How to Support Fuel-Efficient Driving?

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Abstract: Energy efficient personal transportation requires fuel-efficient and route aware driving. Driving coaching systems can provide to drivers all the information and guidance that is needed to learn these skills. However, persuading drivers to change their driving behaviour is a challenging task. We identify functional, design, safety, and persuasive features for systems supporting fuel-efficiency. Moreover, we analyse how these features are supported by state-of-the-art systems targeting reduced fuel consumption. Finally, based on our analysis, we discuss open issues and opportunities for future development of fuel-efficiency support systems. The literature and the reviewed research in the present paper illustrate the needs for overall situation assessment and benefits of careful and multifaceted approach for systems design when it comes to eco-driving: an effective system will make use of a versatile design toolkit in order to obtain enduring behavioural results.

1. Introduction

Eco-driving aims to enable drivers to maximize on-road fuel economy of vehicles with the help of appropriate strategic (vehicle selection and maintenance), tactical (route selection and vehicle load), and operational decisions (driving behaviour) [1-3]. Both the research community and industry look for opportunities to support eco-driving, for example in the form of in-car assistant systems [4]. In addition, contemporary communication technologies provide diverse and flexible instruments to gather and analyse data for more fuel-efficient and safe driving [5]. Sensors worn on the body of the driver or embedded in the car, data from third party services, like spatial, weather or traffic information, all provide opportunities to gain a rounded view of a driver's situation. Analysis of this situation could potentially help drivers to better understand the consequences of their driving habits and the potential of behavioural change. In other words, such analysis supports reflection that can lead individuals to reconsider or even change certain attitudes and behaviours [6].

However, cultivating sustainable change in behaviour is difficult. Studies have demonstrated that it might be difficult to maintain and utilize knowledge about eco-friendly manoeuvres after training [7,8]. Therefore, solutions are required to support drivers in practicing eco-driving. For example, an earlier study has demonstrated that providing continuous feedback after initial eco-driving training can double long-term fuel-saving results [9]. In addition, context-related feedback can favourably influence driver behaviour, even without direct financial benefits [10].

Interactive information technologies designed to change users' attitudes or behaviour are called persuasive technologies [11]. By facilitating the desired behaviour and stimulating compelling experiences to effectively persuade users, persuasive technologies provide new possibilities for technical systems. These technologies create relationships through a variety of cues to establish trust and to support the desired change of user behaviour [12]. A coaching system that aims at sustained change in driving behaviour needs to draw on a systematic approach to system feature selection. By identifying the persuasive intentions, context and expected outcomes, it is possible to select those system features that best deliver the intended persuasive elements to the system users, in our case to drivers [11].

In this article, we consider tactical and operational decisions during driving as part of driving behaviour. As such, systems addressing strategic decisions, e.g. proper tyre pressure, are outside the scope of this article [1, 3]. Therefore, the contribution of this article is as follows: First, based on a literature review, it identifies a set of features for fuel-efficient driving support systems. Second, the article analyses how these features are addressed by recent research. Finally, based on this analysis, we discuss observed open issues and opportunities for future development of fuel-efficiency supporting systems.

The rest of the article is structured as follows: We explore how to deliver eco-driving information to the drivers in Section 2. Section 3 presents features for system supporting fuel-efficient driving and Section 4 analyses how these are addressed by state-of-the-art solutions. Discussion is conducted in Section 5 and the article is concluded with Section 6.

2. Supporting eco-driving

Supporting drivers with eco-driving information has been recognized as a complex task. For example, individual expectations of the systems' disturbance and risk affect the acceptance of technology and the behavioural intention to use it [13]. Moreover, drivers might have different attitudes and motivations towards eco-driving [8,14,15], hence personalization might be required [16].

There is a body of research that analyses different aspects of eco-driving support systems. For example, Vaezipour et al. [17] conducted a qualitative study to explore how to provide ecological and safe driving advice and feedback to drivers via in-vehicle HMI. This study aimed to gain an understanding of drivers' needs, their motivations and requirements, and concerns for use an eco-safe in-vehicle device. Some researchers focused their analysis on the user interfaces of systems supporting eco-driving. For instance, Meschtscherjakov et al. [13] conducted a survey to reveal user acceptance of different in-car user interfaces intended to improve economic driving behaviour. In their study, EcoSpeedometer-like user interface, which integrates a colour-based indicator about eco-driving into display, demonstrated high user acceptance. Jameson et al. [18] also investigated the effectiveness of eco-driving user interfaces. They used an eco-driving support system that advises the driver about the most fuel efficient accelerator pedal angle in real time, and explored different interface options: a visual dashboard display, a multimodal visual dashboard and auditory tone combination, and a haptic accelerator pedal. Strong force feedback system demonstrated better effectiveness amongst the haptic systems. Also, audio-visual information delivery was found to be potential but to require further investigation. Visual and combination of visual and auditory feedback preferences are reported by Tulusan et al. [19]. Similarly, Vaezipour et al. [17] found out that auditory, visual, or a mixture of both feedbacks is most preferred; moreover, they highlight the importance of enabling drivers to customize their feedback preferences.

Timing appeared to be important in delivering information about fuel-efficiency as well. For instance, Tulusan et al. [19] indicate that respondents prefer receiving feedback during driving or immediately after it. A number of findings are presented by Höltl and Trommer [4], e.g. in their analysis, on-trip applications were perceived more positively than others by respondents.

The semantics of the feedback plays a role as well. Mcllroy et al. [20] emphasize that proper feedback informing individuals about their progress in set driving-specific energy-related goals is crucially important. Tulusan et al. [19] reported that information about personal fuel consumption and potential savings is of great interest for drivers. Fors et al. [21] evaluated three different advice strategies for eco-driving systems for trucks in terms of perceived usefulness and compliance: continuous advice, intermittent advice, and a user-selected combination of both. Höltl and Trommer [4] conducted a Europe-wide study focusing on drivers' perceptions of cooperative systems offering assistance on fuel-efficiency. They explored different functions of advanced driver assistance systems (ADAS) in pre-trip, on-trip, and post-trip driving situations. Comparison to other drivers appears to be important also [19].

