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Abstract

This high-fidelity driving simulator study used a paired comparison design to investigate the effectiveness of 12 potential eco-driving interfaces. Previous work has demonstrated fuel economy improvements through the provision of in-vehicle eco-driving guidance using a visual or haptic interface. This study uses an eco-driving assistance system that advises the driver of the most fuel efficient accelerator pedal angle, in real time. Assistance was provided to drivers through a visual dashboard display, a multimodal visual dashboard and auditory tone combination, or a haptic accelerator pedal. The style of advice delivery was varied within each modality. The effectiveness of the eco-driving guidance was assessed via subjective feedback, and objectively through the pedal angle error between system-requested and participant-selected accelerator pedal angle. Comparisons amongst the six haptic systems suggest that drivers are guided best by a force feedback system, where a driver experiences a step change in force applied against their foot when they accelerate inefficiently. Subjective impressions also identified this system as more effective than a stiffness feedback system involving a more gradual change in pedal feedback. For interfaces with a visual component, drivers produced smaller pedal errors with an in-vehicle visual display containing second order information on the required rate of change of pedal angle, in addition to current fuel economy information. This was supported by subjective feedback. The presence of complementary audio alerts improved eco-driving performance and reduced visual distraction from the roadway. The results of this study can inform the further development of an in-vehicle assistance system that supports ‘green’ driving.

Introduction

Minimizing fuel consumption has many advantages to the average motorist, including a reduction in the financial cost and the environmental impact of a journey. Savings will continue to be made with the ongoing design of more fuel efficient vehicles. However, even without complex powertrain modifications, significant gains can be made by modifying driver behaviour to encourage 'eco-driving', a driving style that reduces fuel consumption, greenhouse gas emissions, and accident rates. This paper focuses on the first stage of the design of an in-vehicle eco-driving assistance system that provides guidance to the driver on how to improve fuel consumption whilst driving.

It has long been known that changing driver behaviour has the potential to create substantial fuel savings (Evans, 1979). However, since this early experimental work, many subsequent research studies and policy initiatives have focussed on reducing the environmental impact of road transport through changes in vehicle design or by affecting an individual's choice of vehicle or mode (Stanley et al., 2011). The behaviour of the driver has been identified as an area that should be targeted to achieve substantial improvements in CO_2 emissions (Barkenbus, 2010).

Huge potential fuel savings of up to 60% are considered obtainable with optimisation of all of the components of driving performance, including the elimination of unnecessary idling and stop-start manoeuvres and the adjustment of acceleration and cruising speed behaviours (Gonder et al., 2011). Whilst these savings are unlikely to be achievable in reality, it has been predicted that fuel efficiency can be improved by 5-10% with the provision of appropriate feedback to the driver; perhaps reaching 20% for aggressive drivers (Gonder et al., 2011). Driver education and training has been used to improve an individual's eco-driving performance (Martin et al., 2012). However, these effects are often transient and not sustained in the longer-term (af Wåhlberg, 2007), thus meaning that other methods should be considered to encourage changes in driver behaviour (Delicado, 2012).

In-vehicle eco-driving support

The development of an in-vehicle system to provide eco-driving assistance to the driver is an alternative approach to tackling fuel inefficient driver behaviours. There are systems on the market currently that are capable of providing guidance to the driver before, during or after a trip. This paper focuses on a system that presents eco-driving information during the trip, as many car manufacturers currently do (e.g. Honda *EcoAssist*, Ford *SmartGauge* or BMW *EcoPro)*.

This article reports on a driving simulator study in which a number of potential in-vehicle eco-driving support system interfaces were compared, both in terms of their impact on driver fuel efficiency, and the impact on driving performance in general. The study focused on identifying interface design characteristics that facilitate effective, safe and user-friendly interactions between the driver and the in-vehicle system.

Gonders et al. (2011) highlight the need to inform drivers of the most fuel efficient action rather than simply advising of their errors, as a means of achieving their proposed fuel economy improvements of up to 20%. The deficiency in many current systems is that they only inform the driver about what they are doing wrong. Even some systems that provide guidance on how to improve behaviour, only do so after the event (van der Voort et al., 2001). The work undertaken in this study aimed to develop an in-vehicle system that could continuously support the driver in real-time to achieve optimum fuel efficiency. The feedback provided to the driver informed on the current fuel economy and about the action required to improve their fuel consumption.

What guidance should be provided?

The content of feedback that is provided during a drive is often restricted to relatively simple fuel economy or CO_2 emissions information (e.g. Graving et al., 2010, Boriboonsomsin et al., 2010), or guidance on speed and gear choice (Nouveliere et al., 2012). Whilst useful, these types of in-vehicle displays are providing the driver with a straight-forward measure of their fuel efficiency at that moment. The driver can infer the actions that they must take to reduce their fuel consumption; however the exact action, and scale of such action required may be difficult to identify. For example, it may be easy for a driver to work out that they are currently accelerating too much and so need to release the accelerator to improve their current sub-optimal fuel efficiency. However, the precise reduction in acceleration that is required to achieve optimal fuel efficiency, may be more difficult to grasp. The absence of real-time guidance on how to improve fuel efficiency, and the resulting reliance on driver understanding of the information and underlying eco-driving principles (e.g. Wada et al., 2011) may not provide the most direct route to improving eco-driving performance. The next step in the design of in-vehicle eco-driving assistance systems seems to be the creation of a system that not only provides the driver with an accurate picture of the current fuel consumption, but also guides them towards the most effective response to enhance their performance. One approach would be the provision of real-time feedback on accelerator pedal usage, which impacts on driver acceleration, braking behaviour and speed choice behaviour. Such an approach is adopted in this study.

What modality should be used for eco-driving guidance?

The majority of past research appears to focus on the use of the visual modality for presenting eco-driving advice, via colour-coded or numerical displays of fuel economy (Graving et al., 2010, Nouveliere et al., 2012, Meschtscherjakov et al., 2009). This inspired the design of three visual eco-driving displays for consideration in this study, whereby the effective components of prior designs were retained, whilst developing features of the displays that might require improvement. The provision of multi-modal feedback has been considered for use in in-vehicle applications to assist with eco-driving, with complementary audio signals being shown to have positive effects on fuel efficiency relative to a visual only display (Kim and Kim, 2012). A multi-model eco-driving interface was introduced by testing the three visual interfaces both with and without complementary auditory tones.

There is plentiful evidence to suggest that a continuous, visual in-vehicle display can produce negative side-effects on driving performance due to its potential to distract the driver from looking at the road (see Regan et al., 2009 for a review). The use of haptic feedback to provide eco-driving assistance is a relatively under-researched area. Previous research has focused primarily on its use in forward collision warning systems (de Rosario et al., 2010), gear-shift indicators, and speed management systems (Adell et al., 2008), with improved speed compliance and acceptance of a haptic accelerator pedal providing encouragement for the use of such haptic pedal systems (Adell et al., 2008). The provision of eco-driving guidance via a haptic accelerator pedal would seem an intuitive step given that the accelerator pedal angle is an influential factor in vehicle fuel consumption and it allows for the provision of feedback directly via the vehicle component which requires the response. Prior work has used a haptic pedal system in which excessive pedal pressure (over-acceleration) is counteracted by increasing the pedal's resistive force. This has been shown to reduce vehicle emissions (Azzi et al., 2011) and the number of high accelerations (Larsson and Ericsson, 2009). A similar system underlies the *Honda EcoPedal*. Haptic pedal systems have also been shown to reduce driver workload (Birrell et al., 2010).

