ABSTRACT

Eco-driving has been proposed as an approach to significantly reduce greenhouse gas emissions arising from personal automobile use. Eco-driving is the adoption of a measured driving style, minimising unnecessary breaking and aggressive acceleration. Eco-driving can be seen as a low cost and immediate approach to emission reduction as it involves the modification of drivers’ behaviours as opposed to the development and implementation of newer, more efficient technology. Despite the proposed benefits of eco-driving, numerous challenges are faced in order to encourage the adoption of these behaviours and maintain them long term. This narrative review presents the concept of eco-driving, with a focus on the long-term maintenance of these behaviours, including training programmes and feedback devices. It is clear within current literature that, despite the economic and environmental benefits of adopting eco-driving, drivers require feedback on their actions in order to promote long-term, behavioural, change.

KEY WORDS

Eco-Driving; Personal Transportation; Emission Reduction; Behaviour Change. Automotive

INTRODUCTION

There has been a growing acceptance of the role of man-made emissions in climate change (Thornton & Covington, 2015). Despite accepting the role of anthropometric generated greenhouse gases (GHG) for example Carbon Dioxide (CO2) and Nitrous Oxides (NOx) in changing global temperature, limited concerted steps to combat the carbon footprints of individuals have been taken. Whilst it can be difficult for an individual to consider the impact of their personal energy use, Vandenbergh, Barkenbus and Gilligan (2007) argue that approximately 30-40% of total GHG emissions can be directly attributed to individual energy needs supporting 21st century lifestyles. Dietz, Gardner, Gilligan, Stern and Vandenbergh (2009) propose that emissions could be significantly reduced, with no consequence to lifestyle, if individuals simply acted in a more eco-friendly manner, taking steps to reduce excessive and waste energy consumption. This narrative review examines steps taken within transportation, with particularly focus on the concept of eco-driving to reduce emissions.

This review, aligned from a human factors perspective, will introduce the topic of eco-driving, a behavioural approach in reducing the overall vehicle fuel use, examining the role of training and feedback in supporting eco-driving behaviours long term, extending the work of Young, Birrell and Stanton (2011). Despite evidence demonstrating the initial effectiveness of eco-driving courses (Kurani, Sanguinetti & Park, 2015), these benefits are often short term, with drivers rapidly returning to previous habits (Wahlberg, 2007). Research has, however, demonstrated that regular feedback can be an effective tool in helping drivers to maintain eco-driving behaviours (Meschtscherjakov, Wilfinger, Scherndl, & Tscheligi, 2009), although ambiguity remains regarding the best modality to present eco-driving feedback (McIlroy, Stanton, Godwin, & Wood, 2016). Despite uncertainty remaining regarding the best way to support eco-driving behaviours, it is apparent that their adoption can lead to both reduced GHG emissions (Alam & McNabola, 2014), benefiting the environment and a financial saving (Beusen et al., 2009), benefiting the driver.

TRANSPORTATION CONTRIBUTION TO GHG

A key component of personal energy consumption, and a significant source of GHG emissions, is transport (Fuglestvedt et al., 2010). The most recent statistics regarding emissions were released by the International Energy Agency (IEA, 2017), which is based upon the 2014 energy use statistics of 19 countries with documented energy use records (*Australia, Austria, Canada, Czech Republic, Finland, France, Germany, Greece, Ireland, Italy, Japan, Korea, New Zealand, the Netherlands, Spain, Sweden, Switzerland, the United Kingdom and the United States).* The IEA estimate that transport accounts for 35% of overall global energy use, with passenger cars, including light duty vehicles accounting for 21% of global energy use. Hill et al. (2012) first posited that transport is the second largest source of GHG emissions in the European Union (EU), after electricity generation. Of this, road transportation, specifically automobiles, is the biggest contributor, accounting for approximately 75% of the total transport-related GHG emissions. This is supported by IEA, who suggest that currently transport is responsible for 24% of CO2 emissions.Similarly, in Japan, it has been estimated that automobiles account for approximately 87% of transportation related CO2 emissions (Ando & Nishihori, 2012). Hill et al. calculates that car transportation equates to approximately 20% of the total CO2 EU emissions across all sectors. In addition to being a significant contributor to GHG emissions, transport is one of the few sectors where GHG emissions have grown in recent decades. Between 1990- 2009, there was a 24% decrease in total GHG emissions across the EU; transportation GHG emissions, in contrast, rose by 29% (Hill et al., 2012). Automotive transportation played a significant role in the increasing emissions, although there were also increased contributions from both maritime and aviation, with aviation being the largest growth transport sector. The trend for significant transport emissions is not limited to the EU. In the United States of America (USA), personal transportation accounts for approximately 32% - 41% of total CO2 emissions (Vandenbergh & Steinemann, 2007; Bin & Dowlatabadi, 2005). USA transportation related emissions exceeds emissions from the USA industrial sector and are greater than the total emissions from all other individual countries, with the exception of China (Marland et al., 2007), which is currently the world’s leader in GHG and CO2 emissions (Gregg, Andres & Marland, 2008; Netherlands Environmental Agency 2017; IEA 2017). When considered as a whole, Barkenbus (2010) estimates that approximately 8% of the worlds total CO2 emissions are a result of transportation, primarily automobiles. The idea that automobile use has a significant and long term negative impact on our environment is not novel, with Berntsen and Fuglestvedt (2008) estimating that, based on emissions figures from the year 2000, automobile use has approximately 4 times greater global warming effect than aviation. Extending this analysis, Skeie et al. (2009) estimate that approximately 14% of global mean temperature change will be a direct consequence of transportation, with automobiles being the primary contributor. Seeking ways to minimise transportation, specifically automobile related, emissions, should therefore be considered a priority for helping combat climate change. Due to the scale of transportation GHG emissions, small-scale savings made within this sector can act as a key cornerstone for emission reduction, presenting a prime candidate for collective action.