General surveys exist as well. EcoDriver project provides a comprehensive review of state-of-the-art systems for fuel-efficient driving [22]. There, the division is made in pre-trip, in-trip and post-trip systems. The largest number of identified systems belong to in-trip category and are generally implemented by automobile manufacturers. The most common system design approach relies on a visual interface, uses speed as the control variable (sometimes both speed and acceleration), and targets fuel consumption (and sometimes length of the journey and acceleration) as the outcome variable [22]. Vaezipour et al. [23] provided a review of the published literature on in-vehicle systems to identify and evaluate the impact of eco-driving and safety feedback systems. The review emphasizes the lack of research integrating both eco-driving and safety issues and there are open questions regarding the acceptance of in-vehicle systems supporting driving. Another review was conducted by Mcllroy et al. [20] who bring together various aspects like the effect of the design of a technological object on behaviour, the inter-related nature of goals and feedback in guiding performance, the effect on fuel economy of different driving styles and the various challenges brought by hybrid and electric vehicles. Moreover, researchers argue for the usefulness of implementing Ecological Interface Design approach, considering the system in its entirety by taking into account the inter-relatedness of the system components and functions, for in-vehicle interfaces to encourage fuel- and energy-efficient driving [20].

3. Features for systems supporting fuel-efficient driving

König [24] emphasizes that a driver assistance system should be transparent to the driver, predictable, and meet the driver's expectations. Moreover, such a system should be simple to use and learn and have limits which are clear and well communicated to the driver [24]. Clearly, the exact feature set depends on the goals and purpose of the system.

This article focuses on systems supporting drivers in fuel-efficient behaviour. Based on literature analysis, we selected features found to be important for such systems [20, 22,24], because they define the eco driving outcome. The feature set presented in this article is collected from the driver's perspective, therefore, technical requirements are omitted. To guide the selection of features, we asked 1) which information is used by the system to form the decisions, how the feedback is delivered to the user, and 2) if the system is able to assess overall situation and evolve with the driver progress. These allowed us to explore the general functionality and opportunities of the system [25]. Such features are collected under *Functionality* category in the present study. Along with functionality, analysis of the actual design is important [20], and we explored interface design and target platform for the system: are reflection and knowledge creation supported by the design, and what kind of study was conducted to establish these factors. We group these aspects under *Design* category. A third grouping in the present paper is *Safety*. We identified a potential gap in the existing literature which suggests that safety has not been addressed extensively within the eco-driving domain [23]. Therefore, we explore if eco-driving systems consider measures to reduce distraction, if they are able to assess the safety factors in the type and timing of feedback so as to ensure complete driver control at all times. Finally, knowing that changing driving behaviour towards fuel-efficient driving is difficult [7, 8], we were interested in exploring what methods are used to support behaviour change towards eco-driving. In our analysis, we utilize Persuasive Systems Design (PSD) model [11], found to be useful in many different domains, including transportation [26]. Using the PSD framework as a tool for analysis, we explore how a system can help a driver to improve his or her fuel economy, does the system demonstrate credibility so that users can trust its comments, what kind of social support is available. These features are grouped under *Persuasive* category. Through these four feature groups alongside the features more commonly presented in related work, such as modality and timing of feedback, the present analysis brings in context-awareness, persuasion, and safety. The presented scope allows us to analyse how eco-driving systems assess the overall situation and prompt fuel-efficient behaviour. A system accomplishing its goal to help to save fuel is taken as a given in the present study, and therefore, we do not emphasize this separately.

3.1. Functional features

Functional group gathers functionality that is considered necessary for systems supporting eco-driving to provide the targeted services with the targeted quality. Under functional features, we include data fusion and analysis, feedback provisioning, context-awareness, personalization, and adaptation to the progress.

Data fusion and analysis. Today's technologies enable acquiring diverse information from a vehicle, a driver, and the environment. Therefore, assessment of the overall situation is possible. Based on data fusion and analysis, the system is able to achieve more accurate conclusions regarding fuel savings strategies and to provide adequate feedback to the driver.

Feedback provisioning. An eco-driving support system must provide feedback to the driver. Such feedback can be delivered before the trip, during the trip, or after the trip [4, 19]. Moreover, different modalities can be used, like visual, audio, haptic and their combinations [19]. Also, feedback may have different semantics, like general comments or fuel and money saving comments based on predictive modelling [15, 25]. Finally, we consider thorough analysis of the driven trips to be beneficial, even though such analysis is mainly available in post-trip systems [25].

Context-awareness. To provide relevant feedback about a trip, a driving assistant system should capture and understand the overall situation a driver is in. The situation is determined by diverse information, like vehicle and environment information, traffic status, driver-related information (e.g. health limitations or preferences). Such information, characterising the situation can be generalised as context and applications which use context to deliver relevant information or services to their users are called context-aware [27, 28]. We consider context-awareness a desired feature for a driving assistant system, as it enables system adaptation to the driving situation and provisioning of more relevant guidance. For instance, driving in severe weather conditions cannot be evaluated similarly as driving in normal weather conditions.

Personalization. Drivers are different as they have different experience, preferences, and skills. Therefore, solutions are required to identify personal factors affecting fuel efficient driving. Moreover, the feedback and guidance of such a system should match the driver's profile.

Adaptation to the progress. An eco-driving support system should alter its goals and decision-making according to the driver's progress, so that recommendations are always adequate and realistic for the driver.

3.2. Design features

Design group emphasizes features related to the interaction aspects of eco-driving systems. Under design features, we include usability, human-machine interface, reflection and knowledge, and form factor.

Usability. As any other assisting system, an eco-driving support system should be predictable and meet the driver's expectations [24]. An eco-driving support system should support fundamental features of effectiveness, efficiency and satisfaction [29, 30]. Furthermore, more fine-grained usability attributes include learnability, efficiency, memorability, faultlessness, and satisfaction, as indicated by Nielsen [31].

Human-machine interface. An eco-driving system may present information in different modalities: visually, audibly, or haptically [19, 24]. Both specialized displays and large graphical displays [32] can convey eco-driving information to the driver. Moreover, various input devices (such as touch-screens) can be used to obtain the driver's response to the eco-driving information, therefore, supporting interactivity.

Reflection and knowledge. An eco-driving system can support reflection and knowledge creation. Aspects such as supporting the progress of the driver, identification of areas that may require improvements, gaining knowledge about own driving (in relation to tacit knowledge) are important to build a system with effective eco-driving intervention [33, 34]. Moreover, providing guidelines during the trip may contribute to the overall situation awareness of the driver [33]. Comparison with prior knowledge, the user's knowledge of prior operation, his/her training, and experience are relevant to promote eco-driving behaviour [24], and thus, have to be supported. The system can account for overall knowledge-based decision making [35], related to planning, performance and evaluation of driving. The system can provide situation analysis, explain driving behaviour and compare the behaviour with previous instances. Moreover, an eco-driving system can support reflection-on-action and/or reflection-in-action [6, 36]. The former means post-activity thinking of behaviour, and the latter, in its turn, refers to reflection that takes place during an activity. Both types of reflections are effective, as reflection endorses high elaboration of persuasive content, which is likelier to lead to more sustained behaviour change [37].