The use of a haptic accelerator pedal for in-vehicle information presentation has potential benefits for driver distraction and safety. This study seeks to extend prior work that has considered a single haptic pedal test case (Birrell et al., 2013) by testing an array of six haptic pedal eco-driving assistance systems. Few publications have investigated *how* the haptic interfaces are controlled in terms of their mechanical operation. A notable exception was the investigation of multiple versions of a car-following assistance system that provided advice through the accelerator pedal (Mulder, 2007). Two distinct types of haptic feedback were tested: *force feedback* and *stiffness feedback* (Mulder et al., 2008), with the stiffness feedback systems proving most effective for increasing headway and reducing accelerator pedal activity. The parallels between these systems and those tested in this study are described further in the Methodology and materials section.

Objectives

This study seeks to identify the most appropriate method for the delivery of real-time eco-driving guidance, specifically moment-by-moment feedback on accelerator pedal usage. The relative merits of using the visual, auditory and haptic modalities for communicating the most economical accelerator pedal angle are considered. Six haptic, three visual, and three combined visual-auditory interface systems were created based on Ecological Interface Design (Rakauskas et al., 2010) and prior research in the eco-driving domain, and evaluated for their potential to provide persuasive feedback (Meschtscherjakov et al., 2009). Unlike fuel-saving technologies that are built into the vehicle itself, these eco-driving displays should not only have the potential to create fuel savings, but should also motivate the driver to interact with them so as to achieve these savings. To this end, a paired comparison design has been used to assess the performance benefits and driver impressions of the range of proposed in-vehicle eco-driving solutions. Objective and subjective performance measures were used to evaluate the design of novel systems, therefore advancing prior work that has considered the effectiveness of existing in-vehicle displays only (Graving et al., 2010). The work should be considered the first steps towards the design of an effective and acceptable real-time, eco-driving support system, and thus can provide fundamental guidance in the future design of eco-driving systems. This work will aid the selection of a small subset of the most effective and useable eco-driving assistance systems for further testing in a wider range of eco-driving scenarios and during a prolonged driving experience (Hibberd, Jamson & Jamson, under review). This represents the next stage in system design before system deployment on the roads.

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 standard vehicle accelerator pedal was replaced with a haptic accelerator pedal such that eleven different pedal force vs. pedal angle profiles could be defined. Pedal feedback up to 200N could be commanded via the system (bandwidth in excess of 15Hz).

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 were required to drive along a short section of road (approximately 30s duration). The scenario started with the vehicle moving at 40mph (64.4km/h) in an urban area *(Cruise 1)*. A speed limit sign advised a speed increase to 60mph (96.6km/h) *(Accelerate)*. When this speed was reached, participants were required to maintain this speed until trial end *(Cruise 2)*. Each sub-section lasted for approximately 10s, with the visual scene fading away after 30s. All roads were flat. *Cruise 1 and Accelerate* featured straight roads, while *Cruise 2* involved a large radius curve.

The participant was instructed to use the accelerator pedal to optimise their fuel efficiency whilst obeying the posted speed limits. The participant drove with an eco-driving assistance system that guided them to the correct accelerator pedal angle to achieve this task. The scope of this study did not extend to the development of a realistic eco-driving algorithm underlying the operation of the assistance systems. Instead a simple algorithm was designed and applied across all systems, whereby one of three specific pedal angles was required to drive fuel efficiently depending on whether the vehicle was accelerating (23% depression required), maintaining speed (7% depression) or decelerating (0% depression). Participants were instructed that adherence to the eco-driving guidance would lead to maximum fuel economy. Therefore, fuel efficient performance was achieved by depressing the accelerator pedal to 7% in the *Cruise 1* stage, increasing this to 23% in the *Accelerate* stage, before reducing back to 7% in the *Cruise 2* stage (Table 1).

[TABLE 1 HERE]

Eco-driving system design

Twelve eco-driving assistance systems were tested in this study. In all cases, the system provided feedback about the change in accelerator position required to improve fuel efficiency of current performance. The information delivered can be considered feedback due to its evolution based on driving performance in the moments beforehand, subsequently providing the driver with an opportunity to manage their future driving to ensure fuel efficient performance. The method of delivery and the amount of information varied between systems.

Support system interface: visual display

Using Gonders et al.'s (2011) suggestion of a colour-coded "OEM dashboard display", three distinct visual interfaces were designed for the eco-driving assistance system. For each system, the colour of the central feature of the interface communicated the fuel efficiency of the current accelerator pedal angle:

- Green – participant is driving at (or close to) the optimal accelerator pedal angle;
- Blue – participant is driving inefficiently, specifically they are under-accelerating;
- Red – participant is driving inefficiently, specifically they are accelerating excessively.

Dot system

The system used a coloured dot in the centre of the tachometer, and was inspired by the Honda EcoSpeedometer (see Meschtscherjakov et al., 2009)). This display provides colour-coded information about the accuracy of the current accelerator pedal angle (Figure 1). The direction of pedal adjustment required can be inferred from the colour of the dot, but no information is provided regarding the rate of change.

Given that 100% pedal angle means that the accelerator pedal is fully-depressed, the parameters for colour changes were fixed such that a green dot was displayed when a pedal error of less than ±1% of total travel was achieved. A blue or red dot was displayed for pedal errors of -6% or +6% respectively. The colour of the dot was modulated by blending the RGB component across the 12% range from red, through green, to blue.

[FIGURE 1 HERE]

Gauge system

This system presented a rectangular bar in the tachometer, which could change in both size and colour depending on the current fuel efficiency. The design was based upon a collection of moving bar displays found to be both acceptable and intuitive for conveying fuel consumption information (Rakauskas et al., 2010). A central narrow green bar is presented to indicate that current accelerator pedal angle is optimal. The bar increases in size in proportion to the magnitude of the accelerator pedal error, with increases to the right for over-acceleration, and to the left for under-acceleration. The colour of the bar blends to red (over-acceleration) and blue (under-acceleration), in line with the colour scale defined for the Dot display (Figure 2).

[FIGURE 2 HERE]

Foot system

This system presented an image of a foot on an accelerator pedal (grey), with the desired accelerator pedal angle displayed as a dotted line (white) (Figure 3). The grey line shows the current accelerator pedal angle. The design was inspired by the Nissan EcoPedal (see Meschtscherjakov et al., 2009). The user is required to match the positions of the current and desired accelerator pedal lines to achieve optimal fuel efficiency. The colour of the foot also changes in line with the *Dot* and *Gauge* displays, to provide additional colour-coded information on the fuel efficiency of accelerator use.

[FIGURE 3 HERE]

The three displays provide first-order eco-driving information i.e. whether there is currently an error between actual and desired accelerator pedal angle, and thus whether a change needs to be made. The Gauge and Foot displays provide second-order information about the direction and magnitude of the change required to achieve the desired pedal angle. The Gauge display communicates this in an abstract, but easily-understandable format. The Foot display provides the same information but with relevant contextual cues to allow the user to deduce the actual action on the accelerator pedal that is required to remediate the current pedal error.

Complementary audio

Each of the three visual display described above were presented both with and without accompanying, complementary, directional audio alerts. A predominantly low frequency (512Hz) tone indicated insufficient accelerator depression and a high frequency chime (predominantly at 1770Hz) indicated excessive accelerator depression. This selection was made based on pilot work, to ensure that the two tones were easily distinguishable during background engine noise. The auditory component was included, to test whether the potential benefits of this presentation method outweigh costs such as driver annoyance or frustration (Adell et al., 2008).

Support system interface: haptic pedal

Three methods of accelerator pedal guidance are considered in this study; two (*force feedback* and *stiffness feedback*) based on previous work (Mulder et al., 2011, Mulder et al., 2008) and one novel system (*adaptive stiffness*). Two versions of each type of system were designed (strong and weak guidance), to allow a more in-depth analysis of the impact of specific system parameters on the resulting objective performance and subjective experience of these haptic pedal designs during the eco-driving task.

