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Drivers' ability to learn eco-driving skills; effects on fuel efficient and safe driving behaviour

Samantha L. Jamson *, Daryl L. Hibberd, A. Hamish Jamson

Institute for Transport Studies, University of Leeds, UK

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ABSTRACT

Whilst driving is inherently a safety–critical task, awareness of fuel-efficient driving techniques has gained popularity in both the public and commercial domains. Green driving, whether motivated by financial or environmental savings, has the potential to reduce the production of greenhouse gases by a significant amount. This paper focusses on the interaction between the driver and their vehicle – what type of eco-driving information is easy to use and learn whilst not compromising safety. A simulator study evaluated both visual and haptic eco-driving feedback systems in the context of hill driving. The ability of drivers to accurately follow the advice, as well as their propensity to prioritise it over safe driving was investigated. We found that any type of eco-driving advice improved performance and whilst continuous real-time visual feedback proved to be the most effective, this modality obviously reduces attention to the forward view and increases subjective workload. On the other hand, the haptic force system had little effect on reported workload, but was less effective that the visual system. A compromise may be a hybrid system that adapts to drivers' performance on an on-going basis.

1. Introduction

Whilst the process for gaining one's driving licence varies widely worldwide, the underlying premise of both professionally run training courses and the subsequent driving test, is that of safety. Safe driving has been studied extensively and league tables are produced regularly to monitor the global impacts of road deaths. As an example, the WHO Global status report on road safety (2013) serves as a baseline for the Decade of Action for Road Safety 2011–2020, declared by the UN General Assembly. Being such a high profile concern (road accidents are one of the top ten causes of death worldwide), and with motoring consumers having access to independent assessments of the safety performance of vehicles via EuroNCAP, it is not surprising that vehicle manufacturers have focussed their research and development efforts on safety systems. These safety systems range from those that provide advice (e.g. curve speed warning) to those that intervene in safety–critical situations (e.g. emergency brake assist).

Fuel efficiency ratings are also readily available and published by vehicle manufacturers. Nearly all new car models which are type approved for sale in the European Union have to undergo standard tests to determine their fuel consumption. However, the fuel consumption figures quoted are obtained under specific test conditions, and therefore may not necessarily be achieved in 'real life' driving conditions. A range of factors may influence actual fuel consumption – for example, external

* Corresponding author at: Institute for Transport Studies, University of Leeds, Leeds LS2 9JT, UK. Tel.: +44 (0)113 3436606; fax: +44 (0)113 3435334.
E-mail address: S.L.Jamson@its.leeds.ac.uk (S.L. Jamson).

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temperature, vehicle load and use of auxiliary systems such as air conditioning. In addition, individual driving style can also play an important role in fuel efficiency.

In some countries, driving instructors are encouraged to teach eco-driving skills and some elements are evaluated in both the theory and practical driving test. This is a sensible approach given that studies have estimated that, independent of the vehicle and the technology on board, the driver can have a significant impact on fuel efficiency. van der Voort (2001), for example, cites potential fuel-savings in passenger cars in the region of 10–15%, when fuel-efficient driving styles are practised. These savings can be achieved without impacting on travel times (Barth and Boriboonsomsin, 2009; Beusen et al., 2009). For the commercial sector, savings can be even higher and thus dedicated training courses for truck drivers have been developed and evaluated. Some studies have demonstrated positive long-term effects (Symmons et al., 2008), whilst others have reported that drivers eventually return to their old driving patterns (Beusen et al., 2009).

The automotive market has responded to consumers' interest in greener driving by producing vehicles which have in-built eco-driving systems, providing advice to drivers and feedback on their fuel efficiency. In addition, stand-alone or "nomadic devices" are also available on the market, as are various smartphone applications. Examples include DriveGain (http://drivegain.com) which is an application using GPS data to monitor driver behaviour and provide advice on optimal driving and greenMeter (http://hunter.pairsite.com/greenmeter) which provides in-trip advice for eco-driving. The advantage that eco-driving systems have over the training courses described above is that they are ever-present; support is always at the driver's fingertips if they require it. These eco-driving support systems vary in many ways, including how they source their input data and how the information is relayed to the driver. This paper focusses on the latter point – how best to present eco-driving advice to the driver such that it is easy to follow and has minimal impact on other aspects of driving.

Numerous studies have reported positive effects of a range of eco-driving systems on drivers' fuel efficiency. For example, Rakausas et al. (2010) evaluated a number of visual eco-driving support displays. The displays conveyed a range of information such as average fuel efficiency and instantaneous acceleration and all were successful in reducing fuel consumption in the short term (as was simply asking the driver to drive more fuel efficiently). Instantaneous (continuous) acceleration information was found to be the most effective, although the impact of such continuous visual information on drivers' glance patterns and hence distraction was not evaluated. Whilst visual displays have their advantages (e.g. the information can be "ignored" if necessary, Mollenhauer et al., 1994), the concern that increasing amounts of visual information may compromise driver safety has led to developments in other modalities for both safety and eco-driving applications. Haptic feedback (via the accelerator or brake) for collision avoidance (Lee et al., 2007), headway (Mulder et al., 2008), speed (Adell et al., 2008), and lane departure (Deroo et al., 2012) have received attention. More recently, Birrell et al. (2013) evaluated the effects of a haptic accelerator pedal on driving performance and perceived workload and found positive changes to driver behaviour compared to a baseline condition. Subjective workload also decreased when driving with the haptic pedal leading to the conclusion that this modality was useful in this context as it does not encroach on other attentional resource pools that are used in driving (i.e. mainly visual). The study reported here extends the previous work on haptic feedback by including a direct comparison with visual feedback (as well as a baseline condition). Importantly, the efficacy of the systems is evaluated in the context of both fuel efficiency and safety.

In addition to a direct comparison between modality types, this study examines the concept of skill acquisition – do different modalities increase the pace of learning eco-driving skills? Skill acquisition, such as learning a new language, playing a musical instrument or learning to drive a car, requires the performer to move between several stages. In the first stage, coined the *cognitive stage* by Fitts and Posner (1967), users are exposed to and commit to memory the facts relevant to the skill. This declarative (knowledge) stage is then followed by the *associative stage* whereby the knowledge is transformed into a procedural form, such that the user "knows how" to perform a task. Finally, following repetitions of the task, an *autonomous stage* is reached whereby the procedure can be undertaken without conscious thought.