ECO-DRIVING

Whilst it is fundamentally clear that the most dramatic way to reduce transportation related GHG emissions is to not take car journeys, an option ingrained into some newer drivers during training (Strömberg, Karlsson & Rexfelt, 2015), Barkenbus (2010) proposed that GHG emissions can be significantly reduced just by altering driving style. Barkenbus argued that should individuals adopt a measured driving style, referred to as eco-driving, fuel use and GHG emissions could be dramatically reduced. Eco-driving, the behavioural approach to emissions reduction has been demonstrated to hold significant potential, with previous research suggesting that emissions could be reduced by 5% - 20% (Stillwater & Kurani, 2013) with fuel usage being reduced by between 5% – 10% (Martin, Chan & Shaheen, 2012). Barkenbus (2010) proposes that eco-driving is characterised by behaviours such as modest acceleration, early gear changes, limiting the engine to approximately 2,500 revolutions per minute (RPM), anticipating traffic flow to minimise breaking, driving below the speed limit, and limiting unnecessary idling. Importantly, the use of these techniques, and subsequent emissions and fuel use reductions, can be achieved without significantly increasing journey time (Barth & Boriboonsomsin, 2009). Although Barkenbus notes that eco-driving includes non-driving behaviours, for example, ensuring that the car is well serviced and making appropriate navigation decisions, Sivak and Schoettle (2012) posit that eco-driving has generally been considered in terms of driving style following vehicle selection. Whilst Barkenbus concentrates heavily the operational decisions a driver makes during a journey, Sivak and Schoettle (2012) posit that the concept of eco-driving can be extended to also include strategic and tactical decisions that drivers make. Strategic decisions relate to initial vehicle selection, for example choosing a vehicle that maximises fuel economy as well as on-going vehicle maintenance, for example ensuring tyres are adequately inflated. Conversely, tactical decisions, relate to gestalt decisions about the overall journey being undertaken such as navigational decisions, for example changing route in order to avoid traffic and decisions related to current vehicle load. The wide adoption of eco-driving behaviours is advantageous in that it is an emission reduction technique that is available to all drivers, within all situations. Whilst replacing older vehicles, typically characterised by inefficient internal combustion engines, with more technologically capable, environmentally friendly and fuel efficient drivetrains is desirable, for example the use of electric, hydrogen fuel cell or hybrid vehicles (Chan, 2007; Lorf, Martinez-Botas, Howley, Lytton & Cussons, 2013), or the use of alternative, cleaner fuel sources, such as compressed natural gas (CNG) (Windecker & Ruder, 2013), the initial financial investment required for such vehicles means that, for many, this is an untenable option. Eco-driving, as a behavioural intervention, in contrast, presents an opportunity for all drivers, regardless of circumstance, to reduce the environmental impact of their own personal transportation.

In addition to the environmental benefits of eco-driving, adopting these behaviours has direct financial benefits to the driver, primarily due to reduced fuel consumption and reduced fuel costs per journey (Alam & McNabola, 2014; Mensing et al. 2014). Kurani et al. (2015) reviewed of 32 studies that considered fuel economy and the uptake of eco-driving behaviours. They found, on average, a 9% fuel saving as a consequence of adopting eco-driving techniques, although note that this figure varies considerably, with in-simulator studies typically recording greater potential savings than on-road trials. Due to the financial benefits associated with reduced fuel consumption, the potential benefits of eco-driving are increasingly compelling, especially considering rising fuel prices (Heyes, Daun, Zimmermann & Lienkamp, 2015). Beusen et al. (2009) notes that a 5% fuel saving for a typical driver, a figure equal to the lower estimate from Kurani et al. (2015), would results in approximately a £250 (≈ $350) year financial saving.

