

CLIENT PROJECT REPORT CPR2444

Fatigue and road works

Driving simulator study

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Executive summary

Objectives

The aim of this project was to investigate the extent to which road works impact on the development of driver fatigue and the manifestation of fatigue-related performance impairments. This was accomplished by recruiting a sample of drivers from the general population to undertake controlled drives in the TRL 'DigiCar' driving simulator. This allowed assessment of the relationship between driver fatigue and road works in a safe environment, whilst controlling for confounding factors such as weather, traffic behaviour, road layout, incidents, caffeine intake and driver health conditions.

Method

Thirty-one drivers took part in a repeated-measures design involving two 2.5-hour drives in the driving simulator, performed on separate days:

1. A 'control drive' on a 175-mile stretch of simulated 3-lane UK motorway with no road works in place and the National Speed Limit throughout, and;
2. An 'experimental drive' on a 150-mile stretch of the same 3-lane motorway layout, but segmented into alternating sections with road works and without road works. The road works sections involved a Major Scheme works closure of the hard-shoulder and a 50mph speed limit.

The order in which participants experienced the two drives was counterbalanced to control for order effects. Participants completed both drives at the same time of day, during one of three timeslots: 0900-1200, 1200-1500, or 1500-1800. Participants were required to restrict their sleep to a maximum of 6 hours the night before each drive.

Results

Impact of road works on fatigue

Overall levels of fatigue reported by participants (using the Karolinska Sleepiness Scale, KSS) were highly variable; some reported remaining alert throughout the whole drive whilst others reported a KSS score of 9 'very sleepy, great effort to keep awake'. The level of self-reported fatigue and the rate at which fatigue developed during the drive were not significantly different between the control and experimental drives.

In general, self-reported fatigue increased gradually over the first half of the drive (approx. 1 to 1.5 hours) and then plateaued in the second half of the drive and this pattern was not found to be greatly impacted by the presence or absence of road works.

Impact of road works on driver performance

Analysis of objective driver performance data revealed a significant effect of the presence of road works. Evidence suggested there were greater impairments to driving during the road works (in the experimental drive) compared with the control drive (without road works). This included:

- A greater proportion of time spent above the speed limit and above the enforcement limit in the road works;
- A greater shift in lateral position within the lane, with a tendency to shift to the right-hand side (away from the concrete barrier in the road works section);
- A reduction in the number of deliberate lane changes but an increase in the number and duration of unintentional 'drifts' out of lane in the road works, and;
- Slower reaction times in the road works.

On the other hand, drivers spent a smaller proportion of time travelling with 'unsafe' headways less than 2 seconds in the road works. This suggests that when in the road works, drivers may have been more likely to remain in Lane 1, following the traffic ahead at a comfortable and safe distance. However, the greater frequency and duration of lane drifts and slower reaction times indicate a greater propensity for lapses in concentration when travelling through the road works. Possibly, there may be a greater likelihood of fatigue-related driver errors when travelling in road works resulting from the increased complexity of the driving task.

This was supported by analysis of the transitional periods between road works and non-road works sections. Reaction times, the number and duration of lane drifts, and the proportion of time spent travelling above the enforcement limit, were greater when drivers were transitioning into the road works compared to when they were travelling just prior to the start of the works. Similarly, driver performance was worse in the transitional period just before leaving the road works than in the three-minute period immediately after exiting the works. This suggests that changes in complexity of the road environment can impact on driver performance.

Conclusions

The level of self-reported fatigue and the rate at which fatigue developed while driving in the simulator was not found to be dependent on the presence or absence of road works. This suggests that the presence of road works on the Strategic Road Network is not likely to greatly impact the likelihood of whether or not drivers became fatigued while driving.

However, evidence suggested there were greater impairments to driver performance when driving through motorway Major Scheme road works compared with driving on a motorway without road works. Performance was also worse in the transitional periods at the start and end of the road works compared to the periods immediately before and after the transitions. These findings suggest that the likelihood of driver errors while fatigued may be higher when travelling through road works, possibly due to the increased complexity of the driving task.

The current study examined general trends in fatigue and driver performance in sections of road with and without road works. Statistically significant differences in objective measures of driver performance between these sections showed some evidence of an increased collision risk when travelling through road works. Of particular note was that the severity of lane drifts was greater in road works with narrow lanes than in sections without road works (and standard width lanes). This has potential implications for the management of risk on the SRN; if the use of narrow lanes at road works reduces drivers' ability to maintain a

central position in the lane then their use might increase risk to road users and road workers on the network. It is therefore important to assess the extent to which lane keeping performance differs in road works with different lane widths. Comparisons of driver performance in road works with standard width lanes with performance in road works with narrow width lanes would reveal whether or not the width of the lane is an important factor contributing to risk. A greater understanding of the issues associated with narrow lanes could help to inform the design and implementation of TM at future road works schemes and contribute to a reduction in risk. It is recommended that some initial analysis of this issue is performed using existing datasets gathered during this study and previous DigiCar simulator studies undertaken at TRL.

1 Introduction

1.1 Background

The safety of road users and road workers operating on the Strategic Road Network (SRN) is one of the most important Key Performance Indicators (KPIs) for Highways England and a core ‘imperative’ for the business. Reducing the number of Killed and Seriously Injured (KSI) casualties is part of the overall Strategic Business Plan, and this must be achieved within the Road Investment Strategy (RIS). The RIS will require a major programme of road works across the entire SRN; this may have operational and safety repercussions as road works sites increase in number and length. This means that drivers will be more likely to encounter road works and will have to spend longer driving through them.

When driving through road works, drivers are required to react quickly and efficiently to changing road conditions, such as changed signage, narrowing of lanes, reduced speed limits, contraflow running and increased road side activity by road workers and the machinery they operate. These factors increase the complexity of the driving task which not only represents a risk to the driver and vehicle occupants, but may also increase the risk to road workers operating on the road. Since the consequences of collisions in road works may be increased due to the potential presence of road workers in close proximity to motor traffic, it is important to know if anything can be done to reduce collision risk through road works.

This is particularly important for collision risk arising from fatigue. The Department for Transport (DfT) in the UK estimates that fatigue may be a contributory factor in as many as 20% of all road collisions (Jackson, Hilditch, Holmes, Reed, Merat and Smith, 2011), although it is generally considered that fatigue is underreported as a contributory factor in collision statistics (e.g. Smith, Oppenhuis and Koorey, 2006). The purpose of this project is to investigate how the presence of road works on the SRN impacts on the development of driver fatigue and the manifestation of fatigue-related impairments to driver performance.

1.2 Definition of fatigue

In discussing this area it is important to acknowledge a distinction between ‘fatigue’ and ‘sleepiness’. Fatigue and sleepiness are separate concepts; the former may be defined as a “loss of efficiency and disinclination for any kind of effort” which gradually increases over time (Grandjean, 1979; as cited in Jackson *et al.*, 2011, p. 21), whilst the latter describes a state in which an individual has “difficulty in remaining awake” (Jackson *et al.*, 2011, p. 21). However, there are no commonly accepted definitions, and the use of these terms varies throughout the literature. ‘Fatigue’, in particular, is commonly used as a ‘catch-all’ term which includes the concept of sleepiness. This approach has been adopted here, with ‘fatigue’ used as an umbrella term to describe the effects on driving performance related to either (or both) an increasing propensity to fall asleep and a decreasing inclination for any kind of effort.

1.3 Causes of driver fatigue

1.3.1 Task demand

Driver fatigue is caused by both the physiological and psychological need to sleep and by the characteristics of the driving task itself (Brown, 1994, as cited by Horberry *et al.*, 2008). One important element of the driving task which may contribute to the development of fatigue is *task demand*. This can be explained in terms of both task ‘overload’ and task ‘underload’. Task overload can occur with highly demanding driving tasks and may increase the likelihood of fatigue developing due to a reduced inclination for further effort (Matthews and Desmond, 2002). Similarly, fatigue-related performance impairments may be exacerbated by complex, highly demanding tasks when the limited attentional resources are insufficient to complete the task within comfortable safety margins.

On the other hand, task underload may occur during monotonous or boring driving tasks, and can also lead to fatigue due to a lack of physical or mental stimulation (Williamson, Lombardi, Folkard, Stutts, Courtney and Connor, 2011). For example, greater impairments to performance were observed in a driving simulator study when travelling on straight (lower demand) sections than curved (higher demand) sections (Matthews and Desmond, 2002). Increasing the complexity of the driving task has been shown to reduce the effects of fatigue; inclusion of overtaking tasks within a simulated drive led to reduced subjective feelings of fatigue and reduced duration of blinks (Anund, Kecklun, Kircher, Tapani and Akerste 2009). Task underload may be particularly important when considering the onset of fatigue during long motorway journeys, especially at night. ‘Highway hypnosis’ may make fatigue more likely under monotonous highway driving conditions than more varied urban journeys (Horne and Reyner, 1995; as cited by Horberry *et al.*, 2008).

1.3.2 Time-on-task

In addition to task demand, it is also generally accepted that as time-on-task (i.e. the duration of the journey) increases, the likelihood of fatigue and impairments to driving performance also increase (Jackson *et al.*, 2011). For example, self-reported fatigue (measured using the Karolinska sleepiness scale) was around twice as high (on average) following simulated six-hour drives compared with two-hour drives, and around 0.4 times higher than with four-hour drives (Zhang, Yan, Wu and Qiu, 2014). Fatigue-related driving performance impairments have also been identified after as little as 40 minutes of a repetitive simulated driving task (Thiffault and Bergeron, 2003; as cited by Horberry *et al.*, 2008) and performance following 2 hours and 3 hours of continuous nocturnal driving has been shown to be comparable to the performance of drivers with a blood alcohol concentration (BAC) of 0.05% and 0.08%, respectively (Verster *et al.*, 2011). The latter BAC level represents the UK legal limit.

1.3.3 Time of day

The effects of time-on-task may also be interactive with those of time of day (e.g. Williamson and Friswell, 2008; Verster, Taillard, Sagaspe, Olivier and Philip, 2011). With the task duration held constant, fatigue has been shown to increase more rapidly during an

evening drive starting at 2100 than a morning drive (starting at 0900) or an afternoon drive (starting at 1200) (Zhang, Yan, Wu and Qiu, 2014). Some consider that unless driving duration is greater than 12 hours, the time of day at which the drive takes place has a bigger contribution to fatigue-related performance impairments than time-on-task (Jackson *et al.*, 2011). Indeed, there is evidence of a greater prevalence of fatigue during nocturnal driving than daytime driving which appears to support this hypothesis (e.g. Sandberg, Anund, Fors, Kecklund, Karlsson, Wahde and Åkerstedt, 2011).

Other evidence suggests there are two peaks in fatigue-related accident risk; one between approximately 0200 and 0400 in the morning, and another smaller peak between approximately 1400 and 1600 in the afternoon (e.g. Jackson *et al.*, 2011; Zhang, Yan, Wu and Qiu, 2014). Driving at night could be performed safely if a driver is properly rested, but not if the driver has suffered long periods without sleep (Williamson and Friswell, 2008). Although long periods without sleep may have a greater impact on performance when driving at night, compared to when driving in the day (Williamson and Friswell, 2008), the risk of a fatigue-related accident is not isolated to night-time driving (Jackson *et al.*, 2011).

1.4 Objectives of this research

It is clear from the literature that the characteristics and the timing of the driving task can contribute to the development of fatigue and fatigue-related performance impairments. It is also understandable how fatigue can increase collision risk; the effects of fatigue on driving performance are well established and can include increased blink duration (Anund, Kecklund, Kircher, Tapani and Åkerstedt, 2009), increased reaction times (e.g. Horberry *et al.*, 2008; Grigo and Baldock, 2011), reduced attention (Liu and Wu, 2009; Grigo and Baldock, 2011; Jackson *et al.*, 2011) and poorer spatial awareness (e.g. Liu and Wu, 2009; Grigo and Baldock, 2011). These skills are particularly crucial when encountering changing and complex road conditions, such as road works, but there has been no direct research investigating the prevalence of fatigue-related collisions in road works areas or the interaction of road works infrastructure on the development of driver fatigue. This represents a clear gap in knowledge.

There is some previous evidence which can be used to develop hypotheses about the potential impact of road works on driver fatigue. For example, driving performance was shown to be worst in fatigued drivers when travelling in monotonous driving conditions with low variability in road design (i.e. motorway-type roads with flat, straight cambers) and high variability in roadside stimuli (e.g. signage and other roadside clutter) (Michael, 2009). These conditions are synonymous with motorways and major trunk roads on the Highways England Strategic Road Network (SRN), which include long straight sections with little variation in curvature or gradient, and periodic stretches of road works with an associated increase in roadside signage and other visual clutter such as reflective markings and works vehicles. Further evidence suggests fatigue-related performance decrements may be most prevalent when transitioning from high demand sections of road to low demand sections of road (e.g. Smith *et al.*, 2006; Liu and Wu, 2009). It may be hypothesised that a change in task demand may occur when entering or leaving road works areas, due to the inherent difference in the characteristics of the road environment compared to other sections of road without road works.

