minimally challenges the driver. Adaptive cruise control and other automated driving aids designed to reduce cognitive load may change the nature of the driving task from active control to passive monitoring. This can reduce task engagement and increase passive task-related fatigue (Saxby et al., 2008).

Sleepiness-related fatigue results from the sleep-wake cycle. The two-process model of sleep regulation is the most influential theoretical explanation of sleepiness (Borbély, Achermann, Trachsel, & Tobler, 1989; Borbély, 1982). It states that sleepiness is caused by two different and concurrent biological processes. The homeostatic process regulates sleep and wake balance. Sleepiness increases linearly during wakefulness and resets during sleep. Prolonged waking periods lead to accumulation of sleep deprivation and increased pressure to sleep. The circadian process is synchronised with the time of day and regulates the pressure to stay awake. This is usually highest during early evening and lowest during early morning hours. The balance between these two processes plays an important role in the ability of an individual to resist sleep-related fatigue. Conflict between the homeostatic sleep drive and circadian time of day phase can be stressful and lead to situations where sleep deprivation is high but sleep onset is delayed.

Sleep-related fatigue is common in shift workers and people with inconsistent sleep schedules (Åkerstedt, Torsvall, & Gillberg, 1987; Rosekind et al., 1994). This increases the exposure of some groups of drivers, such as truck drivers, to the effects of fatigue. Single-vehicle truck accidents are most common at night and in the early morning hours, confirming this connection (Harris, 1977). When exposure (e.g. traffic density) was considered, the general road accident risk was shown to peak during similar hours (Folkard, 1997). Shift work is not only problematic because it disrupts sleep patterns but also because night work reduces access to daytime lighting. Bright light is a major factor in feeling vital and has been shown to reduce acute sleepiness, especially in the presence of mental fatigue (Smolders & de Kort, 2014). In the long term, continuous exposure to nighttime artificial lighting can also lead to adverse effects, including further circadian rhythm disruption and an increased risk of developing a sleeping disorder (Cho et al., 2015).

Sleep disorders, especially those that are untreated and unrecognised, are also major factors in sleepiness-related accidents (Aldrich, 1989; George & Smiley, 1999). Their contribution to accident risk differs according to the type of disorder. Some, such as sleep apnoea, affect sleep quality and thus contribute to daytime sleepiness. Conversely, narcolepsy poses a more direct and less predictable threat to traffic safety by exposing drivers suffering from it to sudden loss of consciousness. However, it is much less common than sleep apnoea (Ohayon, Priest, Zulley, Smirne, & Paiva, 2002).

In addition to task-related effects and sleep-related fatigue, individual differences play an important role in experiencing fatigue. They mediate and moderate the effects of other factors and determine how different people react to the same conditions. Individuals can differ widely in their driving skill and ability. Differences also exist regarding how fatigue influences performance. A study of North American long-distance truck drivers revealed that only a small fraction (10%) of drivers accounted for most of the drowsiness observed due to sleep deprivation (Mitler, Miller, Lipsitz, Walsh, & Wylie, 1997). Ingre, Åkerstedt, Peters, Anund, and Kecklund (2006) observed that initial individual differences in driving performance surpassed the effects of different levels of subjective fatigue. Large individual differences in how subjective sleepiness affected performance and blink durations were also observed, with uniformity only noticeable at the highest levels of subjective sleepiness. The causes and mechanisms for these differences are incompletely understood; however, several factors were shown to be associated with both experiencing fatigue and performance change due to fatigue.

Nutritional balance and physical and mental health can explain differences in experiencing fatigue (Lal & Craig, 2001a). Personality traits such as an extroverted personality, a tension-prone personality and negative mood states were associated with increases in fatigue measured jointly with subjective and physiological measures (Wijesuriya, Tran, & Craig, 2007). Time-on-task and environmental effects can both be altered by personality. The same task can be too stimulating and stressful for some individuals and understimulating for others, causing fatigue in both cases but for different reasons. Drivers with high extraversion and sensation-seeking traits were shown to be more at risk of falling asleep and experiencing boredom-induced fatigue in monotonous driving conditions (Thiffault & Bergeron, 2003a).

Experience and expertise can also influence individual susceptibility to fatigue. Due to shift work, many professional drivers spend long hours behind the wheel and are exposed to both night driving and driving with insufficient sleep. Although it would be intuitive to assume that professional drivers are more resilient to the effects of fatigue due to more exposure and automated processes, the reality is more complex.

In the absence of external time pressure, professional drivers can adapt to their driving environment. Professional cab drivers were shown to exhibit only moderate signs of subjective sleepiness and performance reduction during night work (Corfitsen, 1993). Experience can also improve driving performance under the influence of sleep deprivation when engaged in additional tasks (Lenné, Triggs, & Redman, 1998). However, research has also indicated coping-level differences between professional drivers in relation to stressful long-distance drives (Desmond & Matthews, 2009). The start of the long-distance drive might itself initiate a stress reaction in professional drivers. Larger discrepancies between subjective fatigue and performance were also observed in professional drivers in a simulation study (Anund, Ahlström, Fors, & Åkerstedt, 2018). Assuming ecological validity, this would indicate that professional drivers might be less aware of their fatigue levels and performance reduction caused by their state.

1.3 Measuring fatigue

Fatigue can cause changes in subjective feelings, observable behaviour, physiological functioning and performance (Phillips, 2015). Fatigue measures rely on operationalising these changes and can be similarly divided into four categories: subjective self-assessment, observation-based evaluation, physiological and biological measures and cognitive performance measures. Some of these measures have uses beyond research and can be used as a part of fatigue detection heuristics in fatigue countermeasures.

Self-assessment relies on the person’s subjective self-awareness and the ability to describe it accurately. Several validated forms have been developed to rate the levels and components of fatigue for different purposes. Traffic research usually focuses on measuring the level of fatigue rather than nuances of different fatigue traits. Specifically, the emphasis is on situational and acute sleep-related fatigue. The Epworth Sleepiness Scale (Johns, 1991) is an eight-item measure used to assess daytime sleepiness. Its questions are structured to assess the likelihood of falling asleep in different daily situations. Thus, it seeks to provide objective information about the sleep propensity of individuals rather than the subjective sensation of sleepiness. It can be used both in a clinical setting and in traffic research and has been shown to correlate with the likelihood of falling asleep while driving (Maycock, 1996, 1997). Simpler visual analogue scales (Monk, 1989) or single-item Likert scales are likely to be used when assessing acute sleepiness. The Karolinska Sleepiness Scale (KSS; Åkerstedt & Gillberg, 1990) is a simple nine-point (1–9 with higher values indicating increased sleepiness) scale used to rate the acute feeling of sleepiness. It is useful in evaluating the magnitude rather than the quality of change. It has been validated against physiological measures and shown to correlate well with changes in the power of alpha and theta frequency ranges in electroencephalography (EEG) associated with the onset of sleep (Kaida et al., 2006).

The value of self-assessment is that it alone can capture the subjective dimension of fatigue. Its weaknesses also relate to its subjectivity. Individuals and different subgroups may experience fatigue differently and may be prone to habituation (Anund et al., 2018). This complicates evaluation of performance loss based on self-assessment of fatigue. Experiments using subjective assessment and performance measures also showed the tendency of subjective self-assessment measures to saturate rapidly, potentially leading to loss of precision (Nilsson et al., 1997).

In observation-based techniques, fatigue-related symptoms are evaluated by observers, either on site in real time or after the experiment, using video footage of the test participant and the driving session (Belyavin & Wright, 1987; Oron-Gilad & Ronen, 2007). Facial gestures, body movements and posture are the key components of the evaluation, although driving performance can also be evaluated (Anund, Fors, Hallvig, Åkerstedt, & Kecklund, 2013). The observers usually seek behaviour associated with falling asleep, such as head nodding, yawning and eyelid closure. Multiple raters and a standardised checklist of symptoms can be used to increase the reliability of the evaluation. Observation provides a potentially more objective study of fatigue than self-assessment; however, its accuracy ultimately depends on the expertise of the raters and their subjective ability to identify the correct symptoms. Observer-based fatigue measures were shown to exhibit good inter-rater and intra-rater reliability and consistency (Wierwille & Ellsworth, 1994) and moderate association with self-reported sleepiness and blink durations (Anund et al., 2013).

However, with the advent of more precise physiological measures, observation can be largely automated, eliminating the question of rater reliability.