ECO-DRIVING KNOWLEDGE

Despite the environmental and financial benefits of adopting eco-driving, understanding the best way to disseminate this information to drivers remains elusive. This task is further complicated by significant variation in driver knowledge regarding eco-driving behaviours. Strömberg, Karlsson and Rexfelt (2015), compared the eco-driving knowledge of nine older and nine younger drivers in Sweden. They found that whilst the term eco-driving was known to all bar two experienced drivers, the level of knowledge relating to eco-driving varied greatly both within and between groups. Unsurprisingly, as eco-driving is increasingly normalised within newer driving education, younger drivers had similar awareness and depth of knowledge regarding the eco-driving concept. Interestingly however, the quality of the eco-driving training varied considerably between individuals, with some having been taught eco-driving techniques as integral to driving, normalizing the technique. Others however, were taught that eco-driving was a series of techniques that could be used as the driver saw fit. This marked difference in the quality of driver training within a limited sample of just nine younger drivers suggests that greater efforts are needed to standardised eco-driving training. Whist it is unfeasible to track the driving actions of drivers once they pass their test, mandating set driving styles during training may have a large-scale positive impact on future drivers behaviours. Conversely, the more experienced drivers varied greatly in their level of awareness of the eco-driving concept, with one participant having been on several courses focused on the topic. More experienced drivers had an awareness of the concept of eco-driving due to information passed from younger family members and colleagues, but lacked an in-depth understanding. Despite an absence of formal understanding, the potential of eco-driving was generally well received among participants.

Seeking to understand the level of eco-driving knowledge held by members of the general public, McIlroy and Stanton (2017) explored participants’ awareness of eco-driving techniques, using an online questionnaire. McIlroy and Stanton (2017) found that of the 321 respondents, 81% were able to demonstrate knowledge of at least one eco-driving behaviour, for example ensuring tyres are adequately inflated and minimising the engine revolutions. Although identifying that the majority of respondents were aware that their actions could influence fuel usage, it was clear that significant variation regarding overall knowledge was apparent within the sample, with participants displaying limited detailed knowledge of specific techniques. McIlroy and Stanton note however that there is a general correspondence between the techniques suggested by the sample and techniques which are suggested within academic literature to reduce fuel use, for example Barkenbus (2010) and Hooker (1988). The general lack of detailed knowledge possessed by respondents suggests that whilst eco-driving is often viewed as a cost effective way to reduce fuel use (Birol, 2017), requiring no financial investment (Saboohi & Farzaneh, 2009), significant financial investment may be needed by governments and charitable organisations to generate greater driver awareness. Equally, drivers themselves may be required to invest a consider amount of time and effort into developing and maintaining the skills required to see a benefit of eco-driving practices, with studies reporting that some behaviours, including maintain low RPM and early gear changes are difficult to maintain long term (Delhomme, Cristea & Paran, 2013).

One factor that does constrain the dissemination of eco-driving knowledge to the wider public is the lack of established guidelines on how best to achieve eco-driving. Kurani, Sanguinetti, and Park (2015) argue that despite eco-driving behaviours being well known, for example avoiding excessive use of a vehicles air conditioning system, these behaviours are often generic and imprecise. Eco-driving can be best understood when considered in terms of qualitative behaviours rather than quantitative actions. For example, gentle acceleration is a key concept within the eco-driving framework, however what is meant by gentle acceleration can vary significantly between individuals. Because of the lack of consistent and established quantified eco-driving guidelines, it is difficult to directly compare the multiple research studies that populate the literature. The current lack of consistent definitions may also partially explain the dramatic differences recorded within studies exploring the potential benefits of eco-driving, both in terms of overall fuel usage and total emissions. Barkenbus (2010) notes that the achievable fuel use savings documented within the literature as a consequence of adopting eco-driving ranges from 5% to 20%. Dula and Geller (2003) argue that a similar ambiguity exists in literature related to the converse of eco-driving, that of aggressive driving. They also argue that the lack of consistent definitions for aggressive driving makes comparisons between studies difficult, although are supportive of the view that aggressive driving is associated with greater fuel use. Sivak and Schoettle (2012) note that continually driving in an aggressive way, for example with maximum use of the accelerator pedal and heavy breaking, with high vehicle loads and use of ancillary vehicular systems, such as air conditioning can increase fuel consumption by approximately 45%. Although accurately estimating the potential benefits and fuel savings as a consequence of adopting eco-driving behaviours is a difficult task, it is clear that driving style can significantly impact total fuel use and subsequent GHG emissions.

A further constraint on the dissemination of eco-driving advice is the increasing availability of alternative vehicle drivetrains. Traditionally, eco-driving research has focused on internal combustion engines (ICE), however it is clear that drivetrains such as hybrid electric vehicles (HEV), such as the Toyota Prius and plug in electric vehicles (PHEV), such as the Nissan Leaf and Mitsubishi Outlander PHEV, with regenerative braking (Shabbir, & Evangelou, 2014) are increasingly available. HEVs and PHEVs provide a challenge for eco-driving information dissemination as their energy dynamics, they way they consume, use and regenerate energy, differs from traditional ICE vehicles (McIlroy, Stanton & Harvey, 2014), meaning that advice given to owners of these vehicles may need to be specifically tailored. To examine eco-driving techniques of HEV owners, Franke, Arend, McIlroy and Stanton (2016) interviewed 39 Toyota Prius drivers, who regularly logged their fuel use online and achieved higher than average efficiency. Franke et al. found that participants held a diverse levels of understanding regarding their HEV, including many the identification of false beliefs in relation to the energy recuperation system and when best to utilise the on-board electric engine. Franke et al. notes that even within their relatively small sample of fuel-efficient drivers, significant variations in eco-driving strategies were observed, identifying clear differences in the level of knowledge that exists in the driving population. This finding suggests that there is a need for clearer guidelines to be presented to HEV drivers. Of central importance however was that many strategies employed by participants were the same as would emerge when considering ICE vehicles, including anticipation of traffic flow and limiting overall speed on high-speed roads such as autobahns. This suggests that HEV eco-driving strategies build on those already employed.