In light of current knowledge of the risks of driver fatigue and the potential interactive effects of the road environment, a driving simulator study was designed to investigate the specific impact of road works on the development of driver fatigue and the manifestation of fatigue-related performance impairments. It was hypothesised that, when controlling for time-on-task and the time of day at which drives took place, there would be differences in the onset of fatigue and the incidence of fatigue-related performance impairments between a control drive with no road works, and an experimental drive with road works. It was further hypothesised that performance impairments may be particularly prevalent when transitioning from a road works section to a non-road works section, or vice versa. The method employed to test these hypotheses is described in the following sections.

2 Method

2.1 Research question

The purpose of this driving simulator study was to answer the following research question:

Do road works increase the risk of fatigue-related collisions?

Specifically, the study sought to establish the impact of Major Scheme¹ road works (on the Highways England SRN) on the onset and severity of driver fatigue, and the manifestation of fatigue-related impairments to driving performance.

2.2 Overview of experimental design

The study utilised a repeated-measures design to investigate the onset of fatigue and the incidence of fatigue-related incidents in simulated but realistic driving conditions on roads with and without road works.

A sample of thirty-four drivers took part in two 2.5-hour drives each, on separate days.

1. A 'control drive' on a 175-mile stretch of simulated 'D3M'² 3-lane UK motorway with no road works in place and the National Speed Limit throughout.
2. An 'experimental drive' on a 150-mile stretch of the same 'D3M' motorway layout, but segmented into alternating sections with road works ('RW') and without road works ('NRW'). The RW sections involved a Major Scheme road works closure of the hard-shoulder and a 50mph speed limit.

The design of the study incorporated a number of controls in order to reduce the impact of biases on the findings. This included:

- Counterbalancing the order in which participants experienced the two drives, and the order in which the RW and NRW sections appeared in the experimental drive (using a Latin square).
- Matching the duration of the control and experimental drives (which lasted approximately 2.5 hours), thus controlling for time-on-task effects.
- Ensuring the time slot in which participants took part was kept the same for both of their drives (one of three sessions throughout the day; 0900-1200, 1200-1500, or 1500-1800); this ensured that differences in driving performance and fatigue between the Control and Experimental Drive were not biased by the time of day at which the drives were completed.

¹ The term 'Major scheme' is typically used to cover substantial maintenance and improvement road works projects. Within Chapter 8 of the Traffic Signs Manual (TSM), road works are described as either 'standard' or 'relaxation'; major schemes are undertaken using the 'standard scheme' principles.

² Dual 3-lane Motorway; a classification of motorways on the Highways England Strategic Road Network.

- Controlling for individual differences in sleep patterns prior to the study; to ensure participants were not overly rested before taking part in the study, participants were required to restrict their sleep to a maximum of 6 hours the night before each drive.
- Matching the experience between the control and experimental drives as closely as possible, so that the only differences were those associated with the presence or absence of road works. This included presenting a simplified road layout (e.g. with no junctions) and controlling external in-vehicle variables such as the use of a radio (which may impact the development of fatigue).

Driving performance and the development of fatigue were measured throughout the drives. This included capturing objective data on speed, lane positioning and headway, and measuring subjective self-reported fatigue using the Karolinska Sleepiness Scale (KSS). Further details about the method used for this study are provided in the following sections.

The study was approved by the TRL Research Ethics Committee.

2.3 ‘DigiCar’ driving simulator

The TRL Driving Simulator (‘DigiCar’) was used for this study. DigiCar consists of a medium-sized family hatchback (Honda Civic) surrounded by four 3 x 4 metre projection screens giving 210° front vision and 60° rear vision, enabling the normal use of the vehicle’s driving and side mirrors. The road images are generated by four PCs running SCANeR II software (manufactured by Oktal) and are projected onto the screens by five Digital Light Processing (DLP) projectors. Images are refreshed at a rate of 60Hz (every 16.7 msec) whilst data is sampled at a rate of 20Hz (every 50 msec).

Electric actuators supply motion with 3 degrees of freedom (heave, pitch and roll) whilst engine noise, external road noise, and the sounds of passing traffic are provided by a stereo sound system.

2.3.1 *Visual environment and road layout*

A 3D visual model of a generic UK motorway scene was created for the purposes of this trial. The basic visual model consisted of three lanes in each direction, and had slight bends, a central reservation, occasional trees, and landscaping on the verges. There were no junctions or overbridges. The study was conducted during daytime hours and so daytime conditions were replicated in the simulator.

Two versions of the model were employed for the purposes of the trial; one with a continuous stretch of motorway without any road works (the control drive - see Figure 1) and another using the same continuous stretch of motorway with intermittent sections of road works (the experimental drive – see Figure 2).



Figure 1: Screenshot of virtual 'D3M' motorway scene used for control drive

The models consisted of a 50-mile orbital route. For the experimental drive this was a 30-mile section without road works and 20-mile section with road works.

Participants completed 3.5 laps of the route during the control drive (totalling 175 miles). For the experimental drive participants completed 3 laps of the route (totalling 150 miles with 3 road works sections and 3 no-road works sections). Both drives were designed to provide a 2.5 hour journey (approximately) if travelling at the speed limit (50mph in road works, 70mph elsewhere).



Figure 2: Screenshot of virtual 'D3M' motorway scene with road works used for experimental drive

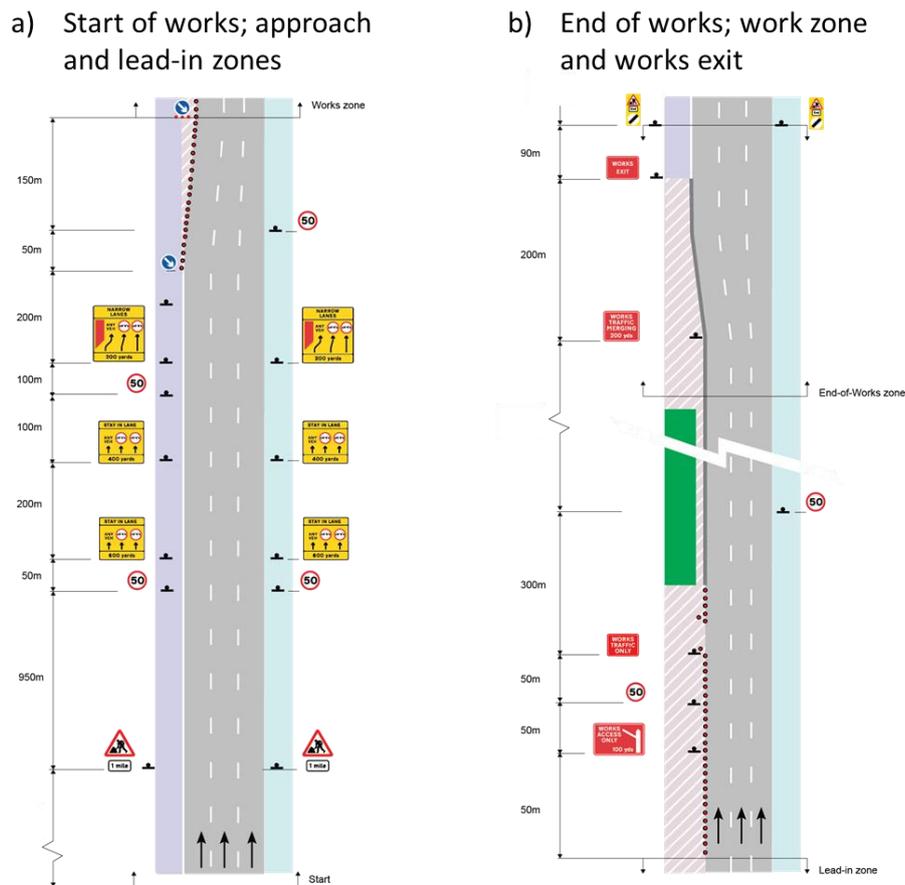


Figure 3: Road works layout employed in the experimental drive

The road works sections in the experimental drive were designed to be representative of Major Scheme road works on the SRN and compliant with Chapter 8 of the Traffic Signs Manual. The works closed the hard-shoulder and part of Lane 1, leaving three narrowed running lanes throughout the works. A 50mph speed limit was in place, with average speed cameras positioned intermittently to simulate traffic enforcement. Static road works vehicles and welfare huts were placed within the closure itself to provide a realistic experience for participants. A schematic detailing the specific features of the road works layout is shown in Figure 3.

2.3.2 Simulated traffic

Simulated traffic was generated to match typical levels observed on real motorways on the SRN during off-peak times (e.g. 10:00-16:00) whose characteristics match those of the simulated route (i.e. D3M). This equated to a carriageway flow of approximately 3,000-4,000 vehicles per hour.

Traffic was programmed to behave similarly to traffic on real roads; this factored in differentials in speeds between vehicles to ensure simulation of 'natural' traffic flows typical for a UK motorway. This including preventing vehicles from undertaking, leading to a slight increase in average traffic speeds from the nearside to the offside lanes. Traffic speeds in Lane 1 (i.e. the first nearside open lane) were set to match the posted speed limit, with each additional open lane subject to a limit 5 to 10mph higher than the previous lane. For

example, in the road works sections, with three open running lanes and a posted speed limit of 50mph through the works, Lane 1 had a virtual limit of 50mph, followed by 55mph in Lane 2 and 60mph in Lane 3.

2.4 Participant sample

Sample power calculations ensure that just the right number of participants is tested to allow for meaningful differences to be identified. The sample size chosen for this study was based on previous statistical power calculations performed for a similar driving simulator study which investigated the development of driver fatigue. These a priori estimates suggested a sample size of 34 would provide sufficient statistical power to detect meaningful differences between the road works and non-road works conditions.

Thirty-four participant drivers were therefore recruited for the study. The study was advertised using TRL's participant database which includes details on key demographics (such as age, gender and driving experience) of over 2,500 local drivers and riders in the Berkshire area who have consented to be contacted for research purposes.

The participant sample eligibility criteria are shown in Table 1.

Table 1: Participant sample target criteria

Item	Requirement
Sex	Approximately 50/50 split between males and females to be broadly representative of UK driving population
Age	Broad range of ages between 21 and 70 years old to exclude young and older drivers
Driving licence status	Full UK driving licence, held for at least three years, to exclude novice drivers.
Driving history	Regular drivers (who drive at least 4,000 miles per year), with experience of driving on motorways at least once or twice per month.
Employment status and type of work	Regular weekday employment, or with regular waking patterns if unemployed. Avoid shift workers and those with atypical sleep-wake patterns.
Caffeine consumption	Exclude those with excessive caffeine consumption (and/or other legal stimulants); to avoid confound associated with alertness due to excessive caffeine consumption/stimulants
Sleeping habits	'Normal' sleep schedules (e.g. 6-8 hours of sleep per night, with regular sleep and wake patterns).
Medical conditions	Avoid medical conditions, or medication, which may affect sleep quality; to avoid confounds from pre-existing sleep conditions or medications

Prospective participants were asked to complete an online recruitment screening questionnaire to collect information about demographics, driving licence status, driving history, sleep patterns, caffeine consumption, and general health. This ensured that the final sample included drivers with characteristics representative of the motorway driving population who have been screened so as to remove possible confounds, such as medical conditions or atypical sleeping patterns.

2.5 Study procedure

2.5.1 *Scheduling the drives*

Participants were required to complete the two drives on separate days, with a minimum of one day between each session. Sessions took place during one of three slots:

- Morning slot: 09:00-12:00
- Afternoon slot: 12:00-15:00
- Evening slot: 15:00-18:00

Participants were required to complete both of their drives during the same time slot. This ensured that any differences in driving performance and fatigue between the control and experimental drive were not biased by the time of day at which the drives were completed.

2.5.2 *Preparation for the drives*

In preparation for the trial drives, participants were required to restrict their sleep to a maximum of 6 hours the night before each drive. The purpose of this was to simulate a typical long work day and ensure that participants were not overly rested before taking part in the trial (rather than as an attempt to 'pre-load' for fatigue). To facilitate this, a sleep schedule was set requiring participants to go to bed at midnight and wake up at 06:00 (or earlier if personal circumstances required). Compliance with this schedule was monitored by requesting participants to send text messages to the research team at 30 minute intervals for two hours before going to sleep and until 08:00 each morning upon waking.

