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• **Title.** The design of an in-vehicle assistance system to support eco-driving.

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Abstract

This driving simulator study was the second of two studies investigating the most effective and acceptable in-vehicle system for the provision of guidance on fuel efficient accelerator usage. Three eco-driving interfaces were selected for test (a second-order display visual display with auditory alerts and two haptic accelerator pedal systems) following a pilot study of 12 different interfaces. These systems were tested in a range of eco-driving scenarios involving acceleration, deceleration and speed maintenance, and assessed through their effects on fuel economy, vehicle control, distraction, and driver subjective feedback. The results suggest that a haptic accelerator pedal system is most effective for preventing over-acceleration, while minimal differences were observed between systems in terms of the effect of the assistance provided to prevent under-acceleration. The visual-auditory interface lowered the time spent looking towards the road, indicating a potential negative impact on driver safety from using this modality to provide continuous green driving support. Subjective results were consistent with the objective findings, with haptic pedal systems creating lower perceived workload than a visual-auditory interface. Driver acceptability ratings suggested a slight favouring of a haptic-force system for its usefulness, whereas the more subtle haptic-stiffness system was judged more acceptable to use. These findings offer suggestions for the design of a user-friendly, eco-driving device that can help drivers improve their fuel economy, specifically through the provision of real-time guidance on the manipulation of the accelerator pedal position.

Introduction

Changes in driver behaviour have the potential to achieving fuel savings of up to 20%, with the delivery of useful and acceptable feedback on driver performance (Gonder, Earleywine et al. 2011). Therefore, substantial reductions of the environmental and financial costs of road transport could be attained through the development of an efficient in-vehicle eco-driving assistance system. This paper reports on a driving simulator study that investigates and compares the designs of three in-vehicle eco-driving assistance systems, which provide real-time guidance to the driver on how to alter accelerator pedal usage to improve their fuel efficiency. This work builds on a previous study which identified that both haptic accelerator pedal and multimodal visual-auditory interfaces are able to bring immediate improvements in fuel economy (see Jamson, Hibberd et al. 2015).

The long-term effects of eco-driving training have been shown to be relatively weak (af Wåhlberg 2007), hence the necessity of ongoing driver support for eco-driving. Therefore, it is important to ensure that the design of an in-vehicle system for continuous, sustained use is appropriate, both in terms of its ability to achieve the improved driver performance, but also to do so without causing negative outcomes for driver safety or annoyance (Adell, Várhelyi et al. 2008).

System modality

The selection of the most appropriate – most effective and least distracting – modality for the system interface is an important consideration when designing an eco-driving assistance system for prolonged use. Currently, the majority of the systems on the market rely on the provision of visual information to the driver (Graving, Rakauskas et al. 2010). Whilst this is an effective method for the delivery of detailed feedback on eco-driving performance after a drive has been completed, it has the potential to overload the driver and distract them from the primary driving task. The negative impact of competing visual tasks on driving performance have been consistently seen, with impairments observed in driver reaction times (Summala, Lamble et al. 1998; Muhrer and Vollrath 2011),event detection (Olsson and Burns 2000), and lateral control (Östlund, Nilsson et al. 2004) .

Prior work has demonstrated a reduction in the distracting impacts of an visual eco-driving interface when combined with a complementary audio signal (Jamson, Hibberd et al. 2015). However, there is substantial evidence in the literature of detrimental effects of an auditory task on driving performance measures such as brake reaction time (Alm and Nilsson 1995; Consiglio, Driscoll et al. 2003; Beede and Kass 2006), longitudinal control (Rakauskas, Gugerty et al. 2004; Ranney, Harbluk et al. 2005), event detection (Beede and Kass 2006), and steering performance (Reed and Green 1999). This suggests a need to consider an alternative presentation modality, such as a haptic accelerator pedal.

Haptic accelerator pedals have been used in a number of in-vehicle applications such as forward collision warning systems (de Rosario, Louredo et al. 2010) and speed management systems (Adell, Várhelyi et al. 2008), to produce positive effects on driving performance. More recently, this technology has been applied in the provision of eco-driving support with encouraging results to suggest that these systems can help the driver maximise their fuel economy (Larsson and Ericsson 2009; Birrell, Young et al. 2013; Jamson, Hibberd et al. 2015). These studies have focused on the investigation of a single haptic pedal test case or have used a simple short duration driving task to measure the effects of a number of systems on driving performance. This work seeks to extend both

of these approaches through the consideration of two variants of a haptic accelerator pedal system providing continuous eco-driving guidance in a longer drive.

User-centred design

User-centred design refers to the need to consider the end-user during the design of any in-vehicle system or task (Sarter and Woods 1995; Waller 1997; Peters and Peters 2002). This approach is particularly important in the design of a system that provides continuous support to the driver throughout the driving task. To this end, while investigating the impacts of three eco-driving assistance systems on driving performance, this study also considers the effects of perceived driver workload (Hart and Staveland 1988; Hart 2006) and acceptance of the systems (Van Der Laan, Heino et al. 1997). This multifaceted approach will facilitate the development of an in-vehicle interface that not only functions to achieve the desired improvements in fuel economy, but provides an interaction experience that the driver understands, does not find too difficult to manage during a challenging driving environment, and if possible, enjoys. The balance of these factors is crucial to the development and implementation of a successful in-vehicle system (Roetting, Huang et al. 2003; Tango and Montanari 2006). Furthermore, the consideration of driver impressions is critical to gain an understanding of their experience of a relatively novel in-vehicle stimulus, provided in the haptic modality (Burnett and Porter 2001; Porter, Summerskill et al. 2005).

Objectives

This study represents the second stage in the design of an in-vehicle eco-driving assistance system for the provision of real-time guidance on the fuel efficiency of accelerator pedal usage. The preliminary study of Jamson et al. (2015) has identified three such systems for further investigation, based on both objective accelerator pedal control data and subjective feedback from the driver. These systems include a haptic force feedback system, a haptic stiffness feedback system, and a visual dashboard display with complementary audio alerts. Each of these systems provides moment-by-moment guidance on the fuel efficiency of current performance and the action required to improve fuel economy where possible. The objective of this study is to provide a more extensive testing scenario for these systems, both in terms of the number and type of driving scenarios encountered and the duration of system use. Previously, drivers had interacted with these systems for 30 seconds in a short speed change task without the provision of speedometer information. This study addresses these limitations in a longer duration driving task, including urban and rural areas, straight and curved sections of road, and a number of different types of task involving a speed change and therefore a focussed period in which accelerator pedal guidance would be required to optimise fuel economy. The outcome of this study will be an in-depth comparison of the impact of these systems on accelerator pedal usage (indexed by the error between system-required pedal angle and driver-selected pedal angle), on vehicle control and driver safety measures, and on driver perceptions following a longer drive. The goal is to identify the eco-driving interface characteristics that are most promising for implementation in a green driving support system.

Methodology and materials

Apparatus

The study used the University of Leeds Driving Simulator featuring a fully operational vehicle cab inside a spherical projection dome. A near 360° simulated driving scene is rendered at 60 frames per second (1024x768 resolution) and presented on the inside of the dome. The simulator incorporates a large amplitude, eight degree of freedom motion to create realistic inertial forces associated with braking and cornering. The driver seated in the cab experiences realistic steering torque and sounds (e.g. environmental audio and engine noise). A 'glass' dashboard allows a modifiable dashboard instrument cluster arrangement visualised via two 7.5" 800x480 LCD colour monitors. The accompanying eco-driving audio was presented via the vehicle speakers. The standard vehicle accelerator pedal was replaced with a haptic accelerator pedal with variable, programmable pedal force vs. pedal travel profiles. Pedal feedback between 0-200N could be commanded.

The simulator system collects data relating to the behaviour of the driver (vehicle control) and vehicle (position, speed, accelerations, etc.) at a rate of 60Hz. Eye-tracking data (e.g. gaze location, fixation duration, eye closure) is collected using a Seeing Machines faceLAB v5.0 stereo camera pair.

Driving scenario

Participants drove a 14km route along a 7.3 metre wide, two-carriageway road with urban and rural sections (approximately 12 minutes driving). The task was to match the speed of the simulator vehicle to the posted speed limits in the most fuel efficient way. This route included sections in which drivers were required to increase (accelerate), decrease (decelerate), or maintain their speed. The scenarios involving a speed change were designed around specific road features:

- Urban section – participants drove from a rural section into an urban section containing one signalised intersection, before re-entering the rural section. The entry and exit from the urban area involved a change in the posted speed limit (rural: 60mph/96.6km/h.; urban: 40mph/64.4km/h)
- Single bend section – participants drove a sharp bend (72m radius, 100m length) in the rural section, preceded by an advisory speed limit sign of 30mph (48.3km/h). The bend varied between a left bend (50%) and a right bend (50%). The speed limit preceding the single bend section was 60mph (96.6km/h).
- Multiple bend (S-bend) section – participants drove a rural section containing eight curves in close succession (125 metre long, 250 metre radii), preceded by an advisory speed limit sign of 40mph (64.4km/h). The first bend in the sequence varied between a left bend (50%) and a right bend (50%). The speed limit preceding the multiple bend section was 60mph (96.6km/h).

