Vibrotactile pedals: Provision of haptic feedback to support economical driving

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Abstract

The use of haptic feedback is currently an underused modality in the driving environment, especially with respect to vehicle manufacturers. This exploratory study evaluates the effects of a vibrotactile (or haptic) accelerator pedal on car driving performance and perceived workload using a driving simulator. A stimulus was triggered when the driver exceeded a 50% throttle threshold, past which is deemed excessive for economical driving. Results showed significant decreases in mean acceleration values, and maximum and excess throttle use when the haptic pedal was active versus a baseline condition. As well as the positive changes to driver behaviour, subjective workload decreased when driving with the haptic pedal verses when drivers were simply asked to drive economically. The literature suggests that the haptic processing channel offers a largely untapped resource in the driving environment, and could provide information without overloading the other attentional resource pools used in driving.

Keywords: Driving; haptic feedback; eco-driving; acceleration; vibrotactile; workload

Statement of Relevance

Overloaded or distracted drivers present a real safety danger to themselves and others. Providing driving related feedback can improve performance but risks distracting them further, however giving such information through the underused haptic processing channel can provide the driver with critical information without overloading the driver’s visual channel.

1. Introduction

The majority of applications for haptic interfaces within the vehicle have been applied to safety related features. Whether this is to assist with maintaining correct headway to the car in front (Mulder et al, 2008), collision avoidance (de Rosario et al, 2010; Ho et al, 2006; Lee et al, 2007), speed management (Adell et al, 2008), or lane departure (Deroo et al, 2012; Suzuki and Jansson, 2003). The potential benefits of multimodal (both visual and haptic) feedback has also been investigated within a navigation system (Van Erp and Van Veen, 2004) and for upcoming deceleration events (Hajek et al, 2011), while van Driel et al (2007) employed an active gas pedal which applied a counterforce on approach to a traffic jam. However, to the authors' knowledge limited scientific research has focused on how haptic feedback can be delivered to directly facilitate an economical driving style which will reduce fuel use and emissions.

Eco-driving has become a regularly used phrase in the motorised transport arena; it is used to describe a driving style which results in an increase in fuel economy. Increasing the miles per gallon of a journey not only results in a financial saving for the driver, but helps to reduce their carbon footprint and the impact of other emissions. One of the golden rules of eco-driving is to avoid excessive acceleration events, reducing the need for high engine loads and helping to regulate a smooth driving style. A reduction in acceleration rates has been shown to be beneficial to both fuel economy and emissions (El-Shawarby et al, 2005; Ericsson et al, 2001; Waters and Laker, 1980). However 'Smart' driving encompasses both fuel efficient and safe driving behaviours, with acceleration rates also being independently linked to the risk of accidents (AAA Foundation, 2009; af Wahlberg, 2006). In addition, the effect of aggressive driving on other vehicle emissions is more marked compared to CO_2 (and subsequently fuel economy), specifically when considering excessive acceleration levels. Research has suggested that aggressive driving styles increased hydrocarbon emissions by between 200 and 600%, and nitrous oxide by 50 to 200% (De Vlieger et al, 2000; El-Shawarby et al, 2005). These findings have led to the recommendations that to facilitate eco-driving throttle use should be 'positive' but not exceed a threshold of 50% (Johansson et al, 1999; van de Burgwal and Gense, 2002).

There is a plethora of economical driving advice available through websites, information leaflets and also through driver training programmes. However, whilst it has been demonstrated that such benefits can be achieved through driver education alone (e.g., Haworth and Symmons, 2001), evidence also suggested that the learnt positive effects of eco-driving may be lost in time, as drivers forget or do not feel motivated to maintain aspects of the eco-driving style (Johansson et al, 2003). A longer-term, sustainable solution would be to provide feedback to the driver in the car. This however does provide its challenges as providing the driver with more information in the vehicle may increase workload and cause distraction, which ultimately affects performance.

Clearly an approach is needed which does not cause the associated negative effects of an additional task, but does facilitate the benefits of adopting an eco-driving style. One such method may be to give information to the driver via unused or underused attentional resources. The commonly cited multiple resource model for human information processing (Wickens, 2002) suggests that performance degradation is limited when complementary independent sensory resources are used to present information. Since driving is a predominantly visual task (Kramer and Rohr, 1982), using these other sensory modalities may reduce overload to the visual channel, leaving an increased capacity for visual driving tasks and theoretically improving performance. Van Erp (2001) has suggested that overload may be avoided by presenting feedback in either an auditory or haptic form, thereby not competing for the driver’s visual resource pool.