Form factor. An eco-driving system can be a part of the original equipment of the vehicle, it can be designed for retrofitting existing vehicle, or provided with the custom hardware device or application running on a universal device like a mobile phone. Form factor may affect who uses the system and how, e.g. teenagers might be more willing to use the application on a mobile phone, when senior drivers could feel more comfortable with proprietary vehicle solution.

3.3. Safety features

Safety group collects features ensuring that an eco-driving system does not behave in a potentially dangerous manner. Safety is a common parameter for evaluation eco-driving support systems [38, 39]. In this article, we concentrate on interaction functionality of the system, therefore, technical implementation and prevention aspects of hardware and software faults are omitted. For more information about the safety in driving assistance systems in general, please refer to [40]. Under safety features, we include attention and distraction, safety is the number one priority, driver is the one who has the control.

Attention and distraction. Driving is considered to be a complex activity. Eco-driving-related feedback can be distracting and can lead to missing important events while driving [41], therefore, the feedback should be clear and easily interpretable [42, 43]. This is a vital requirement for systems providing feedback while driving, as driver distraction is considered to be a major problem in terms of road safety [44].

Safety is the number one priority. A driving assistant system should not give rise to potentially hazardous driver behaviour, e.g. suggesting speeding in inappropriate situations [24]. This generally means that the system should be able to recognise the overall situation and recommend an action according to the safety regulations. Again, this requirement is vital for the systems providing guidelines during a trip.

Driver is the one who has the control. Balancing control between users and the system is an important issue for assistant applications [45]. If an eco-driving support system utilizes a control input to the vehicle, it must allow the driver to overtake the control anytime [46].

3.4. Persuasive features

Persuasive group covers aspects related to changing the behaviour of the driver. Using the Persuasive Systems Design (PSD) model [11], a number of design principles were identified for systems supporting eco-driving. Persuasive aspect of eco-driving is crucial for the long term effect of the intervention [47]. The summarized set of persuasive features (listed under their PSD model categories) includes features that based on general aspects of driving context and eco-driving system goals are deemed most relevant. See Appendix section (Tables 1, 2) for explanation of the features. For best effects and promotion of behaviour change, a system should only use a carefully selected set of persuasive features instead of too many.

Primary task support. A persuasive system should support users in their primary tasks. In the case of fuel-efficient system support, the system should help a driver to improve his/her driving to save fuel. We consider reduction, tunnelling, tailoring, personalisation, self-monitoring, and simulation relevant for systems supporting eco-driving (Appendix, Table 1).

Dialogue support. Obviously, a persuasive system should provide feedback to the user. Here, we concentrate on principles related to implementing the HCI for driving coach systems helping users to move in their goals or target behaviour in fuel efficient driving: praise, rewards, suggestion, similarity, and social role (Appendix, Table 1).

System credibility support. Credibility helps a user to trust a system, and therefore, facilitates accepting of the guidelines provided. All the features listed in PSD model are considered here [11] (Appendix, Table 2).

Social support. This category presents principles devoted to system design motivating users through leveraging social influence. Social support seems to be important in systems supporting eco-driving [19]. All the features listed in PSD model are considered here [11] (Appendix, Table 2).

4. State-of-the-art analysis

To review how driving assistant systems supporting eco-driving address the features presented above, we searched relevant literature with IEEE Xplore, Scopus, and Science Direct digital libraries, and with the Google search engine. Examples of the key-words used for the search are: "eco-driving system/application", "fuel-economy system/application", and "driving assistant". We focus our analysis on systems published not more than five years ago (i.e. at the moment of paper submission - 2011 or later). We were interested in actually implemented systems presented in sufficient details, therefore, studies focused on theoretical aspects of fuel-efficient driving were omitted from the review. The feature selection was based on the outline of important eco-driving factors presented in Section 3. We ended up with nineteen articles satisfying these selection criteria. Some articles demonstrate coaching systems [25,48,49], others provide instructions during a trip [47, 50, 51], and still others provide control input to a vehicle [46,52]. Our analysis is summarized in Appendix section, Table 3. The abbreviations used are explained below the table.

4.1. Functional features analysis

We analyse what kind of information is used by the system for decision-making (DFA), when the feedback is provisioned (FP), what type of feedback is delivered (FT), whether the system is context-aware (CA), and whether the system adapts to the driver (AS), for details, refer to Appendix, Table 3.

Data Fusion and Analysis. The analysed systems used diverse data for decision-making. For instance, almost all use on-board diagnostics to collect driving behaviour related data, like speed. GPS is widely used to get the route driven. However, few systems retrieve advanced information about the route itself [25,53,54]. Traffic information is considered very important as well. Some systems retrieve this information from third party services like [25], or crowdsource from other vehicles [53], others don't use this information directly, but assume that a traffic situation depends on the day of the week and time of the day [55]. Surprisingly, only two systems use weather data for decision-making [25,53], although weather may have impact on driving behaviour, and consequently, on fuel-efficiency. Use of cameras appeared to be important as well, e.g. for detecting traffic signs and lights [50,53]. Only Magaña and Muñoz-Organero [53] utilize traffic incident information which is crowdsourced from vehicles under similar conditions.

Feedback provisioning. Majority of the analysed systems provide feedback during the trip, e.g. [47,56 - 58]. Indeed, real-time feedback is considered to have the advantage of supporting experimentation with new behaviours, as the results of actions are immediately seen. Moreover, such feedback can motivate for short periods of high achievement, and support learning fine control over the vehicle using the feedback as a guide [59]. On the other hand, post-drive systems have larger opportunities in trip analysis and in providing the feedback to improve driving skills [4]. Therefore, systems providing feedback after the trip (e.g. [25, 53, 54]) demonstrate coaching characteristics, reflection and knowledge support (Appendix, Table 3). Only one analysed study provisions the information before the trip as well [49]. There, the authors suggest a learning methodology composed of traditional courses, distance learning platform, and on-board intelligent tutor for more efficient driving for professional heavy vehicle drivers. Therefore, the solid support to gain and maintain eco-driving skills is provided.

Feedback type. The analysed systems delivering eco-driving information during the trip provide it mostly in the form of Instruction, e.g. [50,51,56]. As such, this is logical, as complicated feedback can cause distraction. Systems providing information after the trip have richer capabilities, like Achievements [49,53,54], Statistics [48, 55], Explanation [49, 57], and Fuel saving estimation [25]. For example, a Driving Coach system focuses on analysing driving behaviour, route selection, and the progress of a driver [25]. Therefore, it provides personalised explanatory feedback, which is considered to be of great value [14, 16, 59]. Few analysed systems provide feedback in the form of input control, e.g. [46, 52, 60].

Context-awareness. Some systems provide different functionality based on the available information, e.g. [54]. Some other consider traffic condition or overall situation for eco-driving evaluation or instruction provisioning, e.g. [53, 55, 60]. Some systems are able to adapt decision-making based on context, e.g. the weather conditions [25]. Overall, some levels of context-awareness seem to be supported by the majority of the systems.