2.5.3 *Familiarisation drive*

Upon arrival at TRL, participants were briefed on the requirements of the study and introduced to the DigiCar driving simulator. Participants were asked to drive a short 5-10 minute route in the simulator to familiarise themselves with the controls of the vehicle and get used to the experience of driving in a virtual environment. The familiarisation drive was conducted in a motorway environment and included asking the participant to do a number of practice 'emergency stops' so as to familiarise them with the performance characteristics of the simulated vehicle. Following the familiarisation drive, participants were given an opportunity to ask any final clarification questions before the trial drive began.

2.5.4 Trial drives

During the trial drives, participants were instructed to drive as they normally would on a real road, paying attention to other vehicles, signage, speed limits and road side infrastructure. Both objective data from the simulator, and subjective data from verbal self-reports and researcher observations were collected during the drives so as to monitor the development of fatigue and participants' driving performance (see section 2.6).

At the end of the drive, participants completed a short post-drive questionnaire to obtain further information on self-reported fatigue and qualitative feedback on their driving experience.

2.5.5 Debrief

At the end of each trial drive, the research team ensured that participants were fit and well to travel home; private hire taxi was arranged for participants' onward journeys to ensure they were not put at risk of driving while fatigued. Participants were reimbursed £60 cash as compensation for their time following completion of their second trial drive.

2.6 Data collection

2.6.1 Subjective measures of fatigue

The onset and development of fatigue was principally monitored during the trial drives using two subjective rating scales:

1. The Karolinska Sleepiness Scale (KSS)
2. An Observer Ratings of Sleepiness scale (ORS)

The KSS is a well-established nine-point scale developed for capturing self-reported ratings of sleepiness and validated against electroencephalographic (EEG) and behavioural measures (e.g. Kaida, Takahashi, Åkerstedt, Nakata, Otsuka, Haratani *et al.*, 2006; Shahid, Shen and Shapiro, 2010). The scale ranges from 1 (very alert) to 9 (very sleepy, great effort to keep awake) (see Figure 4).

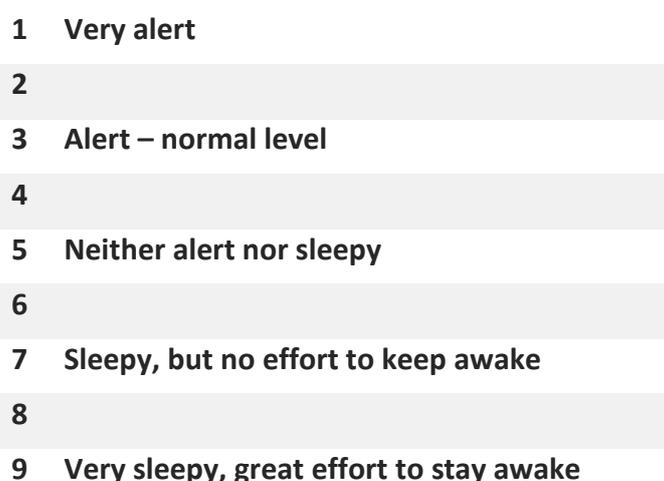


Figure 4: Karolinska Sleepiness Scale (KSS)

The scale was verbally-anchored; a pre-recorded audio prompt instructed the participant to provide a verbal KSS score at the start of the drive, and then at four minute intervals throughout the drive.

Participants were also monitored by researchers via a closed-circuit camera positioned in the simulator vehicle and a standardised ORS scale was used to score participants' visible sleepiness by examining drivers' eye, face and/or head features and movements (see Figure 5). Examples included excessive or hard blinking or squinting of the eyes, yawning, slumping of the body, head nodding or drooping, and rubbing or contortions of the face. Indicators were recorded continuously.

- 1 Alert
- 2 First signs of sleepiness
- 3 Moderate signs of sleepiness
- 4 Severe sleepiness
- 5 Asleep

Figure 5: Observer Ratings of Sleepiness scale (ORS)

The fifth level ('Asleep') was used to capture any moments of sleep that were longer than a brief 'microsleep'; typically, if the research team observed closed eyes for approximately two seconds or longer. The ORS scale was recorded in real-time during the trial drives to serve as an additional subjective measure of fatigue.

2.6.2 Objective measures of driver performance

Objective measures of driver performance were captured through the DigiCar simulator. The TRL DigiCar simulator records data relating to all control inputs made by the driver (including steering, pedals, gears), vehicle parameters (such as speed and RPM), and other parameters to assess behaviour in relation to other vehicles and the environment (such as distance and time headways and lateral position). Data were recorded at a rate of 20Hz but aggregated over 1-minute intervals for the purposes of analysis.

The primary measures for this study were:

- Mean, minimum, maximum and standard deviation of speed (mph)
- Mean, minimum, maximum and standard deviation of headway (s)
- Mean and maximum lateral lane position
- Lane choice
- Incidence of lane changes; where the driver changed from one lane to another within a 5 second window
- Incidence of lane 'drifts'; where the driver 'drifted' out of a lane but did not fully change into a different lane within a 5-second window

Driver reaction times were also measured during the drives using a reaction time task. Once per 5 minutes, a solid red bar was presented to participants in the top of the forward view

ahead, with the precise timing of the presentation within the 5 minute window randomised to counter learning effects. Participants were instructed to flash their headlights as soon as they saw the stimulus presented; the reaction time for each event was then recorded to provide a further measure of performance.

2.6.3 *After the drive*

At the end of each 2.5-hour drive, participants provided an overall rating of fatigue measured using the shortened version of the Profile of Mood States (POMS) (Shacham, 1983). The scale consists of 37 items (divided into six subscales: anger, confusion, depression, fatigue, tension and vigour). The fatigue and vigour subscales of the POMS, in particular, have been shown to provide a reliable and valid measure of the intensity of fatigue in the immediate and short term, that is, the “right now” (O’Connor, 2004). Qualitative feedback was also obtained at the end of each drive.

2.7 **Data analysis**

All the data related to fatigue and driver performance were collated across each drive and aggregated into one-minute intervals to facilitate data analysis and interpretation. The experimental drive was sub-divided into six separate sections depending on whether or not participants were travelling in road works. The control drive was sub-divided into six sections comparable in duration to those in the experimental drive; this allowed for comparisons of aggregated measures of fatigue and driver performance across different sections of the drive.

Statistical comparisons were made to establish the impact of the presence of road works on the onset and severity of fatigue, and the severity of fatigue-related performance impairments. The statistical techniques used for these comparisons were non-parametric repeated-measures tests. Repeated measures (also known as ‘within-subjects’) analysis was required because participants experienced both conditions; the control drive and the experimental drive. Results were classified as ‘statistically significant’ if the p-value was less than 0.05, a common standard in the behavioural sciences. A p-value less than 0.05 indicates that there is a 95% chance that the comparison being made has arisen due to the variable under investigation, and not simply due to random fluctuations (‘noise’) in the data. Hence, results which are ‘significant’ suggest there is a genuine difference between the two groups being measured.

Thematic analysis of the qualitative data was undertaken to identify prominent ‘themes’ in the data and supplement the findings from the primary statistical analysis.

3 Results

3.1 Sample characteristics

The final sample consisted of 31 participants who completed both the control and experimental drives; the sample was reduced from the target of 34 participants due to missing data on some of the trial drives. The *a priori* estimates of statistical power (based on speed, headway and lateral lane shift data from a previous simulator trial which investigated driver fatigue) indicated a sample of 34 would yield a statistical power of between 80 and 100% (depending on the specific metric being tested). Post-hoc power analysis (using data collected in the current study) estimated that the actual sample power achieved (with 31 participants) was greater than 90%.

Table 2 shows the gender and age distributions of the participants. The sample consisted of around 70% males – slightly higher than the target proportion of approximately 50% - and range of ages between 21 and 70 years old in line with the target criteria. Around 50% of the sample was aged 55 years or older.

Table 2. Demographic characteristics

Characteristic	N	%
Gender		
Male	22	71.0
Female	9	29.0
Age		
21-24	3	9.7
25-34	2	6.5
35-54	11	35.5
55-64	9	29.0
65-70	6	19.4
Total	31	

All participants had held a full UK driving licence for more than 3 years and the majority had held a licence for more than 10 years. Only one participant reported driving fewer than 4,000 miles per year and less frequently than once or twice per month on motorways. The driving experience and travel patterns of the final sample were therefore broadly in line with the recruitment criteria outlined in Table 1.

More than 60% of the sample reported typical sleeping patterns of 7-8 hours per night, about 8% reported getting more than this on average, and about 30% reported getting 7 or fewer hours sleep, on average. All participants reported getting at least 5-6 hours of sleep on average, but the mean number of hours sleep achieved on the night before taking part in the trial was 5 (see Figure 6). This suggests the trial procedure was successfully able to

restrict the amount of sleep prior to the trial for the vast majority of participants. Crucially, the number of hours of sleep was comparable between the experimental and control drives. No participants reported sleeping for longer than six hours on the night before the trial; this was also validated through assessment of text alerts received by the research team (see section 2.5.2).

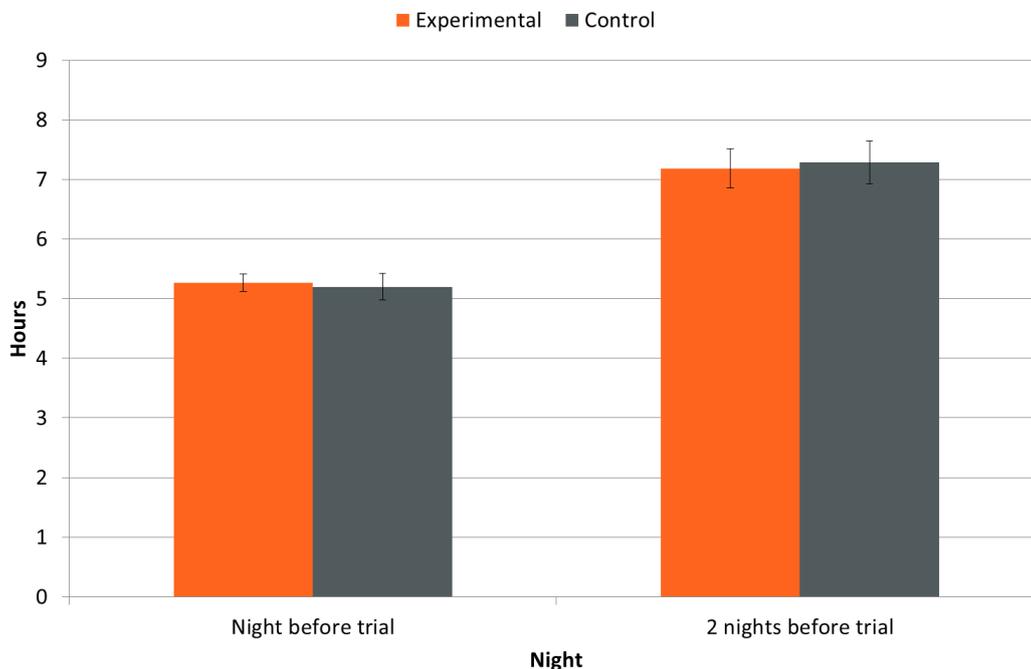


Figure 6: Number of hours of sleep participants had before the trial

Self-reported levels of fatigue in the week preceding the trial drives were assessed using the POMS scale (Sacham, 1983), which ranges from 0 to 20. Scores indicated that on average, participants experienced low levels of fatigue in the week preceding the trial drives. These were very similar between control (mean, $M = 4.42$; Standard Deviation, $SD = 2.90$) and experimental ($M = 4.45$; $SD = 2.90$) drives suggesting prior fatigue levels were comparable between the two conditions.

3.2 Impact of road works on incidence of fatigue

3.2.1 Overall reported levels of fatigue

Mean ORS across the whole sample was 2.3 in both the control and experimental drives and was not significantly different ($p = 0.94$). An ORS score of 5 indicated participants were 'asleep', and as such represented the most extreme fatigue rating and the greatest level of risk. An ORS score of 5 was only recorded for two participants; both of these occurred in control drives.

There was a significant ($p < 0.01$) and strong positive correlation ($r = 0.65$) between the level of fatigue reported by the participant (KSS) and that recorded by the observer (ORS) (see Figure 7). Due to the high degree of correlation between these measures, the analysis for this study primarily focussed on KSS which has a greater resolution than ORS.