A speed reduction (deceleration) was required on the entry and a speed increase (acceleration) on the exit from each scenario. In between the scenarios described above, participants were required to maintain their speed at the speed limit for the road. The urban section was used to collect speed maintenance (cruising) data. The scenarios and their associated speed changes are shown in Table 1.

Table 1: Driving simulator eco-driving scenarios

	Urban	Bend	Multiple Bends (S-bends)
Entry (DECELERATION) **Urban:** 60 mph (96.6kmh) → 40mph (64.4kmh) **Bend:** 60 mph (96.6kmh) → 30mph (48.3km/h) **S-bend:** 60 mph (96.6kmh) → 40mph (64.4kmh)			
During (CRUISE) **Urban:** 40mph (64.4kmh) **Bend:** 30mph (48.3km/h) **S-bend:** 40mph (64.4kmh)			
Exit (ACCELERATION) **Urban:** 40mph (64.4km/h) → 60mph (96.6km/h) **Bend:** 30mph (48.3km/h) → 60mph (96.6km/h) **S-bend:** 40mph (64.4km/h) → 60mph (96.6km/h)			

Each participant drove the road four times, three times using an in-vehicle eco-driving assistance system and once without assistance. In each drive, the participants drove each eco-driving scenario in Table 1 twice, once with and once without a lead vehicle. The lead vehicle drove at the speed limit and was able to adjust its speed in a fuel inefficient manner (by accelerating at a greater rate than advised by the eco-driving algorithm and through use of the brake pedal). The presence of the lead vehicle was designed to increase the demand of the eco-driving task due to the requirement for participants to perform the speed adherence task whilst maintaining a safe headway to the vehicle in front. Oncoming vehicles were presented to prevent the participant overtaking the lead vehicle.

Experimental design

This study used a repeated-measures design, with one primary independent variable: eco-driving *System Type*. The four levels of system type included no system *(Baseline)*, a visual-auditory system (*Visual-Auditory)* and the two haptic systems *(Haptic Force and Haptic Stiffness).* One level of System Type was presented per drive.

Eco-driving assistance systems

Three eco-driving assistance systems were designed based on a prior preliminary work (Jamson, Hibberd et al. 2015). Two haptic accelerator pedal systems and one multimodal visual-auditory system were tested. All three systems provided guidance relating to the fuel efficiency of the accelerator pedal position. There was no guidance provided relating to brake pedal usage. The same eco-driving algorithm was in operation for each system such that the three systems functioned consistently, with differences between them limited to the way in which the interface delivered the information.

The system functioned such that drivers were always encouraged to drive at the posted speed limit for the road, and thus the advice guided them to increase, decrease or maintain their speed depending on the current difference between their speed and the speed limit for the road. System advice focused on guiding the drivers in their transition between speeds, and not in their speed selection. The system operated in a simple way, advising of one of three optimal accelerator pedal angles, depending on whether the driver was required to increase (15% depression), decrease (0% depression) or maintain their speed (7% depression). A transition between two speed limits was advised in a consistent manner, regardless of the start and end speeds. For example, acceleration from 30 to 60mph (48.3 to 96.6 km/h) required the same accelerator pedal angle to achieve optimal fuel efficiency as an acceleration from 40 to 60mph (64.4 to 96.6 km/h). This was also true for the two speed reductions and the two speeds that were maintained (Table 2).

Table 2: Accelerator pedal angles required for optimum fuel efficiency

Speed change	Increase	Maintenance	Decrease
Advised pedal angle	15%	7%	0%

The systems provided real-time, moment-to-moment guidance based on the fuel efficiency of the current accelerator position and the change in pedal position required to improve fuel economy. The driver had no control over system operation and it remained activated for an entire drive. Strict adherence to the eco-driving guidance would allow the participant to maximise their fuel efficiency.

Haptic eco-driving assistance system

The two methods of haptic accelerator pedal guidance considered in this study represent the results of an iterative design process in a prior piloting study (Jamson, Hibberd et al. 2015), and were originally inspired by previous use of haptic pedal systems (Mulder, van Paassen et al. 2008; Mulder, Abbink et al. 2011). In a typical vehicle, there is a proportional relationship between the force applied to the accelerator pedal and the pedal travel (i.e. pedal angle produced). The haptic accelerator pedal eco-driving assistance systems change this relationship by increasing or decreasing the resistance of the accelerator pedal depending on the fuel efficiency of current driver performance. For each of the two haptic pedal systems, three pedal force vs. pedal travel profiles were defined. The eco-driving assistance system selected which of these profiles to apply in its guidance depending on the current speed limit and accelerator pedal position.

Haptic force system

The haptic force system requires the driver to produce a significant extra force of 40N to increase accelerator pedal angle beyond that considered to be optimum for fuel efficiency (0% when decelerating, 7% when maintaining speed, and 15% when accelerating). The driver experiences an immediate increase in the difficulty of pushing the pedal as they are about to over-accelerate. Figure 1 shows how the 0%, 7% or 15% "kneepoint" in each profile was designed to guide the driver towards the idealized throttle angle. In the opposite case of under-accelerating, participants were encouraged to increase the pressure on the accelerator pedal through a weakening of the pedal resistance. This is illustrated by the green line (acceleration profile) on the graph dropping below that of the standard accelerator pedal for pedal angles <15% i.e. until the point of over-acceleration, the accelerator pedal is easier to push than in a vehicle not equipped with the haptic assistance system.

Figure 1: Haptic force system profiles (dotted line = non-haptic pedal).

Haptic stiffness system

The stiffness system communicates an over-acceleration through a distinct change in pedal stiffness rather than a step-change in force for the drivers to overcome. This is demonstrated in Figure 2 as a change in the gradient of the pedal force vs. pedal travel profile (2.9N per 1% pedal travel), compared to the standard non-haptic pedal (0.2N per 1% pedal travel; dotted line). As the driver reaches the point of over-acceleration, the resisting force of the accelerator pedal is consistent regardless of whether the system is currently commanding acceleration, deceleration or cruising. The variation between these three cases is in the pedal angle at which the change in profile gradient (or pedal resistance) occurs (0% when decelerating, 7% when maintaining speed, and 15% when accelerating). Again, the system is able to encourage harsher acceleration when fuel efficiency can be improved by increasing pedal force, through a reduction in the resistance of the accelerator pedal relative to a non-haptic standard accelerator pedal.
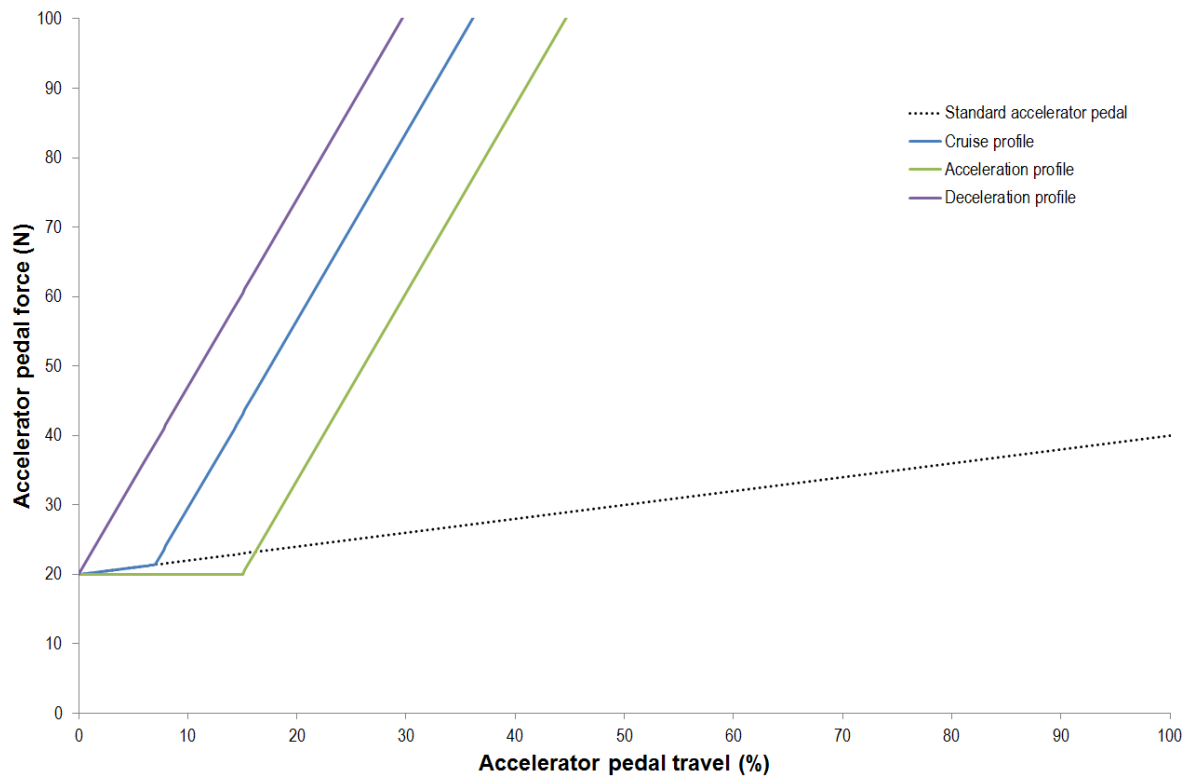
Figure 2: Haptic stiffness system profiles (dotted line = non-haptic pedal).