Adaptation to the progress. Only four systems appear to support adaptation to the driver [25, 49, 53, 54]. For instance, Artemisa system [53] considers driver profile, road type, and traffic conditions to estimate the thresholds of the rules for providing advices. Orfila et al. [54] utilize gamification techniques and assign skill levels to the drivers based on their performance. Driving coach [25] considers the performance of the driver to make sure that fuel prediction models are relevant. In a solution proposed by Rionda et al. [49], system sensitivity to behavioural aspects can be manually tuned by the driving expert.

4.2. Design features analysis

As usability feature assessment would require user study analysis (which is often not available in the related work), we analysed how each system was tested (ST), what modality is used to deliver the feedback (HMI), whether a system provides analysis of the situation, an explanation of driving behaviour or comparison with previous driving to explicitly support reflection and knowledge (RK), and finally, how the system is implemented (FF), for details, refer to Appendix section, Table 3.

System testing. A majority of the systems were tested with real users in real vehicles, [49,53,56]. Different fuel savings were reported by these works, like 7.6% [61], 1.4% and 8.1% depending on interface [44], 7% [49, 56], 11.04% [53], 4.1% [39]. Driving simulator studies are also demonstrated, as these provide safe environment for experiments, [51, 62]. Finally, few works used simulation for their studies, [25, 52, 58]. Even though, simulations provide insights into certain aspects of system performance, they naturally lack user feedback. For simulated studies reported, fuel-efficiency highly depends on the scenario. For example, in the urban scenario, the fuel savings range between 9% and 15% [62]; in comparison to fixed speed and automatic speed control drive for virtually real 2.5 km road, an eco-drive system demonstrated 4.45% and 5% of fuel savings when driven from North to South and 5.70% and 7.04% in the opposite direction [52]; mean fuel savings between 15.9% and 18.4% are reported in [51] and up to 11% in [58]. However, it is difficult to directly compare fuel savings results, as systems, vehicles, and experiment organizations differ a lot.

Human-machine interface. Visual modality is the most popular among the analysed systems, [55, 63]. Moreover, visual modality is used both for the systems providing the feedback during the trip, [57] and after [54]. Audio modality is often used together with the visual one [49, 53]. Muñoz-Organero and Magaña [50] focused on audio feedback and provided two versions of audio signals: sound notifications and voice output, as in their study users had different preferences. Haptic interface is often used to control acceleration [51]. An interesting solution is proposed by Riener [44] providing vibrotactile feedback about driving via the safety belt or the seat equipped with actuators. Such a proposal allows delivering information below the level of conscious awareness; therefore, the driver gets the information without altering the cognitive load [44].

Reflection and knowledge. Extensive feedback can trigger the driver's reflection processes to consider how their choices and actions affect fuel consumption. Such analysis is important to facilitate behavioural change towards fuel-efficient driving [42, 43]. As already discussed, systems providing the feedback after the actual trip can afford such analysis [25, 54, 55, 57]. Excellent support is demonstrated by Rionda et al. [49]. Their solution (which is actually a complete methodology, not just a driving support system) uses different types of activities and supporting tools to help drivers to gain knowledge about eco-driving.

Form factor. Majority of the analysed systems are implemented on the universal device, like mobile phones or tablets, as such solutions do not require expensive hardware installation. Additional hardware might be used as well, e.g. to gather information from the on-board diagnostic port, GPS and other sensors. Some solutions require custom devices [46, 60, 63]. For instance, Riener's solution [44] provides vibrotactile feedback to the driver about the trip. Therefore, his solution requires a specifically designed actuator subsystem. Kang et al. [46] designed a custom system for controlling a vehicle's acceleration and speed. This system can be installed and removed easily from regular vehicles. In contrast, Ecker et al. [57] integrated their solution into an experimental vehicle.

4.3. Safety features analysis

Safety assessment is more vital for systems providing the feedback during the trip. For such systems, we analysed if they claim to consider attention and distraction issues in the implementation (AD), if their system relies on the situation assessment and safety regulations to provide guidelines (S#1), and if the driver is able to take the control when required (DC), for details, refer to Appendix section, Table 3.

Attention and Distraction. It was difficult to judge whether attention and distraction are considered if the authors do not explicitly tell that. Some authors clearly considered the distraction aspect in their system design, like Riener [44], who wanted not to overload the visual channel for providing feedback and decided to have a vibrotactile one. Muñoz-Organero and Magaña [50] utilize audio feedback for the same reasons. To address the distraction issue, visual feedback is often complemented with audio feedback, like in [58, 61]. Rommerskirchen et al. [62] analysed the visual behaviour of the respondents in their study, they concluded that the percentage of the glance times on the HMI is reduced as a driving situation becomes more complex. An interesting solution is proposed by Orfila et al. [54], in their system, user interface buttons are disabled when a given speed is exceeded.

Safety is the number one priority. Here, we emphasize that system design and guidelines it provides are based on situation assessment and safety regulations. Similarly to the previous one, we mark that a system takes safety regulations into account only when it is explicitly mentioned by the authors. We were able to identify only two systems which support it explicitly. Staubach et al. [51] relied on previous research and studies regarding safe speeding and stopping to develop their system. Riener [44] took the safety issue into consideration through overall system design and testing.

Driver is the one who has the control. In our analysis, this is applied to the systems having input control to vehicle operation during the trip. Among analysed systems, only Kang et al. [46] provide to a driver a switch which can be pressed to instantly disable the system if its acceleration behaviour is perceived to be unsafe.

4.4. Persuasive features analysis

Under persuasive features, we explore how the system supports behavioural changes by the driver (PTS, DS), how the system demonstrates the credibility (SCS), and if the system provides means for social interaction (SS), for details, refer to Appendix section, Table 3.

Primary Task Support. Majority of the analysed systems support *Reduction*. Therefore, the systems focus on certain driving related aspects helping to achieve the goal to save fuel. For instance, systems instruct about gear shifting [48,53,54,61] acceleration/deceleration [25,48,50,54,56,60, 61], speeding [25,48,53,54,56], and complying with speed limits [54]. Some systems provide information regarding obstacles ahead, so that the driver is able to adjust the speed or start freewheeling [54,62,63]. Another important aspect observed in the systems is *Self-monitoring*. Many systems provide drivers means to keep track of their performance, both during the trip [63], and after the trip [25]. For instance, Wu et al. [60] provide a visual performance indicator to the drivers during the trip. Liimatainen delivers driving reports after the trip [55]. Rionda et al. [49] implement extensive support to monitor the progress of the drivers. *Personalisation* principle is observed in some systems [25, 53, 54]. For instance, Driving coach [25] identifies personal factors affecting driving behaviour. Moreover, the system favours the guideline type which persuades the driver the most. Magaña and Muñoz-Organero [53] personalise system guidelines to suit the style of the driver. *Simulation* principle was clearly presented by one system. Driving coach provides fuel economy hints by telling potential fuel savings if certain behavioural change could be observed [25].