Experimental psychologists, as far back as the late nineteenth century (e.g. James, 1890) recognise the role played by automaticity in skilled performance and it features in theories of manual control (Shiffrin and Schneider, 1977). Automaticity allows performers to execute a task efficiently, unintentionally and unconsciously. The automatic behaviours are stimulus-driven, requiring limited or no controlled response (Trick et al., 2004). Moving from a controlled response, which requires access to declarative knowledge, to automaticity reduces effort and attentional demand (Logan, 1988). Some components of driving are a good example of this process; gear changing is considered to be an automated task (Baddeley, 2006; Michon, 1985). For a novice driver, gear changing is slower than for expert drivers (Duncan et al., 1991) and becomes automated after sufficient practice. Even after such practice, however, Shinar et al., 1998 report that there is still a cognitive cost in the process of changing gear manually. Using verbal report methodology, Renge (1980) found that novice drivers were more likely to comment on operational issues such as changing gear, steering or applying the brakes. On the other hand, experienced drivers referred to features deemed vital for safe driving, such as lead cars and pedestrians.

The rate of learning of eco-driving skills during experience with an eco-driving system is an important factor to consider when designing such a system. This will allow the delivery of information to be tailored to optimise learning, and also will allow identification of the point in time at which it is appropriate to reduce or remove the guidance to prevent the presentation of redundant in-vehicle information. A key premise behind this study is that drivers who are able to learn eco-driving skills readily do not need constant eco-driving support. In fact, if advice is provided too frequently, this may become annoying for drivers, therefore influencing overall acceptance, and ultimately engagement with the system.

This paper is therefore an attempt to discover which modality is:

- most effective at conveying real-time eco-driving advice (two versions of haptic versus visual),
- which modality is the most easily learnt and
- whether there are any unwanted (safety) side-effects.

2. Method

A driving simulator study was designed to present repeatable, highly-controlled motorway driving scenarios, thus allowing a consistent testing environment for the eco-driving systems. Hills were selected as a suitable test case as they are a common roadway event in which manipulation of the accelerator pedal has the potential to save fuel.

The study used the University of Leeds Driving Simulator, see Fig. 1. The simulator's vehicle cab is based around a 2005 Jaguar S-type, with all of its driver controls fully operational. The vehicle's internal Control Area Network (CAN) is used to transmit driver control information between the Jaguar and one of the network of nine Linux-based PCs that manage the overall simulation. This 'cab control' PC receives data over Ethernet and transmits it to the 'vehicle dynamics' PC, which runs the vehicle model. The vehicle model returns data via cab control to command feedback so that the driver seated in the cab feels (steering torque and brake pedal), sees (dashboard instrumentation) and hears sounds like in normal driving (80 W 4.1 sound system provides audio cues of engine, transmission and environmental noise).

The Jaguar is housed within a 4 m diameter, spherical projection dome. Six visual channels are rendered at 60 frames per second and at a resolution of 1024 × 768. The forward channels provide a near seamless field of view of 250°, and the rear view channel (40°) is viewed through the vehicle's rear and side view mirrors. The simulator incorporates a large amplitude, eight degree of freedom motion system using a railed gantry and electrically-driven hexapod. The motion-base enhances the fidelity of the simulator by providing realistic inertial forces to the driver during acceleration and cornering.

The existing accelerator pedal was replaced with a haptic accelerator pedal which is physically linked to a servo motor mounted on the dynamic platform, (Fig. 1). By controlling the motor torque and position via a Baldor Mint Drive, pedal feedback up to 200 N can be commanded. A modifiable "glass" dashboard instrument cluster arrangement was visualised via two 7.5" 800 × 480 colour LCD monitors built into the existing simulator cab. This dashboard allowed the presentation of the various eco-driving advice. Driver behaviour (vehicle controls) and vehicle data (position, speed, accelerations, etc.) are collected at a rate of 60 Hz. Eye-tracking data were collected using a Seeing Machines faceLAB v5.0 to establish gaze direction.

A within-subjects design was selected in which each participant drove once with each eco-driving system and once without a system (Total = four drives). Participants used only one type of system during each 25 min drive. The potential influence of experimental duration on learning effects was minimised by counterbalancing the order in which participants experienced the four drives. A familiarisation drive allowed participant to become accustomed to the simulator and the various systems.

2.1. Driving scenarios and tasks

The study was conducted on a simulated two-lane motorway (speed limit 70 mph or 112 km/h). Drivers were required to drive up and down a number of hills of the same length and gradient (4%). Traffic density on the hills was manipulated as being either low (800 vehicles/per lane/per hour) or high (1600 vehicles/per lane/per hour). This was done by gradually introducing more vehicle into the scene, such there was a "building up" of traffic. Drivers were required to adjust their use of the accelerator pedal in order to ascend and descend these hills in the 'greenest', most fuel efficient way. The eco-driving systems presented advice to guide the driver to these pedal angles, see Section 2.2. All hills were comprised of four sections, each containing 3 × 252 m 'tiles' (building blocks of the simulated road network and environment). Between the hills, 252 m curved filler sections were used. The hill scenario is illustrated in Fig. 2.

The drivers' task was to drive as fuel efficiently as possible, meanwhile obeying the speed limit of the road and driving safely. They were informed that steady driving is key to fuel efficient driving and that they should focus on economical

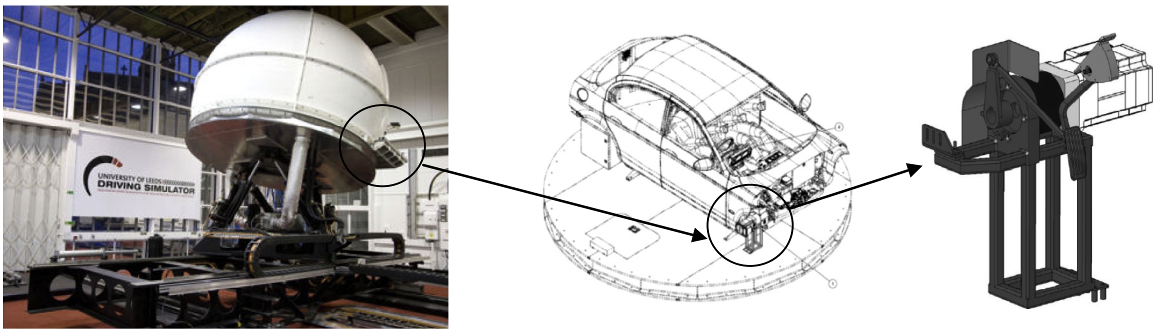

Fig. 1. University of Leeds Driving Simulator and haptic pedal design.