In a typical vehicle, there is a proportional relationship between the force applied to the accelerator pedal and the change in pedal angle produced (the pedal travel). The haptic eco-driving assistance systems change this relationship. In the driving scenario described, two specific accelerator angles were required, one to maintain speed efficiently (7%) and one to accelerate efficiently (23%). Each haptic system therefore consisted of two profiles (pedal force vs. change in pedal angle relationships): one to advise of the 7% angle at constant speed *(cruise* profile*)* and one to advise of the 23% angle during acceleration *(accelerate* profile*)*. The six distinct systems are described below.

Force condition

In the force condition, a significant extra force was required by the driver to further increase accelerator pedal angle beyond that considered inefficient; either 7% during speed maintenance or 23% during acceleration (Figure 4). For the weak force condition, the step change in force was 20N, whilst in the strong force condition it was 40N. The 7% or 23% “kneepoint” in each profile was designed to guide driver towards the idealized throttle angle, by requiring them to significantly increase pedal load to overcome the “kneepoint”.

[FIGURE 4 HERE]

Stiffness condition

In the stiffness condition, the guidance was a distinct change in pedal stiffness, rather than a step force for drivers to overcome (

Figure **5**). The force applied back against the driver's foot increases gradually such that the driver experiences a gradual rather than immediate change in the difficulty of pedal depression. For the weak stiffness condition, the gradient changed from the standard stiffness of 0.2N per percent change in pedal angle to 1.45N per percent change in pedal angle. This was doubled in the strong stiffness condition to 2.9N per percent change in pedal angle.

[FIGURE 5 HERE]

Adaptive stiffness condition

The adaptive stiffness condition used the same profile gradient as the stiffness system; however, it differed in its transition from the cruise to accelerate profiles. The stiffness system gives a clear indication when to remove pedal force (decrease pedal angle) through increased pedal load; it gives no indication of when to increase pedal force (increase pedal angle). The adaptive stiffness system provides guidance when an increase in pedal force is necessary, by reducing the force with which the driver needs to push to create acceleration, relative to the stiffness system (

Figure **6**).

[FIGURE 6 HERE]

Experimental design: paired comparison

A preliminary evaluation of 12 eco-driving assistance systems was undertaken to allow the selection of those most effective and acceptable for further testing in a longer duration drive. A paired comparison design facilitates such an approach. This objective of this study was to refine the design of a haptic eco-driving assistance system and a visual or combined visual-auditory eco-driving assistance system. Thus, the six haptic systems were compared with each other and the six visual and visual-auditory systems were compared. There was no direct comparison of systems involving a visual display with those involving a haptic interface.

A paired comparison design involves the presentation of a pair of systems to the participant, followed by a forced choice judgement between these two systems based on pre-defined criteria – in this case, which system guided them best to the most appropriate accelerator pedal angle.

The participants provided a choice for every possible combination of the two groups of six systems tested (15 haptic pairs, 15 visual/visual-auditory pairs); a fully balanced design. The number of participants in the study did not permit full counterbalancing of the presentation order of the pairs, however partial counterbalancing was used to minimise the impact of order effects (Russell, 1980), such as changes in perception of a system due to familiarity or experimental duration.

The qualitative nature of forming such a subjective opinion and the inherent difficulty in maintaining a linear scale means that a *paired comparison* design is the most robust method to facilitate the comparative judgments. The technique is commonly employed when objects can only be compared in a highly subjective fashion. By summing the number of times a system is preferred over any other, to give a total score, the significance of any difference in the score for one system relative to the scores of the others can be assessed. The method is analogous to the F-statistic in ANOVA (David, 1988).

The null hypothesis tested is that a system will be chosen in 50% of pairs, for all instances of the presentation of a system (*i*):

$$H_0': \pi_i = {}^1\!/_2$$

In the equation below, D_n varies as a χ^2 distribution with $t-1$ degrees of freedom, where $\sum a_i^2$ is the sum of the squares of the scores:

$$D_n = 4\left[\sum_{i=1}^{t} a_i^2 - \frac{1}{4}tn^2(t-1)^2\right]/nt$$

At a particular confidence level, the null hypothesis is rejected if the value of D_n exceeds or equals the corresponding critical value. The above test is comparable to discovering the existence of a main effect in any particular experimental factor. The post-hoc test, which determines to what extent the levels of that factor differ from one another, is obtained from a Least Significance Difference of the overall scores. For a two-sided test at a particular significance level, a critical value (m_{crit}) is calculated such that if the difference between total scores exceeds this value, the difference between those score can be proved at a particular confidence level:

$$m_{crit} = Z_{crit}\sqrt{(1/_2 nt^2)} + 1/_2$$

Where:

Z_{crit} is the Z-score for the percentile point of the significance level in question

n is the number of participants

t is the number of repetitions of each paired comparison per participant multiplied by n

Experimental procedure

Participants performed this study in two separate visits; one involving the six haptic systems, one involving the visual and combined visual-auditory systems. Participants were given a short tutorial on '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 familiarised with the short driving scenario in the absence of an eco-driving system (six trials) before an explanation and demonstration of each system including two practice trials. Participants were not told of the two desired pedal angles required for successful fuel efficient driving. The speedometer functioned throughout the familiarisation drive.

The experimental phase of the study involved 32 trials divided into 16 pairs. All possible pairs of the six systems were presented (n = 15) with one additional practice pair presented first. The participants were instructed to keep their vehicle in the centre of the lane and to use the accelerator pedal in the most fuel efficient way. They were advised of the presence of an eco-driving assistance system to help them achieve this task and the importance of following the guidance to reach the posted speed limits, rather than selecting what they considered to be a fuel-efficient speed. To ensure that the participant was using only the eco-driving guidance to perform the task and not simply matching their speed to the speed limit, the speedometer was not displayed.

For each pair of trials, participants drove the scenario with one assistance system in the first trial, then with a different assistance system on the second trial. They were then required to make a forced choice between the two systems in response to the question: 'Which guided you best to the most appropriate accelerator pedal angle?' Responses were recorded manually. Participants were unaware of the system which had produced their most fuel efficient performance.

Participants

Twenty-one drivers took part in the study, balanced for gender, age, driving experience and annual mileage (

Table **2**). One participant withdrew before the haptic systems drive. All participants had prior experience of the driving simulator so as to minimise individual differences in vehicle control which could impact on performance of the eco-driving task.

[TABLE 2 HERE]

Results

Subjective analysis

Haptic systems

The overall score for each haptic pedal system was calculated as the number of times it was selected as better at guiding the participant to the correct accelerator pedal angle compared to its competitor in the pair. With 20 participants and each system experienced in five paired comparisons, the maximum score for each system was 100. These data were analysed according to a non-parametric test of equality. At the 95% confidence level, the Least Significance Difference method suggests that a significant difference between system scores occurs when the critical score difference (m_{crit}) is 15.

Figure 7 shows the absolute number of pairs in which a particular system was chosen.

[FIGURE 7 HERE]

Table **3** shows which paired comparisons produced significant differences in terms of the number of times one system was selected as being more effective than the other for delivering guidance on accelerator pedal angle i.e. the score difference between a pair exceeds m_{crit}. A clear disposition towards the strong version of a system over its weak counterpart was observed (e.g. strong force vs. weak force). The difference between the different types of haptic systems was less clear. Whilst the strong force system achieved significantly higher scores than both adaptive stiffness systems, this difference was only significant for the weak stiffness system. There was no difference between the perceived effectiveness of the three weak systems, nor between the strong stiffness and strong adaptive stiffness systems.