Physiological methods rely on measuring changes in one or several physiological responses associated with fatigue. Most of these changes are more specifically related to sleepiness or sleep onset. Among physiological measures, EEG has been most prominently researched and used. The approach using EEG to measure fatigue has been to observe changes in the common wave band frequencies found in brain activity, either in the active state or during the transitional state of sleep onset (Lal & Craig, 2001b; Lal & Craig, 2002). The changes are brain region and band-dependent; however, they approximately follow a pattern where reduced cognitive activity is associated with low-frequency waves increasing and high-frequency ones decreasing in amplitude. Four brain-wave groups are commonly compared. The measures can be formed by comparing the ratios, fluctuations, amplitudes or distributions of these different wave patterns. The appearance of low-frequency delta waves (0.5–4 Hz) has been shown to correlate with sleep onset and theta waves (4–7 Hz) with decreased information processing, while alpha waves (8–13 Hz) start to disappear on sleep onset. With the onset of sleep, the alpha rhythm may fluctuate for a while before disappearing. Additionally, an increase in beta waves (13–30 Hz) is related to increased alertness and arousal.

Several aspects of endogenous eye movements have also been associated with fatigue. Sleepiness and time-on-task effects were related to an increase in blink duration (Stern, Walrath, & Goldstein, 1984). The PERCLOS, which is defined as the percentage of the time that the eyelids cover 80% or more of the pupil area, is a common measure of sleepiness used in fatigue detection and countermeasure studies (Wierwille, Wreggit, Kirn, Ellsworth, & Fairbanks, 1994; Sommer & Golz, 2010). The blink frequency and spread of fixations are also affected. Fatigue due to time-on-task effects causes the number of blinks to increase and fixations to become more centrally concentrated (Stern, Boyer, & Schroeder, 1994; Rogé, Pébayle, El Hannachi, & Muzet, 2003). These eye movement patterns were shown to precede changes in alpha wave frequency and amplitude (Santamaria & Chiappa, 1987). Eye movements can be monitored and measured with video-based eye trackers or electro-oculography (EOG); EOG provides higher accuracy but is more intrusive. Therefore, video-based eye tracking is preferred in fatigue detection systems (Sommer & Golz, 2010; Trutschel, Sirois, Sommer, Golz, & Edwards, 2011).

Because of their perceived objectivity, physiological measures are commonly used to validate other measures. A disadvantage of these methods is their potential intrusiveness. This can be problematic in complex experimental setups where inclusion of the measurement equipment is impossible or could affect the ecological validity of the results.

Finally, fatigue can also be measured by changes in task-related performance. Common variables used for driving performance include reaction time, errors of omission, lane position variability, line crossings, steering wheel movements, speeding and crashes (George, 2003). Reaction times and errors of omission serve as proxies for vigilance (Basner & Dinges, 2011), and they can be measured outside driving scenarios. Psychomotor vigilance task (Dinges & Powell, 1985) is widely used for this purpose. Lane-keeping ability measured by the number of lane crossings and standard deviation of lateral position also serve as indicators of vigilance but with more ecological validity. The amplitude and velocity of corrective steering wheel movements include a vigilance component and the ability to execute fine motor movements. The variation in multiple measures, including velocity and amplitude of steering wheel movements, can be used to indicate how pre-planned the driving task is.

Measuring fatigue with performance assumes that fatigue decreases performance and that the observed decrease can be attributed to fatigue. Because impaired performance is also used to define fatigue, this could lead to circular reasoning where the definition confirms that performance loss is due to fatigue and performance loss validates the performance-based definition of fatigue. Thus, the use of other fatigue metrics in tandem is advisable.

1.4 Fatigue and driving performance

Both driving performance and behaviour are altered by fatigue. How these changes translate to accident risk is task-dependent. A performance decrease in certain subtasks can prove to be more dangerous than in others. Differences also exist in the vulnerability of drivers to different types of fatigue-inducing mechanisms. Depending on the conditions, it could take tens of minutes to multiple hours for time-on-task effects to show in the basic performance of rested individuals (Reyner & Horne, 1998; Philip et al., 2005; Saxby et al., 2008). In already tired individuals, the performance might be compromised from the start.

Fatigue leads to a general reduction in vigilance. If attention cannot be sustained, the result is delayed or completely missing reactions to events. Both sleepiness and time-on-task effects were shown to increase attention lapses and brief episodes of unconsciousness known as microsleeps (Dinges, Mallis, Maislin, & Powell, 1998). These lead to increased reaction times (Dinges &

Mallis, 1998) and errors of omission (Doran et al., 2001; Belenky et al., 2003). In driving tasks, these difficulties materialise in lane-keeping difficulties. Tired drivers show more line crossings and higher standard deviation of the lateral position (Pizza, Contardi, Mostacci, Mondini, & Cirignotta, 2004; Åkerstedt et al., 2010). Increased weaving on the road is dangerous because it can increase the risk of head-on collisions and drifting off the road. Similar difficulties in lane-keeping can be observed in drunk drivers (van Dijken et al., 2020).

When reactions are delayed, the subsequent actions can be more rushed and dangerous. Fatigued drivers use larger corrective steering wheel movements to adjust the vehicle position (Thiffault & Bergeron, 2003b). This can be at least partially explained by delayed actions and lane-keeping difficulties, as higher deviation from the proper position would require larger and faster corrective steering wheel movements. Higher amplitude and velocity of steering wheel movements can be dangerous as they increase the risk of sideways skidding and loss of control of the vehicle. If the velocity of a vehicle remains constant, an increase in steering wheel turning angle increases the wheel slip rate, which is the angular difference between the direction that a vehicle is travelling in and the direction in which the wheel is pointing (Gillespie, 1992). When the slip rate exceeds a certain limit, the friction between the tyres and the road surface can no longer counter the lateral acceleration, and tyres start to lose their grip and are successively thrown into skidding motion.

The perception of the surrounding environment is also affected. Tired drivers were less aware of the traffic signs and markings, future road profile and traffic around them (Drory & Shinar, 1982). This can lead to a reactive driving style characterised by less pre-planning and scanning for potential dangers. In addition to higher variability of lateral positioning and larger amplitudes of steering wheel movements, fatigue has also been associated with higher variability in steering wheel movement amplitudes (Thiffault & Bergeron, 2003b).

Behavioural changes can also both reduce and increase accident risk. If fatigue is accompanied by a subjective sensation of increased risk, drivers act to mitigate that risk. Safety margins were shown to increase with the subjective sensation of fatigue when there was no time or other external pressure to act otherwise (van der Hulst, Meijman, & Rothengatter, 2001). The effect of fatigue on driving speed is more ambiguous. Subjective and objective sleepiness has been associated with higher speeds and more speeding (Balkin et al., 2000; de Waard & Brookhuis, 1997; Pizza et al., 2004; Oron-Gilad & Ronen, 2007). This behaviour is questionable from the perspective of risk perception. Partially due to safety reasons, most of the studies on fatigue are performed in driving simulators. This might influence how participants experience risk, and people were found to drive faster in simulator environments in general (Kaptein, Theeuwes, & van der Horst, 1996). However, evidence also exists that some drivers use higher speed as a sleepiness countermeasure (Anund, Kecklund, Peters, & Åkerstedt, 2008).

1.5 Driving environment and fatigue

Environmental factors influence how difficult and stimulating a driving task is. A change in the environment can alter the exposure to different types of fatigue or affect how drivers cope with fatigue. More stimulating driving conditions can break the monotony of the basic driving task and thus reduce passive task-related fatigue. Too much increase in stimuli and task demand can add cognitive load and lead to stress. This can exhaust drivers by increasing active task-related fatigue over time. A demanding driving environment can also influence fatigue coping strategies. Motivation is an important factor in sustaining an action and is reduced in many domains in the fatigued state. It was suggested that fatigued people intentionally choose less effort-demanding forms of action (Craig & Cooper, 1992; Hockey, 1997). When resources are limited, people prioritise and economise tasks. Performance in less central tasks can deteriorate in the early stages of fatigue; however, more important tasks, such as hazard avoidance, remain intact for much longer (van der Hulst et al., 2001). Therefore, fatigue-induced performance loss can also be explained by economisation. If the driving task is more demanding or dangerous, it might force the driver to direct more cognitive resources to tasks that would otherwise require less attention.

Road curvature has been associated with better driving performance in a fatigued state due to changes in coping strategies. Desmond and Matthews (Desmond & Matthews, 1997; Matthews & Desmond, 2002) compared driving performance on straight and curvy roads. They found that driving on straight road segments increased heading error over time when their subjects were first exposed to a fatigue-inducing subtask. No similar effect was observed on curvy roads or when drivers were not tired. Additionally, the performance of tired drivers on straight roads improved when they were prompted to try their best, which led the authors to conclude that a fatigued state hinders the allocation of resources to the driving task when the task appears easy and no external pressure exists to motivate the drivers. Oron-Gilad and Ronen (2007) studied the differences between curvy, straight and mixed road types in well-rested drivers. They found that driving on straight road segments in the mixed road setting increased the standard deviation of the lane position and the standard deviation of the steering wheel movement amplitudes and delayed responses to changes in lane markings. No similar changes were observed on curvy road segments, although subjective and objective fatigue measures increased over time during the whole driving session. The results indicate that the more stable performance on curvy roads might be partially due to task demand. Curvy roads may not allow similar deviation from baseline performance, and drivers may be unable to use economisation-based coping strategies to the same extent to combat fatigue.

