



EcoSonic: Auditory peripheral monitoring of fuel consumption for fuel-efficient driving[☆]

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ABSTRACT

In this paper, we propose to make use of an *auditory* fuel efficiency display as means to support car drivers in adopting an energy-efficient driving style. We report on the development of the *EcoSonic* system as a platform for evaluating such displays and present five design approaches to guide their realization. In a study with 30 participants, we evaluated two prototype auditory displays against the baseline of visual-only eco-driving feedback in a within-subject study. Our selected designs are described in full detail. Key findings include a significantly reduced fuel consumption as well as lower engine speeds compared to the visual display. Furthermore, questionnaire analysis results confirm that the auditory conditions are *less obtrusive* and also seem to allow a more subconscious processing and comprehension of the provided information. Finally, we have found that the *effectiveness* of the display design seems to have a positive impact on its perceived helpfulness and the ability to absorb its information subconsciously.

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1. Introduction

Eco-driving is the use of energy-efficient driving techniques in order to reduce the energy consumption when driving a car. Existing research highlights a range of opportunities and benefits that are associated with adopting such a driving style: First, as the energy consumption and pollution that is produced by both conventional and electric cars is one of today's major causes for greenhouse gas emissions [1], an energy-efficient driving style will have a major impact in terms of alleviating the negative effects of climate change [2]. Even more, contrary to current advances in building more and more efficient engines, eco-driving does not necessarily require to buy a new car, but can be applied to any existing vehicle. Furthermore, eco-driving is becoming even more important with hybrid and electronic cars, as the driving style has an even greater impact on energy consumption when compared to conventional combustion engines [3]. Finally, fuel-efficient driving generally also leads to a safer driving style [4] and can be done without a huge impact on trip time [5].

However, despite these advantages, the behavior change towards adopting these techniques poses to be a challenging one: Currently, there exist a number of visual fuel efficiency displays providing feedback on instantaneous or long-term fuel

economy to support the driver in achieving a lower level of fuel consumption [6]. Observing these displays, however, requires a cognitive effort and can easily distract the user from the actual driving task and thus be detrimental to a safe steering of the car [7]. This is especially problematic insofar as it is precisely in situations when drivers should keep their eyes on the road (e.g. when quickly accelerating or approaching a street crossing or traffic light) that the information from such a display becomes most relevant. Contrary to that, *auditory* displays have shown to be able to convey information in a less distracting way: Preliminary research on in-vehicle auditory interaction already hints at a significantly reduced impact on attention [8] as well as an improved effectiveness in terms of user performance [9], which is also supported by psychological research on multiple resources theory and dual task interference [10].

Although, taken together, this clearly supports the notion of an *auditory fuel efficiency display*, no evaluation of the efficacy and acceptance of such a system has been conducted before. The research presented in this paper fills this specific research gap and confirms preliminary findings concerning auditory in-vehicle interaction.

2. Related work

While to our best knowledge, there is no research specifically studying the use of an *auditory* display for feedback on fuel

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consumption, the topic of eco-driving as well as the evaluation and comparison of *visual* fuel economy displays is well-covered in literature. Furthermore, more and more work is being done on the use of in-vehicle auditory displays in general [11] as well as for specific use-cases, e.g. collision warnings, skill acquisition, or in-car entertainment systems.

2.1. Efficacy of eco-driving

Although the findings for the precise amount of achievable reduction of fuel consumption vary to some degree, there already exist a number of studies evaluating the efficacy of eco-driving, which, taken together, clearly indicate a significant positive impact of eco-driving techniques.

Gonder et al., for example, evaluated the potential fuel savings that can be achieved by implementing different efficiency strategies while driving [12]. Using real-world data from trips collected with GPS devices and a vehicle model of a midsize car, they performed extensive simulations in order to assess the potential savings from specific behavior changes as well as the prevalence of inefficient (or: sub-optimal) driving. They conclude that for aggressively driven trips, the adoption of efficient driving behaviors can result in fuel savings of approximately 20% and even for more moderately-driven trips, a 5–10% reduction of fuel consumption is realistic.

In a recent study conducted by Sullman et al., a driving simulator was employed to train professional bus drivers in using eco-driving techniques [13]. By using consumption data provided by bus companies, they found out that six months after the training, fuel economy had improved by 16.9%.