[TABLE 3 HERE]

For a fully rationale observer, who perceives a clear difference in effectiveness of the six systems, it can be expected that the systems are ranked in order of their effectiveness and paired comparison choices are then based upon this. In the simplest case of three systems, A, B and C, if A is chosen over B, and B is chosen over C, then it would be expected that A would be chosen over C. This consistency of choice is known as a 'consistent triad' (Kendall and Smith, 1940). The consistency of choices between systems provides an indication of how reliably conclusions can be drawn from the data. For participant choices amongst the six systems, the number of 'consistent triads' is calculated as a proportion of the total number of possible triads to give a coefficient of consistence. A higher coefficient means a more consistent pattern of choices, and therefore a greater level of trust in the interpretation. Participants may demonstrate low consistency if they either do not possess the ability to discriminate between the systems or if the systems do not differ substantially enough to create a consistent choice as to which is most effective. There was generally high consistency in participant choices between haptic systems, with 75% of participants having a coefficient greater than or equal to 0.5, and 60% of these being within the 0.75-1.00 range.

Visual and visual-auditory systems

The scores for the visual and visual-auditory systems were analysed in the same way. The additional participant meant a maximum possible score of 105 for each system.

Figure **8** shows the absolute number of pairs in which a particular system was preferred.

[FIGURE 8 HERE]

Table **4** shows that any system with added audio was significantly more likely to be judged more effective than its counterpart without audio. Furthermore, the Foot and Gauge displays were chosen significantly more often than the Dot display, both with and without the audio.

[TABLE 4 HERE]

The coefficient of consistence for the visual and visual-auditory system pairs was high, with 91% of participants producing a coefficient of 0.75 or greater. This demonstrates that participants were capable of establishing an order of effectiveness amongst the systems and for the most part were producing their judgements in a reasoned and selective fashion, rather than at a random. This has positive implications for the use of this procedure and the application of the results.

Objective performance analysis

The performance indicator used to assess the accuracy of eco-driving performance was the root mean squared error in accelerator pedal angle. This is a continuous measure of the difference between the desired accelerator pedal angle (defined by the assistance system) and the actual accelerator pedal angle selected by the participant. This measure is expressed as a percentage error.

In order to assess the propensity of drivers to move their gaze away from the roadway, 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. PRC has previously been demonstrated to be a sensitive indicator of visual distraction (Victor, Harbluk and Engström, 2005) with lower values indicating less attention is focused towards the visual demand of driving. This variable is considered here as a measure of the visual distraction caused by each type of interface. It is critical that the design of an effective interface is not at the expense of a reduction in driver safety resulting from the distracting effects of interface interaction. It was hypothesised that the haptic pedal systems would cause lower visual distraction than the visual interfaces. This approach was also taken to allow the identification of any visual interface which was more visually demanding than the others.

Steering wheel reversal rate refers to the number of times per minute that the steering wheel direction is changed by greater than 1°. This provides a measure of visual distraction from the driving task and is often used as a measure of driver workload. Similar to the investigation of PRC data, this permits an assessment of the potential negative effects of each eco-driving interface, such that the selection of those for further development is not based solely on the effective presentation of eco-driving guidance, but also accounts for the impact that this presentation has on other aspects of driving task performance.

Haptic systems

Participant performance with the haptic pedal systems was subjected to one-way repeated measures ANOVA analysis with six levels of the within-subjects variable of eco-driving system type. For each dependent variable analysed, the data was first checked to ensure that they did not violate assumptions of parametric testing. The performance across the entire 30s scenario was analysed.

There was a strong main effect of System [$F(5,80)=17.025$, $p<.001$, $\eta^2=.52$]. Least Squared Difference post-hoc tests suggest several significant pairwise differences. Of the weak conditions, participants were better at achieving the desired accelerator pedal angle (smaller pedal error) with the force system compared to either the stiffness ($p=.001$) or adaptive stiffness ($p=.016$) systems (

Figure **9**). This trend remained for the strong conditions, with the force system producing lower pedal errors and therefore closer to optimal acceleration performance relative to the stiffness system (p=.010). The performance with the strong force and adaptive stiffness systems did not differ (p=.171), although the same trend was observed. Pedal error did not differ between the stiffness and adaptive stiffness systems for either the strong (p=.480) or weak conditions (p=.950).

[FIGURE 9]

When the strong and weak version of each system type was compared, performance with the strong system produced significantly lower pedal errors than the weak version (force: *p*<.001; stiffness: *p*<.001; adaptive: *p*=.001). The adherence to the eco-driving guidance was better when provided more forcefully.

The operating characteristics of the six haptic assistance systems differ depending on the accelerator pedal action required i.e. depression, release or maintenance. The analysis was therefore conducted separately on the three 10-second sections of the drive: *Cruise 1*, *Accelerate*, and *Cruise 2*. There was a significant effect of System in both speed maintenance sections [Cruise 1: F(5,95)=11.650, p<.001, η^2=.47; Cruise 2 F(2.207,41.936)=7.208, p=.002, η^2=.28], with significantly lower pedal error when using the strong version of each system compared to the weak version. The previously observed significant differences amongst the three strong versions of the haptic assistance systems and amongst the three weak versions of the systems were only observed in the *Cruise 1* section. There was no main effect of System on pedal error during the *Accelerate* stage (p=.382), with pedal errors in the range 6.4-8.3%.

For the haptic systems, there was no difference in PRC regardless of system type (p=.539). The range in mean PRC was 77.9-80.0%. This remained true when sub-scenarios were considered in isolation.

There was no impact of haptic system on this objective performance measure, thus lateral control of the vehicle was consistent across the six system types.

Visual and visual-auditory systems

Participant performance with the visual and visual-auditory assistance systems was analysed using two-way repeated measures ANOVA analysis with two within-subjects factors (Visual Display: three levels; Complementary Audio: two levels).

For the analysis of the full 30s scenario, there was no evidence of a main effect of Visual Display on root mean squared pedal error (p=.697) (

Figure **10**). There was a strong main effect of Complementary Audio [$F(1,20)=15.84$, $p=.001$, $\eta^2=.44$], as participants achieved smaller errors from the optimal accelerator position when using a system with complementary audio (3.9%) compared to one without (4.1%).

[FIGURE 10 HERE]

A further analysis of the 10-second sections of the drive demonstrates that the absence of an overall main effect of Visual Display does not provide an accurate picture of participant performance.

Table **5** shows a significant main effect of this factor on pedal error in each sections. Post-hoc pairwise comparisons identify different visual displays as being more effective for minimizing pedal error in different accelerator pedal usage conditions.

[TABLE 5 HERE]

It was also revealed that the main effect of Complementary Audio on pedal error was present during both the *Accelerate* and *Cruise 2* stages only, [Accelerate: $F(1,20)=5.51$, $p=.029$, $\eta^2=.216$; Cruise 2: $F(1,20)=34.94$, $p<.001$, $\eta^2=.636$].

There was no main effect of System on percent road centre ($p=.220$), with mean PRC varying between 41.7-43.6% across the three visual display types. However, there was a significant main effect of Complementary Audio on performance, [$F(1,18)=15.24$, $p=.001$, $\eta^2=.458$], such that PRC was significantly lower without audio (M=41.1%) than with audio (M=44.4%). This pattern of effects remained true for each of the sub-scenarios considered alone (

Table **6**).

[TABLE 6 HERE]

Steering wheel reversals showed a significant effect of Visual Display, [$F(2,40)=9.972$, $p<.001$, $\eta^2=.333$]. Participants produced significantly more steering wheel reversals when using the Dot display (20.7 reversals per minute) compared to either the Foot (19.4/min) or Gauge (18.4/min) displays. There was no difference in steering control performance with and without the addition of auditory assistance ($p=.641$).