Both of the haptic systems were created through adjustment of the gradient of the force vs. pedal travel curve. The system was not designed with substantial consideration of the neuromuscular characteristics of the leg or pedal in terms of mass and damping properties, and indeed a consideration of these properties would enhance the design of future eco-driving support systems with a haptic pedal component (Abbink, Mulder et al. 2011). The objective in this study was to design systems that produced two noticeably different user experiences, whilst functioning based on the same underlying algorithm. The haptic pedal control was achieved by monitoring the current pedal position, which is then used to select the required pedal torque to command the user based on the force vs. pedal travel profiles for that system.

The change between different force vs. pedal travel profiles within a system was managed such that there was an immediate change in the feeling of the accelerator pedal when a different profile was activated (system bandwidth > 15Hz). For example, consider Figure 2 above and a scenario in which the driver is required to maintain speed and is successfully doing this by producing an accelerator pedal angle of 7%, using a force of approximately 20N. Here, the driver is performing efficiently during a speed maintenance task, and so the eco-driving support system is using the Cruise profile to provide its guidance. If the driver pushes with more force and increases the pedal travel to 8%, this is considered to be an over-acceleration during a cruising phase of the drive, and thus the eco-driving support system would immediately load the Deceleration profile to encourage the driver to reduce the acceleration of the vehicle. This is achieved by commanding a reduction of the force applied to the pedal. The force required to maintain the over-accelerating 8% pedal angle in the Deceleration mode, is substantially higher (>35N) and thus with no increase in applied pushing force, the driver would experience an increased difficulty in pushing the pedal, and thus the pedal travel would reduce (to 0% with no change in driver pushing force) . This effectively counteracts the over-

acceleration that had been produced. In the same scenario, if the driver momentarily decreased pedal force to produce a pedal angle of 6%, the system would activate the Acceleration profile, which results in the same pushing force producing a 15% pedal angle, and thus acceleration and a resulting increase in speed towards that desired for best fuel economy.

Visual-auditory eco-driving assistance system

The visual component of the multimodal display used the principles of a colour-coded display to present the fuel efficiency of the current accelerator pedal position (Gonder, Earleywine et al. 2011). A foot icon was presented in the tachometer (i.e. Nissan ecoPedal; see Meschtscherjakov, Wilfinger et al. 2009), which was green when the participant was driving within 1% of the optimum pedal angle (based on a maximum pedal angle of 100%). The display changed colour to red during over-acceleration and to blue during under-acceleration. The RGB component of the foot icon was blended to show a gradual transition between these colours with variation in accelerator pedal angle. The display was full blue or full red when the error between current and desired pedal angle exceeded -6% and +6% respectively (Figure 3). The visual display also included second-order information on the required change in pedal angle, previously demonstrated to be more effective than first-order information on the current performance error (Jamson, Hibberd et al. 2015). The display included two lines representing the pedal itself (grey= current position; dotted white = optimum position). Participants were required to minimise the distance between these lines to optimise fuel economy.

Insufficient gas pedal pressure   **Appropriate gas pedal pressure**   **Excessive gas pedal pressure**
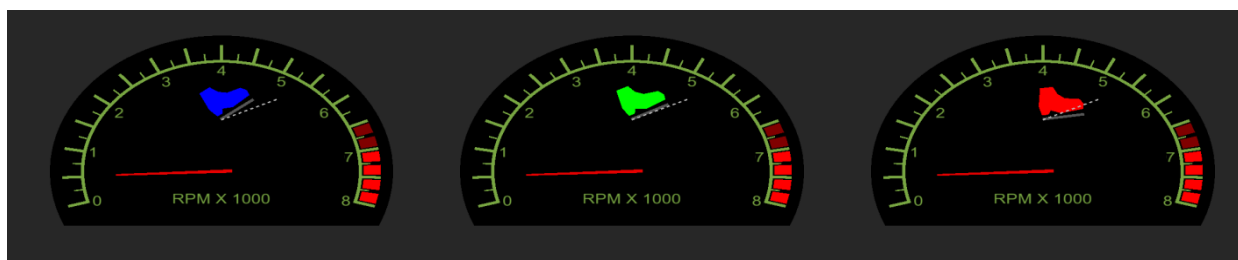

Figure 3: Visual-auditory system

A high pitch auditory tone (1770Hz) sounded to signal the need to decrease pressure on the accelerator and a low pitch tone (512Hz) signalled that an increase in pressure was required. These tones sounded once each time the driver was required to change the pedal angle to improve their fuel efficiency. The alert did not sound again until a change in pedal angle in the opposite direction was required, so as to minimise repeat alerts and possible annoyance (Adell, Várhelyi et al. 2008).

Experimental procedure

Participants performed this study in two separate visits, performing two drives during each visit. The eco-driving system types experienced per visit were determined by counterbalancing.

Participants performed a three-phase familiarisation drive on their first visit to the simulator. Participants were first familiarised with simulator operation and controls by driving through a rural section of road (10 minutes). The second phase involved practising the eco-driving, speed adherence task. A visual display was presented to provide feedback on their eco-driving performance (15 minutes) (Figure 4). The function of each eco-driving assistance system was then explained to the

participant before they had a short opportunity to practice with it on a straight road (15 minutes). This practise was devised to ensure that participants did not have an opportunity to practice the specific scenarios to be tested in the experimental phase. The familiarisation drive on the second visit consisted of the same phases, but with shorter first and second phases. Participants only practised with those systems to be tested on that visit.
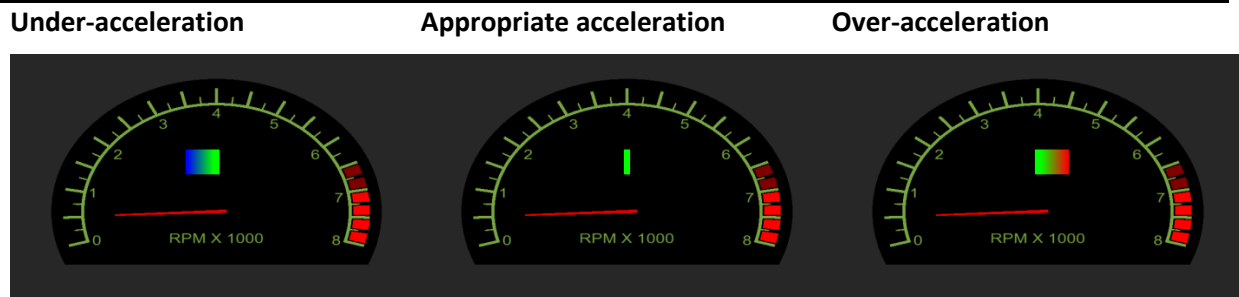
Under-acceleration	Appropriate acceleration	Over-acceleration

Figure 4: Visual eco-driving interface (familiarisation phase only)

The experimental phase consisted of four drives; two per visit to the simulator. Each drive involved a different eco-driving system type (visual, haptic force, haptic stiffness, no system). Each drive contained six acceleration and six deceleration scenarios. The three different types of each scenario were experienced in the first and second half of the drive, once with a lead vehicle and once without. The order of the three road sections (urban, bend, S-bend) producing these scenarios was varied such that a participant did not experience two identical route orders during their four drives. This was to prevent learning of the scenario order and any subsequent impact on driver behaviour. The presentation of the lead vehicle was also controlled such that participants saw it in the first half for two drives and in the second half for two drives. The four levels of eco-driving system type (four drives) were fully counterbalanced to minimise order effects. Each participant performed the four drives in a different order. After each drive, participants completed a workload questionnaire rating the workload associated with the eco-driving, speed adherence task, accounting for the presence of an assistance system where applicable. The NASA-TLX scale was used due to its simplicity and good sensitivity to experimental manipulations in the simulator environment (Hart 2006). For drives with a system, participants also completed the Van der Laan Acceptability Scale (Van Der Laan, Heino et al. 1997); a simple tool for the assessment of driver acceptance of new technologies inside the vehicle.