ECO-DRIVING TRAINING

One approach to the dissemination of eco-driving information to drivers is through prescribed training courses, a technique that has been previously pursued. In a simple comparison between eco-driving advice and a previous eco-driving training, Andrieu and Saint Pierre (2012) explored the fuel use of two sets of French drivers. They found that despite fuel use reduction for both groups being highly comparable, at approximately 12%, the training group more frequently and consistently displayed positive behaviours, leading to the conclusion that whilst informing users about eco-driving is worthwhile, consistent performance was better following the eco-driving course. One weakness of this work however was that the samples use were limited and only based on 2 drives. Exploring the long term impact of eco-driving, Beusen et al. (2009) monitored the fuel use of 10 drivers for a year, and explored the impact of an eco-driving course which participants undertook 6 months into the monitoring period. Throughout the year, vehicular data, including fuel use, was collected from an in vehicle CAN-bus sensor. Beusen et al. found that after the course that participants fuel consumption was reduced by an average 5.8%, signifying the effectiveness of the training course. Additionally, Beusen et al. found that this effect was remained six months later at the end the monitoring period, leading to the suggestion that the savings induced as a consequence of the course were permanent. Following concerns over the validity of this finding, the data collected by Beusen et al. was reanalysed by Degraeuwe and Beusen (2013), with an additional factor added to the analysis, ambient temperature. Ambient temperature is inversely correlation with fuel economy, as temperature rises as occurs during summer months, fuel consumption falls. As the training course was typically offered to drivers in March and June, ambient temperature was rising. Upon reanalysis, accounting for this effect, it was found that although the training course did significantly reduce fuel use upon initial training, this effect was not permanent and disappeared once ambient temperature was accounted for.

Despite evidence highlighting the benefits of eco-driving training, in terms of both fuel use and emission generation, studies have also indicated that the value of eco-driving education deteriorates over time. Geiler and Kerwien (2008, cited in Heyes et al., 2015) explored the impact of an eco-driving training course and found that despite an initial fuel saving of 7% as a consequence of driver attending the course, in a follow up examination 10 months later, this saving had dropped to 4%. Wahlberg (2007) reported similar deterioration in the impact of eco-driving training, specifically examining bus drivers. Wahlberg found that despite the initial success of an eco-driving training course, as indicated by a 6% drop in fuel use, during a follow up investigation 12 months later, it was found that the fuel saving had been reduced to 2%. Similarly, Zarkadoula, Zoidis and Tritopoulou (2007), also investigating bus drivers, found that following an eco-driving training course, overall fuel usage dropped by 10.2%. Zarkadoula notes however this figured had dropped to a 4.35% saving compared to initial fuel use just two months after the course. Similar declining results following an eco-driving intervention were reported by Lai (2015), exploring financially incentivised bus drivers. Although drivers received a monetary bonus for achieving greater fuel efficiency, it was found that the impact of the eco-driving course rapidly declined, even though the incentive scheme remained active. These studies suggest that whilst eco-driving courses do promote fuel-efficient driving and can induce a long-term fuel saving, it is apparent that individuals reintroduce habitual non-eco friendly driving behaviours following the course. Although an overall reduction in fuel usage remains, it is clear that these are much lower than would be expected based on impact of the initial training. These findings suggest therefore that training is insufficient to produce permanent changes in behaviour.

FEEDBACK AND ECO-DRIVING

Providing drivers feedback regarding their current driving and educating them about alternative driving styles has been seen as essential in eliciting long-term changes in behaviours (Tulusan, et al., 2012). It may be that many drivers would adopt an eco-driving approach if they had greater awareness and understanding of the impact and consequences of their current behaviour (Abrahamse, Steg, Vlek, & Rothengatter, 2005). Froehlich et al. (2009) describes eco-feedback technologies as “*technology that provides feedback on individual or group behaviours with a goal of reducing environmental impact”*. Abrahamse, et al. (2005), in a review of literature concerning personal energy use, identified a variety of factors that influence motivation to engage in eco-friendly behaviours. It was noted that whilst commitment was a key factor, feedback regarding current behaviours was an important variable of note. Specifically examining transportation, Froehlich et al. (2009) and Meschtscherjakov, et al. (2009) argue that providing feedback is a cost efficient way to encourage and reinforce eco-driving practices.