Discussion

This study involved a driving simulator based comparison of eco-driving support systems, which guide drivers to the most fuel efficient accelerator pedal angle. Twelve systems were tested, with differences in the modality and design styles of the eco-driving support. The objective was to identify the most appropriate design of this type of system in terms of both objective accelerator pedal performance and subjective impressions of the effectiveness of the system.

Haptic systems

The subjective ratings results showed that the strong version of the three types of haptic accelerator pedal system was identified as more effective for successful completion of the eco-driving task, than its weak counterpart. Furthermore, amongst the strong version of the haptic systems, the force system was chosen as being more effective in providing accelerator pedal guidance than the stiffness or adaptive stiffness systems. These results conflict with Mulder et al. (2008), in which stiffness feedback guidance was judged to be better. However, this prior study used the haptic pedal to warn of unsafe car-following rather than advise of a fuel efficient accelerator pedal angle.

It is promising that the objective measure of eco-driving task performance supported participant choices, with stronger feedback leading to smaller accelerator pedal errors. Furthermore, when comparing within weak or strong versions of each haptic system type, performance was significantly better with the *force* system, while differences between the stiffness and adaptive stiffness systems were not present. It is interesting to note that the advantage of the force system appears to be confined to the speed maintenance sections of the drive. However, this is likely to be because all three system types are designed to provide a strong cue to reduce pressure on the accelerator pedal during over-acceleration, whilst cues to increase pressure on the accelerator pedal are much more subtle. Under-acceleration was frequently observed in this study due to the large increase in pedal angle required to accelerate fuel efficiently, thus the three systems differed very little in terms of the guidance provided in the *Accelerate* stage. Importantly, there appears to be little difference in the impact of the six haptic systems on driver visual distraction, as indexed by percent road centre in this study.

Visual and visual-auditory systems

In the case of the visual and visual-audio systems, there is a significant trend for participants to choose a display with complementary audio as more effective for advising on fuel efficient accelerator pedal usage compared to a visual only display. A comparison of the different visual display designs reveals that the greater information content of the *Foot* and *Gauge* displays (i.e. current pedal error and rate of change of pedal error) is judged to be better as eco-driving support than the information provided by the *Dot* display (i.e. pedal error only).

The objective pedal error data support the findings above to a large extent, despite the observation of a non-significant effect of System. A more detailed analysis per scenario stage revealed that performance with the *Gauge* system was better than with the *Foot* during speed maintenance phases of the drive, whilst the reverse was true during the acceleration phase of the drive. The effect of complementary auditory alerts was substantial, with pedal error shown to be lower when two distinct audio alerts were provided to indicate a need to increase or decrease pedal angle. This is not necessarily an obvious result, as there is no particular reason why an auditory alert should improve adherence to visual guidance. However, it could be that the timing of the tones are useful for the driver in directing them to the visual display at the most crucial times for ensuring good eco-driving.

Surprisingly, there was change in fixations on the road centre across the three visual displays despite obvious differences in content. However, time spent looking at the road centre did improve by approximately 3% when using a system with added audio. This improvement in viewing time did not translate into better lane-keeping performance. Overall, there is evidence of good objective performance on the eco-driving task with the higher order *Foot* and *Gauge* displays that include auditory tones for additional guidance.

Haptic vs. visual and visual-auditory systems

Whilst no attempt was made to compare subjective opinions of haptic systems with visual and visual-auditory systems, it is possible to compare objective pedal error performance. The performance with a visual or visual-auditory display (mean error = 4.1%) exceeded that with a haptic pedal (5.3%) (p=.001). This difference in performance was consistent across both speed maintenance phases (p=.001-.006). The same trend did not reach significance in the acceleration phase of the drive (p=.193) (

Figure **11**).

[FIGURE 11 HERE]

The advantage of a display with a visual component over one without is not unexpected given the demands of the task. The simplicity of the visual displays means that it is easy to immediately understand and apply the information conveyed, and thus if drivers attend to the dashboard display then they have sufficient information to perform the eco-driving task well. With few negative consequences of diverting attention from the road in the simulator setting, glances to the display may have been excessive in number or duration compared to on-road driving, hence the apparent improvement in performance with the visual systems. The less easily interpreted haptic information may have led to an increase in difficulty of the eco-driving task.

The eye-tracking data shows that participants spent longer looking at the road centre during interaction with a haptic system compared to that with a visual or visual-auditory system. There was a difference in PRC in excess of 30% between the two modalities across all sections (

Table **7**). This is expected given the absence of the need to consult the dashboard display during use of the haptic pedal systems, particularly without the availability of a functional speedometer.

[TABLE 7 HERE]

Overall, the pedal error data favours the development of a visual guidance system for providing eco-driving support. However, the percent road centre data illustrate the potential dangers of a visual display in terms of distraction from the forward roadway. Furthermore, the differences in pedal error between the two modalities are relatively small, given the novelty of this type of system in the driving environment and the absence of visual clutter both inside and outside of the vehicle in this study. There is sufficient encouragement for further investigation of both modalities for use within an eco-driving support system. It is particularly important to explore the design of an in-vehicle haptic eco-driving assistance system given the need to consider the potential safety consequences of a visual eco-driving interface (Young et al., 2011).

Some limitations with the design of this study should be noted when interpreting the results. The short duration of the driving scenario does not allow the assessment of the longer-term success of driving with each system nor the possible fatigue effects associated with the use of a haptic pedal. Furthermore, the forced choice judgements provide an indication of participant impressions of system effectiveness, but do not directly inform about which system they would prefer to use. The design of an in-vehicle system should be focussed on providing an interface that is both effective and acceptable to the driver, and thus future work should measure driver preferences between systems.

Conclusions

The main objective of this study was to evaluate preliminary designs to support eco-driving. Overall, this study has demonstrated the benefits of a visual, combined visual-auditory or haptic system for providing useful eco-driving advice to the driver regarding fuel efficient accelerator pedal usage. These systems therefore have the potential to increase financial and environmental savings through their impacts on fuel economy. The next step is to further develop and extensively test these systems in an extended driving task with a wider range of scenarios in which eco-driving guidance would be provided by the in-vehicle system. The analysis of both driver performance, and the acceptance and workload associated with the interaction with the systems should be considered. Based on the results of this study it is recommended to consider the strong force feedback system for further testing as it produced the strongest objective and subjective performance in terms of system effectiveness amongst the haptic systems in this study. It would also be sensible to test the stiffness system during a longer drive, so as to establish which type of haptic guidance is most effective and acceptable and least tiring during prolonged use. Of the visual displays, there is favourable evidence to support the use of either second-order display (Foot or Gauge), due to the provision of information on both current pedal error and rate of change of pedal angle. Complementary audio information is likely to assist the driver in improving their fuel economy, although potential annoyance from prolonged use needs to be considered. The potential for alternative multi-modal combinations (e.g. visual and haptic) may offer an as yet untested method for effective delivery of eco-driving guidance.