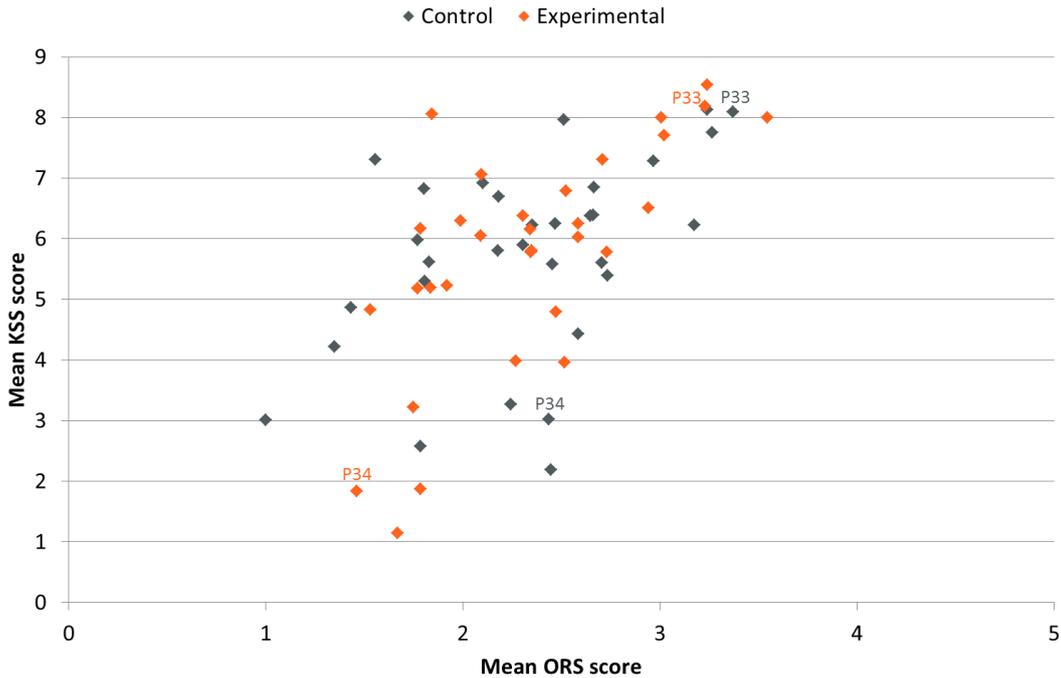


Figure 7: Mean KSS and mean ORS scores for each participant by drive

Mean KSS scores for each participant are shown for the control and experimental drives in Figure 8. There was considerable variability in the reported levels of fatigue with mean KSS scores ranging from 1.1 (very alert) to 8.5 (very sleepy). Mean KSS across the whole sample was 5.8 in both the control and experimental drives and did not differ significantly ($p = 0.89$).

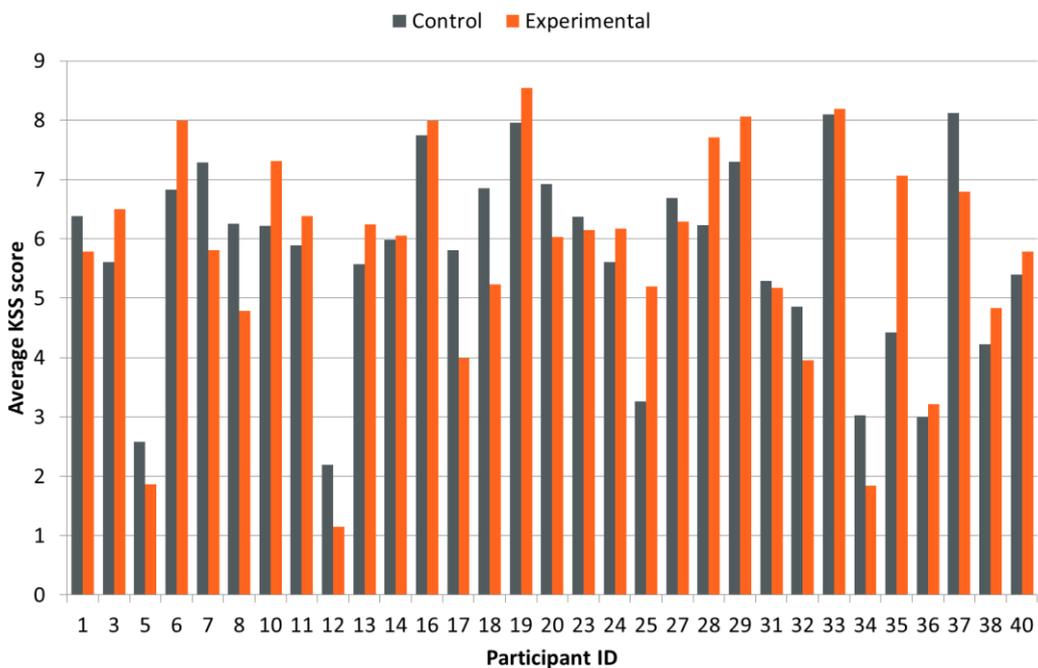


Figure 8: Mean KSS scores reported by each participant in control and experimental drives

Maximum KSS scores reported by each participant are shown in Figure 9. In both the control and experimental drives, nearly half (14 out of 31) of participants reported the maximum

level of 9 on the KSS scale. The mean of maximum KSS scores across the whole sample was 7.7 in the control drive and 7.6 in the experimental drive; maximum KSS scores did not differ significantly ($p = 0.79$) between the control and experimental drives.

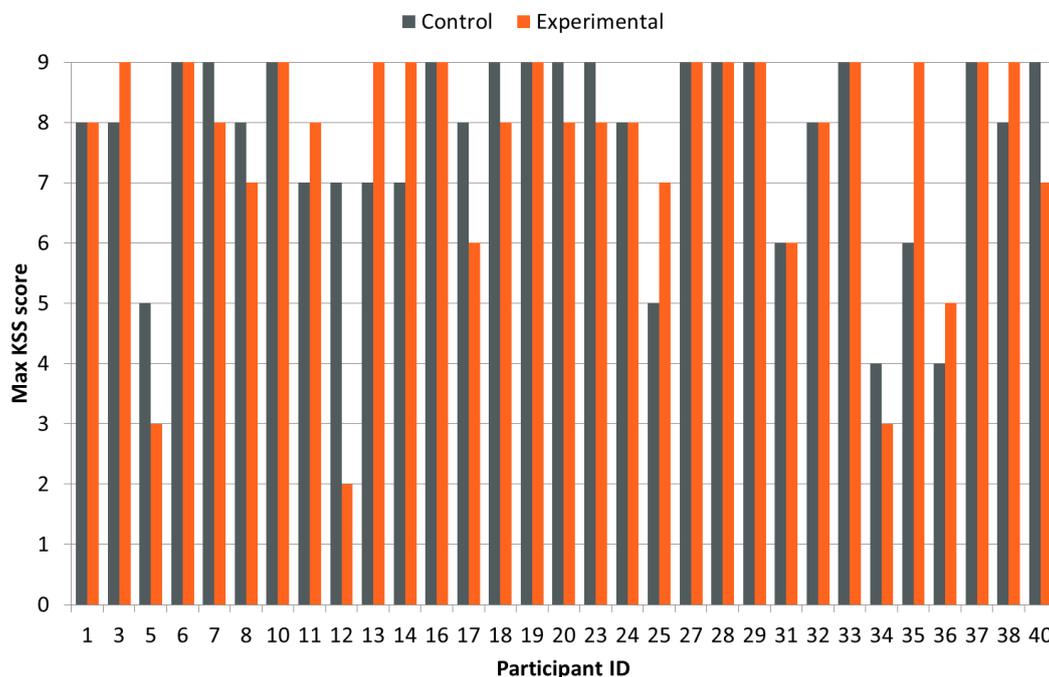


Figure 9: Maximum KSS scores reported by each participant in control and experimental drives

In support of the above comparisons between the control and experimental drive, there were also no significant differences between KSS in the RW sections ($M = 5.8$) and NRW sections ($M = 5.7$) ($p = 0.08$) of the experimental drive.

These findings suggest that participants’ overall levels of self-reported fatigue were similar in the two drives, and were not influenced by the presence or absence of road works in the experimental drive. The following section examines whether the rate of development of fatigue was impacted by the presence or absence of road works.

3.2.2 Development of fatigue

Mean KSS scores (across all participants) for each four minute interval in the control and experimental drives are shown in Figure 10. As illustrated by this figure, there was little difference in the development of fatigue between the two drives; fatigue tended to develop gradually during the first half of the drive and then levelled off after about an hour of driving time. The time to reach a very fatigued state (KSS equal to 8 or 9) is investigated in section 3.2.2.

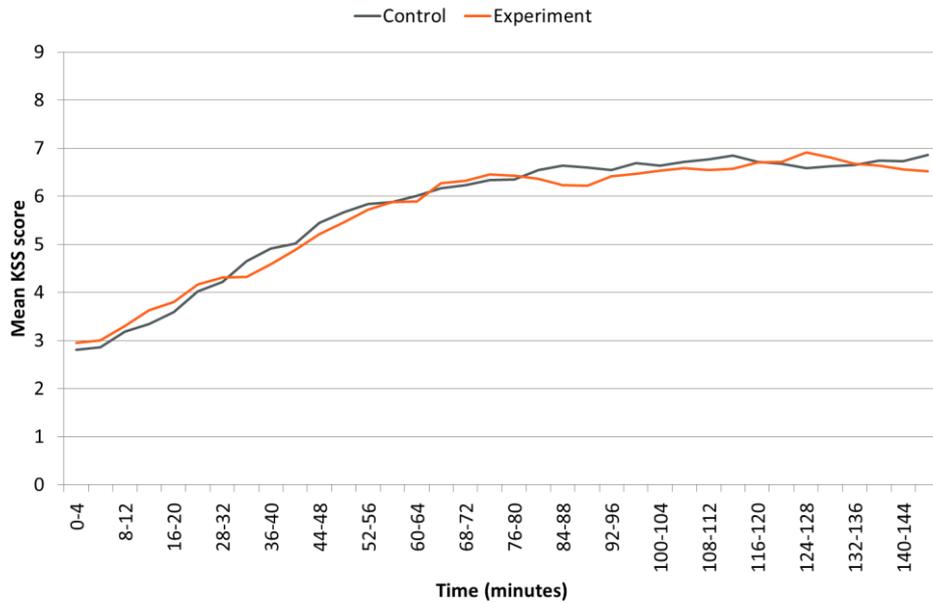


Figure 10: Mean KSS scores across all participants by driving time in control and experimental conditions

The experimental drive was sub-divided into six separate sections depending on whether or not participants were travelling in road works, and the control drive was sub-divided into six sections comparable in duration to those in the experimental drive. Further assessment of how fatigue developed over the course of the drive was made through comparison of the mean KSS scores across these six sections.

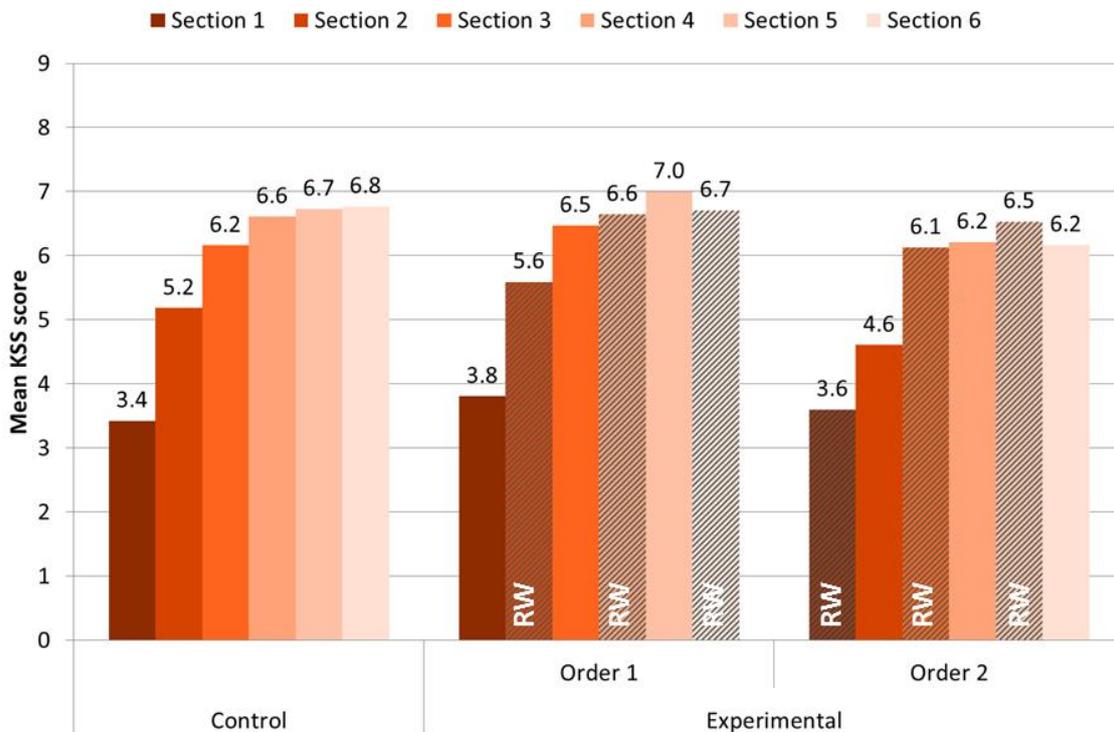


Figure 11: Mean KSS scores in each section of the drive (striped bars represent sections with road works, RW)

Figure 11 shows the mean KSS score in each of the six sections of the control and experimental drives. Statistical comparisons between the six sections revealed a statistically significant difference in KSS scores ($p < 0.01$). In general, self-reported fatigue was lowest in Section 1, increased in Section 2 and Section 3 and then plateaued in Sections 4, 5 and 6.