Other aspects of the driving environments, beyond the road profile, also influence fatigue. Saxby et al. (2008) studied the effects of task demand on subjective fatigue and performance by comparing passive, active and control driving tasks. They found that adding random lateral and vertical wind gusts to a pre-evaluation driving task kept drivers more vigilant and kept their reaction times to braking and steering events shorter than in passive or control conditions. The passive condition, involving only a monitoring task before performance evaluation, had the longest reaction times and reduced long-term task engagement. Although increasing task demand increased the perceived mental workload, the effect on performance was positive.

Barr et al. (2005) studied fatigue in short-haul truck drivers based on video footage. The results indicated that higher traffic volumes, driving in an urban environment and poor visibility were all associated with reduced PERCLOS (time that eyes are closed or nearly closed). All these measures, except for traffic density, were also positively related to reduced eye movements and fewer off-road fixations during driving. This would indicate that environmental factors that increase task demand can motivate the driver to devote more attention to the driving task.

Thiffault and Bergeron (2003b) researched the effect of roadside scenery on driver fatigue on a monotonous road profile. They found that repetitive roadside scenery increased the frequency of high-amplitude steering wheel movements in drivers. Tentative evidence also indicated that the time-on-task effect was higher in the monotonous scenery task. These performance differences might also be personality-dependent, as they found that sensation-seeking individuals had higher standard deviation of steering wheel movements in monotonous scenery (Thiffault & Bergeron, 2003a).

1.6 Research question and hypotheses

Most of the research on driving environment and fatigue has targeted the detrimental effects of task monotony on fatigue and driving performance. Lack of challenge in the driving task can lead to both passive task-related fatigue and economisation of driving subtasks in tired drivers. Increasing the challenge of the driving task can reduce these effects; however, too challenging driving conditions could cause cognitive overload, which can become a source of active task-related fatigue. Attention lapses and rushed reactions due to fatigue can also be more dangerous when driving conditions are compromised.

The current study seeks to clarify the relationship between the driving environment and driver state by researching how driving on slippery roads affects both the performance and sleepiness of drivers during a night drive. Both short and long-term effects are of interest. The key hypotheses can be summarised as

1) Driving on slippery roads raises the alertness of drivers who are otherwise sleep-deprived, increasing their performance and reducing sleepiness. This would indicate an interaction between road condition and time of day.
2) Driving on slippery roads also increases the cognitive load experienced by drivers. Over time, this exhausts drivers who are sleep-deprived and have fewer cognitive resources to spare. Sleepiness increases and performance decreases faster over time in subjects who are already tired. This would indicate a three-way interaction between road condition, time of day and time-on-task.

2. Method

A two-by-two counterbalanced within-subject experiment was performed using an advanced simulator (Sim III) at the Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden. The effects of fatigue were studied by manipulating participants' initial sleepiness with the time of day (day vs night driving) and task demand with road conditions (dry vs slippery). Additionally, time-on-task effects were studied by dividing the driving session into seven equal length segments.

2.1 Simulator

The driving simulator at VTI is one of the most advanced simulators in the world. Its moving base allows drivers to experience acceleration, deceleration and centrifugal forces. Ecological validity is further enhanced by the cabin design, which includes the front part of a Saab 9-3 with a manual 5-shift gearbox and simulates the noise and vibration levels normally experienced inside a real car. The front view was 120° × 30°. Based on experience in using simulators for modelling different driving scenarios in previous studies (Markkula, Benderius, Wolff, & Wahde, 2013) we selected a friction coefficient of 0.24 μ for the slippery road condition and 0.98 μ for the dry road condition. These values were tested in the pilot testing and were retained for the experiment.

2.2 Participants

Twelve young (age range 19–21) male volunteers were recruited for the study from VTI's registry of test subjects. Inclusion criteria were no physical, mental health or sleep problems; no shift work within three months before the experiment; no use of medication; non-smoking; body mass index below 25 and holding a driver's licence. Each volunteer received SEK 3,000 (~€300) for participation in the study.

2.3 Driving scenario

The scenario was a two-lane rural road with occasional curves and other oncoming traffic that made the situation more realistic but was not intrusive. Both dry and slippery road conditions resembled winter daylight conditions with a small amount of fog. The only visual difference between these two conditions was slightly more white traces on the surface in the slippery road condition to increase the ecological validity (Figure 2). The road used in the simulator was built from two segments totalling 10 km in length. At the end, the road geometry unnoticeably looped back to the beginning. This meant that participants drove through the same sections multiple times during the experiment.

	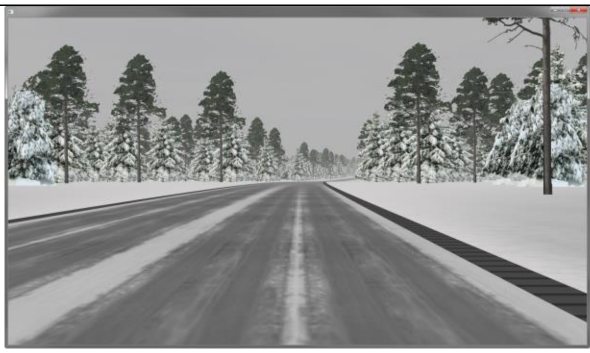
Dry	Slippery

Figure 2. View from the driving simulator in the two road conditions.

2.4 Protocol

During the initial telephone interview, the participants were requested to abstain from alcohol for 72 h before the test days and from smoking and coffee 3 h before arrival at the laboratory. For the night session, they were brought to the laboratory and taken home by taxi. On the first testing day, they were briefed about the procedures and signed a consent form. Before the experiment, the participants had a 10-minute practice drive in the simulator. Each participant came twice to the laboratory (day and night testing) and drove for two sessions (dry and slippery road conditions) on each testing day. The order of conditions was counterbalanced. During each testing day, two participants were tested in the following order: Participant A started his first drive at 9:00 and his second around 11:00, while participant B started his first drive around 10:00 and his second drive around 12:00. During the night session, starting times were around 03:00 and 05:00 for one participant and around 04:00 and 06:00 for the other. During the break between sessions, the participants spent time in a local cafeteria and were offered a sandwich and red tea, decaffeinated coffee or water. Participants were instructed to follow the speed limit of 90 km/h. It was initially planned that each participant would drive for 35 minutes, split into seven five-minute segments. Due to a miscommunication, this was changed so that each participant drove for 52.5 km, split into seven segments of 7.5 km. Consequently, the total driving time varied between the participants. At the end of each driving session, the participants negotiated a cone track by weaving between five cones positioned in the middle of the road at 50 m intervals.

2.5 Measurements and variables

Fatigue symptoms were evaluated using a self-assessment scale, psychophysiological measures and performance-related measures. Subjective sleepiness was assessed with the KSS. A text was projected on the windshield at the end of each of the 7.5 km segments asking the participants for their sleepiness rating. Physiological data (EEG and EOG) were recorded using a Vitaport III system (Temec Instruments BV, Kerkrade, Netherlands). The EEG data are not presented here. Six electrodes were used to record the EOG. Four electrodes were placed vertically (above and below the left and right eye) and two horizontally (at the outside corner of each eye). The EOG was direct current (DC) recorded at a sampling rate of 512 Hz. A small portion of the EOG data was lost due to technical problems during the experiment. Blink durations (Blink) were extracted from EOG data using a MATLAB program developed by the Centre for Applied and Environmental Physiology (Dr A Muzet & Thierry Pebayle, CEPA, Strasbourg, France). It essentially involves a lowpass filter to establish a stable baseline for the signal, establishing a threshold that must be exceeded to score a blink with computation of the start and end points of the blink based on the slope and computation of blink duration performed at mid-slope. To reduce problems with concurrent eye movements and eye blinks, blink durations were calculated as half the amplitude of the upswing and downswing of each blink, and then the time elapsed between the two was computed.

The telemetry of the car and its position on the track was recorded at 20 ms intervals. In total, three measures of driving performance were calculated based on this data for each of the 7.5 km segments. The standard deviation of the lateral position on the track (SDLP) was used to indicate the drivers' ability to keep the car on the correct path. This was calculated from interpolated samples at 1 m intervals on the track. The mean steering wheel movement amplitudes (Stw amplitude) and mean steering wheel movement peak velocities (Stw velocity) were the two other measures used to model the smoothness of the steering actions. These were calculated by identifying steering wheel movements and then calculating the total change (amplitude) and the peak velocity of the change during each of the events before averaging the statistics for each segment. Smaller steering wheel turns of less than 0.5° were labelled as unintentional jitter and filtered out during the calculations.

The number of cone hits at the end of each driving session was calculated from the cone track data. The overall number of cone hits was minimal, and the variability between the sessions was small, which caused difficulty in fitting the statistical model for significance testing. Because of this, a dichotomous variable indicating whether any of the cones were hit during the driving session was used, rather than the total number, to analyse the cone track performance.