Participants had full control of both the longitudinal and lateral control of their vehicle. They were instructed to drive in the centre of the lane and to 'obey the posted speed limit signs' and to 'control the speed of the vehicle in the most fuel-efficient way possible', regardless of the presence of an assistance system. Participants were given a short description of eco-driving:

Eco-driving involves the driving of a vehicle in a fuel-efficient way creating savings for both driver (fuel/maintenance costs) and environment (lower emissions). This style of driving can be achieved through gentle use of the accelerator, appropriately timed gear changes, the avoidance of harsh braking, and anticipation of the situation ahead.

Participants were motivated to engage with the eco-driving task by offering an additional monetary reward for the 'best' performing ecoDriver during the study (all participants received a fixed reward

for their participation). It was emphasised that the selection of a fuel efficient speed was not a component of the eco-driving task, and that the participants focus should be on performing the transition between two speeds in an economical fashion.

Participants

Twenty participants were retained from the preceding rapid prototyping study to minimise training requirements with the eco-driving interfaces. Four naïve participants were recruited to allow for full counterbalancing of the order of system presentation. These participants each had prior experience of the driving simulator and were provided with extensive eco-driving task training to ensure comprehension of the task and system function were comparable to that of the existing participant pool. The 24 participants were balanced for gender, age, driving experience and annual mileage (Table 3).

Table 3: Participant sample characteristics

| | Male (n=12) | | Female (n=12) | |
	Mean	SD	Mean	SD
Age (years)	35.1	14.0	39.2	15.0
Experience (years)	17.0	12.8	21.0	14.4
Annual mileage (mi)	10250	5750	7300	3500

Results

Objective data

Analysis focused on the data from the scenario zones only (200 metres before the first and after the final speed limit sign in a scenario). This was because the scenarios included eco-driving related events and their duration and number were fixed across participants. There was no analysis of driving behaviour outside of these zones. The road network was divided into seven scenarios (three deceleration events, three acceleration events, and one speed maintenance event). Within each scenario, the data was sub-divided into three bins depending on whether the eco-driving assistance system was currently requesting a deceleration, acceleration or maintenance of the accelerator pedal angle. (For the baseline drive, these bins were created based on what the eco-driving system would have advised if it were present). All data within a specific bin therefore refer to performance in a particular system mode. However, the size (time duration) of these bins differ between participants due to differences in eco-driving task performance and thus behaviour of the eco-driving assistance system. This approach was considered preferable to assessing performance combined across all system modes, where good performance in one mode could cancel out bad performance in another mode.

Eco-driving task performance

The eco-driving assistance systems were designed to guide the driver towards the most fuel efficient accelerator pedal angle and thus an appropriate measure of eco-driving performance is the error between desired (system advised) and actual (participant selected) accelerator pedal position (root mean squared pedal error). The analysis of this variable focused on one system mode per scenario;

that mode which the system should be in if the participant were attempting to follow the eco-driving guidance. A preliminary analysis revealed that participants rarely caused the system to enter a mode which did not match the scenario requirements i.e. instances of the system needing to advise an acceleration during a section with a speed limit decrease were nearly non-existent, and only occurred as a result of overshooting the required speed decrease. The data bins used for analysis in each scenario are listed below (Table 4).

Table 4: Eco-driving system profile analysed per scenario

Scenario	Speed change required	System mode analysed
Village	None	Cruise
Village, bend, or S-bend entry	Decrease	Decelerate
Village, bend or S-bend exit	Increase	Accelerate

In addition to the absolute pedal error, the variation in this measure gives an indication of performance on the eco-driving task. Lower standard deviation of pedal error implies fewer corrections of pedal position, which if combined with low root mean squared pedal error, would imply good eco-driving performance. Mean acceleration was also considered as an alternative measure of eco-driving success.

The assessment of eco-driving performance has been confined to the three drives with an eco-driving assistance system only because fuel efficient accelerator use in the real-world would not necessarily equate to economical use of the accelerator pedal in the baseline simulator drive with the simple eco-driving algorithm applied in this study.

All variables described above showed significant deviation from the normal distribution, so non-parametric ANOVA (Friedman's ANOVA) was used to analyse for an effect of System Type on performance. Post-hoc Wilcoxon's Signed Ranks tests were used and corrected for multiple pairwise comparisons. These analyses were limited to data taken from scenarios without a lead vehicle, where the participant has an unimpeded opportunity to follow the eco-driving guidance and will not be hindered by the presence of a lead vehicle not following eco-driving advice.

Speed decrease scenarios

The three scenarios involving a speed limit decrease all showed a significant difference in root mean squared accelerator pedal errors across the three system types ($x^2(2) = 18.083\text{-}18.250$, $p<.001$). The haptic-force system allowed the driver to be more precise in their adherence to the eco-driving advice during deceleration (Figure 5). Across the three scenarios, post-hoc tests demonstrated that performance with the haptic-force system (Median error = 0.85-1.23%) was significantly better than with the haptic-stiffness (Median error = 2.29-3.17%) or visual-auditory systems (Median error = 2.68-3.47%).
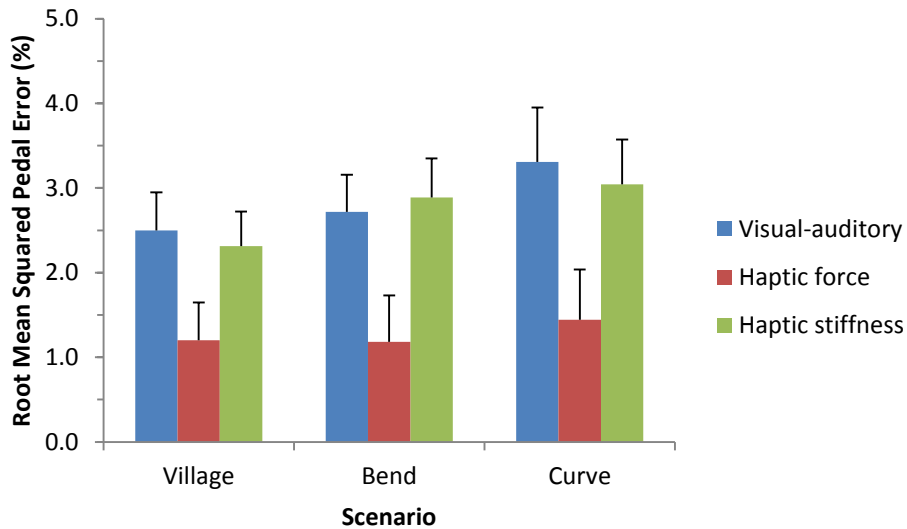
Figure 5: Accelerator pedal error during speed decrease scenarios (error bars show 95% confidence intervals)

The haptic-force system also showed significantly lower standard deviation of accelerator pedal error compared to the haptic-stiffness and visual-auditory systems, across all scenario types (Table 5).

Table 5: System Type effects on standard deviation of accelerator pedal error

Scenario	System Median (%)			X^2	df	p-value
	Visual-auditory	Force	Stiffness			
Village	2.08	0.97	1.75	6.632	2	.036
Bend	1.80	0.85	1.71	12.091	2	.002
Curvy	1.96	1.22	1.58	6.700	2	.035

There was also a significant effect of System Type on mean acceleration, [Village: $x^2(2)=27.750$, p<.001; Bend: $x^2(2)=18.250$, p<.001; Curvy: $x^2(2)=22.750$, p<.001], with significantly greater decelerations observed across all scenarios when driving with a haptic-force system compared to either the haptic-stiffness or visual-auditory systems (Figure 6).
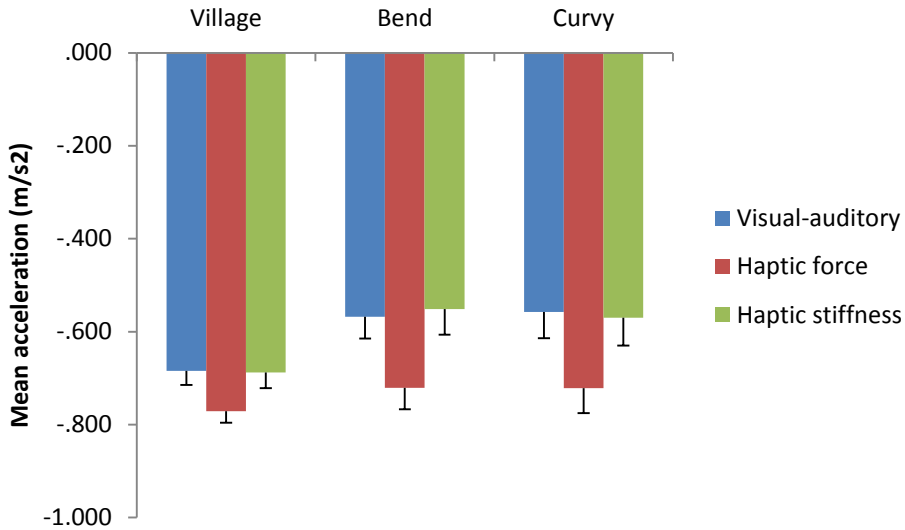
Figure 6: Mean acceleration on speed decrease scenarios (plotted as negative accelerations)