2.2. Distraction by in-vehicle systems

As the number of in-vehicle systems that are available to drivers is steadily increasing, there is a justified apprehension that these systems might cause considerable distraction and reduced driving performance, which in consequence could lead to an increased prevalence of traffic accidents. Several researchers have thus tried to quantify the effects of existing in-vehicle systems and find out the type of interaction that might best be used for those systems in order to alleviate the risk of distraction. For example, in a study with 23 participants, Lansdown et al. evaluated in which way distractions from in-vehicle information systems affect drivers [7]. The participants had to drive a test track in a driving simulator and were presented with simultaneous visual tasks, representing the interaction with additional in-vehicle systems. The researchers found out that those tasks led to significantly reduced headways and increased brake pressure. Additionally, they observed compensatory speed reductions and an increased self-reported workload. Taken together, the authors see these results

as evidence for a clear safety risk when using visual in-vehicle information systems.

On the other hand, there have been studies that hint at the advantages of employing the auditory channel: Jensen et al. conducted a study evaluating the impact of navigation systems on driving performance [8]. They compared different audio-visual output configurations for the system and found that a visual-only output not only led to a considerable amount of eye-glances, but also to a significant decrease in driving performance. While a user questionnaire indicated preference for an audio-visual configuration, the audio-only navigation system performed best in terms of those two aspects.

2.3. Comparison of existing eco-feedback systems

As there already exist a few (mostly visual) systems to provide feedback on eco-driving performance (also cp. Fig. 1a), a number of studies try to assess and compare these systems in terms of efficacy and user acceptance. Tulusan and colleagues conducted a questionnaire survey and several semi-structured interviews in order to learn more about which eco-feedback types might be preferred most by car drivers [15]. The authors learned that a comparison with an average consumption (e.g. of other drivers) seems to be beneficial for drivers to assess and better understand what could have been saved through a more ecological driving behavior. They also point out that most preferable were *unobtrusive* systems, which do not pose any additional workload (and frustration) for the drivers.

Jamson et al. compared the effectiveness of different configurations of either haptic, visual, or audio-visual eco-driving interfaces which provide feedback on a predetermined optimal accelerator pedal angle [16]. While the emphasis of the study was primarily on using a haptic accelerator pedal, the authors point out that for visual displays, the inclusion of complementary auditory feedback not only improved eco-driving performance, but also lowered visual distraction.

Finally, in a driving-simulator study, Hellier et al. evaluated how different levels of engine noise affect the driving style and perceived comfort [17]. They found out that low levels of engine noise led to increases in driving speed and more traffic violations. Surprisingly, the low-noise feedback conditions were also associated with a decrease in driver comfort. The authors conclude that auditory feedback plays a major part in the ability of a driver to make judgements and choices about speed.

2.4. Auditory in-vehicle interaction

While auditory interaction has long played a very minor role for use in automobiles, there recently has been considerable work towards using the auditory modality for in-vehicle interaction [11].

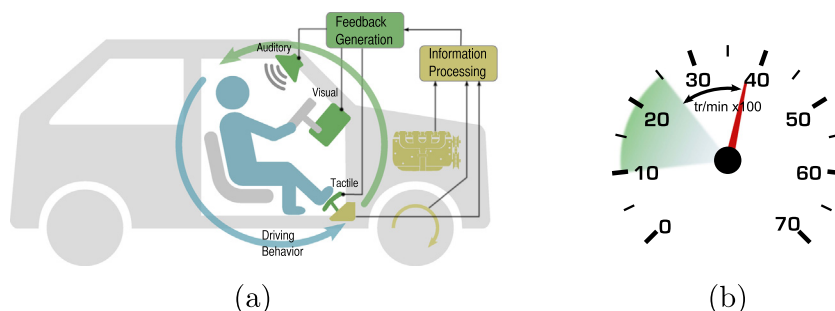


Fig. 1. (a) Feedback loop for an eco-driving display [14]. The driver controls the (acceleration of the) car, which in turn controls the feedback display. The feedback can be generated in visual, auditory, or tactile ways, and gives supports in improving driving behavior. (b) Picture visualizing the basic idea of the metaphorical sonification display concept.

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