2.6 Statistical analysis

The data were analysed with mixed-effects multilevel models; ordinal logistic regression was used for the KSS, linear regression for blink durations and performance measures and logistic regression for cone hit data. All the analyses were performed in R version 3.6.3. A cumulative link mixed model (clmm) function from the package ordinal was used for ordinal regression. Functions lmer and glmer from the package lme4 were used for linear regression and logistic regression. The models were built stepwise by adding intercepts and slopes to the random effects part of the model. The increase in model fit was evaluated with a log-likelihood criterion, and the model with the best fit and a sensible theoretical interpretation was selected. Log-transformations were performed for all the continuous dependent variables to reduce skewness. Time variables were global mean centred to reduce multicollinearity. For significance testing, the Wald test (z-score) was used for the ordinal and logistic regression model estimates and the F-test with the Satterthwaite approximation for degrees of freedom for the linear regression model estimates. Nakagawa's pseudo R^2 were also calculated to estimate model fits (Nakagawa, Johnson, & Schielzeth, 2017).

3. Results

The analysis results are summarised in Tables 1, 2 and 3. Subjective sleepiness (KSS) was higher during the night ($z = 5.60$, $p < .001$) and increased over time ($z = 8.77$, $p < .001$) (Table 1). A three-way statistically significant interaction was also found between time of day, road condition and time-on-task ($z = 2.50$, $p = .012$), suggesting that sleepiness increased more when participants were already tired and the conditions were demanding. The interaction between time of day and time-on-task was close to statistical significance ($z = -1.86$, $p = .063$). Blink durations also increased over time but at a progressively slower pace with time-on-task [$F(1,34.27) = 8.78$, $p = .005$] and time-on-task squared [$F(1,287.40) = 8.83$, $p = .003$] both reaching statistical significance (Table 2). The interaction between time of day and road condition was also statistically significant [$F(1,280.07) = 4.25$, $p = .040$]. Participants had longer blink durations when sleep-deprived and driving in demanding conditions.

Table 1. Ordinal mixed-effects regression model summary for the KSS, including fixed-effects log-odds estimates, threshold log-odds estimates and 95% confidence intervals. Time-on-task is represented in hours and is global mean centred.

KSS			
Fixed effects		**Thresholds**	
Predictor	*Estimate*	*Threshold*	*Estimate*
Time of day (Night)	**6.39** *** **(4.15 – 8.62)**	2|3	**−12.94** *** **(−17.23 – −8.65)**
Road condition (Slippery)	0.34 (−1.48 – 2.16)	3|4	**−5.10** *** **(−7.96 – −2.25)**
Time-on-task	**16.60** *** **(12.89 – 20.31)**	4|5	−2.21 (−4.95 – 0.52)
Time of day (Night) × Road condition (Slippery)	−0.22 (−1.19 – 0.74)	5|6	0.36 (−2.35 – 3.07)
Time of day (Night) × Time-on-task	−4.11 (−8.43 – 0.22)	6|7	2.67 (−0.06 – 5.40)
Road condition (Slippery) × Time-on-task	−3.20 (−7.31 – 0.91)	7|8	**5.18** *** **(2.40 – 7.96)**
Time of day (Night) × Road condition (Slippery) × Time-on-task	**7.46** * **(1.61 – 13.32)**	8|9	**8.26** *** **(5.38 – 11.14)**
N	12 subject		
Observations	336		
Marginal R^2 / Conditional R^2	0.46 / 0.91		

* $p < .05$ ** $p < .01$ *** $p < .001$

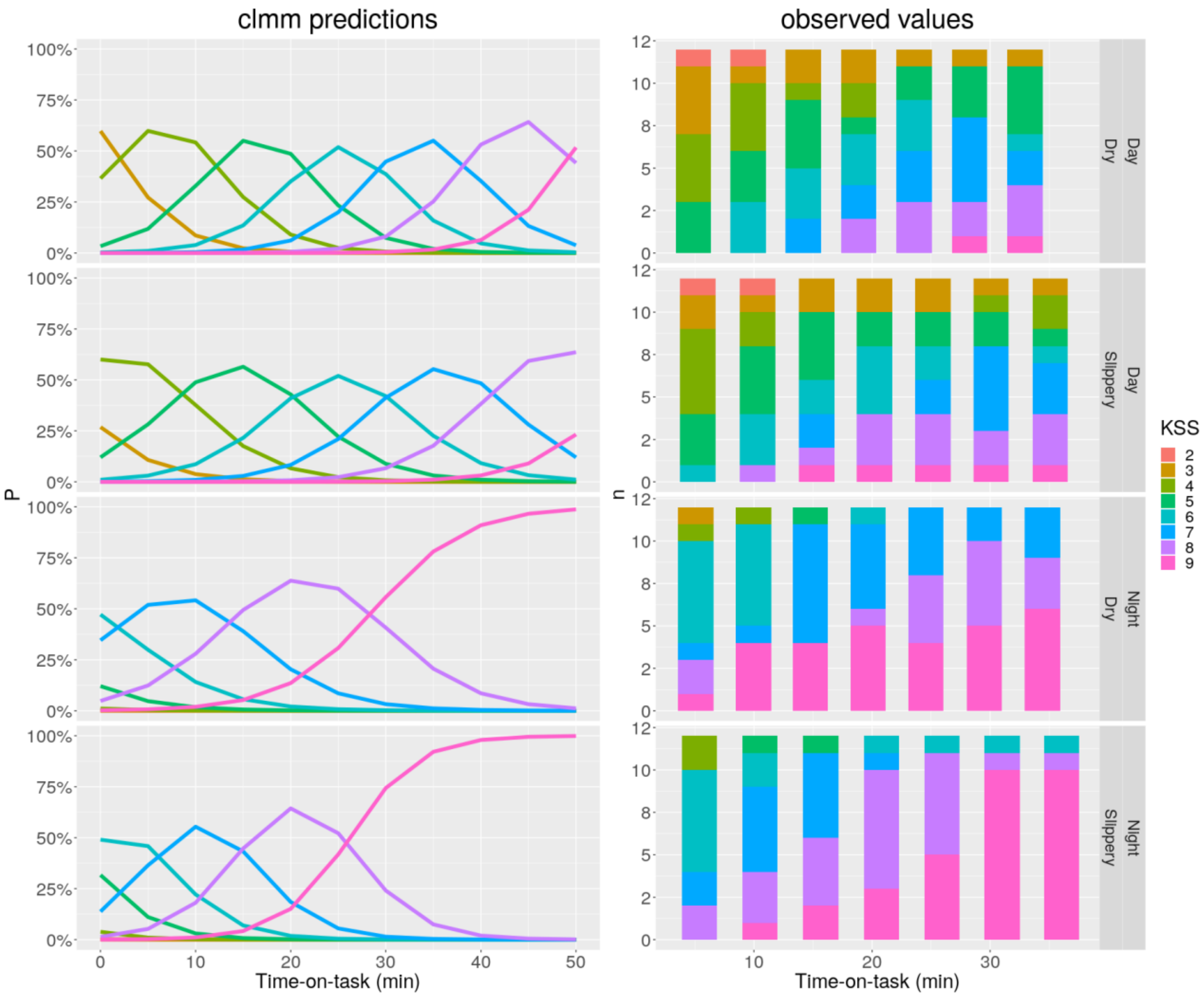

Figure 3. Probabilities of KSS scores based on clmm fixed-effects estimates (left) and frequencies of KSS scores observed in the trials (right) placed at the average end time points of each of the 7.5 km segments.

Predictions based on clmm estimates and observed KSS scores are visualised in Figure 3. The effect of the time of day on sleepiness is apparent from the figure: at night, KSS scores start at a higher level and reach higher values by the end of the trials. Visual inspection also supports the three-way interaction effect between the time of day, road condition and time-on-task: the effect of time on sleepiness is elevated when driving at night in slippery conditions. Most (10/12) of the test participants reached the maximum sleepiness score of 9 by the end of these trials. No KSS values of 1 (“Extremely alert”) are shown in the figure as none of the participants used that value. The predicted probabilities of each of the score categories follow the observed scores adequately, indicating a good model fit. This is also confirmed when inspecting the pseudo R^2 values in Table 1.

Table 2. Model summaries for linear mixed-effects models. Variable estimates and 95% confidence intervals are included. Dependent variables are log-transformed; time-on-task is represented in hours and is global mean centred.