Speed increase scenarios

There was no main effect of System Type on root mean square pedal error in any of the speed increase scenarios, with median pedal error in the range of 2.58-3.40% (Figure 7).
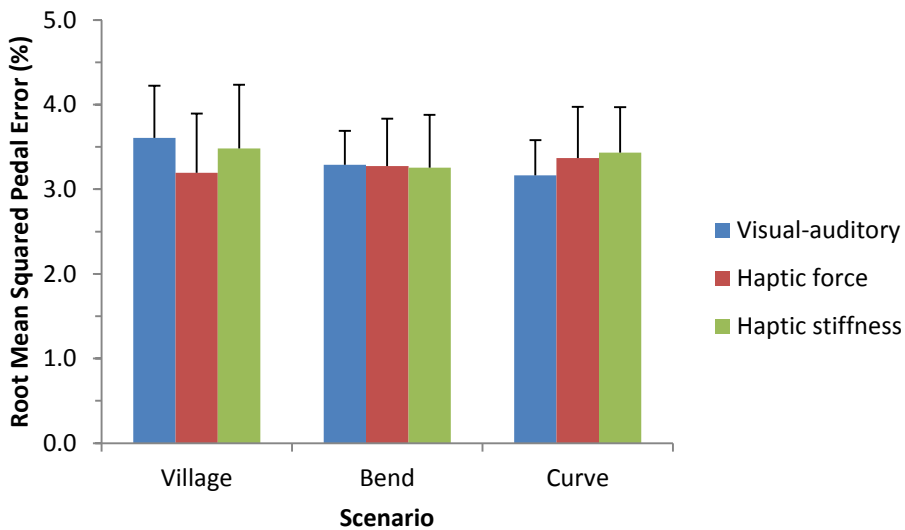

Figure 7: Accelerator pedal error during speed increase scenarios (error bars show 95% confidence intervals)

The standard deviation of pedal error and mean acceleration also showed no differences across the three systems, regardless of the scenario considered.

Speed maintenance scenarios

There was no significant effect of System Type on mean or standard deviation of pedal error in the 40mph (64.4km/h) cruising phase of the drive. This was also true for the analysis of mean acceleration, although there was a noticeable increase in the variability of acceleration in the two haptic system conditions relative to the visual-auditory system condition (Figure 8).
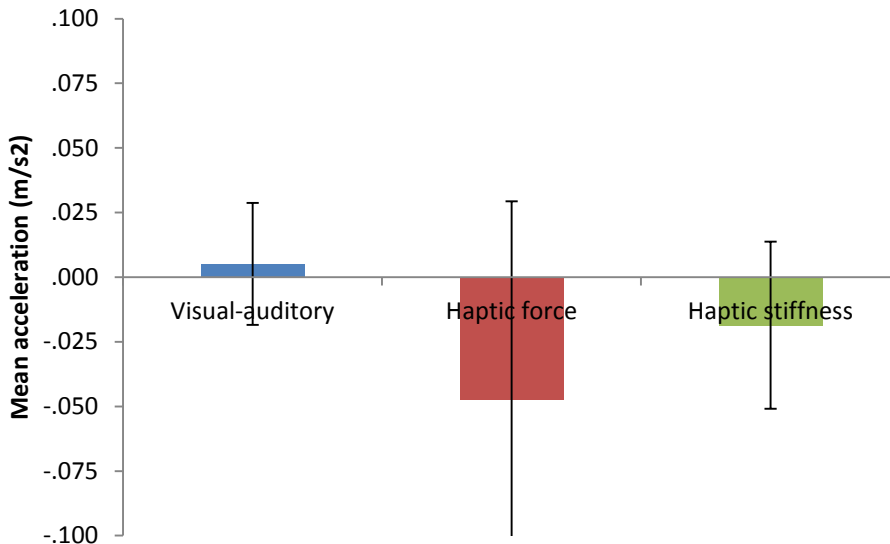
Figure 8: Mean acceleration on speed maintenance scenarios

Driver safety measures

It is important to assess the impact of interacting with an in-vehicle eco-driving system on driver safety measures so as to detect any negative effects of these systems. For these analyses, the baseline data is included to allow comparison with performance during a driving task without system interaction. The lead car presence was also introduced into the analysis to consider whether the presence of an additional vehicle altered the effect of the eco-driving assistance system on these measures of driving performance. The following variables were analysed:

- Percent road centre (PRC) provides a measure of the proportion of driver fixations that fall within a 6°circle centred at the driver's most frequent fixation point. PRC is used as a proxy for visual distraction from the driving task. PRC measurements of less than 15% were excluded from the analysis due to difficulties in determining whether these data points were due to eye-tracking equipment failure or due to looking away from the forward road scene (a maximum of 12.5% of data was excluded from any analysis).
- Standard deviation of lane position (SDLP) was used as a measure of lateral vehicle control. Steering wheel reversal rate (number of times per minute that the steering wheel direction is changed by more than 1°) was also considered.
- Mean speed and mean headway were selected as measures of longitudinal control of the vehicle. There was no effect of System Type or Lead Vehicle on mean speed across all scenarios, and hence no further discussion is offered. There were no significant effects of System Type on mean headway, although there was a trend for closer following during interaction with a visual display relative to the two haptic systems. The higher proportion of distant car-following (<10 metres) largely confounded this analysis.

All variables were tested for deviations from a normal distribution. Where these assumptions of parametric testing were not violated, repeated measures ANOVA was used for the analysis. In cases

of non-normal data, the analysis involved Friedman's ANOVA followed by Wilcoxon's Signed Ranks tests corrected for multiple comparisons.

Speed decrease scenarios

There was a significant main effect of System Type on PRC on the approach to both the bend, [$F_{(3,60)}$=22.801, p<.001, η^2=.533], and the S-bend, [$F_{(3,60)}$=10.662, p<.001, η^2=.348], and a near significant trend for the village entry. Participants spent less time looking at the road centre with the visual-auditory system compared to the two haptic systems or with no system at all. There were no significant differences in performance with a haptic pedal system compared to baseline driving.

There was a main effect of lead vehicle presence on PRC leading up to the bend, [$F_{(1,20)}$=7.261, p=.014, η^2=.266], and S-bends, [$F_{(1,20)}$=14.390, p=.001, η^2=.418], with less time spent looking at the centre of the road when driving without a lead vehicle (Table 6). These two factors did not interact.

Table 6: Percent Road Centre (%) during speed decrease scenarios

Lead Car	Village	Bend	Curvy
Absent	50.4	61.5	55.6
Present	53.1	65.3	61.8

There was a significant effect of System Type on SDLP during the approach to the bend, [$x^2(3)$=9.950, p=.019] and S-bends, [$x^2(3)$=11.150, p=.011]. These effects were due to significantly greater SDLP in the baseline and visual-auditory system conditions compared to driving with the haptic-force system. The trend was comparable for the village entry scenario (Figure 9). There was no effect of a lead vehicle on lateral control.
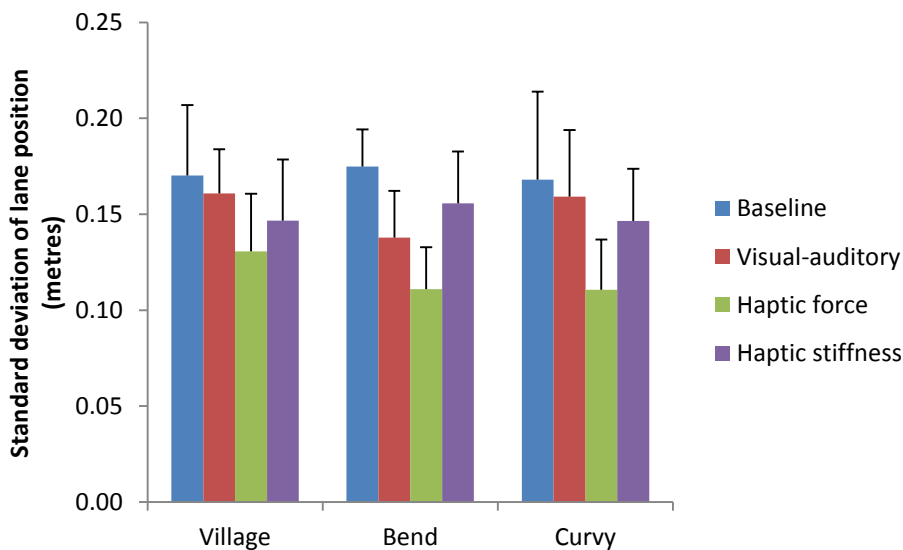