The impact of driver feedback has been demonstrated across a variety of situations and research studies. Lauper et al. (2015) following a longitudinal questionnaire study argued that feedback is essential in maintaining drivers ability to regulate their behaviour and encourage future behavioural implementations. Tulusan, Staake and Fleisch (2012), explored the impact of eco-driving feedback on the fuel use of cooperate drivers, comparing the fuel efficiency of two independent groups of drivers, either with or without access to the smartphone application DriveGain. DriveGain provided live feedback to the driver, including appropriate time to change gear, appropriate speed for the road and route and measure of appropriate breaking. Encouraging eco-driving behaviours within corporate drivers is an important initiative as whilst the average private car drivers travel 8,500 miles a year, corporate drivers travel approximately 21,500 miles (Tulusan et al., 2012). Participants had access to the application for eight weeks, but were free to choose when they wished to use the application. Use of the application was not enforced within the study to encourage more naturalistic results. It was found that of the participants who had access to the application, fuel economy improved by approximately 3%, compared to the control group. These findings are in line with other studies exploring the benefits of eco-driving schemes (Boriboonsomsin, Vu & Barth, 2010; Geiler & Kerwien, 2008; Mensing et al., 2014), despite investigating a population of drivers who would not financially benefit from changing their driving style. Importantly, this study offers clear indication that drivers can adopt eco-driving, without the need for financial incentives when provided with feedback.

Evidence that eco-driving behaviours can be encouraged without financial incentives suggest that drivers have motivations to adopt more environmentally friendly behaviours beyond financial. Dogan, Bolderdijk, and Steg (2014) argue that due to the relatively small economic savings incurred as a result of eco-driving, drivers may consider the required effort to outweigh the benefit. Dogan et al. argue however, that the environmental saving message could overcome this perceived effortful behaviour due to a fundamental motivation to make a positive impact. Dogan et al. draw upon the work of Heyman and Ariely (2004) and suggest that fundamental differences in motivation, monetary, a financial reward, or social, a concept of having a positive impact on society and the environment, can be considered to encourage eco-driving behaviours. Dogan et al. presented an eco-driving questionnaire to 305 respondents, who received either financial, environmental or no information about the impact of a series of driving scenarios, for example waiting at a railway crossing and driving with inadequately inflated tyres. When considering the value eco-driving behaviours, it was found that respondents presented with environmental feedback viewed the benefits for adopting eco-driving behaviours as significantly greater than respondents presented with financial or no information. Similarly, respondents presented with environmental information gave greater indication that they would be willing to change their current behaviour in response to the feedback than participants presented with financial information. Although both types of feedback were effective at encouraging eco-driving responses, Dogan et al. noted that environmental feedback resulted in stronger intentions to change. Taken together with the work of Tulusan et al. (2012), it is clear that the intention to make a positive environmental impact can be sufficient to motivate the intention for behavioural change, beyond financial gain. This suggests that a variety of motivations should be addressed when considering ways to encourage the adoption of eco-driving. Central to encouraging this behaviour change, however, is the adequate provision of feedback.

 As discussed previously (Tulusan et al., 2012), the use of in-vehicle visual feedback, provided by a smartphone application, has been demonstrated to be effective in encouraging the uptake of eco-driving behaviours. In this way, eco-driving feedback can be provided with minimal initial expense, and does not require extensive vehicle modifications. Visual feedback can be a valuable, as well as low cost approach to encouraging eco-driving behaviours (Froehlich et al., 2009; Meschtscherjakov et al., 2009; Tulusan et al. 2012). Evidencing the value in visual displays for eco-driving feedback, van der Voort, Dougherty and Maarseveen (2001) presented participants in a driving simulator with visual feedback regarding their current driving style. They found that provision of visual feedback was able to reduce fuel use by 16% compared to everyday driving. Interestingly however, they also found that just asking participants to drive in a fuel efficient way lead to a 9% fuel saving, suggesting that active reminders can dramatically reduce fuel use. Building on these findings, it is unsurprising that visual feedback regarding driving style is increasingly built into newer, high specification, production automobiles. As an example, Honda has begun to implement a speedometer that changes colour based on vehicle performance and the rate of acceleration (Azzi, Reymond, Merienner & Kemeny, 2011). Visual feedback is advantageous in that it can often be more detailed than haptic or auditory information, and can be further enhanced via the use of symbols and agreed upon colour coding, for example the idea that green is associated with positive and red associated with negative outcomes is a cross cultural standard (Madden, Hewett, & Roth, 2000). Due to the potential of different symbols, it should be possible to provide personalised feedback in order to target effective motivational messages to different individuals based on whether they are monetarily or socially motivated (Heyman & Ariely, 2004; Dogan et al., 2014). Young, Birrell and Stanton (2009) developed a visual feedback interface to encourage the uptake of eco-driving behaviours. The interface, which provided visual feedback was developed following a combination of Cognitive Work Analysis (Rasmussen, 1986), applied to eco-driving (Birrell, Young, Jenkins & Stanton, 2012) and user questionnaire feedback. Despite Young et al. (2009) identifying significant development opportunities following user tests, it was clearly seen that visual feedback benefited participants by providing information relating to current driving style and providing useful eco-driving information.