Acknowledgments

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Figure 1

Insufficient pedal pressure → increase pedal angle	**Appropriate pedal pressure → maintain pedal angle**	**Excessive pedal pressure → decrease pedal angle**

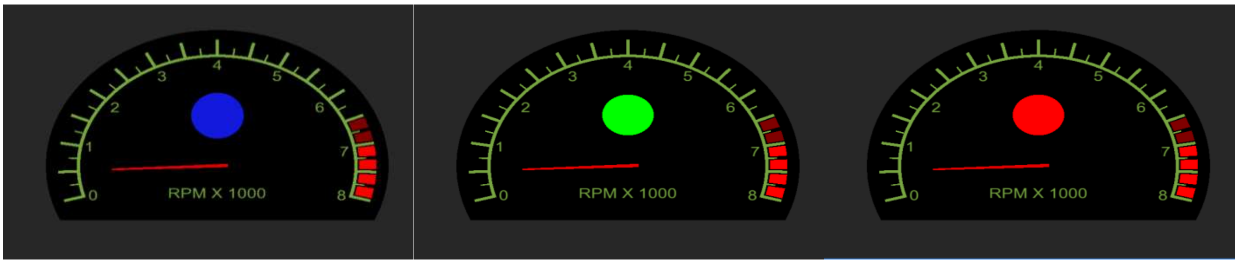


Figure 2

Insufficient pedal pressure → increase pedal angle	**Appropriate pedal pressure → maintain pedal angle**	**Excessive pedal pressure → decrease pedal angle**

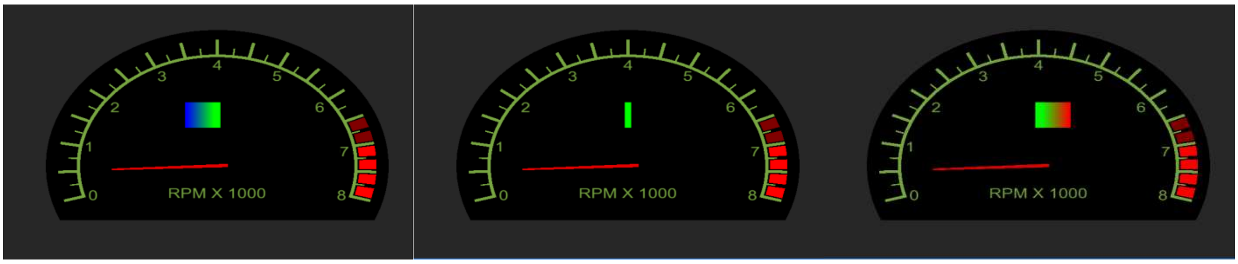


Figure 3

Insufficient pedal pressure → increase pedal angle	Appropriate pedal pressure → maintain pedal angle	Excessive pedal pressure → decrease pedal angle

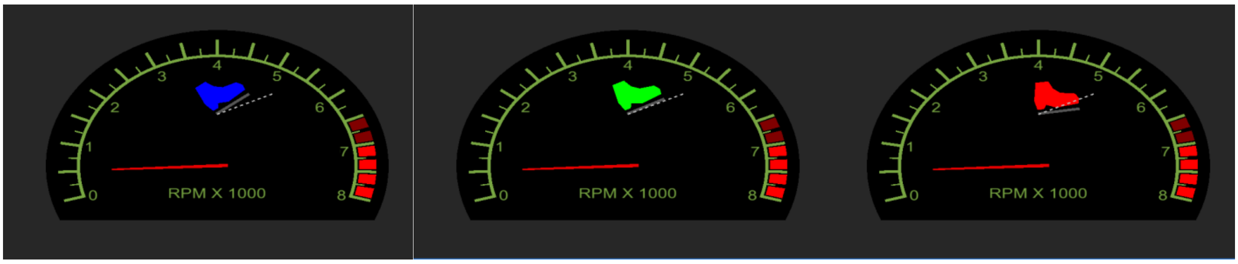
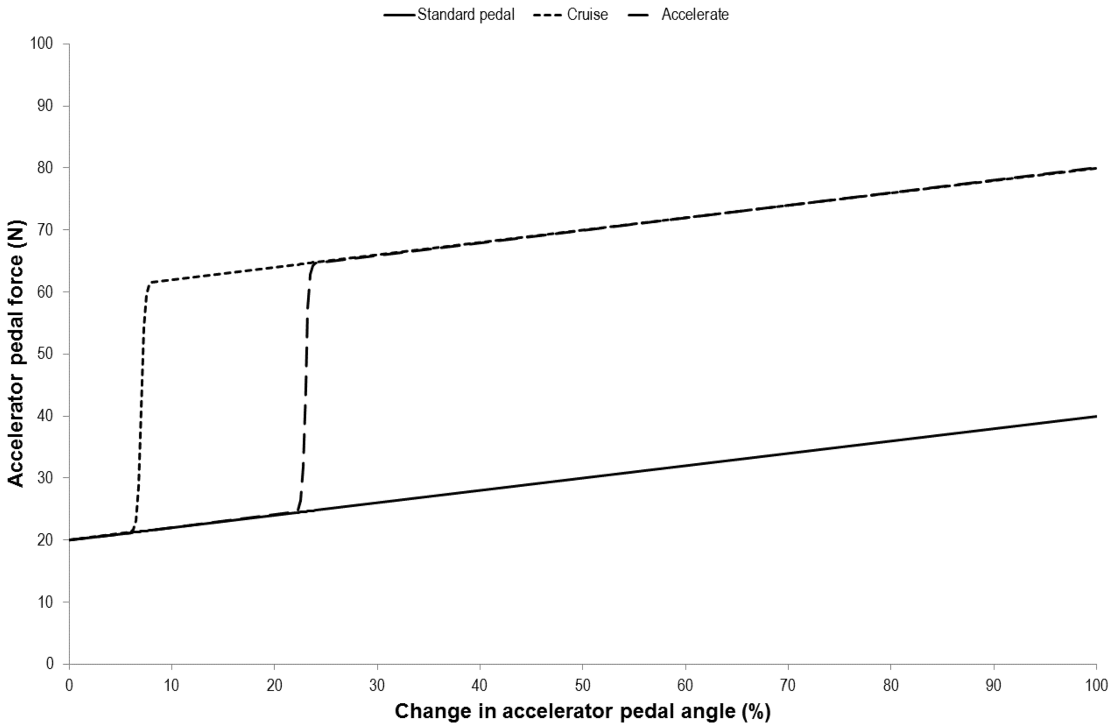
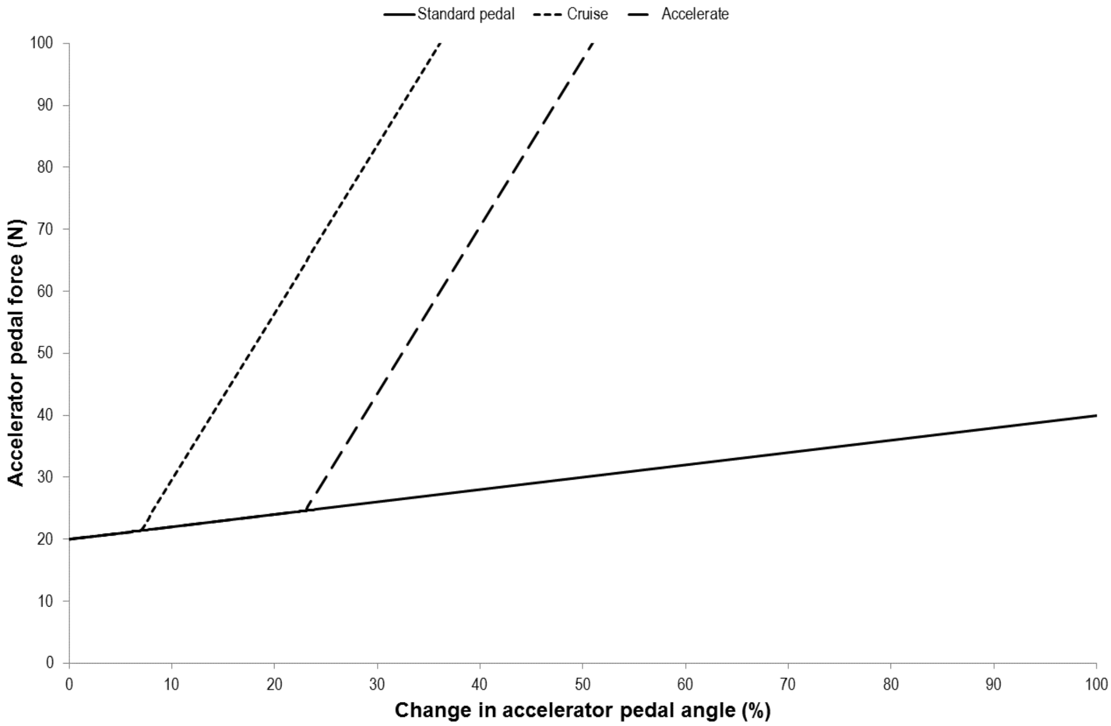