The development of fatigue over time was also examined using a 'survival analysis'. This is a statistical technique used to assess the time until one or more events happen, and the impact of specific factors on the occurrence of those events. In the context of this study, two survival analyses were performed; one to estimate the time to reach a KSS score of at least 8, and another to estimate the time to reach the maximum KSS of 9. This also enabled assessment of whether the time to onset (i.e. the survival time) differed between control and experimental drives.

The survival curves are shown in Figure 12 and Figure 13; these illustrate how the proportion of 'surviving' participants who have not yet reached a KSS of 8 or 9, respectively, declines as the driving duration increases. Comparative curves are shown for the control and experimental drives.

Survival times for a KSS of 8 and 9 were found to be significantly dependent on whether or not participants were driving in the control and experimental condition ($p = 0.03$ and $p < 0.01$, respectively). However, the magnitude of these differences appears negligible: the mean survival times for a KSS of 8 were 120 and 124 minutes for the control and experimental drives, respectively, and for a KSS of 9, survival times for control and experimental drives were 133 and 134 minutes, respectively. These patterns suggest that participants reached a KSS of 8 and 9, on average, slightly quicker in the control drive (with no road works) than in the experimental drive. However, the small magnitude of these differences support the findings from other analyses described above, which suggest the onset of fatigue was not greatly impacted by the presence or absence of road works.

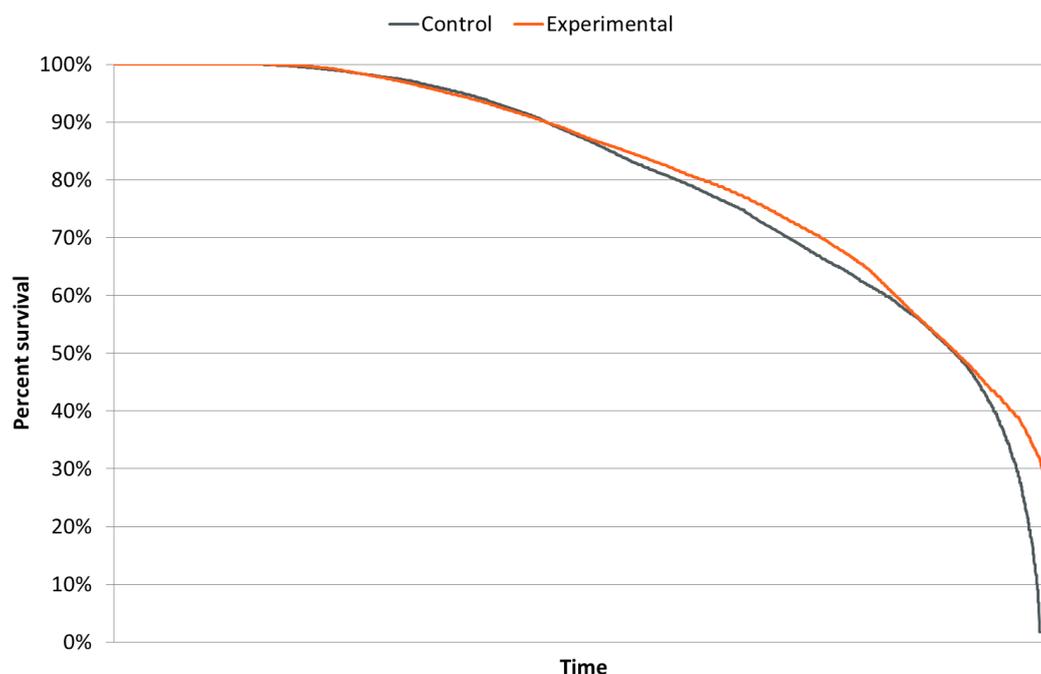


Figure 12: Survival curve for KSS = 8 (proportion of participants who do not reach KSS of 8)

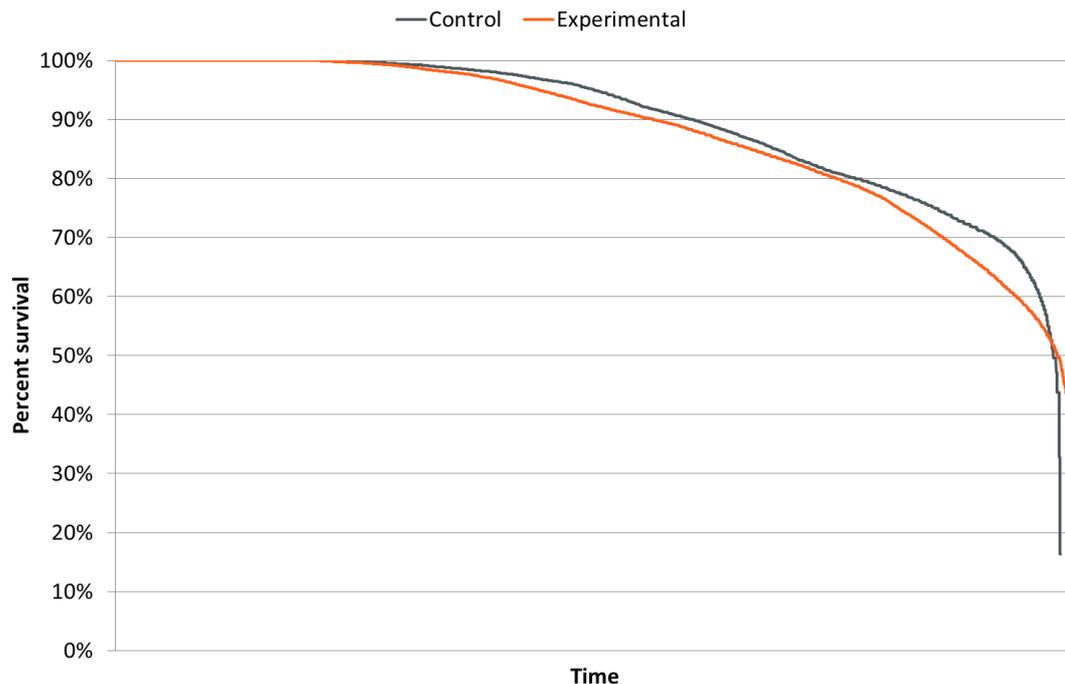


Figure 13: Survival curve for KSS = 9 (proportion of participants who do not reach KSS of 9)

3.2.3 *Fatigue in the transitions in and out of road works*

To test the hypothesis that transitioning between high complexity and low complexity road environments impacts fatigue, the level of fatigue reported by drivers when entering and exiting the road works zones was examined.

Four zones of interest were defined in the experimental drive. The 'transition into road works' zone began just prior to the advance sign area at the start of the road works (i.e. the 1-mile board) and finished 1-mile into the coned works area (i.e. downstream of the taper). The three minute period prior to this 'transition into road works' zone was defined as the 'before transition' zone. The 'transition out of road works' zone was defined as the three minute period before the driver exits the road works. The 'after transition' zone was defined as the three minute period *after* the 'transition out of road works' zone.

Mean KSS was slightly but significantly higher in the 'before transition' zone ($M = 6.3$) than in the 'transition into road works' zone ($M = 6.0$) ($p = 0.047$). Mean KSS was also significantly higher in the 'transition out of road works' zone ($M = 6.6$) than in the 'after transition' zone ($M = 5.8$) ($p < 0.01$). These findings³ suggest that the level of self-reported fatigue was impacted by the transitions between sections with and without road works; possibly, the change in road environment had a slight alerting effect on drivers.

³ Based only on Sections 2, 3, 4 and 5 of the experimental drive (to avoid drives with no 'before transition' or 'after transition' zones in Section 1 and Section 6, respectively)

3.3 Impact of road works on fatigue-related performance impairments

3.3.1 Summary of driver performance measures

Driver performance data were recorded in the TRL DigiCar at 20Hz and then aggregated over 1-minute intervals to facilitate analysis. Mean, minimum, maximum and standard deviations were calculated for a range of measures including speed, headway and lateral lane position. The number of full and partial lane changes, and drivers' lane choices, were also recorded.

3.3.1.1 Speed

Table 3 presents a summary of the statistics relating to speed, including the proportion of time spent travelling above the speed limit (70mph in the control drive and in the NRW section of the experimental drive, and 50mph in the RW section of the experimental drive), and the proportion of time spent travelling above the enforcement limit (Speed limit + 10% + 2mph, in line with ACPO guidance⁴).

Speed performance was broadly comparable in the control drive and NRW sections of the experimental drives; speeds were on average around 63mph (well below the 70mph speed limit) and variability in these speeds was, on average, around 2mph. In the RW section of the experimental drive, average speeds were much lower (around 50mph, in line with the speed limit), and variability was lower (1.4mph, on average). The proportion of time spent speeding was considerably greater in the RW sections of the experimental drive; 42% of the time drivers were travelling above 50mph⁵ and 2.2% of the time they were above the enforcement limit of 57mph.

Table 3: Aggregated speed statistics for control and experimental drives

Measure	Control	Experimental	
		No road works (NRW)	Road works (RW)
Mean speed (mph)	63.2	63.5	50.1
Maximum speed (mph)	85.3	80.9	73.3
Mean standard deviation of speed (mph)	2.1	2.4	1.4
Proportion of time spent above speed limit	2%	3%	42%
Proportion of time spent above enforcement limit	0.0%	0.0%	2.2%

⁴ Association of Chief Police Officers (ACPO) Speed Enforcement Policy Guidelines 2011-2015 suggest that a Fixed Penalty or speed awareness education may be appropriate when the speed is 10% +2mph above the speed limit (Paragraph 9.6). These are only guidelines and a police officer/ force can enforce at a speed lower than this limit assuming they have considered the tolerance of measurement equipment (Paragraph 9.7).

⁵ Increasing the threshold to 51mph and 52mph reduced this proportion to 22% and 16%, respectively.

3.3.1.2 Headway

Headway was defined as the distance (m) from the front of the participant's vehicle to the rear of the vehicle ahead. A short headway represents an increased collision risk since this offers a reduced stopping distance; this is exacerbated if maintained over long periods (i.e. close following behaviour). The Highway Code suggests that on roads carrying fast moving traffic, drivers should allow a gap of at least two seconds between themselves and the vehicle in front, with this distance doubled on wet or icy roads.

Headway is recorded in DigiCar up to a maximum of 245m; values greater than this are recorded as missing and so were removed from the analysis. Mean, minimum and standard deviations of headway are presented in Table 4.

Table 4: Aggregated headway statistics for control and experimental drives

Measure	Control	Experimental	
		No road works (NRW)	Road works (RW)
Mean headway (m)	87.0	101.7	123.0
Minimum headway (m)	0.0	0.4	1.4
Mean standard deviation of headway (m)	26.8	29.2	15.4
Proportion of time spent with headway less than 2s	40%	30%	13%

Mean headway was longer in the experimental drive ($M = 109\text{m}$, $SD = 24\text{m}$) than the control drive ($M = 87\text{m}$, $SD = 26\text{m}$); these differences were statistically significant ($p < 0.01$). Mean headway was also significantly longer ($p < 0.01$) and less variable in the RW sections of the experimental drive than the NRW sections. As a result, there was a much smaller proportion of time (13%) spent with a headway less than 2 seconds compared to the NRW section of the experimental drive (30%) and the control drive (40%).

3.3.1.3 Lane position

Lateral lane position measures the position of the vehicle within a lane, and so can be used to determine the amount of lateral movement within the lane, including the extent to which the driver departed to the nearside or offside of lane markings. Values are coded with negative values to the right of the centre of the lane, and positive values to the left. Table 5 presents the mean lateral lane position and the mean standard deviation of lateral lane position.

The mean lateral lane position was 6cm to the left in the control drive and 10cm to the right in the experimental drive; this represented a statistically significant difference ($p < 0.01$). Comparison between the control drive and the NRW section of the experimental drive shows similar values, however in the RW section of the experimental drive, the mean values suggest a tendency for drivers to travel slightly to the right of the centre of the lane.