Despite the advantages offered by visual eco-driving feedback, a fundamental limitation of visual feedback is that it can be inherently distracting (Azzi et al., 2011). As a consequence of diverting drivers’ attention from driving, visual feedback devices can potentially negatively impact driver safety, for example by impairing their ability to detect potential hazards (Recarte & Nunes, 2003). A driver cannot concurrently examine both the ever-changing road situation and the visual feedback (Young, Regan, & Hammer, 2007). This is true even for head up displays (HUDs) whereby the driver does not have to actively look away from the road. Issues relating to information focus, whereby the user examines the displayed information rather than the dynamic environment in which they are traveling has been well documented in other transportation sectors with a history of HUD use, for example aviation (Crawford, & Neal, 2006). Specifically within the automotive domain, Summala, Lamble, and Laakso (1998) found that attending to panel displays significantly impaired driving performance and reaction times. This is especially apt when considering traveling at higher speeds, for example during motorway, freeway and autobahn journeys and could have significant safety implications.

Kircher, Fors, and Ahlstrom, (2014) argue that in order to be an effective tool and modify behaviour, feedback must be inherently distracting. When this positioning is accepted, the issue is less whether feedback is distracting, but rather becomes how and when feedback information should be made available to the driver. Kircher et al. investigated, within a driving simulator study, the time drivers examined a visual feedback device and found, as would be anticipated, that participants spent significantly longer examining the device when feedback was shown, and largely ignored the device when no feedback information was displayed. They note however that the time drivers spent examining the feedback device may be artificially inflated in a driving simulator study compared to the real world. Participants are aware of the study, are operating within an artificial environment, with significantly reduced risks and do not have access to other potential distractors which they may have in the real world, including the radio, access to refreshments and other on-board systems. Kircher et al. suggest that research is needed to identify when the most appropriate time would be to provide feedback to the drivers, for example under what traffic conditions and at which navigational points of the journey to both inform the driver and minimise potential negative distraction effects. Davidsson and Alm (2014) note however that this is not a simple task as different drivers have different needs based upon their current driving context and previous experience, and as such feedback systems need to not only adapt to drivers current actions but also their long term needs. Rouzikhah, King and Rakotonirainy (2013) explored the impact of visual eco-driving feedback, as presented in text form, on participant perceived workload, during a series simulated drives. Rouzikhah et al. (2013) compared baseline driving, with no secondary task, driving with access to eco-driving feedback, driving whilst changing a CD and driving whilst being required to enter navigation information. Rouzikhah et al. (2013) found that although there were significant differences in participants’ perceived workload between changing a CD and entering navigational information compared to the baseline task, participants did not report an increased workload when examining the eco-driving feedback. Rouzikhah et al. notes that although both changing CD and entering navigational information tasks were more physically demanding, leading to increased physical workload within these scenarios, the eco-driving message should have increased cognitive demand. Examining the data generated within the simulator revealed however that participants did not appear to alter their driving style following provision of the eco-driving feedback, suggesting that although the eco-driving message was not distracting, it was not cognitively engaging enough to modify behaviour. This finding supports the work of Kircher, et al. (2014) who suggests that feedback must be inherently distracting to encourage behavioural modification.

An alternative use of real time visual feedback is to offer post journey advice. In addition to providing drivers useful real time eco-driving advice, smartphone applications can be used to provide drivers with a detailed breakdown of their journey statistics, including fuel use and emissions. This technique gives drivers access to extensive post journey feedback, which can be compared across multiple journeys. Husnjak, Forenbacher and Bucak (2015) used a smartphone application to measure fuel use and CO2 emissions for both a standard drive and a drive whereby eco-driving techniques were employed. Although the application did not provide in-journey advice, Husnjak et al. found that, on a single repeated route, fuel consumption was reduced by 23% and CO2 emissions was reduced by 31% as a consequence of seeing information related to the previous journey. By considering this improvement, it may be that encouraging awareness of the presence of the feedback device results in a social facilitation effect (Allport, 1924) whereby drivers feel under observation and hence improves fuel performance. The long-term facilitative impact of these devices has however been questioned. Rolim, Baptista, Duarte, Farias and Pereira (2016) compared the change in performance of a group of 40 drivers, who either had or had not received weekly feedback relating to their driving style and fuel efficiency following extensive monitoring. They found that rather than improving drivers’ fuel economy, the feedback reports reduced fuel efficiency, with the drivers displaying a higher number of accelerations and a greater number of overall journeys, especially shorter journeys of less than 2 kilometres. Rolim et al. (2016) found that although negative feedback would trigger subsequent improvement in driver behaviour, the opposite was true when participants received positive feedback, with drivers failing to maintain their improvements and reverting to previous habits. This suggests that rather than just providing feedback, drivers must be active agents and desire to achieve maximum fuel economy from their vehicle. Building on this approach, multiple online communities have developed, for example ecomodder.com and fuelly.com which actively encourage members to share their current fuel economy statistics and techniques with others, actively encouraging competition and fostering social facilitation.