Figure 4



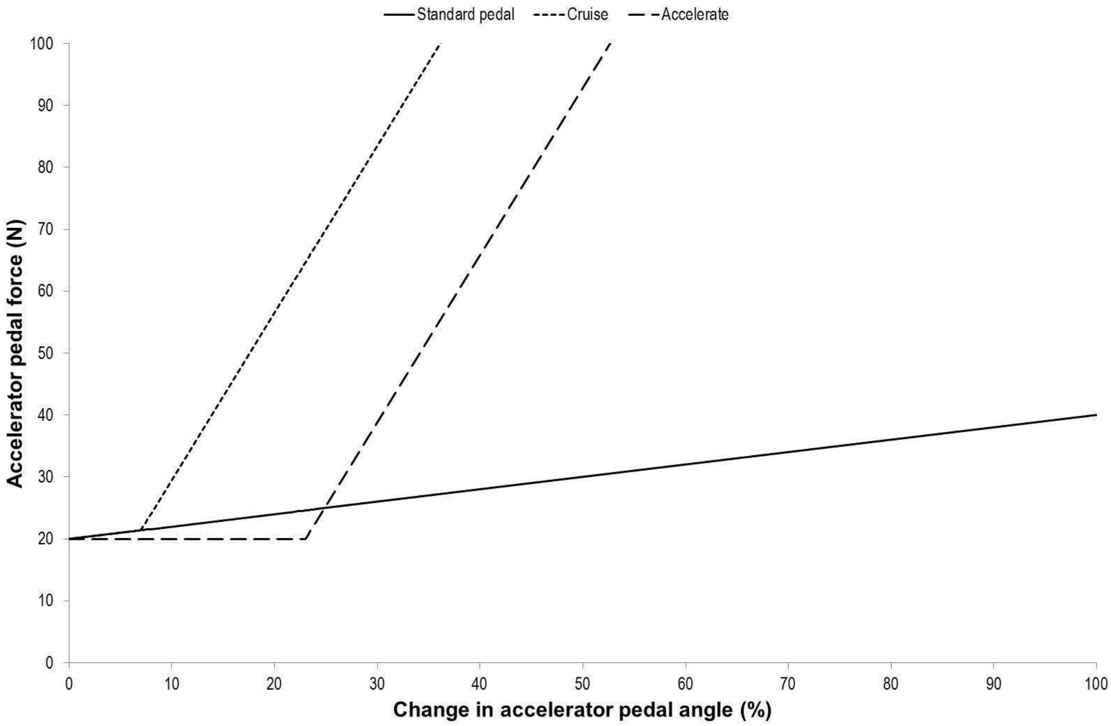
Standard pedal
Cruise
Accelerate
100
90
80
70
60
50
40
30
20
10
0
Accelerator pedal force (N)
0
10
20
30
40
50
60
70
80
90
100
Change in accelerator pedal angle (%)

Figure 5



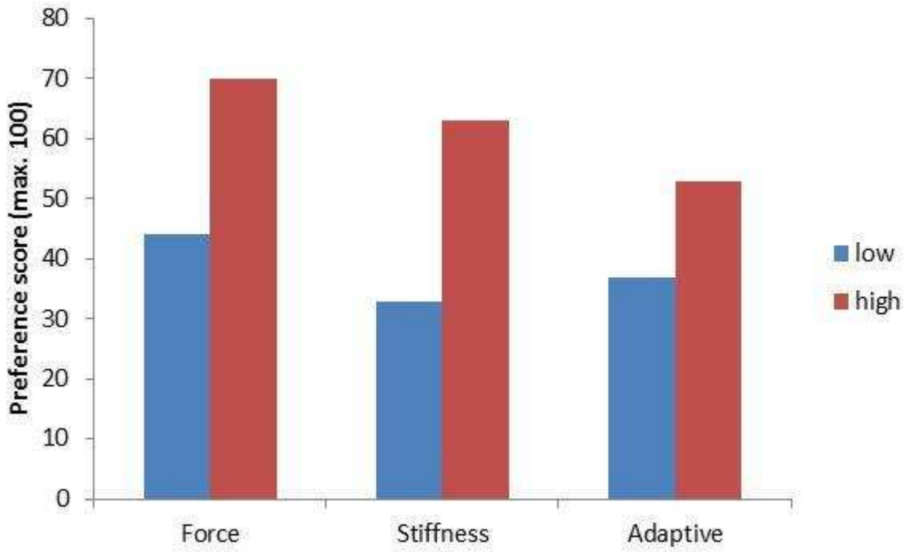
Standard pedal
Cruise
Accelerate
Accelerator pedal force (N)
Change in accelerator pedal angle (%)
0
10
20
30
40
50
60
70
80
90
100

Figure 6



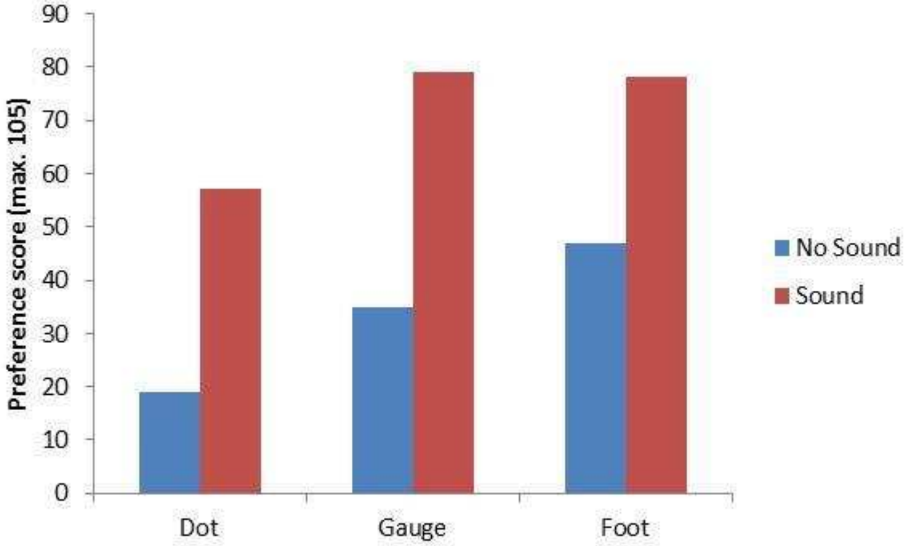
Standard pedal
Cruise
Accelerate
100
90
80
70
60
50
40
30
20
10
0
Accelerator pedal force (N)
0
10
20
30
40
50
60
70
80
90
100
Change in accelerator pedal angle (%)

Figure 7



80
70
60
50
40
30
20
10
0
Preference score (max. 100)
Force
Stiffness
Adaptive
low
high

Figure 8



90
80
70
60
50
40
30
20
10
0
Preference score (max. 105)
Dot
Gauge
Foot
No Sound
Sound