There is a growing body of research which present the potential benefits of providing driving related information via haptic in-car interfaces. Van Erp and Van Veen (2004) investigated in-vehicle navigation information presented to the driver via vibrating elements mounted in the seat, against traditional visual feedback. They found that the haptic navigation display reduced the driver’s workload, and led to the fastest reaction time when combined with a visual display. Ho et al (2006) found faster braking reaction times and greater safety margins when vibrotactile feedback was applied to the torso, versus no feedback, when assessing rear-end collision potential in a driving simulator. Further studies have assessed the use of a haptic accelerator pedal to deliver multimodal feedback including De Rosario et al (2010) who reported faster braking response times when a forward collision warning was presented via a haptic pedal compared to a visual interface, as well as significantly faster times to match the speed of the lead vehicle, which may be due to additional visual capacity released by the haptic feedback. Mulder et al (2008) investigate the effect of a counterforce accelerator pedal on headway parameters in a car following task. Results showed that some improvement in car following performance was achieved, while control activity (represented by steering and pedal input) also decreased. Hajek et al (2011) suggested that giving concurrent multimodal feedback to warn the driver of an unexpected upcoming deceleration event (i.e. presenting both a visual warning on the dashboard, simultaneously as a counterforce is applied to the accelerator pedal) in a driving simulator resulted in an average reduction in fuel consumption of 7.5%. This increase in fuel economy was achieved as drivers would release the accelerator pedal (typically within 2 seconds of the warning for 80% of cases) and coast either to a stop or until the desired speed was attained. In the no feedback conditions drivers would typically not be aware of the deceleration event – as either it was out of sight or traffic flow could not be anticipated – meaning the mechanical brakes would have to be applied. Whilst no actual eco-driving advice was offered to the driver, Hajek and colleagues' study suggests that improvement in fuel efficiency can be achieved by advanced warnings for the driver.

Within the vehicle manufacturers themselves haptic warnings are emerging specifically to alert drivers to safety discretions such as lane departure or compromised headway. This feedback is currently supplied either through the seat (as with certain Citroen models), or steering wheel (BMW 5 Series) or the accelerator pedal (Continental's Accelerator Force Feedback Pedal). The 2013 Cadillac XTS takes this one step further integrating haptic feedback into its collision mitigation and avoidance systems, where a haptic warning is provided in the appropriate location within the seat (cushion and back), so as the area of the seat that vibrates is spatially mapped to the corresponding direction of the collision threat. In addition to this primary focus on safety, economical driving related haptic feedback is emerging on the market. In 2009 Nissan launched its 'ECO Pedal' initiative; this applies a counterforce to the pedal when it deems acceleration to be excessive by the driver. Nissan's internal research data suggest fuel savings of between 5 and 10% can be achieved in normal driving (Nissan, 2008). The Continental Accelerator Force Feedback Pedal has also moved into the eco market with Continental suggesting that by providing a pulsing stimulus through the accelerator pedal to suggest when a gear change is needed, fuel savings of 7.7% can be achieved (Continental, 2010).'

This paper presents an exploratory study aimed at investigating the effects of providing vibrotactile feedback via the accelerator pedal to facilitate eco-driving, and not safety, which makes findings interesting and highly relevant. It is hypothesised that the delivery of haptic feedback will result in positive changes to throttle use and acceleration behaviours of drivers. Providing driving related feedback to the driver in the vehicle can improve performance but risks increasing driver workload or even causing distraction. However, it is also hypothesised that giving such information through the underused haptic processing channel will provide the driver with important information without overloading the driver's visual channel, which may result in modulating subjective workload.

2. Methodology

2.1 Participants

Twelve participants (eight male and four female; mean age 21.3 years, SD = 0.78 years) were recruited from Brunel University to take part in the study. All participants held full UK driving licences, had at least one year's driving experience and had normal or corrected to normal vision.