Figure 9: Standard deviation of lane position in speed decrease scenarios

Speed increase scenarios

The same pattern of results was observed for PRC as in the speed decrease scenarios, with significant System Type effects in all three scenarios, due to participants looking ahead for more of the time with the haptic systems or without a system compared to their behaviour when interacting

with the visual display (Village: [F(19.52,37.089)=13.904, p<.001, η^2=.423], Bend: [F(2.163,43.267)=15.119, p<.001, η^2=.431], Curvy: [F(3,60)=11.503, p<.001, η^2=.365]. Post-hoc testing revealed that each of these effects was due to significantly less time spent looking at the road centre with the visual eco-driving support system compared to either haptic system or in the absence of a system(Figure 10). Lead vehicle presence again increased the proportion of time spent looking at the road ahead, with performance remaining worst with the visual-auditory system, both with and without a lead vehicle.
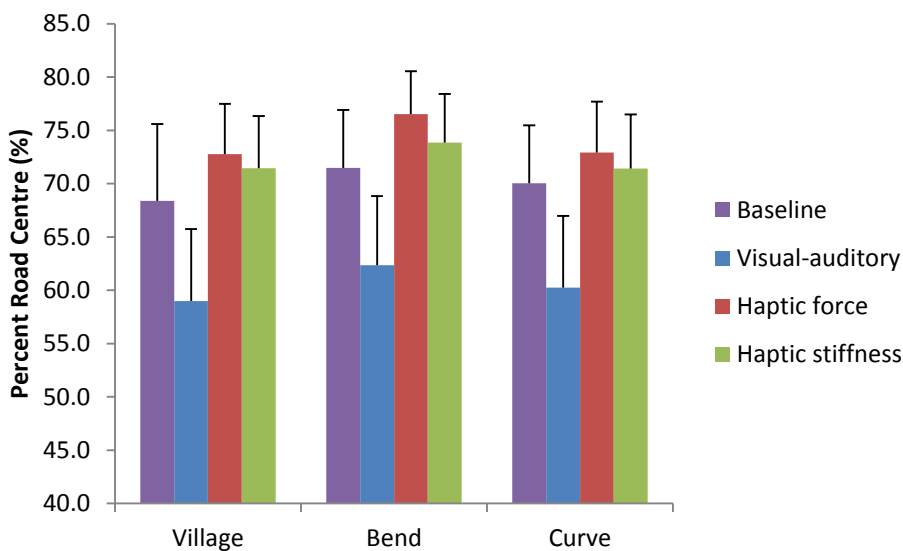

Figure 10: Percent road centre during speed increase scenarios

The effect of System Type on SDLP in the speed increase phases of the drive was heavily dependent on scenario. There was evidence of a significant effect on SDLP during exit from the village, [x^2(3)=12.950, p=.005], with greater SDLP when driving with the visual eco-driving support compared to an absence of support or guidance via the haptic force system (Figure 11). This trend was observed upon exit from the bend scenario (p=.100). In contrast, there was little evidence of an effect of System Type on SDLP exiting the S-bend section (p=.969).
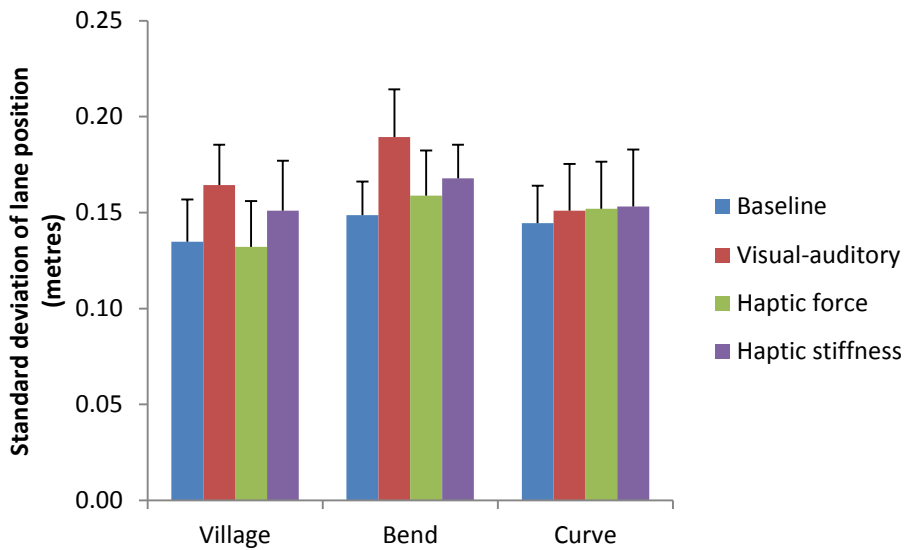
Figure 11: Standard deviation of lane position in speed increase scenarios

Speed maintenance scenarios

There was no significant effect of System Type nor Lead Vehicle on PRC in the speed maintenance phase, although the mean tendency was in the predicted direction, with fewer fixations on the road centre with the visual-auditory system (Figure 12).

Figure 12: Percent road centre during speed maintenance scenarios

There was no effect of System Type or Lead vehicle on SDLP or steering reversal rate during the speed maintenance phase of the drive, which took place on a straight road.

Subjective data

Workload

The ratings for the six NASA-TLX subscales were summed to provide a 'total workload' score (out of 60) for each participant. These distribution of these scores differed significantly from the normal

distribution (Kolmogorov-Smirnov test p-value < .05), hence these data were subjected to non-parametric analysis of variance (Friedman's ANOVA) followed by Wilcoxon Signed Rank post-hoc tests. There was a significant effect of System Type on total workload, $x^2(3) = 11.748$, p=.008. Post-hoc testing revealed lower overall workload during the eco-driving task when interacting with the haptic-force system (Median = 13.0) and the haptic-stiffness system (Median = 18.7) compared to either the no system condition (Median = 21.4) or the visual-auditory system condition (Median = 23.9) (Figure 13). This result was broadly consistent across the NASA-TLX subscales of mental demand, temporal demand, overall performance, effort and frustration. The tendency was not observed for the physical demand subscale.
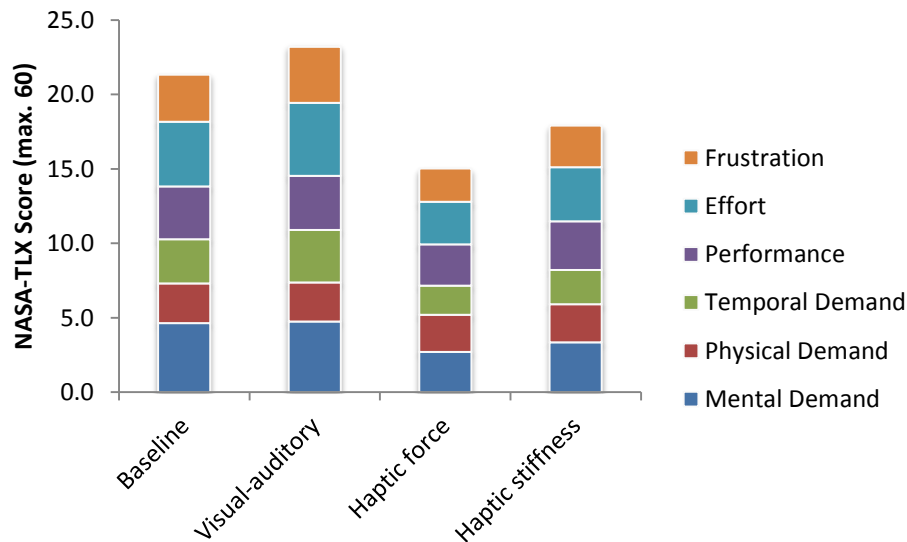