Figure 9

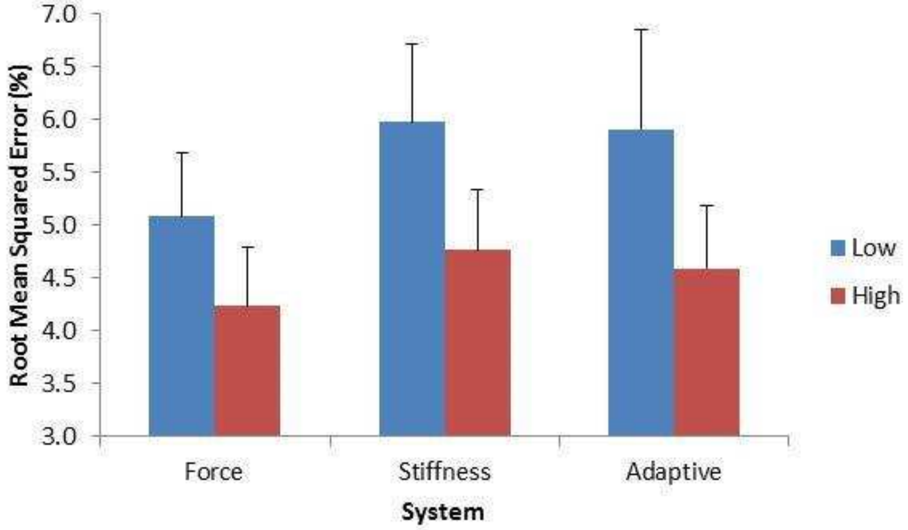

7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
Root Mean Squared Error (%)
Force
Stiffness
Adaptive
System
Low
High

Figure 10

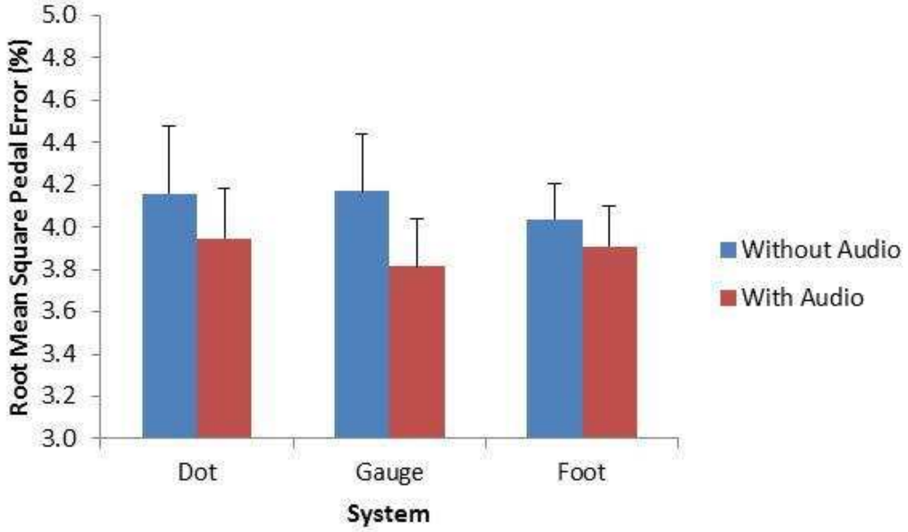

5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
Root Mean Square Pedal Error (%)
Dot
Gauge
Foot
System
Without Audio
With Audio

Figure 11

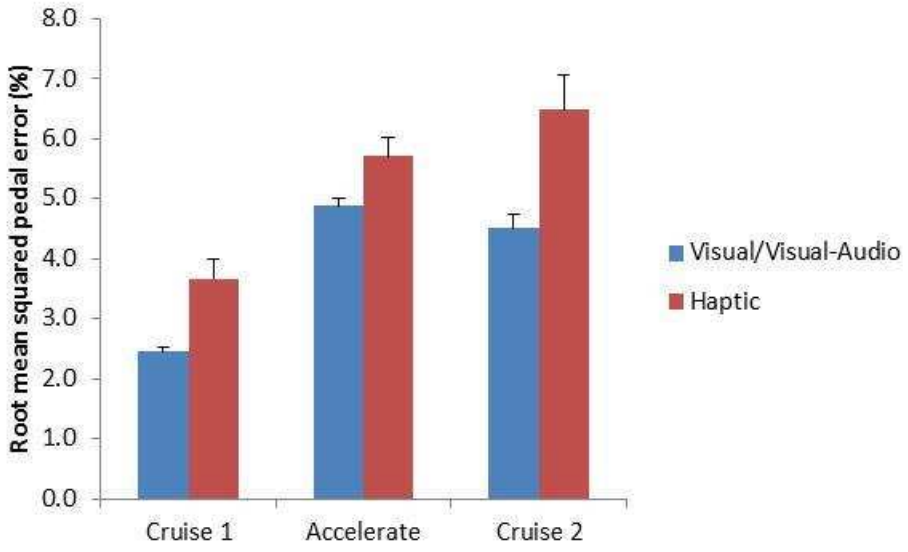

8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Root mean squared pedal error (%)
Cruise 1
Accelerate
Cruise 2
Visual/Visual-Audio
Haptic

Table 1

Sub-section	Cruise 1	Accelerate	Cruise 2
Advised speed	40mph (64.4km/h)	60mph (96.6km/h)	60mph (96.6km/h)
Optimum pedal angle	7%	23%	7%
Duration	10s	10s	10s

Table 2

	Male (n=10)				Female (n=11)			
	Mean	**SD**	**Max**	**Min**	**Mean**	**SD**	**Max**	**Min**
Age (years)	33.2	13.9	60	20	35.9	13.9	59	22
Experience (years)	15.5	13.3	43	2	15.4	11.9	34	2
Annual mileage (mi)	12200	7350	25000	5000	8200	4050	15000	3500

Table 3

Force/L	X					
Force/H	*sig*	X				
Stiffness/L	*ns*	*sig*	X			
Stiffness/H	*sig*	*ns*	*sig*	X		
Adaptive/L	*ns*	*sig*	*ns*	*sig*	X	
Adaptive/H	*ns*	*sig*	*sig*	*ns*	*sig*	X
	Force/L	**Force/H**	**Stiffness/L**	**Stiffness/H**	**Adaptive/L**	**Adaptive/H**

Table 4

Dot	X					
Dot/Audio	*sig*	X				
Gauge	*sig*	*sig*	X			
Gauge/Audio	*sig*	*sig*	*sig*	X		
Foot	*sig*	*ns*	*ns*	*sig*	X	
Foot/Audio	*sig*	*sig*	*sig*	*ns*	*sig*	X
	Dot	**Dot/Audio**	**Gauge**	**Gauge/Audio**	**Foot**	**Foot/Audio**

Table 5

Phase	F	df	p	Effect size (η^2)	Root mean squared pedal error (%)			Sig. pairwise comparisons
					Dot	**Gauge**	**Foot**	
Cruise 1	5.97	2,40	.005	.230	2.53	2.29	2.49	Gauge < Foot and Dot
Accelerate	5.10	2,40	.017	.349	4.95	5.01	4.59	Foot < Gauge and Dot
Cruise 2	4.10	2,40	.024	.170	4.44	4.40	4.68	Gauge and Dot < Foot

Table 6

System	**Cruise 1**	**Accelerate**	**Cruise 2**
No Audio	39.8	39.0	42.3
With Audio	40.5	44.7	49.0
p-value	**.290**	**.003**	**<.001**
Effect size (η^2)	**.062**	**.388**	**.515**

Table 7

System	Cruise 1	Accelerate	Cruise 2
Visual/visual-audio	40.2	41.9	45.7
Haptic	70.8	83.6	84.3

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Table 12: System effects per phase of the scenario. (Green shading indicates significantly lower pedal error than non-shaded)

Table 13: Percent road centre (% of total viewing time) with visual display systems

Table 14: Mean Percent Road Centre (%) with visual/visual-auditory and haptic systems. All comparisons significant at $p<.001$