	Blink	**SDLP**	**Stw amplitude**	**Stw velocity**
(Intercept)	**−1.97 ***** **(−2.12 – −1.82)**	**−1.78 ***** **(−1.93 – −1.63)**	**0.28 **** **(0.15 – 0.41)**	**2.20 ***** **(2.05 – 2.36)**
Time of day (Night)	0.07 (−0.04 – 0.18)	0.18 (−0.02 – 0.39)	0.09 (−0.05 – 0.23)	0.04 (−0.08 – 0.16)
Road condition (Slippery)	−0.03 (−0.10 – 0.05)	−0.03 (−0.23 – 0.17)	0.04 (−0.07 – 0.14)	−0.01 (−0.12 – 0.09)
Time-on-task	**0.28 **** **(0.10 – 0.47)**	**0.51 *** **(0.08 – 0.93)**	0.11 (−0.13 – 0.34)	0.10 (−0.12 – 0.31)
Time-on-task^2	**−0.70 **** **(−1.16 – −0.24)**	−0.35 (−1.29 – 0.58)	**0.72 **** **(0.24 – 1.19)**	0.29 (−0.17 – 0.75)
Time of day (Night) × Road condition (Slippery)	**0.05 *** **(0.00 – 0.10)**	**−0.11 *** **(−0.21 – −0.02)**	**−0.07 **** **(−0.11 – −0.02)**	**−0.07 **** **(−0.12 – −0.03)**
Time of day (Night) × Time-on-task	0.02 (−0.19 – 0.23)	0.24 (−0.18 – 0.66)	**0.23 *** **(0.02 – 0.44)**	**0.31 **** **(0.11 – 0.51)**
Road condition (Slippery) × Time-on-task	0.03 (−0.17 – 0.23)	0.01 (−0.41 – 0.43)	0.03 (−0.18 – 0.24)	0.08 (−0.12 – 0.28)
Time of day (Night) × Road condition (Slippery) × Time-on-task	0.12 (−0.16 – 0.40)	0.37 (−0.20 – 0.95)	0.07 (−0.22 – 0.35)	−0.17 (−0.45 – 0.11)
N	12_{subject}	12_{subject}	12_{subject}	12_{subject}
Observations	329	336	336	336
Marginal R^2 / Conditional R^2	0.07 / 0.86	0.13 / 0.73	0.07 / 0.82	0.05 / 0.83

* $p < .05$ ** $p < .01$ *** $p < .001$

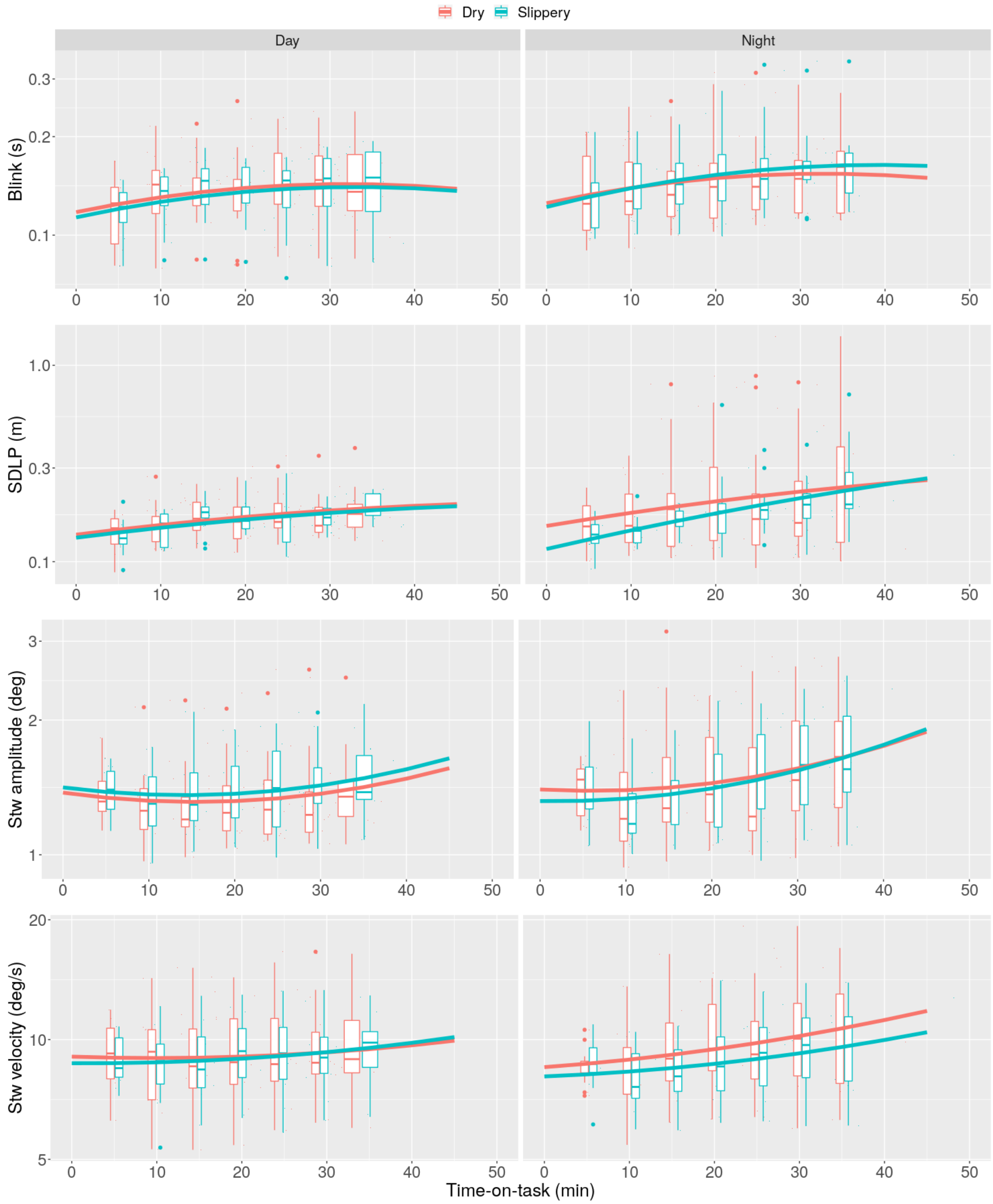

Figure 4. Model predictions based on the estimated fixed effects plotted over box plots of the original data. Box plots are located at the average end time points of each of the 7.5 km measurement segments. Note that y-axes are log-scaled to reduce skewness and improve readability.

The interaction between time of day and road condition was statistically significant and unidirectionally positive over all the three performance indicators: SDLP [$F(1,282.95) = 5.11$, $p = .025$], Stw amplitude [$F(1,282.72) = 7.19$, $p = .008$] and Stw velocity [$F(1,282.81) = 9.47$, $p = .002$]. Additionally, the interaction between road condition and time-on-task had a positive and significant effect on the Stw amplitude [$F(1,283.06) = 4.42$, $p = .033$] and Stw velocity [$F(1,283.37) = 9.04$, $p = .003$]. Participants generally performed better when their initial fatigue was combined with demanding conditions; however, their performance in steering decreased over time when they started in a fatigued state.

Time-on-task had a positive significant effect on the standard deviation of the lateral position [$F(1,27.14) = 5.51$, $p = .026$] and time-on-task squared on the steering wheel movement amplitude [$F(1,293.29) = 8.78$, $p = .003$]. The three-way interaction between time of day, road condition and time-on-task, and the main effects of time of day and road condition, did not approach significance in any of the performance indicators.

Model predictions based on fixed-effects estimates are visualised against the real data points in Figure 4 and can assist in interpreting the results. The figure shows how blink durations increase over time before reaching a saturation point at around 35 minutes. The time-variant growth curve of the SDLP appears to be visually steeper in nighttime slippery conditions, but this fails to reach statistical significance. The steering wheel manipulation performance follows a parabolic curve with accelerated growth over time. Large individual differences between subjects are observed in the wide spread of the box plots.

Table 3. The number of driving sessions where at least one cone was hit, cross-tabulated by road condition and time of day. The total number of cone hits is included in parentheses.

		Time of day		
		Day	Night	Total
Road condition	Dry	1/12 (2)	0/12 (0)	1/24 (2)
	Slippery	2/12 (2)	3/12 (4)	5/24 (6)
Total		3/24 (4)	3/24 (4)	6/48 (8)

The number of driving sessions where cones were hit and the total number of cone hits are summarised in Table 3. The road condition was the only significant predictor of cone track performance ($z = 2.048$, $p = .041$). Most of the runs where cones were hit were driven on a slippery road. The distribution of the total number of cone hits is consistent with the number of driving sessions where cones were hit.

4. Discussion

The results from the present experiment are mixed. Partial support was found for both hypotheses. The first hypothesis, stating that increasing task demand improves performance and reduces signs of subjective and objective fatigue, was confirmed in performance only. Sleep-deprived subjects had smaller changes in lateral positioning and smaller and smoother steering wheel movements when driving in slippery conditions. This change was not observed for either subjective sleepiness or blink durations. Contrary to the hypothesis, blink durations increased instead of decreasing. Additionally, although subjective sleepiness increased over time, driving on a slippery road did not compensate for this effect. If the accumulation of subjective and physiological sleepiness had slowed due to more demanding driving conditions, this would have indicated a reduction in passive task-related fatigue. Because this did not occur, it is more likely that improved performance is due to motivation-related mechanisms. Drivers were forced to change their coping strategies and pay more attention to both lane positioning and steering wheel manipulations because of the increased difficulty of driving and dangers involved. This behavioural explanation is further supported by the time of day having no significant main effect on the driving performance. Thus, sleep-deprived participants performed better in demanding conditions even though their base performance level was not impaired due to sleepiness.