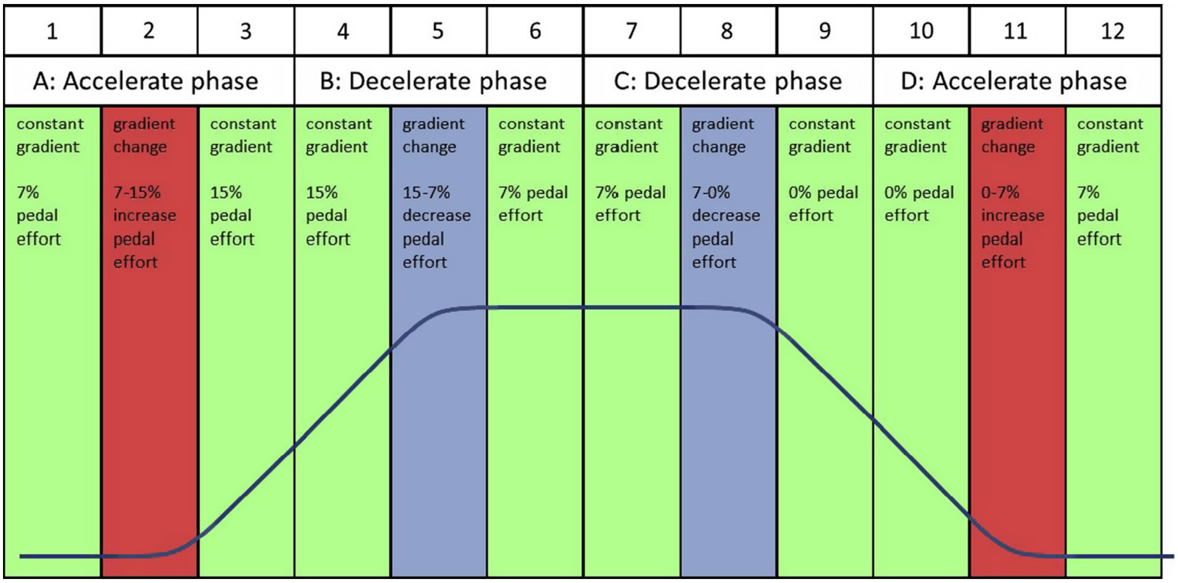

Fig. 2. Hill-driving scenario (colours represent required accelerator pedal action).

maintenance of the requested speed, and not the selection of a fuel-efficient speed itself. This was to avoid large between-participant variation in the selection of the most fuel-efficient speed. During each of the three drives with an eco-driving system, advice was provided on accelerator pedal usage, which the drivers were asked to follow. If followed effectively, the eco-driving guidance would enable the driver to maintain a constant speed over both the uphill and downhill sections. This follows one of the golden rules of eco-driving: to maintain as constant a speed as possible. Participants were incentivised to engage with the system using the offer of an additional reward for the best-performing 'eco-driver'. The reason behind this was to induce in the participants some sense of reality – simulator studies cannot replicate the fuel savings incentive derived from more fuel-efficient driving techniques. We thought this was particularly important, given our interest in safety aspects too. In the baseline drive, participants were required to judge how to drive fuel efficiently without guidance.

2.2. Eco-driving systems

The eco-driving systems provided guidance on how to achieve optimal fuel efficiency through accelerator pedal usage. The systems were based on an underlying eco-driving algorithm, which defined a "correct" pedal position for optimal fuel efficiency given the current vehicle speed, road gradient and required final speed (set to the speed limit of the road). The advice was therefore designed to guide a driver from their current performance to a more 'optimal' level of eco-driving performance. The system was not able to adjust its guidance based on the volume and position of the ambient traffic, and therefore it was the decision of the driver whether to obey the eco-driving guidance if it advised them to perform in a way which might compromise their safety e.g. to accelerate when following a lead vehicle moving slower than the speed limit. The eco-driving systems were switched on and off with a multi-functional control stalk attached to the steering wheel. The drivers were informed when to engage and disengage the system via a recorded message – "Please turn the ecodriving system on/off" – and were requested not to use this control at any other time.

2.2.1. Visual eco-driving system

The visual eco-driving system used Gonder et al. (2011) principle of a colour-coded "OEM dashboard display" and was inspired by the Nissan EcoPedal as described by Meschtscherjakov et al. (2009). A foot symbol positioned on a moving accelerator pedal and displayed in the tachometer was used to present eco-driving information (Fig. 3). Depending on how fuel-efficient the driver was performing, the foot symbol altered colour.

A green foot indicated that the driver was driving at (or close to) the most fuel-efficient accelerator pedal angle (target angle). A blue foot symbolised insufficient acceleration and therefore a need to increase pressure on the accelerator pedal to achieve the target angle. A red foot symbolised the opposite case – excessive acceleration – and a need to decrease pressure on the accelerator pedal to improve fuel efficiency. These three colours represented the midpoint and the extremes of an eco-driving success scale. The colour of the foot Gouraud-blended between the three options over a 5% range, such that a pedal error of +6% would produce a pure red foot symbol.

This visual display also provided second-order information in the form of the current and required accelerator pedal position. A solid line was displayed to show current pedal position and a dotted line to show required pedal position. The

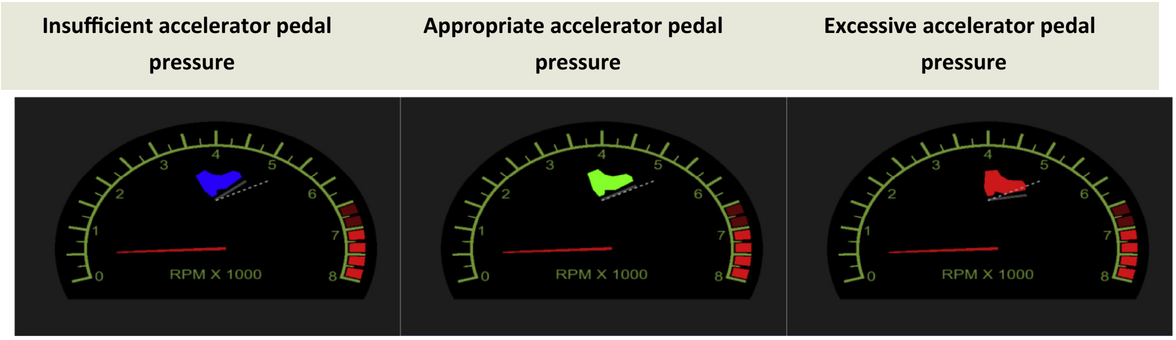

Fig. 3. Visual eco-driving system.

foot/accelerator pedal combination move in the display, similar to the motion of an accelerator pedal in reality. This information shows the driver both the direction and relative distance of travel required to improve and ultimately optimise their eco-driving performance. The eco-driving task is accomplished by matching the position of the grey 'current position' line with the dashed 'desired' position line. This will cause the foot symbol to remain green in colour.

2.2.2. Haptic eco-driving systems

The haptic feedback systems were based on Mulder et al.'s (2008) *force* and *stiffness* feedback. Both haptic feedback systems operate using the same underlying algorithm as the visual dashboard displays and therefore are continuously advising on a fuel efficient accelerator pedal position. However, this information is presented to the driver differently between these two systems.