Dialogue Support. The most used principle in dialogue support category is *Suggestion*. Suggestions are applied in both during the trip and after the trip systems. Systems suggest to shift the gear, adjust speed, etc. *Praise* is considered in some systems [25, 53 - 55, 61]. Few systems provide *Rewards* for an achievement [53, 54]. For instance, Artemisa [53] may unlock achievements based on the driver performance.

System Credibility Support. This category was difficult to identify from the articles, as full details are often not described. We identified many systems to possess *Trustworthiness* principle. That is, the systems provide their analysis based on the actual driving behaviour and traffic situation, therefore, we consider them unbiased and fair. Due to Reduction principle of Primary Task Support category, many systems possess *Verifiability* concept. This is related to the fact that it is easy to verify why certain driving behaviour is assumed to be not fuel-efficient. We mark the systems providing screenshots of their interfaces to possess *Surface credibility* principle, as they seem to have competent look and feel. Among the systems analysed, we mark one system demonstrating *Expertise and Authority* principles [49].

Social support. Among the systems analysed, only three provide social support [53, 55, 57]. Ecker et al. [57] demonstrate *Social comparison* and *Competition* principles as their system provides a real-time ranking of the drivers. Similarly, Artemisa [53] allows drivers to compare their scores indicating eco-driving performance. Liimatainen uses a slightly different approach, as the system is aimed to be used in a professional bus fleet organisation [55]. His system generates two kinds of reports about fuel-efficient driving: personal report for the driver (only own performance analysed) and special reports for managers (performance from all drivers is available). Therefore, drivers possess peer pressure in their behaviour. Drivers have personal meetings with their managers to discuss the performance.

5. Discussion

Kurani et al. [42] and Woodcock et al. [43] suggest that eco-feedback interfaces should deliver information when required and present it in an easily interpretable way. In the persuasive systems design paradigm, the objective has been described by Fogg [64] as placing hot triggers in the path of motivated people. Assuming availability of information supporting decision-making, relevant summary information should support drivers in setting and achieving their goals. Moreover, eco-driving information should be presented in a grounded context, so that the drivers can understand the relative impact of their behaviour [42, 43]. Finally, positive reinforcement is suggested for behavioural change encouragement [43].

As can be seen from our analysis, more and more systems are developed to support drivers during the trip [53, 54, 56]. Many of these systems provide just instructions to follow for the driver, e.g. [39, 47, 50, 51, 56]. Such systems can be called assistants to achieve fuel savings. Such a prescriptive approach, activating compliance [65] is not unusual, and in the context of driving, where the driver’s attention necessarily is on the primary task, reducing larger observational tasks or overall main goals into smaller, executable single tasks is necessary. However, it is arguable if these systems can be considered to teach eco-efficient driving, as there is no explanation of how concrete behavioural habits affect fuel consumption, or when the studies do not indicate a link between a system feature and its effect on driver behaviour. More research into the effect of exact system features on driving behaviour is needed, so that such systems do not become “black boxes” [65].

Systems providing comments after the trip handle this role better, e.g. [25, 53, 55]. Such systems are able to provide comments clarifying for a particular driver how she/he can improve driving behaviour in order to save fuel. A concrete indication of what to do, how, and when provides the driver with a practical, functional suggestion. This information helps to understand how fuel-efficient driving could be achieved and appears to be important, from the drivers’ point of view [15, 59]. This is logical, as the driver has more time to analyse driving behaviour and reflect on causal effects of certain driving habits.

From the state-of-the-art analysis presented in this article, we have observed that systems use gradually more data sources to base their analysis on. This becomes possible with the constant development of sensing and communications technologies. On-board diagnostics and GPS are used in almost all recent works. In addition, many systems utilize embedded sensors and mobile phone cameras [50, 56], third party services [25, 53], even crowdsourcing information [53]. We consider this as a positive trend, as that way, a more complete view on the situation at hand can be assessed and more adequate support could be provided.

Some systems demonstrate abilities to adapt to context, e.g. [25, 51, 53, 54]. Moreover, some even adapt to the driver's progress, e.g. [25, 53, 54]. Also, means to manually tune the system to the driver's progress are considered [49]. Such adaptation is essential for systems coaching and evaluating the performance of the driver, so that both novice and advanced users have appropriate treatment. Support and persuasive systems tend to be more effective when the users perceived the content to be personally relevant [11]. Systems that are adaptive to their users' needs, progress and styles can be considered to deliver such relevance. Systems providing driver-progress neutral instructions do not need to adapt to the driver's progress, as they do not focus on coaching or evaluating the performance of drivers.

The fast development of mobile technologies contributes to the selection of the platform for implementing eco-driving support systems. However, systems aiming to control the vehicle still require special purpose solutions, e.g. [46, 60].

Visual modality to provide feedback dominates in the reviewed articles [54, 56]. Some systems provide both visual and audio feedback, like [53]. Utilization of only audio or haptic feedback modalities is rare [44, 50]. Information delivered to drivers should be simple and easily interpretable [32, 42, 43]. Moreover, the timing of the feedback dictates the design of the user interface. After the trip systems may afford richer details, while during the trip systems must show only essential information. Three principles were defined earlier to support design of the visual interface for the eco-driving system supporting after-the-trip fuel efficiency recommendations: 1) the most relevant and important information is to be shown first; 2) explaining the context gives more insight; and 3) graphs (visuals) work better than text [66]. These principles are exemplified with Figs. 1, 2, and 3 that demonstrate the mobile client for Driving coach system [25, 66]. Our analysis reveals that many systems (not necessarily providing the feedback after the trip) support these principles with their user interface design [53, 54].

Many analysed eco-driving systems referred to safety in general, but only a few identified clearly how these issues have actually been taken into consideration, making the analysis of safety features challenging in the present review. Distraction issue was considered the most. For instance, Orfila et al. [54] disable user interface buttons during the drive. Riener [44] not to overload the vision channel of the driver, suggested to deliver eco-driving information with light vibration patterns originating from tactor elements integrated into the safety belt or the car seat. One system comments on measures taken to avoid potential hazardous system behaviour, like not to encourage drivers to speed [51]. Another system clearly explains how the driver can overtake the control in the case of perceived unsafe acceleration behaviour of the eco-driving system [46].

