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Good vibrations: Using a haptic accelerator pedal to encourage eco-driving

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A B S T R A C T

This article presents the experimental analysis of an in-vehicle, vibrotactile eco-driving support system, focussed on encouraging maximisation of the coasting phase of the vehicle when approaching slowing or stopping events in order to take advantage of vehicle momentum. The simulator study assessed the effects of three different time-to-event stimulus timings (four, eight, and twelve seconds) on objective driving performance metrics, and on subjective measures of acceptance, ease of use, and intention to use. The shortest time-to-event had a marginally damaging effect on performance, and was not well received by participants. Both medium and long time-to-event stimuli performed well on subjective measures, and both facilitated increased eco-driving performance. The longest lead-time stimulus was the most effective, resulting in an 11% simulated fuel saving compared to baseline. Findings are discussed in terms of the importance of the timing of information, and regarding the need for longer-term research on the potential effects of system failure on performance and safety.

1. Introduction

The impact of transport on local and global emissions is well documented, and rising. In the UK, across sectors, total CO_2 emissions in the fourth quarter of 2014 fell 1.6% compared to the third quarter of that year; transport's emissions, on the other hand, rose by 0.3% over the same period (Department for Energy, 2015). In the UK, 27% of total greenhouse gas emissions can be attributed to transport. Of this figure, 58% comes from private cars and taxis (Department for Transport., 2011). Though there exists a wide variety of mitigation strategies aimed at reducing transport's environmental impact, this paper is concerned with just one; eco-driving (e.g. Barkenbus, 2010; Lauper, Moser, Fischer, Matthies, & Kaufmann-Hayoz, 2015).

Eco-driving is the over-arching term for the set of behaviours and driving styles that result in lower fuel consumption. Though training drivers to eco-drive has been shown to be successful (at least in the short term) in reducing fuel consumption, more attention has been paid to the encouragement of fuel-efficient driving styles through in-vehicle devices such as eco-meters or eco-driving support systems (e.g. Birrell & Fowkes, 2014; Birrell & Young, 2011; Kircher, Fors, & Ahlstrom, 2014; Stillwater & Kurani, 2013; Van der Voort, Dougherty, & van Maarseveen, 2001). The vast majority of eco-metres are visually based; that is to say they provide a visual indication of, for example, instantaneous power flow or miles per gallon

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(or litres per 100 km; e.g., Kim, Dandekar, Camez, and Harrelson (2011)). If one should follow Wickens' multiple resource theory, further burdening the visual modality in an environment that is already dominated by visual information (as the driving environment is) may lead to workload increases and subsequent performance decreases (e.g. Wickens, 2002). This has partly motivated the increasing trend in the investigation of haptics for in-vehicle information systems.

Haptic information, i.e., information acting on the sense of touch, has been applied to a number of in-vehicle systems, including safety (e.g. Deroo, Hoc, & Mars, 2013; Mulder, Pauwelussen, van Paassen, & Abbink, 2010), navigation (e.g. Van Erp & Van Veen, 2004), and eco-driving support (e.g. Hajek, Popiv, Just, & Bengler, 2011; Staubach, Schebitz, Köster, & Kuck, 2014). In a recent review of empirical research, Pejtermeijer, Abbink, Mulder, and de Winter (2015) concluded that in-vehicle haptics generally improve driver performance, for both warning and guidance systems; the current study therefore continues this research stream, focussing specifically on eco-driving performance, and in particular building upon work from Birrell, Young, and Weldon (2013) and Staubach, Shebitz, Köster, et al. (2014), and upon our own work in the area (McIlroy, Stanton, Godwin, & Wood, 2016).