Partial support was also found for the second hypothesis, stating that the performance of sleepy drivers deteriorates and sleepiness increases over time when driving in slippery conditions. Here, the effect appeared in self-reported sleepiness only. The three-way effect was not significant in physiological or performance-related measures. Steering wheel manipulations became more sudden and larger over time when subjects were already sleepy; however, this change did not increase with task difficulty. Based on previous research and because by the end of the slippery trials, 10 out of 12 sleep-deprived subjects had reached maximum subjective sleepiness, it is slightly unexpected that increasing task difficulty did not negatively affect driver performance. The most likely explanation is linked to the driving time. Participants took 25–46 minutes to complete the 52.5 km trip. Further analysis revealed that although driving speed decreased and driving time increased both in slippery and nighttime conditions, the exposure time might still have been too short. Previous research has shown that well-rested drivers can drive for several hours before signs of performance impairment are observed (Reyner & Horne, 1998; Philip et al., 2005). Even if the change is faster in already tired individuals, lane-keeping and steering wheel manipulation are basic tasks that might be more resilient to performance loss. Moreover, although self-assessment of fatigue has been shown to correlate with performance, it was shown to saturate well before a decrease in performance was observed (Nilsson et al., 1997). It is therefore plausible that a significant three-way interaction would have appeared if the driving sessions had been longer.

These results are consistent with previous research on the subject, showing that increased driving task demand can improve performance in tired drivers (Desmond & Matthews, 1997; Matthews & Desmond, 2002; Oron-Gilad & Ronen, 2007; Saxby et al., 2008). A change in driving demand does not necessarily have to originate from the main task; it can also be imposed artificially through additional tasks. Secondary tasks have been used to increase alertness and task engagement and improve performance when the main task is monotonous (Atchley & Chan, 2011; Neubauer, Matthews, & Saxby, 2014). Tasks and games that rely on sensory modalities other than vision to stimulate the driver have also been proposed as alertness-maintaining fatigue countermeasures during long driving sessions (Oron-Gilad, Ronen, & Shinar, 2008; Verwey & Zaidel, 1999). Altering task demand is ultimately a balancing act. Large cognitive loads were associated with increased fatigue, reduced secondary task engagement and degraded performance in the main task (Head & Helton, 2014). Results from the current study show that although the advantage that these secondary task countermeasures could provide are most prominent in situations where drivers are tired, the danger of adverse effects is also highest in similar circumstances.

In addition to providing support for the main hypotheses, the results also revealed large individual variability in response to changes in fatigue and task demand. Similar effects were previously reported in similar research settings (Ingre et al., 2006); however, the impact of these factors on performance was surprisingly large considering that the participants in the current study formed a relatively homogenous group of young males aged 19–21. The model fit statistics reveal that while fixed-effects coefficient estimates could model the subjective sleepiness relatively well, the marginal R^2 values for performance-related variables are low. This indicates that the fixed effects poorly explain the variability in performance. If this is compared with high conditional R^2 values, indicating total model fit, most of the variability is in individual differences. Huge differences in individual responses to the experimental conditions are also apparent from the box plots in Figure 4. Clearly, unexplained, potentially internal factors exist, influencing both the baseline driving performance and how individuals react to changes in fatigue levels and road conditions. These factors were not captured by this study design.

4.1 Limitations of the current study

Several factors could have influenced the results from the current study, and these should be considered before drawing conclusions. Most obviously, the driving time was limited to a short duration, not allowing proper observation of long-term consequences of increased fatigue levels. Additionally, due to miscommunication during the planning of the experiment and the subsequent standardisation of the driving distance rather than the time, different participants drove for different durations. This enabled the participants to adjust the total exposure time and could have caused differences in fatigue coping strategies. Some participants may have chosen to rush to the finish, while others decelerated to reduce the cognitive load. Consequently, the time driven varied widely between subjects and conditions. The experiment was not designed to research differences in individual coping strategies that might have been lost in variation between individuals.

Secondly, although the standard deviation of lateral position and steering wheel movement amplitudes are commonly used as driving performance metrics, they offer only limited information on the link between fatigue and accident risk. Most importantly, they do not indicate when the change in performance is sufficiently large to have clear safety implications. Generally, higher amplitudes and velocities of steering wheel movements lead to higher slip angles; however, it is difficult to determine when this angle becomes sufficiently high to cause risk of sideways skidding. This threshold ultimately depends on many factors. Among these are the distribution of weight in the vehicle, road friction coefficient and tyre characteristics (Gillespie, 1992). Ecologically valid modelling of this dynamic is challenging. Because of this, simpler proxy variables were used, with the rough assumption that higher values indicate higher risk. Similarly, no method to determine a danger threshold for the SDLP exists. Limited attention decreases and weaving within one's lane may not be dangerous in undemanding conditions. The current experiment involved a simple driving task with few potential hazards. No overtaking by other motor vehicles, pedestrians crossing the road or cyclists riding in the same lane required sudden reactions from our participants. This could have allowed participants to economise their driving without considerably increasing their accident risk. When increased task demand improved performance under fatigue, it could have acted only to compensate for the increased risk level. Therefore, a better performance does not indicate that driving is intrinsically safer than before. The cone track at the end of each run allowed testing of the driving performance when the hazard risk suddenly increased. The driver state or the interaction between the driver state and road condition did not influence the success rate on the cone track. This supports the interpretation that the participants in the current study could successfully adjust their allocation of cognitive resources even in a sleep-deprived state to match task demand, and it is unclear how much the driving ability of the participants benefited from the slippery road conditions.

Thirdly, the participants represented only a small and homogenous segment of the driving population, which may raise concerns about the generalisability of the results. Driving is a combination of skill and style. Our results are likely to contain elements of both rather than measuring only raw performance. Young men are known to represent an outlier group within the general driving population, characterised by high risk-taking behaviour (Williams, 2003). The accident risk for young males peaks at the transition to adulthood, which our participants have barely passed. This sensitive developmental time point could theoretically have led to high individual variability in responses to changes in time of day and driving conditions. The driving experience of our participants was also uncontrolled. Theoretically, large individual differences in driving exposure and skill could have existed, further contributing to high variability in the results.

Finally, driving simulators are limited in their ability to model real-life driving scenarios. Driving simulators are widely used in traffic-related research and are indispensable, especially when safety risks are involved. The simulator that we used in this study represented state-of-the-art technology. However, with artificial environments, one must also consider the ecological validity of the setting. Although simulators enable highly detailed measurements and isolation of the research setting, they lack other aspects. The car handling is usually only modelled on sufficient detail, and the driving environment lacks the dynamicity of real-life environments. Thus, driving in simulated environments can lack the sensation of risk. This could result in increased levels of boredom and could inflate the level of subjective fatigue experienced.

4.2 Conclusion and future considerations

Previous research has shown that driving on demanding road profiles can reduce the effects of passive task-related fatigue and prevent loss of performance due to time-on-task effects. The current study demonstrated that an increase in task demand caused by changes in the driving environment may also have negative consequences. Prolonged driving in demanding road conditions can further exhaust drivers who are already sleepy. Because slippery roads reduce the error margin, drivers are forced to reduce fatigue-induced economisation of their behaviour and direct more of their already strained cognitive resources to the driving task.

Even though the reduction of economisation-based coping strategies rapidly leads to exhaustion, the current study was unable to fully explore how this might affect driving performance. Further research should be conducted on the combined long-term effects of high task demand and high subjective fatigue levels on driving task performance. If the eventual reduction in driving performance in demanding driving conditions is sudden rather than gradual, this could have serious implications for traffic safety.

The current study also reaffirmed large differences in how fatigue influences the behaviour and performance of individuals. Most of the variability in fatigue response was unexplained by the research design; in the future, more attention should be focused on finding factors that explain individual variability in response to both fatigue and task demand. Even if no change in performance is noticed in general, vulnerable subgroups may be susceptible to early influences of fatigue. Findings in this field could also assist in recognising subgroups that can benefit most from secondary task-based fatigue countermeasures.

References

Åkerstedt, T., & Gillberg, M. (1990). Subjective and objective sleepiness in the active individual. *International Journal of Neuroscience*, *52*(1–2), 29–37.

Åkerstedt, T., Ingre, M., Kecklund, G., Anund, A., Sandberg, D., Wahde, M., ... Kronberg, P. (2010). Reaction of sleepiness indicators to partial sleep deprivation, time of day and time on task in a driving simulator–The DROWSI project. *Journal of Sleep Research, 19*(2), 298–309.