Different persuasive principles were found in the analysed articles to motivate driver behaviour change. First, majority of the systems split the complex task of saving the fuel to smaller, easily comprehended and executable steps, like managing of acceleration and proper speed [54, 56, 61]. Also, many systems support monitoring the progress of the driver [49, 53]. In view of driving being an activity where only a few distractions are acceptable, breaking down the overall task into simple, manageable actions is necessary in order to achieve an immediate behavioural response to a cue.

Driving support systems have an ideal position to utilise the 'simulation' feature, owing to the very concrete and even immediate connection between behaviour and observable outcome. One system demonstrated explicitly the cause and effect relations through a potential fuel savings comment that tells the driver the fuel savings in actual numbers, provided, of course, that certain behaviours were followed on the latest trip, e.g. fewer stops [25]. Considering that money savings, fuel consumption, and CO2 emissions form the top three priorities of the type of information drivers want to see [15], simulating the actual effects of expected behaviour - perhaps even during and not only after a trip - would appear a potentially effective and attractive way of convincing drivers that recommended driving style is, indeed, worth it.

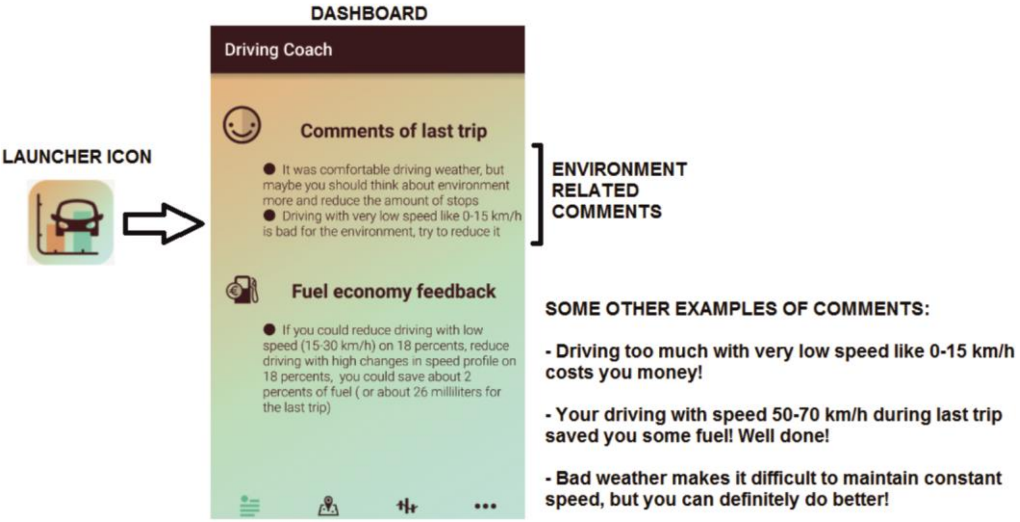

Fig. 1. *Most relevant and important information is to be shown first (Here, comments about the last trip and potential savings).*

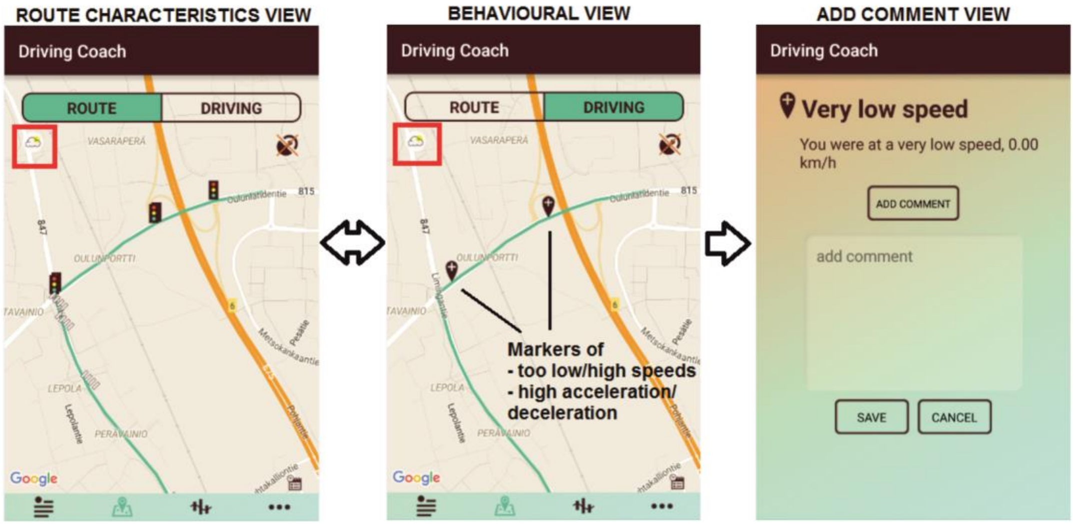

Fig. 2. *Explaining the context gives more insight (Here the weather of the trip, some route characteristics, and bad behavioural occurrences are visualized for the route driven).*

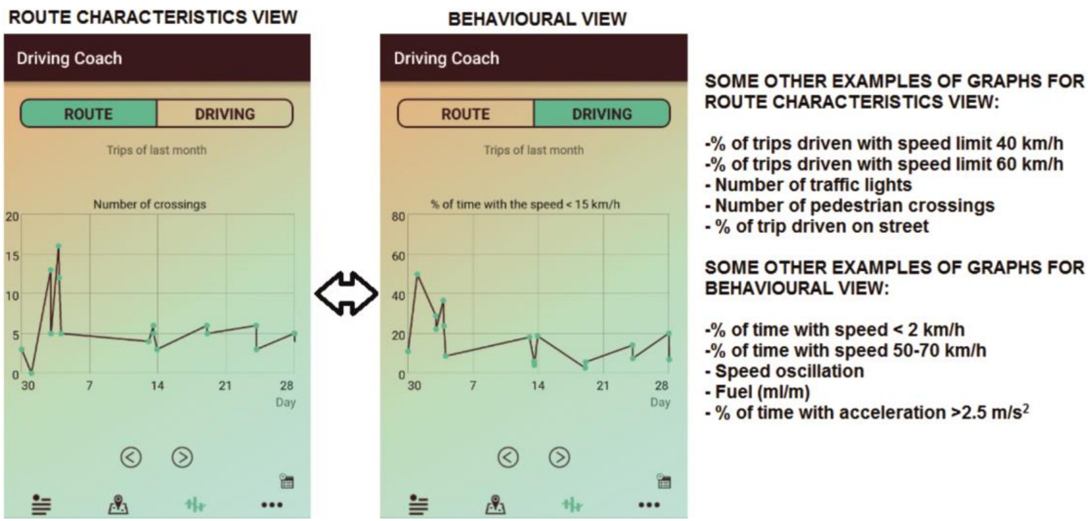

Fig. 3. *Graphs work better than text (see, Gilman et al. [25] for a full list of factors).*

Even though comparison to other drivers appears to be important to motivate for fuel-efficient driving [19], only a few systems consider social support [53,55,57]. Social support is mainly present through social comparison and competition, scoring the drivers' performance and therefore providing means for competing with each other. This is probably because of the nature of the driving activity and transportation application domain. However, we may expect stronger social effect from the peers when the system is targeted for companies, e.g. similar to [55].