ECO-DRIVING FEEDBACK IN OTHER SENSORY MODALITIES

Despite the potential of visual feedback, eco-driving feedback has been successfully provisioned in other physical modalities, primarily haptic or touch based feedback. Building on Wickens’ (2002; 2008) multiple resources theory, Van Erp and Padmos (2003) suggests that driving is fundamentally a visual task, and notes that providing feedback in the form of other sensory modalities may be informative enough to impact behaviour but not sufficiently distracting to reduce performance. Haptic feedback within automotive vehicles is most commonly realized by applying a resistive force to the accelerator pedal. Haptic feedback utilizing the accelerator pedal has been trialled as both a form of speed management (Adell & Varhelyi, 2008) and as a method for encouraging eco-driving (Azzi et al., 2011). Larsson and Ericsson (2009) installed haptic force feedback into four postal delivery service vehicles. They found that the maximum acceleration force drivers’ applied to the pedals was significantly reduced. As accelerator force is a significant predictor of fuel usage and emission, this suggests that haptic feedback can be a valuable tool in supporting eco-driving. Adell and Varhelyi (2008) installed Active Accelerator Pedals (AAPs) into 281 test vehicles to examine the impact of haptic feedback on speeding. The AAPs provided a counterforce to the drivers’ effect of acceleration as they approached and exceeded the speed limit. AAPs were active within the installed vehicles for between six months and a year whenever the vehicle was within the designated test city and could not be turned off. Participants completed questionnaires at the start and end of the investigation, whereby demographic details were collected and their attitudes towards the feedback devices assessed. It was found that participants opinions of the AAPs were largely positive with 79% rating the device as “Good” or “Very Good”, however drivers’ participants’ driving enjoyment of driving was reduced whilst using the AAPs, and drivers reported that individual journeys took longer to complete. Participants noted however that they had a greater awareness of safety and travelled at lower speeds during the study, suggesting that the AAP had achieved its primary goal of decreasing road speed. Interestingly, despite the positive self reported results, it was found that only 35% of the participants would be willing to pay to keep the device once the study was over, suggesting that despite perceived benefits, generally users were not willing to financially invest into the system. Adell and Varhelyi note that the participants found the AAP *“useful but not satisfactory” (P50)* suggesting that hurdles to adoption were still present, as demonstrated by participants’ lack of willingness to pay for the system. Nevertheless, this work does demonstrate the potential for haptic feedback in influencing drivers’ behaviour.

The influence of a haptic feedback pedal has been examined within studies focused on supporting eco-driving (Azzi et al., 2011; Birrell, Young & Weldon, 2013). Using an independent group design, Azzi et al., compared the efficiency of visual feedback, a haptic force pedal and a combined system to examine the most effective way to provide eco-driving feedback to drivers, based on fuel usage and emissions. Using a driving simulator, participants were required to drive a set route within a traffic-free urban environment. It was found that participants provided with feedback recorded significantly lower emissions than participants assigned to a control group provided with no feedback. Limited differences were observed however as a consequence of the type of feedback offered, suggesting that the haptic force pedal was as successful at reducing emissions as the visual feedback displays, without many of the associated disadvantages, relating to split attention previously discussed. It was found that the combination of haptic and visual feedback resulted in significantly lower emissions than visual feedback alone, suggesting that the haptic feedback was highly salient to the driver. These results suggest that haptic feedback would be advantageous in encouraging eco-driving behaviours. Birrell et al. (2013) also exploring haptic feedback, explored the impact of a vibration alert when excessive force was applied to the accelerator pedal. Within a repeated measures simulator study, participants drove a set route within an urban and extra urban environment, across three conditions. Participants were instructed to either drive normally, drive as fuel efficiently as possible or provided with haptic feedback from the pedal if they produced excessive force on the accelerator, presented as a vibrational alert. Birrell et al. found that across the three conditions, average speed and journey time did not significantly differ. It was found that although average accelerator position did not change across the conditions, the maximum accelerator force applied within the conditions did significantly vary. Participants applied less maximum accelerator force when asked to drive fuel efficiently and applied a lower still maximum force when provided with haptic feedback. As fuel usage and emissions are heavily correlated with accelerator force, this finding suggests that just asking participants to follow an eco-driving approach can reduce fuel usage and subsequent emissions. Furthermore, this study suggests that haptic feedback can be used to positively encourage eco-driving behaviours with no significant negative consequences to journey statistics including time taken.

Despite these encouraging findings, haptic feedback does have several notable disadvantages that could reduce acceptance and use. Adell and Varhelyi (2008) identified cost as a significant barrier, as, unlike visual feedback devices, which are typically low cost and easy to install, for example via the use of a smartphone application, haptic devices must be engineered and retrofitted to a vehicle at comparatively considerable cost. This retrofitting is further complicated when considering that not all older automotive vehicles are suitable for the adaption, potentially reducing uptake further. A second key limitation is the impact of driver comfort and potential strain that could result from the use of haptic feedback pedals. Jamson, Hibberd and Merat (2013), following a short simulator study suggest that over the course of prolonged journeys, drivers could experience fatigue and discomfort using a feedback pedal. Jamson et al. notes that further research is needed to explore the long-term effect of haptic feedback on driver comfort and the potential for adaption to the feedback. This comment is especially telling considering Adell and Varhelyi (2008) previous finding that the use of a haptic feedback pedal was seen to decrease drivers recorded comfort and enjoyment with driving following long term use. The short term exposure and limited sample within these studies however restricts the impact of these findings beyond a variable of interest in future research.