Figure 13: Total workload score on NASA-TLX per System Type

Acceptability

The scale consists of a series of nine five-point ratings scales, which can be grouped to produce two summary scales, termed Usefulness and Satisfaction, which are utilised for determining the overall acceptability of a new system. The scores on each summary scale were analysed by one-way, three-level Friedman's ANOVA. There was no difference in System Usefulness across the three systems (p=.195), although there was a tendency for the haptic-force system to be considered most useful. There was no difference in System Satisfaction across the three systems (p=.122), although in this case, the tendency was for the haptic-stiffness system to be considered most satisfying to use (Figure 14). There was a substantial but non-significant difference between Satisfaction scores for the haptic-stiffness and the visual-auditory systems.
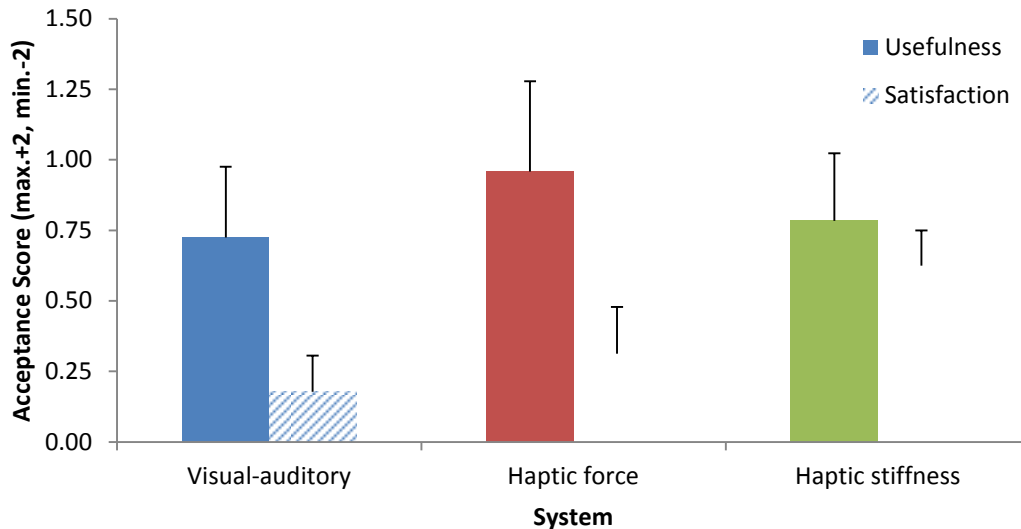
Figure 14: Usefulness and Satisfaction Ratings for the three eco-driving support systems

Discussion

This simulator study has tested the effectiveness of three eco-driving assistance systems for providing real-time guidance to the driver about the most fuel efficient accelerator pedal position. The three systems – one visual-auditory, and two haptic accelerator pedals – have been compared in terms of their success in improving driver fuel economy, their impact on vehicle safety and control measures, and driver impressions during their use.

Objective results

The eco-driving support systems were designed to guide the driver towards one of three accelerator pedal angles, dependent on whether the individual was required to increase, decrease or maintain their speed at a given time. The analysis focused on each of these scenarios separately, and differences in objective performance were observed.

The primary objective measure of eco-driving performance was root mean squared pedal error. A significant difference between the systems was observed for this variable on speed decrease (deceleration) scenarios only. The haptic force system was more effective than the haptic stiffness or visual-auditory system for encouraging drivers to release the accelerator pedal completely (0% pedal depression) and use the vehicle's engine braking for the speed reduction required. This effect was not present for speed increase (acceleration) or speed maintenance (cruising) scenarios. The reason for this may be due to the subtleness of the guidance provided by the haptic systems in these two types of scenario. In these cases, the physical experience of the pedal is not as noticeably different to the standard non-haptic pedal used with the visual-auditory display. This would appear to suggest that the decreased resistance of the haptic pedal used to alert the driver to under-acceleration is not an effective cue in its current form. The same pattern of results was also observed with standard deviation of pedal error, suggesting that the haptic force system leads to drivers making fewer changes to their pedal position in response to the advice. Mean acceleration is another variable that

can be used to assess the effectiveness of the eco-driving support. In the speed decrease scenarios, the participant was required to fully release the accelerator pedal to accurately obey the eco-driving guidance, and thus higher deceleration is an indication of better performance. Higher decelerations were observed with the haptic force system than the haptic stiffness or visual systems, meaning that this method of guidance delivery is most effective for encouraging drivers to release the accelerator entirely to lower their speed. There was no effect of System Type on this variable during speed increase scenarios, again suggesting that the subtlety of the haptic guidance does not allow these systems to encourage better performance than a visual display on the vehicle dashboard.

The presentation of additional information to a driver during the driving task has the potential to create negative effects on performance due to distraction. Visual distraction from the forward roadway was assessed through a measure of visual glance behaviour; percent road centre (PRC). The predicted effects were for the visual eco-driving support to lead to a reduction in PRC, with little or no effect of a haptic support system on this variable. This was observed in a number of speed increase and speed decrease scenarios, with drivers spending more time looking away from the road centre with the visual display than with either haptic accelerator pedal system, or in the absence of eco-driving support. This remained true, regardless of the presence of a lead vehicle, suggesting that drivers do not effectively modulate their attention to the visual interface when the driving task demand increases. This is a concern given the likelihood of missing safety-critical events in the external world when attention is directed away from the roadway, particularly when car-following. Importantly, eye-tracking data showed no difference in performance with a haptic support system compared to baseline performance, suggesting that the use of this modality may provide a safer method for delivery this information whilst avoiding the negative effects of visual distraction.

The lateral and longitudinal control of the vehicle was also considered in this study. It would be expected that lateral control of the vehicle would be impeded by the interaction with an additional visual task. This was observed in certain scenarios, with poorer SDLP during use of the visual-auditory system compared to the haptic force system (in certain scenarios only). The absence of emphatic system effects on measures of lateral control are likely to be due to the majority of speed changes occurring on straight roads, where the steering task is less demanding.

Subjective results

The subjective data collected largely support the findings of the objective analysis. When drivers were asked to rate the workload they experienced during their attempts to modulate their speed in the most fuel efficient way, participants rated the haptic accelerator pedal systems more favourably than the multimodal visual-auditory interface. This suggests that a system that presents eco-driving guidance in a non-visual way can help to alleviate driver workload. This is encouraging given the vast array of in-vehicle systems that present information to the driver visually.

Participants found the eco-driving task less demanding with a haptic system than without a system, suggesting that drivers find it easier to be fuel efficient with an assistance system. In fact, the highest ratings on the Effort subscale were given for the baseline drive, suggesting that all three eco-driving systems provide valuable assistance in the fuel efficiency task.

A surprising result was the absence of a difference in the rated physical demand of interacting with the three eco-driving assistance systems, despite two systems using an accelerator that could resist

the driver's foot movements with forces of up to 200N. Prior work has demonstrated an increase in workload when receiving haptic rather than visual support (Lam, Mulder et al. 2008), and thus this is a promising result because it suggests that haptic feedback to the driver's right foot is not causing excessive physical demand or stress. The differences in perceived workload observed between the two haptic systems were minimal across all subscales, although the tendency was for the force system to be rated more favourably.

In light of these results, it would suggest that drivers might experience lower additional demand from a haptic eco-driving assistance system relative to one using a visual interface. However, it should be noted that the prior comparisons of mean ratings disguise substantial variations in workload ratings for each system across participants. An inspection of Figure 15 shows that each system received both very high and very low ratings across the participant group, although fewer very low scores are observed for the visual-auditory system.
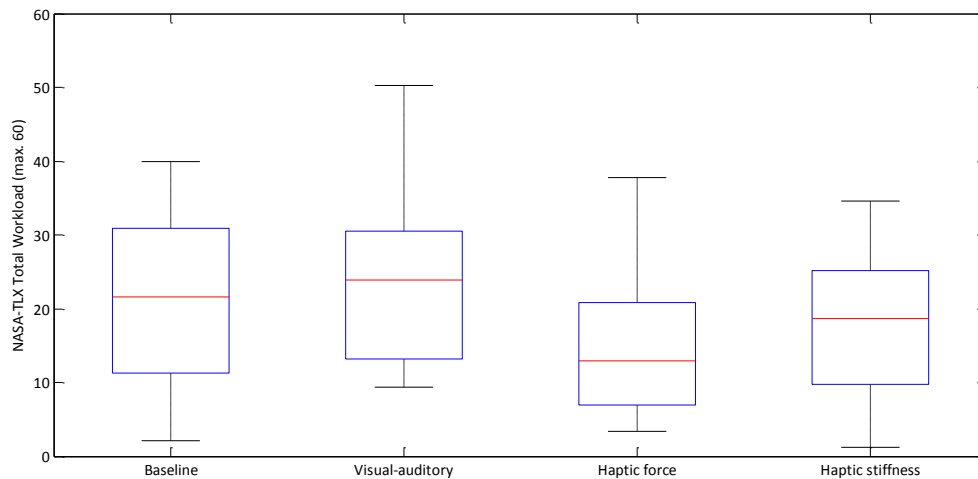

Figure 15 – Median total workload score [Baseline = 21.3; Visual-auditory = 23.2; Force = 15.0; Stiffness = 17.9]. Error bars show 100% range

The Van Der Laan Acceptability Scale was less effective for discriminating between the three types of eco-driving system, with no significant difference between systems on either the Usefulness or Satisfaction subscales. However, the tendencies suggest that the haptic force system is the most useful, whilst the haptic stiffness system was actually preferred. This fits with the type of guidance being provided by the two systems, particularly when the driver is required to increase their speed. The haptic force system acts with a very high force to prevent over-acceleration, effectively making adherence to the eco-driving guidance mandatory. This is effective in terms of minimising pedal error, but may not be acceptable to the driver, who would prefer more control over their acceleration performance. The guidance offered by the haptic stiffness system is more subtle, whilst remaining obvious. This might be considered more acceptable to the driver because they are being provided with meaningful guidance whilst retaining the option to ignore it if they wish. This potential trade-off between system utility and acceptability should be further explored in a prolonged drive.