In the *force* feedback condition, a significant extra force (40 N) was required by the driver to further increase accelerator pedal travel beyond that prescribed by the algorithm to be the most fuel efficient. The precise accelerator pedal angle (kneepoint) at which this extra force was applied varied depending on whether the driver was currently accelerating, decelerating or maintaining their speed. This kneepoint was introduced to guide the driver towards the 'ideal' accelerator pedal angle. In the *stiffness* feedback condition, the guide kneepoint was produced by a distinct change in pedal stiffness, rather than a step force for drivers to overcome. The gradient of the pedal force vs. pedal travel line changed from the standard stiffness of 0.2 N per percent pedal travel to 2.9 N per percent pedal travel. In both cases, the above pedal manipulations were designed to alert the driver at the moment of excessive acceleration. These two systems were also capable of informing the drivers that insufficient pressure was being applied to accelerator whereby the pedal becomes less resistant in those circumstances were fuel efficiency can be improved by increasing pedal force.

2.3. Hypotheses

The road network was specifically designed to answer two research questions.

i. Learning: Do drivers learn to eco-drive at different rates depending on the type of system?

Three hills with 4% gradient were presented to the driver in each drive. This research question was answered by investigating how objective driving performance changed across these three occurrences of the same type of hill.

ii. Prioritisation: Do drivers prioritise safety over eco-driving?

After an initial period of driving up and down three hills with low density ambient traffic, three hills were presented with high density ambient traffic. The increase in the volume of vehicles was designed to prevent the driver being able to successfully achieve the eco-driving task without reducing their safety. A comparison of safety measures between the high and low density traffic sections was performed to answer this research question.

2.4. Participants

22 drivers took part, balanced for gender, age, driving experience and annual mileage (Table 1).

Questionnaires were completed after each drive to provide an indication of the workload involved in driving economically (with or without an eco-driving system).

Table 1
Participant sample characteristics.

	Male ($n = 10$)				Female ($n = 12$)			
	Mean	SD	Max.	Min.	Mean	SD	Max.	Min.
Age (years)	34	11	59	22	40	15	67	22
Experience (years)	15	10	31	6	23	14	50	3
Annual mileage (mi)	11,700	5900	25,000	6500	7150	3650	15,000	3000

2.5. Data collection

Driving performance data were analysed from the hill regions of the road network only. Each hill was divided into four sections for data collection (as shown in Fig. 2). This allowed performance to be analysed not only for the entire hill drive, but also for each section of the hill (accelerate ascent, decelerate ascent, decelerate descent, accelerate descent).

The primary variable used to determine the accuracy of eco-driving performance was *root mean squared pedal error*, which is used to indicate the extent to which participants managed to achieve the ideal 'green' accelerator position throughout the ascent and descent of the hill. Successful eco-driving performance was defined as being the absence of an error between the accelerator pedal angle required for fuel efficient performance (the target angle based on the eco-driving guidance) and the accelerator pedal angle selected by the driver. Large mean discrepancies between these two values qualified as poor eco-driving whilst minimising this error terms qualified as good (or successful) eco-driving. In addition, in order to assess the propensity of drivers to move their gaze away from the roadway in order to attend to secondary tasks (including the eco-driving interface), eye-tracking data were processed to obtain *Percent Road Centre* (PRC). PRC was defined as the proportion of gaze data points, labelled as fixations, which fell within the road centre area, a 6° circular region located around the driver's most frequent fixation location. (This most frequent fixation location was measured during the baseline drive and used for data extraction across all drives). PRC has previously been demonstrated to be a sensitive indicator of visual distraction (Victor et al., 2005) with lower values indicating less attention focused towards the visual demand of driving. The NASA-TLX, multi-dimensional workload scale was administered immediately after each of the four drives (no system, visual, force and stiffness) to obtain an estimate of driver workload during each drive and hence an indication of the workload associated with use of a particular system. The tool has been demonstrated to be simple to use and with good sensitivity to experimental manipulations in the simulator environment (Hart, 2006).

3. Results

The data included in the analysis did not violate assumptions of parametric testing, thus repeated measures ANOVAs were performed. The independent measures were: System (four levels: baseline, visual, haptic force, haptic stiffness), Repeat (three levels: first, second, third drive) and Section (four levels: road sections A–D). In the analysis in Section 3.2 (prioritisation of safety over eco-driving) an additional variable of Traffic Density (two levels: low, high) was included. Only performance in the low density was considered in Section 3.1 (Learning) as drivers were unconstrained by the surrounding traffic. In all cases, where Mauchly's test of sphericity produced a significant result, the Greenhouse–Geisser correction was applied. For each analysis, a series of Bonferroni-corrected pairwise comparisons was undertaken to establish simple effects.

3.1. Learning varies with system type

A significant main effect of System on mean pedal error was observed, [$F(3,63) = 16.529$, $p < .001$, $\eta^2 = .440$]. Post-hoc tests indicated that mean error was significantly higher in the baseline condition compared to all three systems. In addition, pedal errors were significantly lower when using the visual interface compared to either haptic interface. However, when standard deviation of pedal position was considered, (which provides a measure of the consistency of the accelerator position), a significant main effect of System was observed, [$F(3,63) = 6.139$, $p = .001$, $\eta^2 = .226$]. Variation in pedal angle was significantly lower when using the haptic force system compared to the absence of eco-driving assistance.

The main effect of Repeat did not reach significance, suggesting that there was no improvement in eco-driving performance over time. Furthermore, the interaction of System x Repeat was also not significant, suggesting that none of the systems nor the baseline condition produced a reduction in mean pedal error across the three hills considered, Fig. 4.

When driving performance was analysed by hill Section, a main effect was observed, [$F(1.97,41.37) = 9.317$, $p < .001$, $\eta^2 = .307$]. Overall, performance was superior during the two hill ascent sections (A and B) compared to performance in the final section of the hill (D). This is likely to be due to the nature of the eco-driving task at these points. For example, whilst the driver has their foot on the pedal for the entire duration of Sections A and B, they are required to remove their foot from the pedal to decelerate the vehicle in Section C. As a result, participants reach the beginning of Section D without pressure on the accelerator and therefore are less likely to perceive the guidance to re-accelerate at the foot of the hill when presented via a haptic pedal. This means that for two out of the three systems, Section D begins with guidance that the participant may not be able to perceive. This explanation is supported by the significant System x Section interaction,

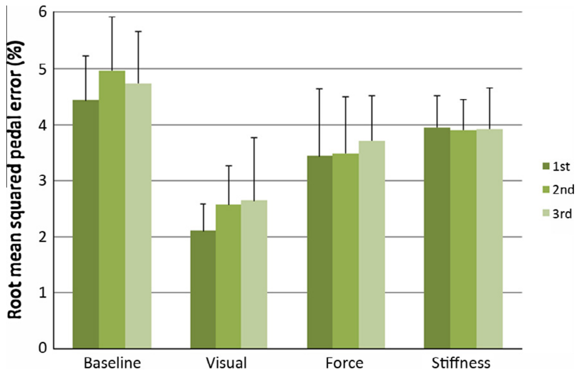

Fig. 4. Root mean squared pedal error by Repeat.