In addition to visual and haptic feedback, auditory feedback has been used to support eco-driving. One study to explore the impact of auditory feedback was provided by Zhao, Wu, Rong, and Zhang (2015) examined the role of generic and adaptive feedback, provided by a visual display and voice prompts in improving participants’ fuel efficiency. Participants were required, within a driving simulator study, to drive a route three times, either with no feedback, with generic eco-driving tips or with dynamic eco-driving tips, based on their previous actions. Zhao et al. found that participants achieved a 3.43% saving when presented with generic eco-driving reminders. When provided with dynamic feedback however, the fuel saving rose to 5.45%. These findings suggest that despite savings being possible based solely on creating greater awareness of eco-driving, personalization and direct feedback based upon drivers actual actions can be more effective. Despite the effectiveness of auditory feedback, research has primarily used this modality to support visual and haptic interfaces (Staubach et al., 2014)

As it has been seen, visual, auditory and haptic sensory channels have been suggested as potential sources of feedback to encourage the uptake and maintenance of eco-driving behaviours. Although evaluation of each feedback method has been undertaken, and comparison between two modalities has been considered, limited work has directly sought to compare the effectiveness of all three methods of feedback in a single study. This gap was considered by McIlroy, Stanton, Godwin and Wood (2016). Within a simulator study, the effectiveness of visual, auditory and vibrotactile haptic feedback was compared, both to normal driving behaviour and when the drivers were told explicitly to eco-drive. McIlroy et al. found that although simply asking participants to drive economically was sufficient to reduce fuel use, this effect was increased by the inclusion of the feedback devices. McIlroy et al. found that the increased fuel efficiency was largely a consequence of an increase in coasting behaviour, gently decelerating the vehicle over a greater distance reducing the need for breaking, which emerged within the feedback trials, but had not been part of the initial repertoire of behaviours which participants used when told to drive economically, suggesting participants were unaware of this prior to feedback provision. Regarding the effectiveness of the different feedback manipulations, it was found that visual feedback was the least effective at promoting fuel-efficient driving. Limited differences were however observed between the auditory and haptic, with both reducing fuel usage by similar margins. It was found however that when considering participants subjective ratings of the alternative feedback modalities, auditory feedback received the lowest ratings, suggesting that despite a similar effectiveness rating, the haptic feedback would be more readily accepted. Within a similar study considering multiple feedback modalities, Staubach, Schebitz, Koster and Kuck (2014) examined the impact of an eco-driving feedback device that utilised haptic and visual feedback to encourage greater coasting behaviours. Participants were required to complete four simulated drives with and without the feedback device, within both an urban (speed limit 50km/h) and rural (speed limit 70km/h) environment. Objective data was collected from the simulator relating to participants’ driving and subjective data was collected within a post scenario questionnaire. Staubach et al. found that, depending on scenario, a mean fuel saving of 15.9% - 18.4% was achieved using the feedback device, primarily as a consequence of reduced stopping and greater coasting. Although a fuel saving was identified, it was found that the feedback device remained distracting, with participants spending time looking at the visual aspect of the display and not the road environment. In addition it was found that participants often ignored the initial warning from the pedal, suggesting that the saving achieved could have been much higher had participants responded when prompted.

With rising evidence that the enactment of eco-driving behaviours can be of significant benefits both economically and environmentally, the question of how to encourage the long-term adoption of these behaviours is key. From the research presented it is clear that eco-driving can be encouraged by making drivers more aware of both the environmental consequences of failing to engage in an eco-driving approach, and also the financial benefits of following eco-driving techniques. Providing drivers with feedback regarding their driving habits does however appear central to the adoption of eco-driving behaviours. Understanding the best way, in terms of both the most effective and least distracting, to present this feedback to drivers, for example via visual, haptic or auditory feedback remains an open question.

CONCLUSIONS

 From the research reviewed, it is clear that that both overall energy consumption and associated greenhouse gas emissions from personal transportation can be reduced with the uptake of eco-driving behaviours (Barkenbus, 2010; Sivak & Schoettle, 2012). Eco-driving involves a variety of behaviours including gentle acceleration, anticipating traffic and reducing unnecessary idling. Eco-driving training however has been shown to have limited long term impact, despite encouraging initial fuel reduction, with research (Wahlberg, 2007; Zarkadoula, Zoidis & Tritopoulou, 2007) indicating that this effect is short term with drivers rapidly returning to their habitual behaviours. To counter this return to habitual behaviours, it is important to consider both individual motivations to eco-drive, including financial and environmental as well as provide feedback on current driving performance. Eco-driving feedback has been offered in a variety of modalities, including visual and haptic. Despite the advantages of feedback devices in promoting eco-driving behaviours, caution is warranted in their use due to the potential of driver distraction.

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