2.2 Equipment

The Brunel University Driving Simulator (BUDS) was used for this study. BUDS is a fixed-based immersive simulator with a 2006 Jaguar S-Type as the donor car. The driving simulator software is provided by STISim, which enables a real-time, anti-aliased, 3-D graphical scene of the projected virtual world. The images are projected onto three 2.4 m x 1.8 m (viewable area) screens, thus giving the forward facing scene plus the left and right peripheral scenes, giving a 150˚ horizontal and 45˚ vertical field of view. The simulator is controlled by a Logitech multimedia driving unit (G25 Racing Wheel) consisting of steering wheel, gear lever and pedal block (including clutch pedal), fitted as a UK-standard right-hand drive vehicle allowing manual transmission. The vehicle dynamics (weight, engine size, acceleration, gear ratios etc) of the simulated vehicle were similar to those of a standard family saloon car. The frame rate and data capture rate throughout the study were fixed at 20 Hz.

The vibrating alert on the accelerator pedal was activated when the throttle exceeded a predetermined threshold of 50% (i.e., half the pedal's travel potential, not 50% of the vehicle's acceleration limits). The 50% threshold was set for this study following recommendations from two reports which analysed the effects of an eco-driving style on fuel consumption and emissions (Johansson et al, 1999; van de Burgwal and Gense, 2002). The prototype haptic pedal (figure 1) was fitted to the existing pedal block, and consisted of a mechanical arm which, on contact with the base plate of the pedal block, activated a local vibration alerting the participant that they had exceeded 50% throttle. The vibration was provided by a 3-volt motor which drove an offset weight attached to the spindle, creating a vibration at approximately 160 Hz (or 9600 rpm) generating a force feedback of approximately 10 N (or 1g). The mechanical arm on the back of the pedal held a micro-switch in place, ensuring that the switch remained activated when the throttle input exceeded the predetermined threshold.

The aim of this current paper was not to define or review optimal vibration thresholds either for user acceptance or vibration perception, for this reason a vibrotactile frequency was selected that was deemed noticeable by participants in a pilot study. For a discussion on the determining of vibration thresholds see Morioka and Griffin (2008) and Jeon et al (2009). With this being a simulator study no vibration resulted from the vehicle moving over terrain or mechanical vehicle reverberations.

Insert Figure 1 About Here

2.3 Driving Scenario and Experimental Conditions

The simulated driving scenario used for this study lasted approximately five minutes, and consisted of a mixed urban and extra-urban driving route. Speed limits varied from 30 to 50 mph throughout the scenario, and traffic light controlled intersections were located within the urban sections. Two driving lanes (each 8m wide) were present for each direction of traffic, with light traffic density used throughout specifically programmed not to obstruct the driver. To increase the realism of the scenario, buildings, pedestrians and trees etc were added where appropriate.

In order to assess the influence of the haptic pedal on eco-driving parameters, three experimental conditions were used:

- Baseline – Participants were asked to drive normally and were not specifically informed of eco-driving techniques.
- Eco – Participants were asked to drive economically, both according to their own perceptions, and it was also suggested that a simple rule for driving economically is to avoid excessive throttle use.
- Haptic – Participants were asked to drive economically, with the haptic pedal indicating when they had exceeded 50% throttle.

2.4 Procedure

Participants were given a full verbal and written explanation of the study before signed, informed consent was gained. Following this a two-minute practice run (using a different scenario to that described above) was given for participants to familiarise themselves with the simulator and driving setup. When comfortable with the simulator, participants completed the baseline condition first, then they were randomly assigned to complete the eco or haptic condition second, with the remaining condition completed last. The experimental aims of the study would have been compromised if the order of the conditions was fully randomised, as some participants would have been exposed to the notion of using a maximum of 50% throttle as an eco-driving technique before they completed their baseline run. Whilst this creates a potential source for error within the study, it was essential to achieve the study aims. Before each trial, participants were reminded that the primary task was to complete the driving scenario safely and adhere to posted speed limits, adopting eco driving techniques in the appropriate conditions was a secondary task. Following each of the experimental runs the participants completed the NASA Task Load Index (TLX; Hart and Staveland, 1988) subjective workload questionnaire.

2.5 Data Collection and Analysis

A series of driving parameters were collected to assess the effectiveness of the haptic pedal in achieving the desired economical driving behaviours, these included mean and maximum vehicle acceleration and throttle position. Another acceleration parameter was a measure of excess throttle, calculated as a product of the magnitude of the throttle position (when over the 50% threshold) and time spent over the threshold. This measure could also be interpreted as the area under the curve (but above the 50% line) of the throttle position versus time history (figure 2). In addition, the mean driving speed and the time taken to complete the driving scenario, as well as the percentage of time that the driver was stationary at traffic lights were also recorded. Subjective workload was also measured using TLX following the completion of each experimental condition.