Birrell et al. (2013) provided an investigation of a vibrotactile stimulus, presented through the accelerator pedal, for the encouragement of eco-driving. Participants were provided with a vibrational stimulus when they exceeded a 50% throttle depression threshold, beyond which was argued to be excessive for economical driving. Not only were excessive acceleration behaviours reduced under stimulus presentation conditions (argued to be positive for fuel economy), but the benefits were realised alongside decreases in subjective workload ratings in comparison to when drivers were simply asked to drive economically. Where Birrell et al. (2013) focussed on excessive accelerations, Staubach and colleagues looked at both acceleration and gear change behaviours, and compared both haptic information (in the form of force-feedback or counter pressure in the accelerator pedal) and visual information. In their earlier work it was found that the combination of visual and haptic information (compared to each individually) best supported idealised acceleration and gear shift behaviours, with the participants having preference for visual only information (Staubach et al., 2012). In a subsequent study, user acceptance of the system was again high (Staubach, Schebitz, Krehle, Oeltze, & Kuck, 2013). In this study the system provided information ahead of a slowing event (e.g. a road curvature), suggesting to the driver the optimal point at which to remove the foot from the accelerator pedal (Staubach et al., 2013). Indeed, this aspect of eco-driving, i.e., the anticipation of the road ahead in order to maximise the coasting phase of the vehicle ahead of slowing and stopping events (thereby minimising kinetic energy losses), has, in isolation, been shown to have a significant effect on overall fuel economy (Thijssen, Hofman, & Ham, 2014), and it was this aspect that provided the focus for Staubach and colleagues' subsequent work.

The term coasting, as used in this context, refers to the forward movement of the vehicle *without* depression of the accelerator pedal. When coasting in neutral (i.e., out of gear), the engine is still idling, consuming just as much fuel as when it's idling at standstill, whereas in almost all modern vehicles there is no fuel injected when coasting in gear. The engine is turning over, so technically it is running, but it's not consuming any fuel (which is true for both automatic and manual transmission). In Staubach, Schebitz, Fricke, et al. (2014) the timing of the coasting advice (i.e., the distance ahead of the event at which information was presented) was investigated, with a two-stage process being tested. In the first stage the information was provided at the time when coasting in neutral (with deceleration caused only by air and rolling drag) would have them come to a stop for a red traffic light. Should the participant have disregarded this advice, a second signal was provided at the point at which coasting in gear (therefore also including the effect of engine braking on deceleration) would have them stop at the correct time (i.e., at a later time point than for coasting in neutral). Though increased coasting phases were supported (compared to baseline) the earlier advice was not well received by participants, the reason for which was put down to the advice coming before the participant could see the reason for that advice, e.g. the traffic lights (Staubach, Schebitz, Fricke, et al., 2014).

Finally, in the study reported by Staubach et al. (2014) the system was further developed, this time including advice on the timing of gear changes. In this study the increased use of coasting in conjunction with the earlier gear changes resulted in fuel savings of 15.9 and 18.4% for urban and rural scenarios respectively. The system was generally well received; however, though acceptance of the timing of the coasting advice was not expressly investigated, some participants did state that the advice was presented too early (Staubach, Shebitz, Köster, et al., 2014).

Staubach and colleagues are not the only researchers to have investigated the possibility of supporting the coasting phase of the vehicle for fuel efficiency. Hajek et al. (2011) describe an active accelerator pedal doing just that, finding 7.5% fuel savings compared to baseline. Previous work of our own built on Hajek et al. and Staubach et al.'s research, and on Birrell et al.'s (2013) work, in a simulator study of eco-driving in which feedback was presented in various modes and combinations of modes (McIlroy et al., 2016). The work focussed on the act of coasting in gear and, in addition to receiving vibrotactile coasting advice ahead of slowing and stopping events (i.e., curves, traffic lights, stop signs, lower speed limits), the participants were also provided with an alert to discourage them from depressing the pedal beyond 70% of its travel (a threshold adapted from Birrell et al. (2013)). The vibrotactile stimulus, presented through the accelerator pedal, was compared with auditory and visual information of the same content, and all combinations thereof. These were all compared with baseline (i.e., no additional information) and with a condition in which participants were simply asked to drive efficiently (i.e., also no additional feedback). For almost all metrics (e.g. throttle position mean and standard deviation, fuel consumption, brake pedal standard deviation, time spent over 70% of throttle travel) performance significantly improved from baseline to when participants were asked to drive economically, but did not significantly change on the addition of the extra eco-driving advice. The distance spent coasting was the only variable that *did not* alter significantly when asking participants to drive econom-