As can be seen, the analysed systems fulfil diverse sets of features, depending on system purpose. For instance, systems providing feedback during the trip must consider attention and distraction but this is not so relevant for after the trip systems. Similarly, systems aiming to score and teach the driver should consider the driver's progress.

5.1. Open issues and opportunities

Based on conducted analysis, in addition to already discussed findings, we have identified the following opportunities for fuel-efficiency support systems.

The review has demonstrated wide adoption of mobile phones to be used as the platform for eco-driving assistant, which is in line with related work [17]. Moreover, with the growing interest to Car sharing and Mobility as a Service [67] initiatives, affordable and portable solutions that could be easily integrated and used in different vehicles are required. Therefore, we see the opportunities in development of the integrated solutions with standardised protocols and interfaces, suitable for a wide range of devices.

Vehicles are becoming increasingly equipped with sensing and communication technologies, therefore, collecting and processing data from environment, other vehicles and sources becomes possible [68],[70]. Such capabilities provide great opportunities in assessing the overall situation the vehicle is in, therefore, more accurate support for the driver would be possible. Moreover, it is interesting to explore deeper integration of user information into in-vehicle systems, via behaviour analysis, connectivity to third party services or wearables [69]. On one hand, this will support the development of more personalized solutions and could enable additional functionality (e.g. by analyzing data from wearables). On the other hand, such advances in technology provide a challenge for in-vehicle system design, as research is required regarding which information should be delivered to the driver and how, as well as proper methods should be applied to tackle privacy concerns [17, 69].

Employing a well-justified selection of persuasive system features is another avenue for making most of an eco-driving system. Prompting reflection in-action or on-action [6], providing well-timed suggestions for concrete actions [11, 64], and encouraging message elaboration through well-designed feedback [37] are all features that can be utilized with intention with the view of achieving lasting behaviour change over time.

A driver in a car offers a system developer a captive audience and to make most of the opportunity, a system developer should consider means of maximising the effect of the system. The reviewed research shows that systems that adapt to the context as well as the user, systems that use persuasive features to actively support target behaviour, and systems that encourage reflection can be designed and developed in a manner that is not disruptive or obtrusive. The literature and the reviewed research in the present paper illustrate the benefits of careful and multifaceted approach to systems design when it comes to eco-driving: an effective system will make use of a versatile design toolkit in order to obtain enduring behavioural results.

6. Conclusion

Supporting fuel-efficient driving requires consideration of technology, official regulations and social-related aspects. Different solutions have been proposed to provide support for eco-driving; for instance, systems controlling vehicle acceleration and speeding, systems instructing drivers to perform certain actions while driving, and systems providing comprehensive trip analysis after the drive. Such systems may have different goals, like saving fuel during the trip, teaching a driver for better driving behaviour, and promoting better situation-awareness. To maintain sustainable change in driving behaviour, thorough methodological approach, similar to Rionda et al. [49] could be of great value. Therefore, hybrid solutions able both to provide support during the trip, as well as to give thorough analysis of the trip after the drive are needed.

This article presented features for systems supporting drivers in their fuel-efficiency course, classified into functional, design, safety, and persuasive based on their role. Recent state-of-the-art eco-driving systems were analysed in terms of fulfilment of these features. General trends and challenges were discussed as well.

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9. Appendices

Table 1 Persuasive design principles [11] and corresponding system requirement example

Principle	Example
Primary Task Support	
Reduction	The system should cut overall behaviour change goal into small, easily executable actions, e.g. focusing on certain behavioural aspects, like speeding.
Tunnelling	Sequence of steps to follow to save fuel.
Tailoring	The system may differentiate between novice and experienced drivers in what information is delivered.
Personalisation	The system could learn what content and delivery style produce the best compliance and behavioural response with each user, then emphasize these methods over others in content delivery.
Simulation	For instance, the system can explain if certain behaviour is executed, then certain amount of fuel could be saved.
Self-monitoring	System should enable reflection both in action and on action [6].
Dialogue support	
Praise	System offers acknowledgement on progress and achievement by means of words, images, symbols, sounds or other means.
Rewards	System gives users virtual rewards or “unlocks” additional features (as a reward) when goals are achieved.
Suggestion	The users should be offered helpful, succinct and practical suggestions, like concrete ways of keeping fuel consumption low.
Similarity	System imitates their users in some way. For instance, to motivate teenager drivers to save fuel, some specific words could be used.
Social role	System can adopt a user profile appropriate social role such as a virtual specialist or personal coach.

Table 2 Persuasive design principles [11] and corresponding system requirement example

Principle	Description
System credibility support	
Trustworthiness	For instance, the recommendations are based on calculations of own driver's performance and not on product endorsements.
Expertise	Information provided by the system is based on identifiable expertise and competence [11].
Surface credibility	System design should ensure that each view of the system offers only relevant content. The system should have high usability and user experience value.
Real-world feel	For example, driving coach system provides the possibility to contact developers and provide feedback.
Authority	System refers to people in a position of authority, such as governmental organisations of traffic or environment.
Third-party endorsements	Driving assistant application may show the logo of specific transportation organisation approving its service quality.
Verifiability	For instance, user could check easily that idling affects fuel consumption.
Social support	
Social learning	Eco-driving system should support social interaction between users for the purpose of sharing users' targets, achievements, tips, etc.
Social comparison	System offers means for its users to see how others are performing the target behaviour and what the outcomes are.
Normative influence	For instance, driving coach system could share the speeding information between users, therefore the users would feel "peer pressure" and potentially could change their behaviour to speed properly.
Social facilitation	System should show how many other people are using the system within as set time period (presently, in the last hour(s), current week, etc. selecting the most appropriate for the present system implementation).
Competition	The system should offer a mechanism that allows users to compete with each other (targets/tasks) [11].
Cooperation	The system should enable users to create and set common targets such as reduction of fuel consumption or the amount of money saved by improved fuel-efficiency.
Recognition	The system should offer public recognition in a socially shared space, for example by nominating highest achievement during a day/week/month [11].