Insert Figure 2 About Here

Although the driving scenario used for the study totalled approximately five minutes in length, only two specific sections of the run were used to calculate the throttle and acceleration parameters. This was decided because the primary objective of the study was to evaluate participants' acceleration behaviour, therefore sections when cruising at a constant speed would have been of comparatively little interest, with potential differences as a result of haptic feedback being lost amongst mean data for the entire scenario. For this reason two sections of the scenario were highlighted as being appropriate. The first section (occurring about a third of the way through the driving scenario and lasting for approximately half a minute), began from stationary at a set of traffic lights, the participant then accelerated to a self-selected speed (speed limit of 30 mph), then decelerated to a stop for a second set of traffic lights. The second highlighted section (figure 2) occurred towards the end of the run (after approximately 4 minutes) and was longer than the first at about one minute. This again began stationary at a set of traffic lights, the participant then accelerated to a self-selected speed (speed limit 30 mph) which was maintained for a short distance until they decelerated to a stop for a second set of traffic lights, and once more accelerated to the 40mph speed limit. In total this gave the participants three acceleration and deceleration events with a short section of steady speed, from which the acceleration and throttle parameters could be calculated. However, when considering the mean and maximum driving speed, run time and time stationary this was calculated over the entire length of the driving scenario.

The main effects of the experimental conditions on driving performance parameters were statistically analysed using a MANOVA, with related Bonferroni corrected pairwise comparisons evaluating potential differences between the conditions. The TLX data were analysed using Friedman and Wilcoxon Signed Rank tests. Statistical testing was completed using SPSS 15.0 and significance was accepted at $p<0.05$.

3. Results

The driving data collected revealed some interesting effects between the experimental conditions adopted for this study (table 1). Statistical analysis revealed that both mean and maximum driving speed did not differ significantly ($p>0.05$) between the conditions over the entire driving scenario, nor did run time or percentage of time stationary. In addition, no difference ($p>0.05$) was observed for mean throttle position throughout the abridged section of the scenario. The acceleration parameters did change with the conditions; a significant main effect was observed with mean acceleration ($F_{(2,33)} = 12.2$, $p<0.001$) and maximum acceleration ($F_{(2,33)} = 7.0$, $p<0.01$). These differences were primarily made up of a significant reduction in acceleration parameters (assessed using Bonferroni corrected pairwise comparisons) from the baseline to eco and haptic conditions, but not between the eco and haptic conditions (table 1). Also seen in this study was a significant decrease ($F_{(2,33)} = 16.1$, $p<0.001$) in the maximum throttle input, with pairwise comparisons revealing significant differences between the haptic condition and both the baseline and eco conditions. The final driving parameter was excess throttle where a significant main effect was also observed between the three conditions ($F_{(2,33)} = 3.9$, $p<0.05$). However, pairwise comparisons revealed this difference was only significant between the haptic and baseline conditions.

Insert Table 1 About Here

As well as the driving data presented above, notable differences were also observed when considering the subjective ratings of workload during the driving scenario for each experimental condition (table 1). A significant main effect between the conditions (*df* = 2, x^2 = 5.9, p<0.05) was revealed by the Friedman test, with the ratings given for the haptic condition being significantly lower than those given in the eco condition, but no difference observed when considering experimental conditions verses the baseline.

Given the number of participants utilised for this study, as well as the limited exposure (aka driving) time, a post-hoc power analysis (assessed from Baseline to Haptic conditions) is included in the results to help the reader judge the significance of the results presented above (table 2). The power of the principal results from this study (changes to mean acceleration and max throttle use) were extremely high at greater than 0.95. However when considering the derived parameter of ‘Excess Throttle’ this was lower at 0.565, and may be indicative of the high standard deviation of the data. The power analysis also revealed that to determine differences between the Baseline and Haptic conditions with respect to the TLX ratings, 35 participants would need to be used in this study. However between the Eco and Haptic conditions a power of 0.765 was returned, which is the focus for the discussions below.