Åkerstedt, T., Torsvall, L., & Gillberg, M. (1987). Sleepiness in shiftwork. A review with emphasis on continuous monitoring of EEG and EOG. *Chronobiology International, 4*(2), 129–140.

Aldrich, M. S. (1989). Automobile accidents in patients with sleep disorders. *Sleep, 12*(6), 487–494.

Anund, A., Ahlström, C., Fors, C., & Åkerstedt, T. (2018). Are professional drivers less sleepy than non-professional drivers? *Scandinavian Journal of Work, Environment and Health, 44*(1), 88–95.

Anund, A., Fors, C., Hallvig, D., Åkerstedt, T., & Kecklund, G. (2013). Observer rated sleepiness and real road driving: An explorative study. *PLOS One, 8*(5), 1–8.

Anund, A., Kecklund, G., Peters, B., & Åkerstedt, T. (2008). Driver sleepiness and individual differences in preferences for countermeasures. *Journal of Sleep Research*, *17*(1), 16–22.

Arnedt, J. T., Wilde, G. J., Munt, P. W., & MacLean, A. W. (2001). How do prolonged wakefulness and alcohol compare in the decrements they produce on a simulated driving task? *Accident Analysis & Prevention, 33*(3), 337–344.

Atchley, P., & Chan, M. (2011). Potential benefits and costs of concurrent task engagement to maintain vigilance: A driving simulator investigation. *Human Factors, 53*(1), 3–12.

Balkin, T., Thome, D., Sing, H., Thomas, M., Redmond, D., Wesensten, N., ... Belenky, G. (2000). *Effects of sleep schedules on commercial motor vehicle driver performance.* Retrieved from https://rosap.ntl.bts.gov/view/dot/33880

Barr, L. C., Yang, C. D., Hanowski, R. J., & Olson, R. (2005). Assessment of driver fatigue, distraction, and performance in a naturalistic setting. *Transportation Research Record, 1937*(1), 51–60.

Basner, M., & Dinges, D. F. (2011). Maximizing sensitivity of the Psychomotor Vigilance Test (PVT) to sleep loss. *Sleep, 34*(5), 581–591.

Belenky, G., Wesensten, N. J., Thorne, D. R., Thomas, M. L., Sing, H. C., Redmond, D. P., ... Balkin, T. J. (2003). Patterns of performance degradation and restoration during sleep restriction and subsequent recovery: A sleep dose-response study. *Journal of Sleep Research, 12*(1), 1–12.

Belyavin, A., & Wright, N. A. (1987). Changes in electrical activity of the brain with vigilance. *Electroencephalography and Clinical Neurophysiology, 66*(2), 137–144.

Borbély, A. A. (1982). A two process model of sleep regulation. *Human Neurobiology, 1*(3), 195–205.

Borbély, A. A., Achermann, P., Trachsel, L., & Tobler, I. (1989). Sleep initiation and initial sleep intensity: Interactions of homeostatic and circadian mechanisms. *Journal of Biological Rhythms, 4*(2), 37–48.

Cho, Y., Ryu, S.-H., Lee, B. R., Kim, K. H., Lee, E., & Choi, J. (2015). Effects of artificial light at night on human health: A literature review of observational and experimental studies applied to exposure assessment. *Chronobiology international, 32*(9), 1294–1310.

Corfitsen, M. T. (1993). Tiredness and visual reaction time among nighttime cab drivers: A roadside survey. *Accident Analysis & Prevention, 25*(6), 667–673.

Craig, A., & Cooper, R. E. (1992). Symptoms of acute and chronic fatigue. In A. P. Smith & D. M. Jones (Eds.), *Handbook of human performance: State and trait* (Vol. 3, pp. 289–339). Cambridge, MA: Academic Press.

Dawson, D., & Reid, K. (1997). Fatigue, alcohol and performance impairment. *Nature, 388*(6639), 235–235.

de Waard, D., & Brookhuis, A. (1997). Behavioural adaptation of drivers to warning and tutoring messages: Results from an on-the-road and simulator test. *International Journal of Heavy Vehicle Systems, 4*(2–4), 222–234.

Desmond, P. A., & Matthews, G. (1997). Implications of task-induced fatigue effects for in-vehicle countermeasures to driver fatigue. *Accident Analysis & Prevention, 29*(4), 515–523.

Desmond, P. A., & Matthews, G. (2009). Individual differences in stress and fatigue in two field studies of driving. *Transportation Research Part F: Traffic Psychology and Behaviour, 12*(4), 265–276.

Dinges, D. F., & Mallis, G. (1998). Managing fatigue by drowsiness detection: Can technological promises be realized? In L. R. Hartley (Ed.), *Managing Fatigue in Transportation: Proceedings of the 3rd International Conference on Fatigue and Transportation* (pp. 209–229). Oxford, United Kingdom: Elsevier.

Dinges, D. F., & Powell, J. W. (1985). Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. *Behavior Research Methods, Instruments, & Computers, 17*(6), 652–655.

Dinges, D. F., Mallis, M. M., Maislin, G., & Powell, J. W. (1998). *Evaluation of techniques for ocular measurement as an index of fatigue and as the basis for alertness management.* Retrieved from https://rosap.ntl.bts.gov/view/dot/2518/dot_2518_DS1.pdf.

Doran, S. M., Dongen, H. P., & Dinges, D. (2001, 5). Sustained attention performance during sleep deprivation: Evidence of state instability. *Archives Italiennes de Biologie, 139*(3), 253–267.

Drory, A., & Shinar, D. (1982). The effects of roadway environment and fatigue on sign perception. *Journal of Safety Research*, *13*(1), 25–32.

Folkard, S. (1997). Black times: Temporal determinants of transport safety. *Accident Analysis & Prevention*, *29*(4), 417–430.

Fuller, R. (2011). Driver control theory: From task difficulty homeostasis to risk allostasis. In B. E. Porter (Ed.), *Handbook of traffic psychology* (pp. 13–26). Cambridge, MA: Academic Press.

George, C. F. (2003). Driving simulators in clinical practice. *Sleep Medicine Reviews*, *7*(4), 311–320.

George, C. F., & Smiley, A. (1999). Sleep apnea & automobile crashes. *Sleep, 22*(6), 790–795.

Gillespie, T. D. (1992). *Fundamentals of vehicle dynamics.* Warrendale, PA: Society of Automotive Engineers.

Grandjean, E. (1979). Fatigue in industry. *Occupational and Environmental Medicine, 36*(3), 175–186.

Harris, W. (1977). Fatigue, circadian rhythm, and truck accidents. In R. R. Mackie (Ed.), *Vigilance: Theory, Operational Performance, and Physiological Correlates* (pp. 133–146). New York, NY: Plenum Press.

Head, J., & Helton, W. S. (2014). Sustained attention failures are primarily due to sustained cognitive load not task monotony. *Acta Psychologica, 153*, 87–94.

Hockey, G. R. (1997). Compensatory control in the regulation of human performance under stress and high workload: A cognitive-energetical framework. *Biological Psychology, 45*(1–3), 73–93.

Horne, J. A., & Reyner, L. A. (1995). Sleep related vehicle accidents. *The BMJ, 310*(6979), 565–567.

Ingre, M., Åkerstedt, T., Peters, B., Anund, A., & Kecklund, G. (2006). Subjective sleepiness, simulated driving performance and blink duration: Examining individual differences. *Journal of Sleep Research, 15*(1), 47–53.

Johns, M. (1998). Rethinking the assessment of sleepiness. *Sleep Medicine Reviews, 2*(1), 3–15.

Johns, M. W. (1991). A new method for measuring daytime sleepiness: The Epworth sleepiness scale. *Sleep, 14*(6), 540–545.

Kaida, K., Takahashi, M., Åkerstedt, T., Nakata, A., Otsuka, Y., Haratani, T., & Fukasawa, K. (2006). Validation of the Karolinska Sleepiness Scale against performance and EEG variables. *Clinical Neurophysiology, 117*(7), 1574–1581.

Kaptein, N. A., Theeuwes, J., & van der Horst, R. (1996). Driving simulator validity: Some considerations. *Transportation Research Record, 1550*(1), 30–36.

Lal, S. K., & Craig, A. (2001a). A critical review of the psychophysiology of driver fatigue. *Biological Psychology, 55*(3), 173–194.

Lal, S. K., & Craig, A. (2001b). Electroencephalography activity associated with driver fatigue: Implications for a fatigue countermeasure device. *Journal of Psychophysiology, 15*(3), 183–189.

Lal, S. K., & Craig, A. (2002). Driver fatigue: Electroencephalography and psychological assessment. *Psychophysiology, 39*(3), 313–321.

Lenné, M. G., Triggs, T. J., & Redman, J. R. (1998). Interactive effects of sleep deprivation, time of day, and driving experience on a driving task. *Sleep, 21*(1), 38–44.