Conclusions

It is hoped that some of the lessons learnt regarding eco-driving guidance presentation will be applicable to the ongoing development of such in-vehicle assistance systems. Overall, there is encouraging evidence to suggest that drivers are able to detect and respond to changes in the 'feel' of the accelerator pedal to adjust their acceleration profile. The haptic force feedback system is most effective for guiding drivers to the most fuel efficient accelerator pedal position during an extended drive, although the advantage seems to be largely confined to scenarios in which drivers are required to decelerate. There is little observable difference in eco-driving performance between a haptic stiffness system and a visual foot pedal display with auditory alerts. Measures of lateral and longitudinal control argue for the use of either of the haptic systems instead of a visual display, and this is further supported by eye-tracking data. The subjective analysis shows that both haptic systems create a lower overall workload than the visual-auditory display, and although acceptability of all systems appears good, there is some evidence to suggest an advantage for a haptic accelerator pedal, both in terms of system usefulness and satisfaction.

However, these results should be considered in light of the limitations of the study. Whilst the ecological validity of the experimental context has been improved relative to prior work, by testing the systems in a longer drive with an increased number of driving scenarios (Jamson, Hibberd et al. 2015), it will be important to further test these systems in a wider range of driving scenarios that require speed changes e.g. the approach to junctions, driving on gradients, or in busier traffic. In the latter case, the potential conflict between eco-driving guidance and the actions required to maintain safety will be an interest area to study. Perhaps most importantly, it will be necessary to study how the parameters of a haptic accelerator pedal system can be adjusted to improve the effectiveness of eco-driving guidance during acceleration or cruising phases of a drive.

Acknowledgments

References

Abbink, D. A., M. Mulder, et al. (2011). "Measuring Neuromuscular Control Dynamics During Car Following With Continuous Haptic Feedback." IEEE Transactions on Systems, Man and Cybernetics, Part B **41**(5): 1239-1249.

Adell, E., A. Várhelyi, et al. (2008). "Auditory and haptic systems for in-car speed management – A comparative real life study." Transportation Research Part F: Traffic Psychology and Behaviour **11**(6): 445-458.

af Wåhlberg, A. E. (2007). "Long-term effects of training in economical driving: Fuel consumption, accidents, driver acceleration behavior and technical feedback." International Journal of Industrial Ergonomics **37**(4): 333-343.

Alm, H. and L. Nilsson (1995). "The effects of a mobile telephone task on driver behaviour in a car following situation." Accident Analysis & Prevention **27**(5): 707-715.

Beede, K. E. and S. J. Kass (2006). "Engrossed in conversation: The impact of cell phones on simulated driving performance." Accident Analysis & Prevention **38**(2): 415-421.

Birrell, S. A., M. S. Young, et al. (2013). "Vibrotactile pedals: provision of haptic feedback to support economical driving." Ergonomics **56**(2): 282-292.

Burnett, G. E. and M. J. Porter (2001). "Ubiquitous computing within cars: designing controls for non-visual use." International Journal of Human-Computer Studies **55**(4): 521-531.

Consiglio, W., P. Driscoll, et al. (2003). "Effect of cellular telephone conversations and other potential interference on reaction time in a braking response." Accident Analysis & Prevention **35**(4): 495-500.

de Rosario, H., M. Louredo, et al. (2010). "Efficacy and feeling of a vibrotactile Frontal Collision Warning implemented in a haptic pedal." Transportation Research Part F: Traffic Psychology and Behaviour **13**(2): 80-91.

Gonder, J., M. Earleywine, et al. (2011). Final Report on the Fuel Saving Effectiveness of Various Driver Feedback Approaches, National Renewable Energy Laboratory.

Graving, J. S., M. E. Rakauskas, et al. (2010). "A Binary Response Method to Determine the Usability of Seven In-Vehicle Fuel Economy Displays." Proceedings of the Human Factors and Ergonomics Society Annual Meeting **54**(19): 1546-1550.

Hart, S. G. (2006). "Nasa-Task Load Index (NASA-TLX); 20 Years Later." Proceedings of the Human Factors and Ergonomics Society Annual Meeting **50**(9): 904-908.

Hart, S. G. and L. E. Staveland (1988). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. Advances in Psychology. P. A. Hancock and N. Meshkati, North-Holland. **Volume 52:** 139-183.

Jamson, H., D. L. Hibberd, et al. (2015). "Interface design considerations for an in-vehicle eco-driving assistance system." Transportation Research Part C: Emerging Technologies **Special Issue "Technologies to support green driving"**: In Press.

Lam, T. M., M. Mulder, et al. (2008). "Haptic Feedback in Uninhabited Aerial Vehicle Teleoperation with Time Delay." Journal of Guidance, Control, and Dynamics **31**(6): 1728-1739.

Larsson, H. and E. Ericsson (2009). "The effects of an acceleration advisory tool in vehicles for reduced fuel consumption and emissions." Transportation Research Part D: Transport and Environment **14**(2): 141-146.

Meschtscherjakov, A., D. Wilfinger, et al. (2009). Acceptance of future persuasive in-car interfaces towards a more economic driving behaviour. Proceedings of the 1st International Conference on Automotive User Interfaces and Interactive Vehicular Applications. Essen, Germany, ACM**:** 81-88.

Muhrer, E. and M. Vollrath (2011). "The effect of visual and cognitive distraction on driver's anticipation in a simulated car following scenario." Transportation Research Part F: Traffic Psychology and Behaviour **14**(6): 555-566.

Mulder, M., D. A. Abbink, et al. (2011). "Design of a Haptic Gas Pedal for Active Car-Following Support." IEEE Transactions on Intelligent Transportation Systems **12**(1): 268-279.

Mulder, M., M. M. van Paassen, et al. (2008). "Haptic gas pedal feedback." Ergonomics **51**(11): 1710-1720.

Olsson, S. and P. C. Burns. (2000). "Measuring Driver Visual Distraction with a Peripheral Detection Task." from http://www-nrd.nhtsa.dot.gov/departments/nrd-13/driver-distraction/PDF/6.PDF.

Östlund, J., L. Nilsson, et al. (2004). Deliverable 2—HMI and Safety-Related Driver Performance. Human Machine Interface And the Safety of Traffic in Europe (HASTE) Project.

Peters, G. A. and B. J. Peters (2002). Automotive Vehicle Safety. London, Taylor & Francis.

Porter, J. M., S. Summerskill, et al. (2005). BIONIC – 'eyes-free' design of secondary driving controls. Accessible Design in the Digital World Conference 2005. Dundee, Scotland.

Rakauskas, M. E., L. J. Gugerty, et al. (2004). "Effects of naturalistic cell phone conversations on driving performance." Journal of Safety Research **35**(4): 453-464.

Ranney, T. A., J. L. Harbluk, et al. (2005). "Effects of Voice Technology on Test Track Driving Performance: Implications for Driver Distraction." Human Factors: The Journal of the Human Factors and Ergonomics Society **47**(2): 439-454.

Reed, M. P. and P. A. Green (1999). "Comparison of driving performance on-road and in a low-cost simulator using a concurrent telephone." Ergonomics **42**(8): 1015.

Roetting, M., Y.-H. Huang, et al. (2003). "When technology tells you how you drive--truck drivers' attitudes towards feedback by technology." Transportation Research Part F: Traffic Psychology and Behaviour **6**(4): 275-287.

Sarter, N. B. and D. D. Woods (1995). "How in the World Did We Ever Get into That Mode? Mode Error and Awareness in Supervisory Control." Human Factors: The Journal of the Human Factors and Ergonomics Society **37**: 5-19.

Summala, H., D. Lamble, et al. (1998). "Driving experience and perception of the lead car's braking when looking at in-car targets." Accident Analysis and Prevention **30**(4): 401-407.

Tango, F. and R. Montanari (2006). "Shaping the drivers' interaction: how the new vehicle systems match the technological requirements and the human needs." Cognition, Technology & Work **8**(3): 215-226.

Van Der Laan, J. D., A. Heino, et al. (1997). "A simple procedure for the assessment of acceptance of advanced transport telematics." Transportation Research Part C: Emerging Technologies **5**(1): 1-10.

Waller, P. F. (1997). Transportation and Society. Traffic & Transport Psychology - Theory & Application. T. Rothengatter and E. Carbonell Vaya. Oxford, UK, Pergamon**:** 1-8.