Table 5: Aggregated lateral lane shift statistics (all participants) by drive and section

Measure	Control	Experimental	
		No road works (NRW)	Road works (RW)
Mean lateral lane position (m)	0.06	0.02	-0.25
Mean standard deviation of lateral lane position (m)	0.41	0.42	0.26

This pattern is illustrated in Figure 14 which shows the mean lateral lane position for all 31 participants. Typically, participants travelled slightly to the left of the centre of the lane in the control drive and slightly to the right in the experimental drive. This may be due to the presence of narrow lanes and a concrete barrier on the nearside of Lane 1 in the road works sections.

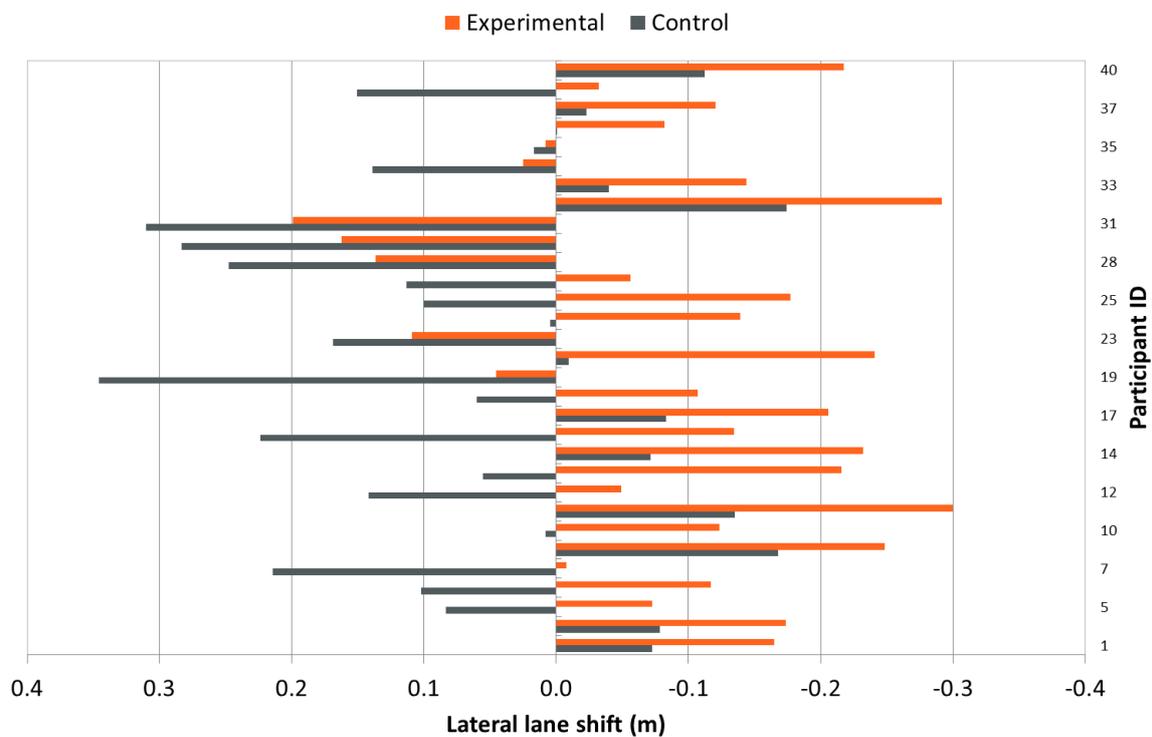


Figure 14: Mean lateral lane shift for each participant in control and experimental drives

3.3.1.4 Lane choice

Figure 15 shows driver lane choices in the control and experimental drives. In the RW section of the experimental drive, participants spent a greater proportion of time travelling in Lane 1 (60%) compared to the NRW section (20%) and the control drive (24%).

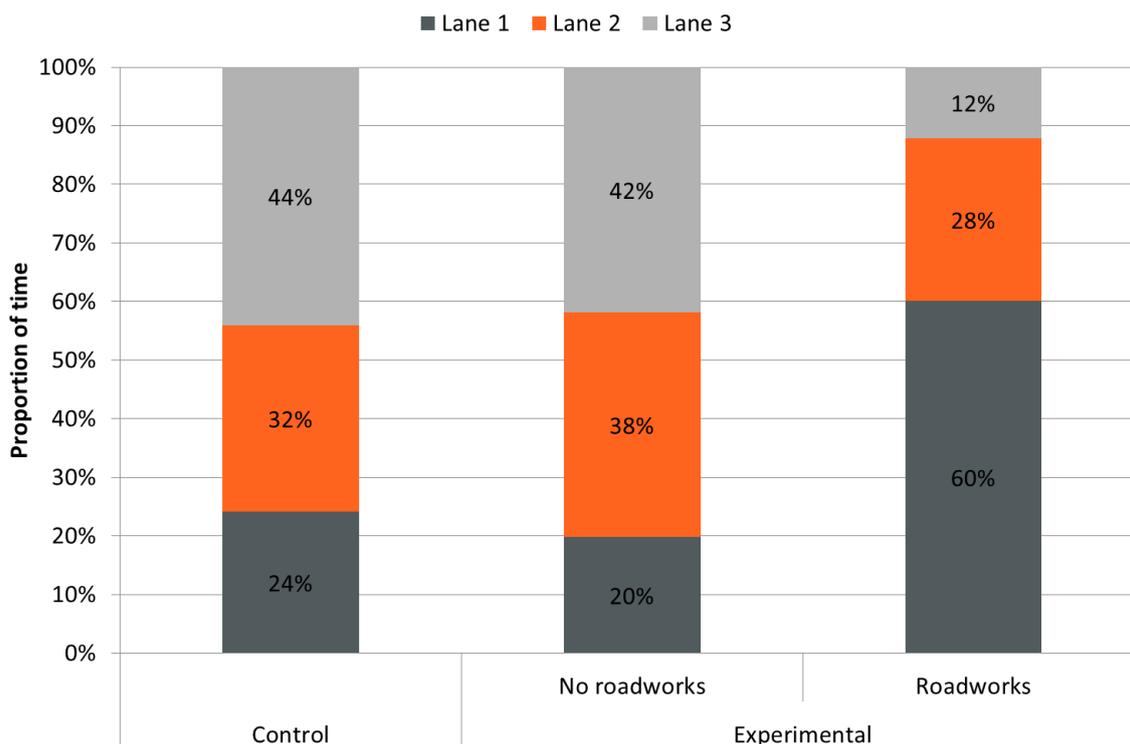


Figure 15: Proportion of time spent in each lane (aggregated across all participants)

The number of lane changes and the number of lane *drifts* were also recorded for each drive (see Table 6).

Table 6: Lane change and drift statistics (all participants) by drive and section

Measure	Experimental		
	Control	No road works (NRW)	Road works (RW)
Mean number of lane changes per 100 miles driven	90	118	31
Mean number of lane drifts per 100 miles driven	7	8	18
Mean duration of lane drifts (s)	2.35	2.01	3.31

As described in section 2.6.2, lane changes were defined as incidences where the driver changed from one lane to another within a 5 second window, and lane drifts were defined as incidences where the driver ‘drifted’ out of a lane but did not fully change into a different lane within a 5-second window.

Participants changed lane most frequently in the NRW section of the experimental drive ($M = 118$ lane changes per 100 miles driven) and least frequently in the RW section of the experimental drive ($M = 31$ lane changes per 100 miles driven). In contrast, lane drifts were more common and lasted longer in the RW section of the experimental drive. The occurrence of lane drifts (i.e. unintentional deviations from a lane) are a strong indicator of

fatigue; these findings therefore support the hypothesis that fatigue-related performance impairments were worse in road works.

3.3.1.5 Reaction times

During all drives participants were required to undertake a series of reaction time tasks (see section 2.6.2). On average, reaction times were slowest in the road works section of the experimental drive ($M = 1.99$ s) and quickest in the control drive ($M = 1.65$ s). The difference in reaction times between the control and experimental drives was significant ($p = 0.01$).

Figure 16 shows the distribution of reaction times for the control and experimental drive. The vast majority (over 60%) of reaction times recorded were between 1-2 seconds. Typical stopping distances estimated by the Department for Transport are based on reaction times of 0.67 seconds and assume an alert and unimpaired driver⁶; a very small proportion of reaction time events were less than 1 second suggesting the levels of impairment observed in this study were, typically, greater than is considered safe. There was a greater incidence of participants failing to react ('no reaction') in the RW section of the experimental drive; supporting the hypothesis that reaction times were particularly impaired in this condition.

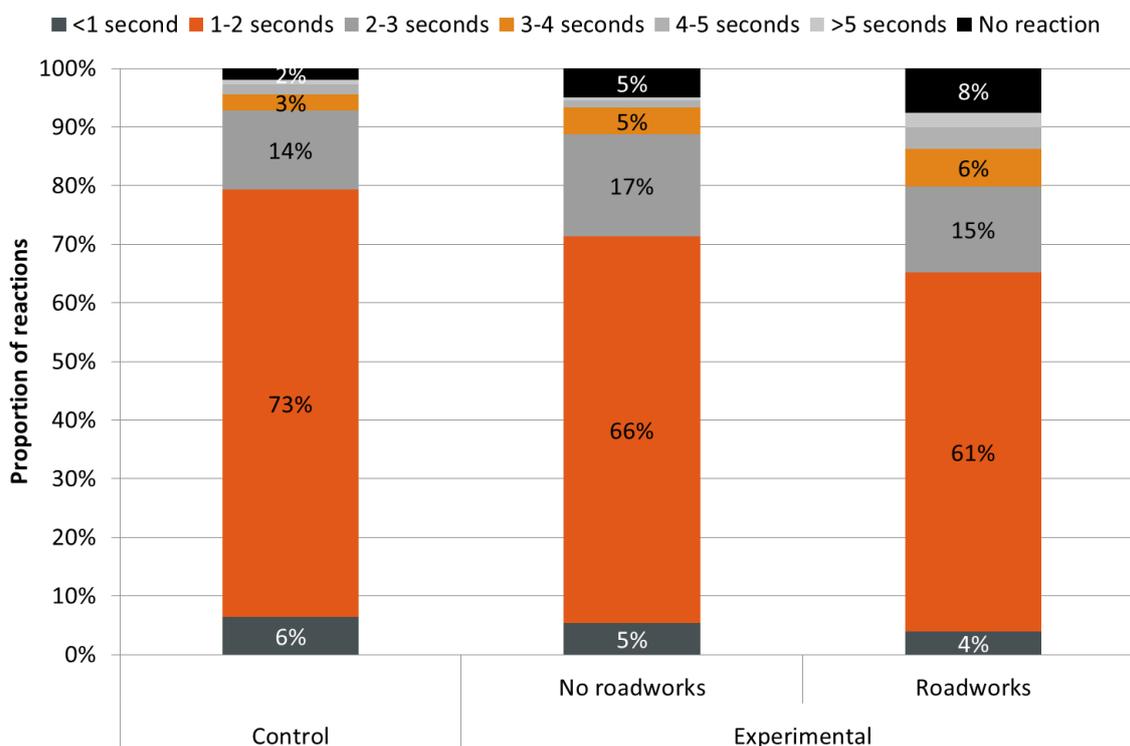


Figure 16: Distribution of reaction times by drive and section

3.3.1.6 Comparison between road works and non-road works sections

Table 7 presents summary statistics of the key performance measures for the non-road works and road works sections of the experimental drive. The orange cells highlight the

⁶ <http://www.brake.org.uk/rsw/15-facts-a-resources/facts/1255-speed>

condition which is likely to represent an increase in collision risk. With the exception of the proportion of time spent travelling at unsafe headways, performance was lower in the RW sections of the experimental drive than in the NRW sections; statistical comparisons showed that the differences were significant ($p < 0.05$).

Table 7: Comparison of fatigue-related performance measures between the non-road works and road works sections of the experimental drive

Performance measure	Experimental	
	No road works	Road works
Proportion of time spent travelling above the enforcement threshold	0%	2%
Proportion of time spent driving at unsafe headway (less than 2 seconds)	30%	14%
Number of lane drifts	199	422
Average duration of lane drift (s)	2.02	3.31
Average reaction time (s)	1.71	1.99

On balance, the road works sections are seemingly higher risk; the proportion of time spent above the speed limit, the number and duration of lane drifts and the average reaction times were higher than in the sections of the drive with road works.

3.3.2 *Development of fatigue-related performance impairments*

The analyses described in section 3.2 showed that there were no significant differences in the level of self-reported fatigue or the development of fatigue between the control and experimental drives. Despite the apparent similarities in the level of fatigue experienced during the two drives, it is possible that the manifestation of fatigue-related performance impairments were impacted by the presence or absence of road works. To investigate this driver performance was compared across the six sub-sections of each drive in order to identify the extent to which performance changed as fatigue increased.