Markkula, G., Benderius, O., Wolff, K., & Wahde, M. (2013). Effects of experience and electronic stability control on low friction collision avoidance in a truck driving simulator. *Accident Analysis & Prevention, 50*, 1266–1277.

Mascord, D. J., & Heath, R. A. (1992). Behavioral and physiological indices of fatigue in a visual tracking task. *Journal of Safety Research, 23*(1), 19–25.

Matthews, G., & Desmond, P. A. (2002). Task-induced fatigue states and simulated driving performance. *The Quarterly Journal of Experimental Psychology: Section A, 55*(2), 659–686.

May, J. F., & Baldwin, C. L. (2009). Driver fatigue: The importance of identifying causal factors of fatigue when considering detection and countermeasure technologies. *Transportation Research Part F: Traffic Psychology and Behaviour, 12*(3), 218–224.

Maycock, G. (1996). Sleepiness and driving: The experience of UK car drivers. *Journal of Sleep Research, 5*(4), 229–231.

Maycock, G. (1997). Sleepiness and driving: The experience of heavy goods vehicle drivers in the UK. *Journal of Sleep Research, 6*(4), 238–244.

Mitler, M. M., Miller, J. C., Lipsitz, J. J., Walsh, J. K., & Wylie, C. D. (1997). The sleep of long-haul truck drivers. *New England Journal of Medicine, 337*, 755–762.

Monk, T. H. (1989). A visual analogue scale technique to measure global vigor and affect. *Psychiatry Research, 27*(1), 89–99.

Nakagawa, S., Johnson, P. C., & Schielzeth, H. (2017). The coefficient of determination R^2 and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded. *Journal of the Royal Society Interface, 14*(134).

Neubauer, C., Matthews, G., & Saxby, D. (2014). Fatigue in the automated vehicle: Do games and conversation distract or energize the driver? *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 58*(1), 2053–2057.

Nilsson, T., Nelson, T. M., & Carlson, D. (1997). Development of fatigue symptoms during simulated driving. *Accident Analysis & Prevention, 29*(4), 479–488.

Ohayon, M. M., Priest, R. G., Zulley, J., Smirne, S., & Paiva, T. (2002). Prevalence of narcolepsy symptomatology and diagnosis in the European general population. *Neurology, 58*(12), 1826–1833.

Okogbaa, O. G., Shell, R. L., & Filipusic, D. (1994). On the investigation of the neurophysiological correlates of knowledge worker mental fatigue using the EEG signal. *Applied Ergonomics, 25*(6), 355–365.

Oron-Gilad, T., & Ronen, A. (2007). Road characteristics and driver fatigue: A simulator study. *Traffic Injury Prevention, 8*(3), 281–289.

Oron-Gilad, T., Ronen, A., & Shinar, D. (2008). Alertness maintaining tasks (AMTs) while driving. *Accident Analysis & Prevention, 40*(3), 851–860.

Partinen, M. (2004). *Väsymys ja nukahtaminen kuolemaan johtaneissa liikenneonnettomuuksissa* [Fatigue and falling asleep in fatal traffic accidents]. Helsinki, Finland: Liikennevakuutuskeskus.

Philip, P., Sagaspe, P., Taillard, J., Valtat, C., Moore, N., Åkerstedt, T., ... Bioulac, B. (2005). Fatigue, sleepiness, and performance in simulated versus real driving conditions. *Sleep, 28*(12), 1511–1516.

Phillips, R. O. (2015). A review of definitions of fatigue – And a step towards a whole definition. *Transportation Research Part F: Traffic Psychology and Behaviour, 29*, 48–56.

Pizza, F., Contardi, S., Mostacci, B., Mondini, S., & Cirignotta, F. (2004). A driving simulation task: Correlations with Multiple Sleep Latency Test. *Brain Research Bulletin, 63*(5), 423–426.

Radun, I., & Radun, J. (2008). *Väsyneenä ajaminen: Mikä on tilanne Suomessa?* [Fatigue and driving. The situation in Finland]. Helsinki, Finland: Liikenneturva.

Rajaratnam. S. M., W., & Jones, C. B. (2004). Lessons about sleepiness and driving from the Selby rail disaster case: R v Gary Neil Hart. *Chronobiology International, 21*(6), 1073–1077.

Reyner, L. A., & Horne, J. A. (1998). Falling asleep whilst driving: Are drivers aware of prior sleepiness? *International Journal of Legal Medicine, 111*(3), 120–123.

Rogé, J., Pébayle, T., El Hannachi, S., & Muzet, A. (2003). Effect of sleep deprivation and driving duration on the useful visual field in younger and older subjects during simulator driving. *Vision Research, 43*(13), 1465–1472.

Rosekind, M. R., Gander, P. H., Miller, D. L., Gregory, K. B., Smith, R. M., Weldon, K. J., ... Lebacqz, J. V. (1994). Fatigue in operational settings: Examples from the aviation environment. *Human Factors, 36*(2), 327–338.

Santamaria, J., & Chiappa, K. H. (1987). The EEG of drowsiness in normal adults. *Journal of clinical Neurophysiology, 4*(4), 327–382.

Saxby, D. J., Matthews, G., Hitchcock, E. M., Warm, J. S., Funke, G. J., & Gantzer, T. (2008). Effect of active and passive fatigue on performance using a driving simulator. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 52*(21), 1751–1755.

Shen, J., Barbera, J., & Shapiro, C. M. (2006). Distinguishing sleepiness and fatigue: Focus on definition and measurement. *Sleep medicine reviews, 10*(1), 63–76.

Smith, R., Cook, L. J., Olson, L. M., Reading, J. C., & Dean, J. M. (2004). Trends of behavioral risk factors in motor vehicle crashes in Utah, 1992–1997. *Accident Analysis & Prevention, 36*(2), 249–255.

Smolders, K. C., & de Kort, Y. A. (2014). Bright light and mental fatigue: Effects on alertness, vitality, performance and physiological arousal. *Journal of Environmental Psychology, 39*, 77-91.

Sommer, D., & Golz, M. (2010). Evaluation of PERCLOS based current fatigue monitoring technologies. In *2010 Annual International Conference of the IEEE Engineering in Medicine and Biology* (pp. 4456-4459). New York, NY: IEEE.

Stern, J. A., Boyer, D., & Schroeder, D. (1994). Blink rate: A possible measure of fatigue. *Human Factors, 36*(2), 285–297.

Stern, J. A., Walrath, L. C., & Goldstein, R. (1984). The endogenous eyeblink. *Psychophysiology, 21*(1), 22–33.

Thiffault, P., & Bergeron, J. (2003a). Fatigue and individual differences in monotonous simulated driving. *Personality and Individual Differences, 34*(1), 159–176.

Thiffault, P., & Bergeron, J. (2003b). Monotony of road environment and driver fatigue: A simulator study. *Accident Analysis & Prevention, 35*(3), 381–391.

Trutschel, U., Sirois, B., Sommer, D., Golz, M., & Edwards, D. (2011). Perclos: An alertness measure of the past. *Proceedings of the Sixth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design* (pp. 172–179). Iowa City, IA: University of Iowa.

van der Hulst, M., Meijman, T., & Rothengatter, T. (2001). Maintaining task set under fatigue: A study of time-on-task effects in simulated driving. *Transportation Research Part F: Traffic Psychology and Behaviour, 4*(2), 103–118.

van der Linden, D., Frese, M., & Meijman, T. F. (2003). Mental fatigue and the control of cognitive processes: Effects on perseveration and planning. *Acta Psychologica, 113*(1), 45–65.

van Dijken, J. H., Veldstra, J. L., van de Loo, A. J., Verster, J. C., van der Sluiszen, N. N., Vermeeren, A., ... de Waard, D. (2020). The influence of alcohol (0.5‰) on the control and manoeuvring level of driving behaviour, finding measures to assess driving impairment: A simulator study. *Transportation Research Part F: Traffic Psychology and Behaviour, 73,* 119–127.

Verwey, W. B., & Zaidel, D. M. (1999). Preventing drowsiness accidents by an alertness maintenance device. *Accident Analysis & Prevention, 31*(3), 199–211.

Wierwille, W. W., & Ellsworth, L. A. (1994). Evaluation of driver drowsiness by trained raters. *Accident Analysis & Prevention*, *26*(5), 571–581.

Wierwille, W. W., Wreggit, S. S., Kirn, C. L., Ellsworth, L. A., & Fairbanks, R. J. (1994). *Research on vehicle-based driver status/performance monitoring; development, validation, and refinement of algorithms for detection of driver drowsiness.* Retrieved from https://rosap.ntl.bts.gov/view/dot/2578

Wijesuriya, N., Tran, Y., & Craig, A. (2007). The psychophysiological determinants of fatigue. *International Journal of Psychophysiology, 63*(1), 77–86.

Williams, A. F. (2003). Teenage drivers: Patterns of risk. *Journal of Safety Research, 34*(1), 5–15.