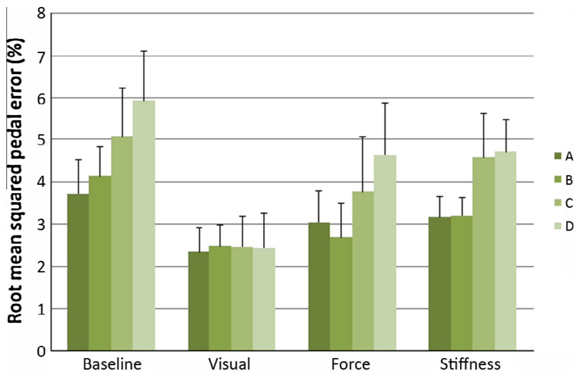

Fig. 5. Root mean squared pedal by hill Section.

[$F(9,189) = 3.833$, $p = .002$, $\eta^2 = .154$]. Fig. 5 shows more consistent pedal errors across hill sections when using the visual interface, compared to greater pedal errors in Section D when using either haptic interface.

Moving onto glance behaviour as an indication of driver distraction, there was a significant main effect of System on PRC, [$F(3,54) = 25.671$, $p < .001$, $\eta^2 = .440$]. Fig. 6 shows that the time spent looking towards the road centre was significantly lower when interacting with the visual eco-driving system compared to either haptic system or baseline.

Overall, the provision of visual guidance, despite encouraging accurate eco-driving performance (see root mean squared pedal error analysis) increases the distraction from the forward roadway. The provision of haptic guidance creates lower visual distraction than a visual interface. However, in addition, there is a tendency for the haptic systems to improve visual attention to the driving scene compared to baseline driving.

Further analysis showed neither an effect of Repeat on PRC, nor an interaction of System x Repeat.

3.2. Driver prioritisation of safety over eco-driving

The six hills that the drivers experienced were divided into two sets of three characterised by either low or high density traffic. The eco-driving task remained the same throughout these six hills. However, the increased traffic density on the latter three hills prevented the driver from accurately following the eco-driving advice if they wished to maintain a safe distance to the vehicle in front, and avoid a collision. Good eco-driving performance in both the high and low density traffic would suggest that participants are prioritising the eco-driving task over the maintenance of an adequate safety margin. In contrast, poorer eco-driving performance in the high density condition would imply that participants account for this more demanding driving scenario by focusing on the maintenance of safety over fuel efficiency.

With regards driving performance, the main effect of Traffic Density on root mean squared pedal error was significant, [$F(1,20) = 1553.472$, $p < .001$, $\eta^2 = .987$], with higher mean pedal errors observed in the high density traffic compared to the low density traffic. A significant interaction of System x Traffic Density showed that the difference in eco-driving performance across systems is largely evident in the low density driving conditions, [$F(3,60) = 3.741$, $p = .016$, $\eta^2 = .158$], Fig. 7. There remains a slight tendency for better performance with the visual and haptic force systems, suggesting that these systems provide better guidance on accelerator usage in busier traffic as well.

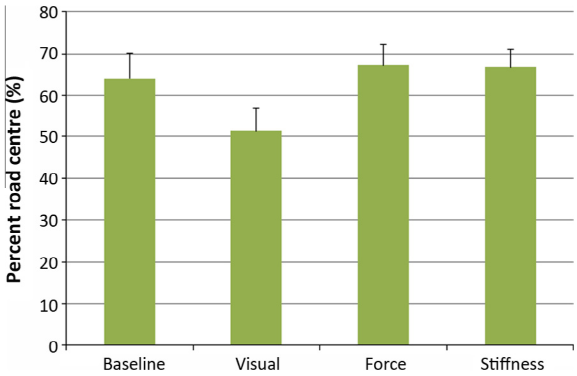

Fig. 6. Percent road centre by System.

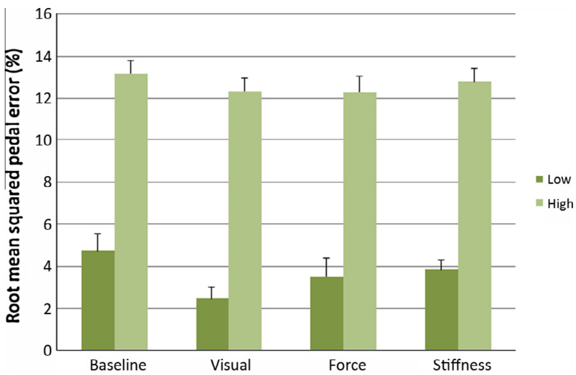

Fig. 7. Root mean squared pedal error by System and Traffic Density.

There was neither a significant effect of Repeat ($p = .218$) nor a significant interaction of System x Repeat ($p = .985$), thus suggesting that participant performance did not improve over time, either with or without an eco-driving assistant.

If drivers prioritise safety over eco-driving, then it would be expected that PRC would increase with increasing traffic density, perhaps more so when the driver is engaging with the visual interface than either of the haptic interfaces. There was a significant main effect of Traffic Density on PRC, [$F(1,17) = 65.713$, $p < .001$, $\eta^2 = .794$], with more looking towards the road centre during the high density traffic compared to the low density traffic. Furthermore, the significant interaction of System x Traffic Density on PRC suggests that changes in attention to the forward roadway are affected by the type of eco-driving advice being provided, [$F(3,51) = 4.486$, $p = .007$, $\eta^2 = .209$], Fig. 8.

For both high density and low density traffic conditions, PRC was significantly lower when using the visual interface. However, the effect size was substantial larger in the low density traffic conditions (0.588) compared to the high density traffic conditions (0.302). In fact, the increase in PRC from low to high traffic density driving was approximately twice as large when interacting with the visual display, than with any other system, suggesting that drivers amend their gaze behaviour to preserve their safety more in this case. PRC showed no variation with repetition of the hill driving scenario nor across different sections of each hill.

With regards to longitudinal control of the vehicle, mean headway provides an indication of drivers' relative priorities of successful eco-driving and maintaining safety. In the low density traffic, it was largely possible to maintain the required speed (thus adhere to the eco-driving advice) whilst keeping a safe following distance. In contrast, during high density traffic, it was only possible to adhere to the eco-driving advice by accepting a shorter mean headway during the drive. The analysis of the variables above (root mean squared pedal error and PRC) suggested that drivers neglected the eco-driving task to preserve their safety. However, the findings for mean headway showed that driver priorities were not as simple as that. There was a significant main effect of Traffic Density on mean headway, [$F(1,10) = 27.385$, $p = .001$, $\eta^2 = .733$], with participants driving closer to their lead vehicle on average during the high density traffic compared to the low density traffic. This would suggest that although drivers are less able to perform the eco-driving task successfully in the more congested conditions, they are willing to approach the vehicle in front more closely – perhaps to obey the eco-driving advice more accurately or to avoid braking. The same result was observed when minimum headway was analysed, with significantly shorter minimum distance to the lead vehicle during high density traffic compared to low density traffic.