Insert Table 2 About Here

4. Discussion

Results from this study suggest that the use of a vibrating, haptic pedal to warn drivers when they exceed a 50% threshold had some positive effects on acceleration and throttle parameters associated with eco-driving. These adjustments in driving behaviour came at no significant cost to journey time, or the percentage of time sat stationary at traffic lights. Also seen was a reduction in driver workload when driving with the haptic pedal verses being asked to drive economically.

4.1 Throttle Use

An interesting finding was that average throttle position did not differ between the conditions, but maximum throttle did (table 1). Maximum throttle (averaged for all participants) decreased from nearly 100% in the baseline condition to 89% in the eco condition, and by a further 11% to 78% when participants received haptic feedback (figure 3). From this (reduced maximums but unchanging means) we could assume that a more stable and consistent throttle use pattern emerged from the haptic feedback. Since research has shown emissions data (excluding CO_2) to be extremely sensitive to large differences in throttle position (represented by instantaneous acceleration; De Vlieger et al, 2000; El-Shawarby et al, 2005) a more stable, or less variable, throttle position can be assumed to be wholly beneficial to reducing vehicle emissions. These results suggest that a haptic pedal indicating when a driver has exceeded a set threshold will reduce maximum throttle position, but not mean throttle position over a journey.

Insert Figure 3 About Here

Excess throttle use decreased from the baseline condition to when participants were asked to drive in an economical way, and further decreased when the haptic pedal gave additional feedback (figure 3). The implications of this are that drivers spent less time with the throttle depressed beyond the 50% threshold, and what time they did spend over 50% was of a lower magnitude. Within a simulator it is not possible to measure actual fuel consumption or emissions, however given the recommendations of Johansson et al (1999) and van de Burgwal and Gense (2002), that an eco-driving technique should not involve throttle positions of greater than 50%, this result can be seen as a positive for the haptic pedal. The interesting point here is that mean throttle use was unchanged but excess throttle decreased significantly from both baseline driving.

4.2 Vehicle Acceleration

Mean acceleration values were seen to decrease by over 25% in the eco and haptic conditions compared to the baseline (figure 4); this is despite mean throttle positions not changing between the experimental conditions. A study conducted by Birrell and Young (2011) showed a 15% decrease in mean acceleration was observed when a Smart driving visual interface gave acceleration (in addition to gear change and safety advice) feedback during driving in an urban scenario in a driving simulator. Comparing these results suggests that haptic feedback given at the point of control (namely on the pedal itself) has a larger effect to reduce acceleration rates compared to a visual display. This may be oversimplifying the matter as in the Birrell and Young (2011) study a multitude of Smart driving feedback was given, rather than just acceleration advice as in this current study. Further research should be conducted to compare the efficacy of different modes of feedback (haptic, auditory and visual), as well as multimodal feedback (a combination of two or more modes) and its effect on safe and fuel efficient driving.

Whilst a reduction in mean acceleration values for a specific journey have not been identified in the literature as having a major impact of fuel economy, occurrences of heavy, or excessive accelerations have (El-Shawarby et al, 2005; Ericsson et al, 2001; Waters and Laker, 1980). To the contrary a study conducted by af Wahlberg (2002) found that mean acceleration levels actually increased by 22.5% from pre to post a taught eco-driving course. This study was conducted using bus drivers and also showed a significant decrease in fuel consumption of nearly 15%. These results suggest that the relationship between acceleration levels and fuel economy is not as simply defined as say, the driving speed to fuel economy correlation. Eco driving advice suggests ‘positive’ but not excessive acceleration (Young et al, 2011), thus enabling the higher (and more fuel efficient) gears to be engaged sooner. From an engineering standpoint positive acceleration also maintains the vehicles engine working in the more fuel efficient torque bands, also comparatively less energy is lost to frictional forces which apply drag to the car. Advice from the Institute of Advanced Motorists (IAM) advocate that drivers adopt a ‘progressive’ driving style and encourage the use of ‘block’ gear changes, meaning that a driver can stay in a lower gear until they reach their desired cruising speed and then block change up to the highest possible gear (IAM, 2007). This technical driving information goes against some eco-driving suggestions which promote gear changes before 2,500 rpm in petrol cars (EcoDrive, 2006; Energy Saving Trust, 2007). The authors of this current paper (based on results of this study and an understanding of the surrounding literature) suggest that limiting maximum throttle use and reducing excessive acceleration events, combined with appropriate use of block changes will have a more positive effect on smart (both fuel efficient and safer) driving than simply focusing on gear change at a particular point. If however sequential, ascending gear change is either necessary or adopted by the driver then the rule of gear change before 2,500 rpm is an appropriate one to abide by.