3.3.2.1 *Speed*

The proportion of time spent above the speed limit and above the enforcement limit, in each of the six sections, is shown in Figure 17 and Figure 18, respectively. On average, for those participants who experienced road works in Sections 2, 4 and 6 of the experimental drive (order 1), the proportion of time spent above the enforcement threshold was highest (6%) in the first set of road works (i.e. in Section 2). However, a slightly different pattern was found for participants who experienced road works in Section 1, 3 and 5 (order 2). Possibly, the increased prevalence of speeding in Order 1 resulted from the unanticipated transition from the 70mph speed limit in the first section of the drive with NRW to a 50mph speed limit in the second section of the drive with RW. Drivers in Order 2 started their drive in the

50mph section, and so were not impacted by an unexpected drop in speed limit in the same fashion.

From these patterns there is no strong indication that speeding behaviour changed as a result of increasing fatigue through the drive.

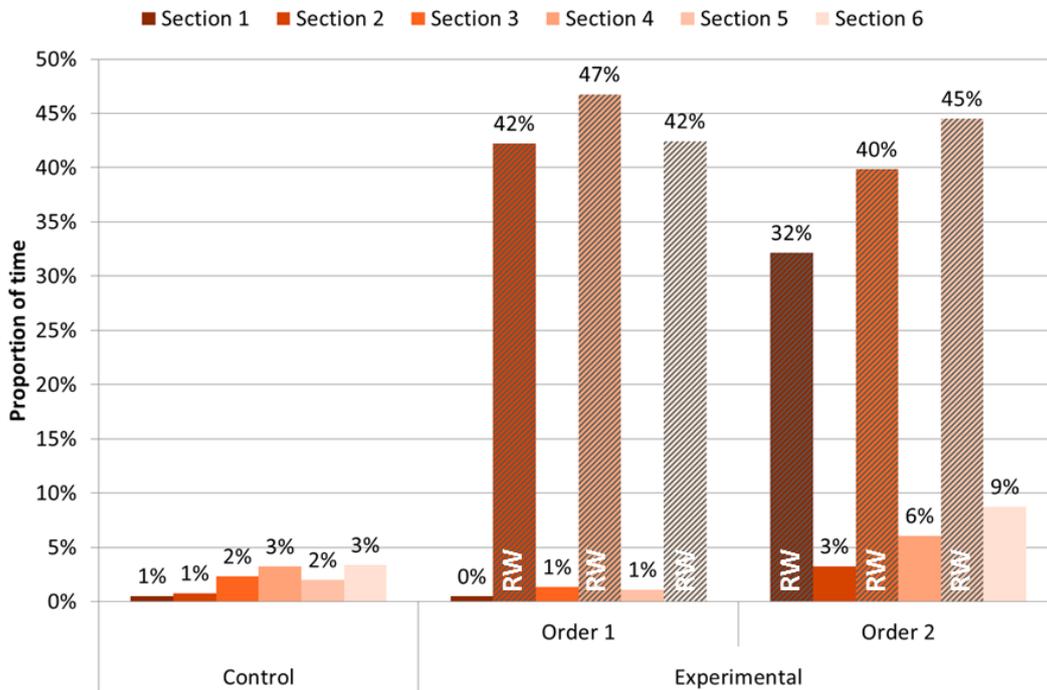


Figure 17: Proportion of time spent above the speed limit (striped bars represent sections with road works)

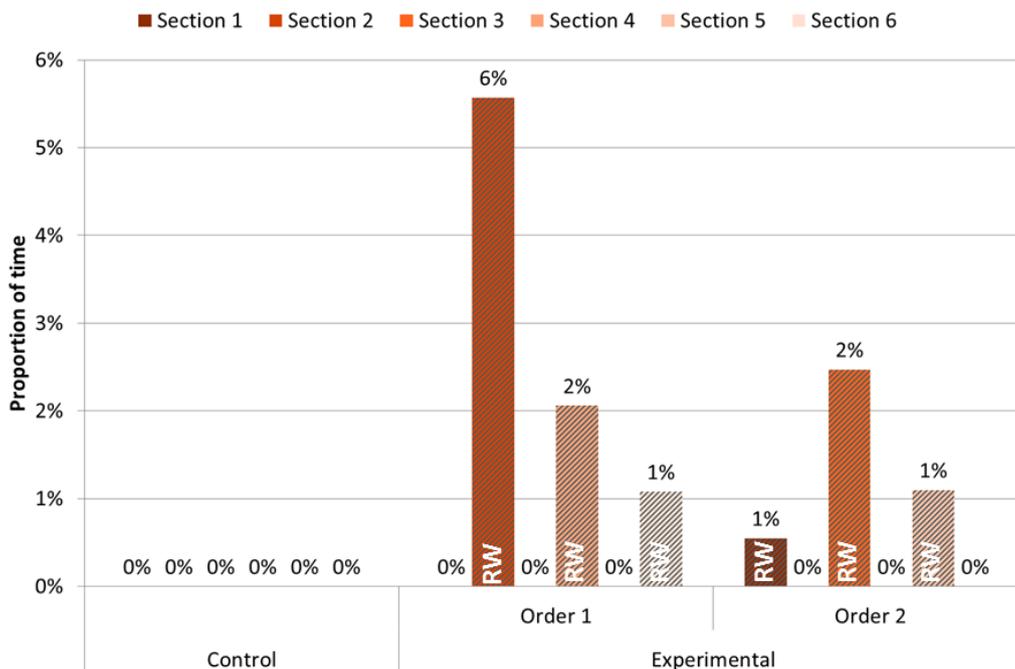


Figure 18: Proportion of time spent above the ACPO enforcement limit (striped bars represent sections with road works)

3.3.2.2 *Headway*

The proportion of time spent at unsafe headways was lower in the RW sections of the experimental drive; however, there was no clear increasing or decreasing trend across the sections of any of the drives. This suggests that the proportion of time spent at unsafe headways was not linked to the increasing levels of fatigue observed in the drives.

3.3.2.3 *Lane choice*

In the control drive and NRW sections of the experimental drive, there was no clear trend for increasing or decreasing number of lane drifts across the six sections of the drive. However, in the RW sections of the experimental drive, there was a trend for a decreasing number of lane drifts through the drive. Whilst the number of lane drifts decreased with driving time, the mean duration of lane drifts increased in both the NRW and RW sections of the experimental drive. This suggests that lane drifts became less frequent but more severe as the driving duration increased. The severity of the lane drifts was higher in the RW sections than the NRW; this trend suggests that the reduction in lane keeping performance observed in the RW section may have been linked with the increase in fatigue through the drive.

3.3.2.4 *Reaction times*

There was no clear increasing or decreasing trend in mean reaction times between the six sections of the drive. This suggests that the participants' reaction times were not linked to the level of self-reported fatigue.

3.3.3 *Driver performance in the transitions into and out of road works*

As described in section 3.2.3, four zones of interest were defined in the experimental drive in order to assess the impact of the transitions in and out of road works on driver fatigue and performance.

Table 8 shows the key driver performance metrics for the 'before transition' and 'transition into road works' zones. The orange cells highlight the condition in which each performance measure is likely to represent an increase in collision risk⁷.

⁷ Due to limited sample size within these transition zones it was not possible to perform statistical comparisons.

Table 8: Comparison of performance measures between the ‘before transition’ and ‘transition into road works’ zones⁸

Performance measure	Experimental	
	Before transition	Transition into road works
Proportion of time spent travelling above the enforcement threshold	0%	1%
Proportion of time spent driving at unsafe headway (less than 2 seconds)	31%	10%
Number of lane drifts	20	13
Average duration of lane drift (s)	1.39	2.07
Average reaction time (s)	1.71	2.14

The table suggests that with the exception of time spent travelling at unsafe headway and the number of lane drifts, driver performance is typically worse in the transition into the road works than prior to this point. The equivalent figures for the transition out of road works are shown in Table 9.

Table 9: Comparison of performance measures between the ‘transition out of road works’ and ‘after transition’ zones⁸

Performance measure	Experimental	
	Transition out of road works	After transition
Proportion of time spent travelling above the enforcement threshold	5%	0%
Proportion of time spent driving at unsafe headway (less than 2 seconds)	15%	11%
Number of lane drifts	49	22
Average duration of lane drift (s)	5.63	2.28
Average reaction time (s)	2.02	1.95

In this case, comparison of the key performance metrics suggests that driver performance was worse in the transitional period just before leaving the road works than in the three-minute period immediately after exiting the works.

⁸ Sections 2, 3, 4 and 5 of the experimental drive only.

3.4 Qualitative data reported by participants

At the end of each drive, participants were asked to provide feedback on their experience. Common themes which emerged from these data are described in the following sections.

3.4.1 Perceived impact of road works on fatigue

Participants were asked to describe, in their own words, how fatigued they felt during the drive and when or where they became aware of their fatigue. Some participants reported feeling more fatigued when driving through road works, although this was not supported by participants’ reported KSS scores (see section 3.2). The lower speed limit, a monotonous sensation, and a perception of more consistent traffic flows, with reduced lane changing, were among the reasons why some participants felt they were more fatigued in the road works sections.

3.4.2 Relationship between road works and driver workload

Participants were asked to indicate the level of effort they felt was required to perform different aspects of the driving task: maintaining a consistent speed; lane keeping; maintaining a safe headway, and – in the experimental drive only - changing between speed zones. Figure 19 displays participants’ ratings of the level of effort required when the speed limit was 50mph versus 70mph in the experimental drive.

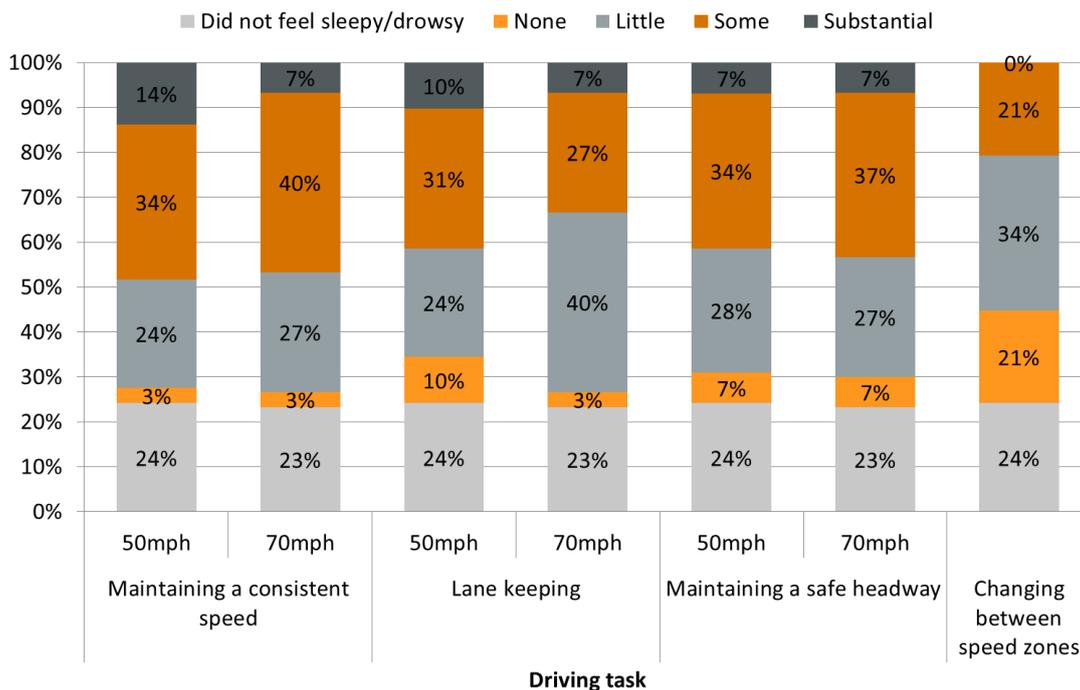


Figure 19: Level of effort required for aspects of the experimental drive

Compared with 70mph, a larger proportion of participants reported that a ‘substantial’ amount of effort was required to maintain a consistent speed in the 50mph speed limit. This corresponds with the finding that speeding was more prevalent in the road works section (section 3.3.1.1).

A slightly larger proportion of participants stated that at least ‘some’ effort was required to keep in the lane when the speed limit was 50mph compared with when it was 70mph; this is supported by the finding that lane drifts were more common and lasted longer in the road works than in the no road works section (see section 3.3.1.3). Possibly, the presence of narrow lanes within these sections may have increased the perceived task demand.

The reported level of effort required to maintain a safe headway was similar between the road works and no road works sections. There was however a difference in driving performance; drivers spent a greater proportion of time travelling at an unsafe headway (less than 2s) in the NRW sections than in the RW sections (see section 3.3.1.2).

3.4.3 Decision to stop driving

After both drives, participants were asked to indicate whether they had felt sleepy or drowsy, and if so, whether they would have stopped driving had they been in a real car on a public road. Table 10 shows participants’ responses for the two drives.