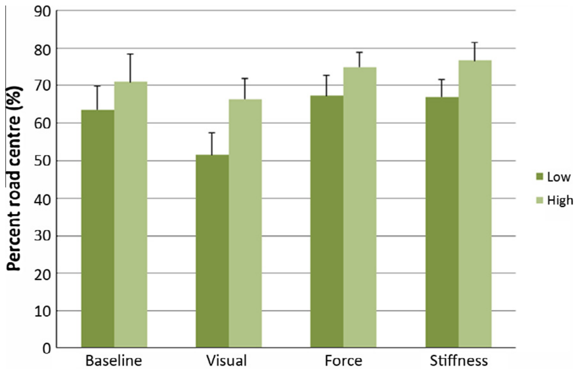

Fig. 8. Percent road centre by System and Traffic Density.

Whilst there was no main effect of System, a significant System x Traffic Density interaction indicated that only in high density traffic did drivers follow the vehicle in front significantly closer when using the visual interface than when driving without an eco-driving system, Fig. 9.

3.3. Workload

The NASA-TLX workload scale is sub-divided into six subscales. The ratings provided for each subscale were compared between levels of System using non-parametric Friedman's ANOVA and Wilcoxon Signed Rank post hoc tests. The alpha value used to test for significance was adjusted to account for the number of post hoc tests performed ($\alpha = .0083$). The ratings for the six NASA-TLX subscales were summed to provide a 'total workload' score for each participant.

A significant effect of System was observed, $x^2(3) = 26.564$, $p < .001$. Post-hoc testing revealed lower overall workload with the haptic-force system compared to all other conditions. The visual display was rated as creating greater overall workload than either baseline driving or a haptic stiffness interface (Fig. 10). This suggests that the total perceived workload demand when eco-driving is substantially reduced by the presence of a non-visual system. Whilst the visual display provides

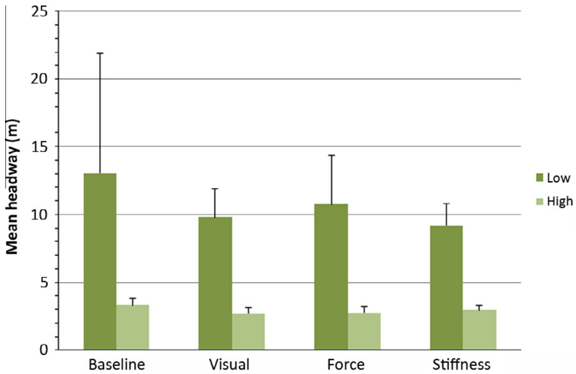

Fig. 9. Mean headway by System and Traffic Density.

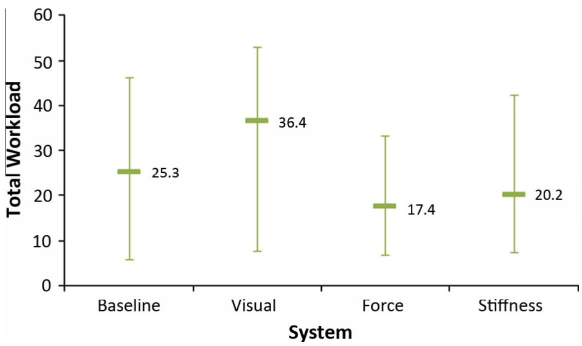

Fig. 10. Median total workload score by System (errors bars display range).

the most unequivocal guidance regarding the driver's success in the eco-driving task, this benefit can create an additional information processing load that can be perceived negatively by the driver.

4. Conclusions

This paper has presented the work from a driving simulator study which investigated the rate of learning of eco-driving and the relative prioritisation of driver safety and fuel efficient driving, when using three in-vehicle eco-driving systems. These systems were designed to enable the driver to achieve optimal fuel efficiency through the provision of advice about accelerator pedal angle. Through investigation of root mean squared pedal error, it has been shown that eco-driving can be improved by providing such advice.

In terms of which type of eco-driving system is most effective, there are two considerations. The error between desired pedal angle for economical driving and the angle selected by the driver was lower with the visual than either haptic system. However, a steady accelerator pedal position is always a useful indicator of fuel efficient driving. For this measure, it was observed that the haptic force system led to driving with the most consistent accelerator pedal position. The haptic stiffness system does not appear to provide guidance that allows this system to compete with the visual or haptic force interfaces when these variables are considered. Verbal feedback from the participants would suggest that whilest less invasive than the haptic force system, the haptic stiffness system can often lead to situations in which the driver is not sure whether they are adopting the most fuel efficient pedal angle, and therefore needs to move their foot for confirmation. This would suggest that the haptic force system has greater utility for providing unequivocal eco-driving guidance regarding efficient accelerator pedal position. In addition, as in other studies which have evaluated haptic feedback, the physical properties and algorithms need careful consideration if acceptance is to be maximised (Adell et al., 2008; Meschtscherjakov et al., 2009).

The results above should not be used to select a system without consultation of a measure of driver safety, in this case PRC. Whilst good eco-driving performance would be expected with the visual display due to the ease of viewing and extracting the information, it should be noted that drivers engaging with this system looked significantly less to the road ahead than when using either haptic pedal interface. This likely means that drivers are more distracted from the primary driving task when using the visual eco-driving system and thus there are potentially greater negative impacts on driver safety in those cases where a safety–critical event happens in the driver's forward view. Visual distraction has been found to lead to increases in lateral deviation and also a tendency in drivers to decrease pressure on the accelerator (Merat and Jamson, 2008; Engström et al., 2005). The lifting of the accelerator pedal when looking at the visual system could encourage a "chicken and egg" scenario where drivers are locked into a vicious circle of fluctuating pedal pressure. Encouragingly, there was evidence to suggest that drivers look at the road ahead for longer when using a haptic eco-driving interface than no interface, perhaps due to a reduced need to consult the speed and rev displays on the vehicle dashboard. Kircher et al. (2014) recommend that intermittent visual eco-driving information is recommended over continuous information as it leads to shorter dwell times. However, even though a haptic solution might be the preferred option in the context of gaze direction, the additional cognitive distraction that such a system might impose on a driver (drivers may be thinking about the haptic system whilst looking at the road ahead) was not evaluated in this study. Even though in this study drivers reported less workload when using the haptic advice, other studies have reported greater gaze concentration towards the road centre (Engström et al., 2005; Recarte and Nunes, 2003) under cognitive distraction. More importantly, reaction time to events which occur in the forward scene has been found to increase in these studies.