Insert Figure 4 About Here

Findings from this current study also showed a significant reduction in maximum acceleration values from the baseline to eco condition. Whilst figure 4 shows an observable reduction in maximum acceleration from baseline to haptic conditions, this difference was not statistically significant. As mentioned above excessive acceleration levels have been linked to an increase in fuel use. Ericsson (2001) derived 16 independent driving factors from over 19000 driving patterns in real-traffic urban driving, and concluded that ‘acceleration with strong power demands’ was the parameter that had the most important effect on fuel consumption and emissions. A reduction in maximum acceleration values (as observed in this current simulator study) has been shown to have positive effects on eco parameters such as fuel consumption (Ericsson et al, 2001; Waters and Laker, 1980). El-Shawarby et al (2005) suggest that exploiting the vehicle’s maximum acceleration capabilities can use up to 60% more fuel than mild or normal acceleration levels. Safety aspects of ‘Smart’ driving are also positively affected by a reduction in acceleration rates, as they have been shown to be independently linked to the risk of accidents (af Wahlberg, 2006). In addition a high number of excessive acceleration events (amongst other parameters) are a prerequisite for a driver with an ‘aggressive’ style, with aggressive driving being associated with 56% of all fatal crashes in the US (AAA Foundation, 2009).

Waters and Laker’s 1980 study also suggested optimal acceleration values to maximise fuel economy during a simple stop/start cycle, as 0.69 $m.s^{-2}$ (or 0.07g). Figure 4 shows that the maximum acceleration was reduced much closer to these levels when using the haptic pedal, or significantly closer when asked to drive in a fuel efficient way (eco condition). Acceleration values collected using driving simulators are typically higher than that of real world driving, this is attributed to the lack of ‘motion cuing’ in static driving simulators (Reymond et al, 2001). This may explain some of the differences observed between theoretical optimal acceleration values and those gained from this simulator study.

4.3 Time and Speed Parameters

The lack of difference to either mean or maximum driving speed (table 1) can be taken as a positive effect for the haptic pedal. It suggests that decreases in high throttle events came at no expense to mean driving speed, which will ultimately relate to journey time. Results presented by Ericsson (2001) indicate that speed itself does not cause large environmental problems within urban traffic. Instead, the focus should be on changing individual driver behaviour, environments and vehicles in a way that does not promote heavy acceleration, power demand and high engine speeds.

A typical criticism of adopting an economical driving style is that it leads to increases in journey times. This is certainly true if we consider simply a reduction in speed on motorways or highways. However reducing speed is not the only – nor is it the optimal – strategy for optimising eco-driving (Young et al, 2011). Johansson et al (2003) found certain characteristics of driving behaviour that were significantly correlated with good fuel economy, such as avoiding unnecessary stops, low deceleration levels, minimising the use of 1st and 2nd gears, increased use of 5th gear, and block changing gears where possible. All of these aspects can theoretically be achieved without impacting on journey time. In fact the IAM guidelines encourage progressive driving, with planning ahead to moderate driving behaviours before an event (such as unnecessary stops and starts) which may actually lead to decreases in journey times. Results from this simulator study showed that the changes in throttle use and acceleration values were achieved with no significant affect on journey time (table 1). This fact has been observed previously in numerous studies within the literature. When drivers adopted a self selected 'aggressive' driving style (within posted speed limits) this led to an increase in fuel use by 40%, but journey times were unaffected (De Vlieger, 1997; De Vlieger et al., 2000). Similarly, Evans (1979) asked drivers to 'minimise fuel consumption' or 'maintain fuel economy meter in green or orange region'. These instructions resulted in decreases in fuel consumption of 10.4% and 5.4% respectively with no overall impact on trip time.