Table 10: Self-reported fatigue and decision to stop driving

Measure	Control	Experimental
Did you feel sleepy/drowsy?		
Yes	93%	87%
No	7%	13%
(If yes) Would you have stopped driving?		
Yes	82%	88%
No	18%	12%

A high proportion (more than 85%) of participants reported feeling sleepy or drowsy after both drives. Of those who did report feeling sleepy or drowsy, the majority of participants stated that they would have stopped driving in the experimental drive (88%) and in the control drive (82%).

Participants who stated that they would have stopped driving were also asked to state how long into the drive they would have made a decision to stop; the responses are summarised in Table 11.

Table 11: Decision to stop driving due to sleepiness or drowsiness

Time to decision to stop (minutes)	Control	Experimental
Minimum	30.0	20.0
Maximum	130.0	130.0
Mean (SD)	75.7 (28.0)	75.7 (33.0)

The results show that in both drives, on average participants would have chosen to stop after just over 75 minutes of driving. The range of responses for both drives was similar.

Participants were also asked to indicate when in the drive they would have liked to have seen services or other rest break opportunities had they been driving on a real road. Most participants described a specific point in the drive at which they would have liked to have stopped, which corresponded with the data in Table 11. In other instances, participants stated a preference for repeated rest break opportunities. The desired rest break intervals varied and were described in different ways (e.g. every hour for some, or every 50 miles for others). A few participants reported that they wanted to see services as frequently as every 30 minutes or every 30 miles so that they could make a choice about whether or not to stop knowing that it would not be long until the next rest opportunity.

More participants wanted to see at least two service stations in the experimental drive (n = 8) than in the control drive (n = 2). Two participants made reference to the road works, stating that they wanted to see services after the second section of road works. These two participants reported mainly feeling fatigued in the road works section of the drive.

3.4.4 Self-reported signs of fatigue

After each drive, participants who reported feeling fatigued were asked to describe what alerted them to their fatigue, in their own words. Analysis of these data revealed that responses fell into two broad categories: cognitive and physiological signs, and driving performance indicators. That is, participants were alerted to their fatigue by internal sensations and experiences and/or via their interaction with the vehicle, the road or other road users.

Table 12 shows the types of cognitive and physiological signs reported by participants after the experimental and control drives.

The data indicate that most types of the cognitive and physiological signs reported were common to both the experimental and control drives. Blurred vision, gazing, agitation and a trance-like feeling were only reported after the experimental drive. This is supported by other qualitative comments which suggested that some participants experienced 'monotony' when driving through the road works. However, due to the limited number of reports and the qualitative nature of these data, it is not possible to conclude whether or not these sensations were unique to the experimental drive.

Table 12: Self-reported cognitive and physiological signs of fatigue

Category	Specific signs	Experimental	Control
Sleepiness	<ul style="list-style-type: none"> • Difficulty staying awake • Micro-sleeps • Falling asleep 	✓	✓
General tiredness	<ul style="list-style-type: none"> • Lethargy • Weariness 	✓	✓
Impaired concentration	<ul style="list-style-type: none"> • Reduction in concentration • Difficulty concentrating 	✓	✓
Sensations in eyes	<ul style="list-style-type: none"> • Difficulty keeping eyes open • Heavy eyelids 	✓	✓
Head movements	<ul style="list-style-type: none"> • Head nodding • Head dropping 	✓	✓
Sensations in head	<ul style="list-style-type: none"> • Heavy head • 'Fuzzy' head 	✓	✓
Yawning		✓	✓
Vision changes	<ul style="list-style-type: none"> • Blurred vision • Gazing 	✓	
Trance-like feeling		✓	
Agitation		✓	

Table 13 shows the types of driving performance indicators of fatigue reported by participants at the end of the experimental and control drives.

These data indicate that most types of interactions with the vehicle, road and other vehicles that signalled fatigue were common to both the experimental and control drives. Indicators relating to the lateral position of the vehicle were most common. Difficulties relating to speed were noted in the experimental drive but not in the control drive. This pattern supports the driver performance data which showed participants spent a greater proportion of time driving above the speed limit and enforcement limit in the RW sections of the experimental drive than the NRW sections. This also corresponds with the finding that the proportion of participants who said they felt sleepy or drowsy and needed a 'substantial' amount of effort to maintain a consistent speed was greater in the 50mph sections than in the 70mph sections of the experimental drive.

It is noteworthy that some participants did not identify any cognitive or physiological signs of their fatigue, and did not become aware of their fatigue until their driving performance was already impaired. This highlights a need for drivers to develop awareness of the early signs of fatigue so that action can be taken to prevent unsafe driving.

Table 13: Self-reported driving performance indicators of fatigue

Category	Specific signs	Experimental	Control
Position in lane	<ul style="list-style-type: none"> • Difficulty staying in the lane • Drifting into another lane 	✓	✓
Position on carriageway	<ul style="list-style-type: none"> • Driving on the hard shoulder • Waking up in a different lane 	✓	✓
Driving style	<ul style="list-style-type: none"> • Driving reactively • Less planning or forward thinking before manoeuvres • Being 'brash' • Making errors 	✓	✓
Steering	<ul style="list-style-type: none"> • Making sharp steering adjustments 	✓	✓
Interactions with other vehicles	<ul style="list-style-type: none"> • Collisions with other vehicles 	✓	✓
Perceptual difficulties	<ul style="list-style-type: none"> • Misjudging the distance of other vehicles • Difficulty telling whether the brake lights of other vehicles were illuminated 	✓	✓
Speed	<ul style="list-style-type: none"> • Varied speed • Difficulty adhering to the speed limit 	✓	

4 Discussion

The purpose of this study was to investigate the extent to which road works impacts on the development of driver fatigue and the manifestation of fatigue-related performance impairments. This was accomplished by recruiting a sample of drivers from the general population to undertake controlled drives in the TRL 'DigiCar' driving simulator, allowing assessment of the relationship between driver fatigue and road works in a safe environment, whilst controlling for confounding factors such as weather, traffic behaviour, road layout, incidents, caffeine intake and driver health conditions.

Fatigue was principally measured in two ways; self-reported fatigue using the Karolinska Sleepiness Scale (KSS) and observer ratings of fatigue using the ORS scale. These two measures were found to be highly correlated, and so the principal analysis focussed only on KSS. The overall levels of fatigue reported by participants were highly variable; some reported remaining alert throughout the whole drive, others reported a KSS score of 9 'very sleepy, great effort to keep awake'. A high percentage of participants reported that they would have stopped driving due to fatigue if they had been travelling on a real road. Overall levels of fatigue were not significantly different between the control and experimental drives, and the time at which participants would have chosen to stop was similar.

In general, self-reported fatigue increased gradually over the first half of the drive (approx. 1 to 1.5 hours) and then plateaued in the second half of the drive; this is in line with previous studies which have shown the relationship between time-on-task and driver fatigue (e.g. Jackson *et al.*, 2011). The rate at which fatigue developed was not found to differ between the control drive and the experimental drive. Taken together, this evidence indicates that the presence of road works in the experimental drive did not impact on the severity of fatigue experienced by drivers, or the rate at which fatigue developed during the drive.

Despite the similarities in self-reported fatigue experienced during the two drives, evidence suggested a tendency for greater impairments to driving during the experimental drive (with road works) compared with the control drive (without road works). This included:

- A greater proportion of time spent above the speed limit and above the enforcement limit in the road works;
- A greater shift in lateral position within the lane, with a tendency to shift to the right-hand side (away from the concrete barrier in the road works section);
- A reduction in the number of deliberate lane changes but an increase in the number and duration of unintentional 'drifts' out of lane in the road works, and;
- Slower reaction times in the road works.

On the other hand, drivers spent a smaller proportion of time travelling with 'unsafe' headways less than 2 seconds in the road works. These findings suggest that when in the road works, drivers were more likely to remain in Lane 1, following the traffic ahead at a comfortable and safe distance. However, the greater frequency and duration of lane drifts and slower reaction times indicate a greater propensity for lapses in concentration when travelling through the road works. Lane drifts were longer in the road works sections than the non-road works sections; the frequency of those lane drifts decreased, but the *duration* of the lane drifts increased during the drive. This evidence suggests that not only was lane

keeping performance worse in the road works (where the lanes were narrowed) but that those impairments worsened with the duration of the drive. This trend may be linked with increasing fatigue; there may be a greater likelihood of driver errors while fatigued due to the increased complexity of the driving task when travelling in road works.

This was supported by analysis of the transitional periods between road works and non-road works sections. Reaction times, the number and duration of lane drifts, and the proportion of time spent travelling above the enforcement limit, were greater when drivers were transitioning into the road works compared to when they were travelling just prior to the start of the works. Similarly, driver performance was worse in the transitional period just before leaving the road works than in the three-minute period immediately after exiting the works. This suggests that changes in complexity of the road environment can impact on driver performance. These findings support the hypothesis that fatigue-related performance impairments may be most prevalent when transitioning from high demand sections of road to low demand sections of road, and vice versa (as reported by Smith *et al.*, 2009 and Liu and Wu, 2009).

Michael (2009) found driving performance to be worst in fatigued drivers when travelling in monotonous driving conditions with low variability in road design (i.e. motorway-type roads with flat, straight cambers) and high variability in roadside stimuli (e.g. signage and other roadside clutter). These types of conditions are synonymous with motorways and major trunk roads on the Highways England SRN. This supports the findings from the current study, which shows evidence of reduced performance when drivers were travelling through road works (where roadside stimuli were more variable) compared with when they were travelling on sections of motorway without road works.

One of Highways England's key strategic aims is to reduce the number of fatalities on the SRN, and so it is of great importance to understand the factors which increase collision risk. The current study examined general trends in fatigue and driver performance in sections of road with and without road works, using subjective measures of fatigue and objective measures of performance. The findings suggest that subjective levels of fatigue were, generally, not impacted by the presence or absence of road works, yet there were some significant differences in objective measures of driving performance which suggested an increased risk of collision when travelling through the road works.

Further research could be undertaken to examine the occurrence and severity of momentary 'fatigue events', when drivers are most at risk of collision, including how they interact with characteristics of the road environment (such as road works entry and exit tapers and other traffic management infrastructure). Future work should target objective measures of fatigue which are likely to be more sensitive to continual changes in driver state than subjective rating scales. These might be physiological measurements such as heart rate and heart rate variability, skin conductance, body temperature, respiration rate, and the number and duration of eye blinks and eye closures. When combined with objective driver performance data obtained through the 'DigiCar' driving simulator, measurement of these physiological responses would allow capture of a rich dataset on driver state and the factors which impact risk. This analysis could also be used to inform the design and implementation of environment-based countermeasures for driver fatigue, such as the use of rumble strips or roadside signing.

Of particular note from this study was that the severity of lane drifts was greater in road works with narrow lanes than in sections without road works (and standard width lanes). This has potential implications for the management of risk to customers on the SRN; if the use of narrow lanes at road works reduces drivers' ability to maintain a central position in the lane then their use might increase risk to road users and road workers on the network. It is of great importance therefore to assess the extent to which lane keeping performance differs in road works with different lane widths. Comparisons of driver performance in road works with standard width lanes with performance in road works with narrow width lanes would reveal whether or not the width of the lane is an important factor contributing to risk. Some preliminary investigation into this topic could be undertaken utilising the DigiCar simulator data captured in the current study and comparable data collected for previous studies undertaken by TRL. A greater understanding of the issues associated with narrow lanes could help to inform the design and implementation of TM at future road works schemes and contribute to a reduction in risk.

5 Conclusions and recommendations

This driving simulator study investigated the impact of travelling through Major Scheme motorway road works on the severity and onset and of fatigue, and the manifestation of fatigue-related performance impairments.

The level of self-reported fatigue and the rate at which fatigue developed during the 2.5 hour simulated drives was not found to be dependent on the presence or absence of road works. This suggests that driving through road works did not greatly impact the likelihood of whether or not drivers became fatigued in the study.

However, evidence suggested there were greater impairments to driver performance when driving through motorway Major Scheme road works compared with driving on a motorway without road works. Performance was also worse in the transitional periods at the start and end of the road works compared to the periods immediately before and after the transitions.

These findings provide evidence that the likelihood of driver errors while fatigued may be higher when travelling through road works, thereby increasing the risk of collision. Of particular note was that the severity of lane drifts was greater in road works with narrow lanes than in sections without road works (and standard width lanes). This has potential implications for the management of risk on the SRN; if the use of narrow lanes at road works reduces drivers' ability to maintain a central position in the lane then their use might increase risk to road users and road workers on the network. It is therefore important to assess the extent to which lane keeping performance differs in road works with different lane widths. A greater understanding of the issues associated with narrow lanes could help to inform the design and implementation of TM at future road works schemes.

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