Overall, repetition had little effect on drivers' ability to follow the eco-driving guidance. There was no improvement in pedal error across three repetitions of an identical hill-driving scenario. This was true regardless of the type of eco-driving system considered. This result implies that drivers are not able to improve their eco-driving performance over just three repetitions of a scenario in which eco-driving guidance is provided. Perhaps, three repetitions of the scenario were not sufficient to gauge change, and this should be a consideration in future research. It could also be that further improvement was not possible (the error values were less than 4%); alternatively, it could be that providing repetitive guidance leads drivers to ignore the eco-driving advice or assume that they can perform effectively without it. This application of acquired knowledge and the apparent neglect of eco-driving information over time may argue for the provision of eco-driving guidance during the learning phase of an eco-driving task, which then fades away or increases in specificity as an individual becomes adept at eco-driving. This could avoid potentially annoying the driver with feedback that has little use to them, whilst keeping them motivated to be a 'good eco-driver'. A system that reintroduces eco-driving support upon detection of deterioration in performance may also capture a driver's attention more effectively for both the eco-driving information and the task. Wada et al. (2011) argue that the long term success of eco-driving displays relies partly on ensuring that the system adapts to drivers' skills. These authors argue that factors such as boredom and low motivation may lead to reduced use of eco driving displays by drivers, but that matching the skill required for interacting with the system with that of drivers ensures the long term use of the display.

Drivers displayed poorer adherence to eco-driving advice (observed as large pedal errors) when driving in high density traffic. This suggests that when the demand and safety–criticality of the driving task increases, drivers choose to pay less attention to the need to save fuel. The fact that this has been observed in a simulated environment may mean that the prioritisation of driver safety is even more emphatic during real-world driving. If drivers prioritise safety over eco-driving, it would be expected that the time spent looking at the road centre not only increases with increasing traffic density, but perhaps also increases to a larger extent when interacting with a visual eco-driving system. Both of these predictions were observed in this study, with the increase in time spent looking at the road centre between the high and low density conditions almost twice as large for the visual interface compared to the two haptic interfaces. This would suggest that not only do drivers increase their focus on safe driving during times of high demand, but also that they are aware to some extent that the visual display causes high distraction, and therefore they need to re-direct their visual attention to a greater extent than when using a haptic interface. This is encouraging because it implies that if a visual eco-driving system is installed in their vehicle, drivers may be able to manage their interaction with it to maintain their safety. Similar results regarding drivers' ability to self-regulate their workload were found by Kircher et al. (2014); their results suggest that when the visual demand of the traffic situation was low, drivers looked at a display more quickly, more often and for a longer time than when the visual demand was higher. They argue that this is a strong indication that drivers consider the traffic situation before they glance at a display. However, driving events can unfold at a very rapid rate and if attending to a display disrupts normally glance patterns, safety could be compromised. However, a cautionary note should be added regarding visual displays that offer intermittent advice. This bottom-up (stimulus-driven) capture of attention has been reported in numerous laboratory studies and is hypothesised to be a "hard-wired" reaction in order to be able to response quickly to new objects entering the visual field (Yantis and Hillstrom, 1994).

The subjective feedback on workload experienced during the use of each eco-driving system tends to favour the haptic force system, with particularly poor ratings given for the visual interface. The workload ratings from the NASA-TLX showed that the visual display created highest mental demand, physical demand, temporal demand, effort and frustration. Interestingly, despite the evidence of better objective performance (indexed by root mean squared pedal error) with the visual system, when compared with the two haptic systems, participants rated their overall performance lower with the visual system. This is encouraging as it suggests that the provision of haptic pedal guidance does not add unnecessary load to the driver. The haptic force system tended to achieve better ratings than the haptic stiffness system. The drivers appear to be unaware of the extent to which this more subtle eco-driving system was improving their fuel efficiency. A system that provides guidance through the same modality as normal driving (i.e. through the accelerator pedal) is perhaps deemed more intuitive.

In summary, drivers require assistance to successfully modulate accelerator usage to optimise their fuel-efficiency. The provision of constant guidance on 'green' accelerator pedal position is an effective method for improving a driver's eco-driving performance. The availability of continuous feedforward information allowed drivers to not only minimise their error relative to optimum eco-driving performance, but also to decrease the variation in their performance. Guidance provided by a visual display on the dashboard was the most effective for minimising the difference between desired and achieved accelerator pedal position. This unambiguous presentation modality is easily understood and responded to. However, there is substantial evidence that this modality creates increased distraction from the primary driving task, thus highlighting a potential risk from visual only presentation. Furthermore, perceived workload ratings suggest that interacting with the visual display can be difficult, even though it produces high levels of eco-driving performance.

A haptic force system was most effective for minimising accelerator pedal position variation during an eco-driving task. Drivers found the unequivocal guidance regarding optimum pedal position to be a useful cue in managing their eco-driving performance. The haptic stiffness system guidance appears to be too subtle to minimise errors to the extent possible with the two competing systems. Both haptic displays fared well in terms of perceived workload. The observation of lower workload relative to those situations when the driver attempts to improve their fuel efficiency without guidance highlights the impressive impact of this modality on driving performance. The best compromise might be to develop an eco-driving system that provides both visual and haptic force guidance. The redundant information presentation method might act to reduce visual distraction by the dashboard display, whilst offering the clarity and comprehensibility of the two most effective means of communicating eco-driving information.

With regards to learning, there is little evidence to suggest that a driver's interaction with the accelerator pedal can be significantly improved with only three instances of the same eco-driving scenario. This would support the provision of continuous information; given the potential for distraction, it might be preferable to provide continuous eco-driving guidance, but only during a range of carefully selected 'eco-driving scenarios' i.e. those where substantial improvements in fuel economy are possible. Alternatively an eco-driving system that is supported by a workload manager (see e.g. Hibberd et al., 2013) which regulates when non-critical information is presented to a driver, dependent on driver workload, may warrant further investigation.

Finally, drivers showed poor adherence to the eco-driving advice during high traffic density driving. In high workload scenarios, drivers appear to be prioritising safe driving over fuel efficient performance. An eco-driving system could vary the presentation of advice such that it does not present unnecessary and potentially distracting information to the driver when they are unlikely to engage with it. It would be necessary to do a more extensive examination of those driving scenarios in which driver and passenger safety is likely to be prioritised over adherence to eco-driving information. This recommendation holds true for each of the three eco-driving displays tested. However, it is more pertinent with the visual display, where drivers have shown a more marked increase in time spent looking at the road during the transition from low to high workload driving, which is indicative of a greater neglect of the eco-driving information. The discovery that drivers tend to direct their gaze towards the road more during high density traffic than low density traffic implies that they are able to take some responsibility for their own distraction. This is encouraging given those situations where only visual presentation of eco-driving feedforward guidance is possible (i.e. no haptic provision).