4.4 Driver Workload

Participants rated their perceived workload from the driving task (using TLX) following each of the experimental runs. Participants rated workload to be significantly lower in the haptic compared to the eco condition (figure 5). This is despite the fact that in both conditions participants were asked to drive economically, and use the 50% throttle rule as a guideline for economical driving; the only difference being with the haptic condition drivers were alerted to this threshold. A similar result was seen by Van Erp and Van Veen (2004) who found a decrease in workload when navigation advice was administered using haptic feedback. The results from the current study suggest that simply asking a driver to limit throttle use to 50% does result in beneficial changes to throttle use and acceleration values, at least in the short-term, but a resulting drawback is that workload was increased, presumably as drivers were concentrating on achieving 50% throttle. This observation might occur as it may be unreasonable to expect anyone other than highly skilled drivers to be able to pinpoint a set threshold on the accelerator. Even if they could, such a task is likely to increase the attentional demands on the driver, which in turn may increase risk if the driver becomes overloaded, as observed with this current study.

Insert Figure 5 About Here

4.5 Future Research

The research presented in this paper was an exploratory study and raises interesting issues which need to be addressed in greater detail in future research. Such studies could include comparisons with a visual and/or auditory display, to investigate if vibrotactile alerts still offer the advantages proposed in this study. A replication of this study should be conducted with an increased number of participants to investigate responses from differing age ranges and driving experience to haptic feedback. A limitation to this, and all simulator studies, is that no force feedback or vibrational feedback is available from the car or road itself, this may change driver's behaviours in the real world or mask any benefits observed in the simulator. Therefore, given the safety critical nature of pedals in cars, further on the road testing needs to be conducted. In addition future studies need to build on the existing literature to determine the most appropriate vibrotactile characteristics for an accelerator pedal, taking into account vibrations from the road, vehicle as well as those specifically transferred from the engine to the accelerator pedal. These can be produced by engine vibrations causing the throttle linkage and cable to vibrate, resulting in low amplitude vibrations to occur laterally (i.e. not in the direction of pedal stroke), the frequencies of which are related to engine speed (rpm) regardless of vehicle speed[1]. Later versions of the haptic pedal may utilise a variable threshold, rather than fixed at 50%, to allow greater throttle use at lower speeds or in lower gears. Other features could be included such as counterforce being applied to the pedal or different stimuli (constant or pulsing vibration) representing different feedback advice.

A wider ergonomic issue is how much information can be presented via the haptic processing channel, and also how this information is processed by the users. A study by Suzuki and Jansson in 2003 showed that some drivers, when given a unilateral vibration on the steering wheel to indicate a lane deviation had occurred, actually turned the wheel in the wrong direction needed to correct the deviation. Anecdotal evidence from this current study also suggested non-expected behavioural responses to the vibrating pedal. During the practice runs a small number of participants interpreted the haptic feedback to suggest that a gear change was needed, rather than excessive throttle was being used. This was clarified in the participant briefing, but further highlights that further research is need to better understand user expectations when it comes to perceiving haptic feedback. The latter is an issue for consideration by researchers, vehicle designers and also the standardisation community.

5. Conclusion

This study shows that haptic feedback can successfully be used to deliver eco driving feedback, a vibrotactile stimulus on the accelerator pedal which is triggered when the throttle is depressed beyond a predetermined threshold of 50% resulted in positive changes to driving parameters compared to a baseline condition. As hypothesised a significant decrease in mean acceleration values, maximum throttle

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[1]Information taken from a document produced for Toyota Technical Training, entitled 'Noise, Vibration and Harshness - Course 472', see http://users.757.org/~ken/T/Toyota%20Training%20472%20-%20NVH.pdf

position, and excess throttle use were observed. In addition, further decreases in maximum and excess throttle were observed in the haptic condition compared to when participants were simply asked to drive economically. As well as the positive changes to driver behaviour, a decrease in subjective workload was observed when driving with the haptic pedal over eco-driving. It could be argued that simply informing drivers of eco-driving rules would allow them to adjust their driving style accordingly. However, a haptic pedal solution has several advantages. Firstly, as has been pointed out already, such education-based interventions tend to be short-lived. The most significant advantages of a haptic pedal is that by providing the driver with instant feedback on when those thresholds have been reached, it not only relieves them of additional workload, but actually maintains a level of automaticity on the task. There is considerable evidence that haptic interfaces impose significantly fewer demands than visual or auditory displays – and, indeed, that haptic information can to some extent be automatically processed (Gustafson-Pearce, 2007; Sklar and Sarter, 1999; Van Erp and Van Veen, 2004). Moreover, since driving is a predominantly visual task (Kramer and Rohr, 1982), the haptic processing channel offers a largely untapped resource in the driving environment, and could be used to provide information without overloading the other attentional resource pools used in driving (cf. Wickens, 2002).

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