References

Adell, E., Varhelyi, A., Hjalmdahl, M., 2008. Auditory and haptic systems for in-car speed management – a comparative real life study. Transport. Res. F: Traffic Psychol. Behav. 11 (6), 445–458.

Baddeley, A.D., 2006. Working memory: an overview. In: Pickering, S.L. (Ed.), Working Memory and Education. Elsevier Inc, Burlington, MA, pp. 3–26.

Barth, M., Boriboonsomsin, K., 2009. Energy and emissions impacts of a freeway-based eco-driving system. Transport. Res. D: Transport Environ 14 (6), 400–410.

Beusen, B., Broekx, S., Denys, T., Beckx, C., Degraeuwe, B., Gijsbers, M., Scheepers, K., Govaerts, L., Torfs, R., Panis, L.I., 2009. Using on-board logging devices to study the longer-term impact of an eco-driving course. Transport. Res. D: Transport Environ. 14 (7), 514–520.

Birrell, S.A., Young, M.S., Weldon, A.M., 2013. Vibrotactile pedals: provision of haptic feedback to support economical driving. Ergonomics 56, 282–292.

Deroo, M., Hoc, J.-M., Mars, F., 2012. Influence of risk exception on haptically cued corrective manoeuvres during near lane departure. Ergonomics 55, 465–475.

Duncan, J., Williams, J., Brown, I., 1991. Components of driving skill: experience does not mean expertise. Ergonomics 34, 919–937.

Engström, J., Johansson, E., Östlund, J., 2005. Effects of visual and cognitive load in real and simulated motorway driving. Transport. Res. F: Traffic Psychol. Behav. 8, 97–120.

Fitts, P.M., Posner, M.I., 1967. Human Performance. Brooks/Cole, Belmont, CA.

Gonder, J., Earleywine, M., Sparks, W. 2011. Final report on the fuel saving effectiveness of various driver feedback approaches. Milestone report for the National Renewable Energy Laboratory. Task No. FC10.2700. <http://www.afdc.energy.gov/uploads/publication/Final_Report_on_the_Fuel_Saving_Effectiveness_of_Various_Driver_Feedback_Approaches.pdf>.

Hart, S.G., 2006. NASA-Task Load Index (NASA-TLX); 20 years later. In: Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting. Human Factors & Ergonomics Society, Santa Monica, CA, pp. 904–908.

Hibberd, D.L., Jamson, S.L., Carsten, O.M.J., 2013. Mitigating the effects of in-vehicle distractions through use of the Psychological Refractory Period paradigm. Accid. Anal. Prevent. 50, 1096–1103.

James, W., 1890. Principles of Psychology. Holt, New York.

Kircher, K., Fors, C., Ahlstrom, C., 2014. Continuous versus intermittent presentation of visual eco-driving advice. Transport. Res. F: Traffic Psychol. Behav. 24, 27–38.

Lee, J.D., Mcgehee, D.V., Brown, T., Nakamoto, J., 2007. Driver sensitivity to brake pulse duration and magnitude. Ergonomics 50, 828–836.

Logan, G.D., 1988. Toward an instance theory of automatization. Psychol. Rev. 95, 492–527.

Merat, N., Jamson, H., 2008. The effect of stimulus modality on signal detection: implications for assessing the safety of in-vehicle technology. Hum. Factors 14, 145–158.

Meschtscherjakov, A., Wilfinger, D., Scherndl, T., Tscheligi, M. 2009. Acceptance of future persuasive in-car interfaces, towards a more economic driving behaviour. In: Proceedings of the First International Conference on Automotive User Interfaces and Interactive Vehicular Applications, Essen, Germany.

Michon, J.A., 1985. A Critical View of Driver Behaviour Models: What do We Know, What Should We do? Plenum Press, New York.

Mollenhauer, M.A., Lee, J., Cho, K., Hulse, M.C., Dingus, T.A., 1994. The effects of sensory modality and information priority on in-vehicle signing and information systems. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol. 38, pp. 1072–1076.

Mulder, M., Mulder, M., van Passen, M.M., Abbink, D., 2008. Haptic gas pedal feedback. Ergonomics 51, 1710–1720.

Rakausas, M.E., Graving, J.S., Manser, M.P., Jenness, J.W., 2010. Determining the accuracy and acceptance of using driver interface display components and fuel economy information types. In: Proceedings of the Human Factors and Ergonomics Society, 54th Annual Meeting, pp. 1536–1540.

Recarte, M., Nunes, L., 2003. Mental workload while driving: effects on visual search, discrimination, and decision making. J. Exp. Psychol.: Appl. 9, 119–137.

Renge, K., 1980. The effects of driving experience on a driver's visual attention. An analysis of objects looked at: using the 'verbal report' method. Int. Assoc. Traffic Safe. Sci. Res. 4, 95–106.

Shiffrin, R.M., Schneider, W., 1977. Controlled and automatic human information processing: II. Perceptual learning, automatic attending and a general theory. Psychol. Rev. 84 (2), 127–190.

Shinar, D., Meir, M., Ben-Shoham, I., 1998. How automatic is manual gear shifting? Hum. Factors 40 (4), 647–654.

Symmons, M.A., Rose, G., Doorn, G.H.V., 2008. The effectiveness of an ecodrive course for heavy vehicle drivers. In: 2008 Australasian Road Safety Research Policing and Education Conference, no. November, Adelaide, Australia, 2008, pp. 187–194.

Trick, L.M., Enns, J.T., Mills, J., Vavrik, J., 2004. Paying attention behind the wheel: a framework for studying the role of selective attention in driving. Theor. Issues Ergon. Sci. 5 (5), 385–424.

van der Voort, M.C., 2001. Design and Evaluation of a New Fuel-Efficiency Support Tool (Ph.D. dissertation), University of Twente.

Victor, T., Harbluk, J.L., Engström, J.A., 2005. Sensitivity of eye-movement measures to in-vehicle task difficulty. Transport. Res. F: Traffic Psychol. Behav. 8 (2), 167–190.

Wada, T., Yoshimura, K., Doi, S., Youhata, H., Tomiyama, K., 2011. Proposal of an eco-driving assist system adaptive to driver's skill. In: Proceedings of the 14th International IEEE Conference on Intelligent Transportation Systems, Washington, DC, USA.

World Health Organisation, 2013. Global status report on road safety. <http://www.who.int/violence_injury_prevention/road_safety_status/2013/en/>.

Yantis, S., Hillstrom, A.P., 1994. Stimulus-driven attentional capture: evidence from equiluminant visual objects. J. Exp. Psychol. Hum. Percept. Perform. 20, 95–107.