Table 3 Analysis of requirements fulfilment by state-of-the-art systems

		Functional requirements					Design requirements				Safety requirements			Persuasive requirements			
Ref	**Purpose of the system**	**DFA**	**FP**	**FT**	**CA**	**AS**	**ST**	**HMI**	**RK**	**FF**	**AD**	**S#1**	**DC**	**PTS**	**DS**	**SCS**	**SS**
[25]	System aims to coach drivers to drive better.	RC (number of traffic lights, crossings, pedestrian crossings, type and functional class of the road),OBD,W,T, GPS	AT	E, FSE, S	Yes	Yes	S	V	Yes	R,SU	--	--	--	R,P, SM, S	P,S	T,V, SC	No
[44]	To minimize driver overload, system delivers eco-driving information through tactile safety belt or seat interface.	RC (GPS), OBD	DT	I	NA	No	VUS	H	No	R, SC	Yes	Yes	--	R	--	T	No
[46]	Fuel consumption sensing and control system for modern vehicles, implemented in embedded platform, to improve fuel efficiency and reduce carbon emissions. System controls the vehicle's acceleration and speed to provide a fuel-efficient drive on its path.	OBD, vehicle properties, road conditions, GPS?	DT	IN	NA	No	VUS	--	No	R,SC	NA	NA	Yes	--	--	NA	No
[47]	System aims to bring information on safety and fuel efficiency together on an integrated, adaptive, and intelligent interface presented on a smartphone app.	RC (lane departure warning (LDW) camera), OBD, GPS, ES (3-axis accelerometer)	DT	I	Yes	Yes	VUS	V, A	No	R, SU	Yes	Yes	--	SM, R	--	T	No
[48]	Smartphone application aiming to reduce fuel consumption of the drivers.	OBD, ES	DT, AT	I, S,A	Yes	No	VUS	V	NA	R,SU	NA	NA	--	R	S	V	No
[49]	Multimodal training and learning programme for more fuel-efficient driving.	OBD	BT, DT, AT	(*)	No	(**)	VUS	A, V	Yes	R,SU	NA	NA	--	SM	S	E,A, SC	NA
[50]	System minimizes use of braking by calculating optimal deceleration patterns.	RC (traffic sign), OBD, External sensors (mobile phone camera, GPS),C (database of recognised traffic signs)	DT	I	No	No	VUS	A	No	R,SU	Yes	--	--	R	No	NA	No
[51]	System provides recommendations regarding gear shifting and acceleration/deceleration behaviour.	OBD (of simulator),RC (traffic signs),TL	DT	I	Yes?	No	SUS	V,H	No	NA	NA	Yes	NA	R	S	T, SC	No

[52]	System computes optimum control inputs based on road gradient conditions.	RC (terrain)	DT	IN	Yes?	No	S	NA	No	NA	NA	NA	No	--	--	NA	No
[53]	Driving assistant that makes recommendations in order to reduce the fuel consumption.	OBD,W,T,RC (slope, road type, traffic signs),TI,C, GPS, ES (phone camera)	DT, AT	I, A	Yes	Yes	VUS	V,A	NA	R,SU	Yes	NA	--	R,P, SM	P,R, S	T,V, SC	SC, Com
[54]	Driving assistant which provides advice according to upcoming events, a real-time evaluation of driving behaviour and the analysis of past actions.	RC(road grade, road slope, junctions, speed limits, curvature), OBD,GPS	DT, AT	I,A	Yes?	Yes	VUS	V	Yes?	R,SU	Yes	NA	--	R,P	P,R, S	T,V, SC	NA
[55]	System for fair measurement of fuel consumption and comparing individual driver's fuel consumption with average in a group of drivers.	OBD, GPS	AT	S, A	Yes	No	VUS	V	Yes	R	--	--	--	SM	P	T, SC	SC, SF, Nor, R?, Com
[56]	System provides recommendations for more fuel-efficient driving.	OBD, ES (3-axisaccelerator)	DT	I	No	No	VUS	V	No	R,SU	NA	--	--	R	S	T, SC	No
[57]	Educate/encourage eco-driving by means of competition/challenge.	OBD, GPS(driving history with comparison to current performance), real-time ranking with other drivers taking part	DT	E/I,A	Yes	No	NA	V	Yes	R	No	NA	--	SM	S	NA	SC, Com
[58]	Systems gives eco driving guidelines suited for the current situation and vehicle.	OBD	DT	I	Yes	No	S	V, A	No	R,SU (tablet)	Yes	NA	--	R,SM	--	T	No
[60]	System computes optimal acceleration/ deceleration and presents optimal values via interface or automatic control.	RC (GPS), ES(camera)	DT	I, IN	Yes	No	SUS	V, A	No	R, SC	NA	NA	(***)	SM,R	--	T, SC	No
[61]	System reduces fuel consumption by encouraging two behaviours: reduced rates of acceleration, and early upshifting through the gears.	OBD	DT	I	NA	No	VUS	V, A	No	R	Yes	NA	--	SM, R	P?	T	No
[62]	Achieve better fuel-efficiency through anticipatory ADAS, specifically, if the system also works under difficult conditions.	RC (traffic signs coming up); TL (red lights coming up)	DT	I	Yes	NA	SUS	V	No	NA	Yes	NA	--	R	S	T, SC	NA

[63]	System gives precisely timed instructions and hints when there is a speed limit ahead (curve, road-sign, stop sign etc.) to achieve freewheeling.	RC (GPS, height profile, velocity restrictions)	DT	I	Yes?	No	SUS	V, A	No	R, SC	NA	NA	--	SM, R	--	T, SC	No

Functional requirements:
DFA – Data Fusion and Analysis. The values are: RC (route characteristics), W (weather), T (traffic information), OBD (on-board diagnostics), ES (external sensors), TI (traffic incidents), TL (traffic lights), C(crowdsourced information)
FP-Feedback provisioning. The values are: BT (before the trip), DT (during the trip), AT (after the trip)
FT-Feedback type. The values are: I (instruction to take), E (explanation), FSE (fuel-savings estimation), S (statistics), A (Achievements, Summaries, Results), IN (control input)
CA - Context-awareness support. The values are: Yes, No, NA (no information available)
AS - Adaptation support to driver’s progress. The values are: Yes, No, NA (no information available)
Design requirements:
ST – System testing. The values are: VUS (vehicle-based user study), SUS (simulator-based user study), S(simulation), No (no study), NA (no information available)
HMI – Human-Machine Interface. The values are: V (visual), A (audio), H (haptic), NA (no information available)
RK – Explicit support for reflection and knowledge. The values are: Yes, No, NA (no information available)
FF – Form factor. The values are: O (original), R (retrofitted), SC (separate device custom), SU (separate device universal), NA (no information available)
Safety requirements:
AD – Consideration of Attention and Distraction. The values are: Yes, No, NA (no information available), -- (not applicable, e.g. if FP=BT or FP=AT)
S#1 – Safety priority 1. The values are: Yes, No, NA (no information available), -- (not applicable, e.g. if FP=BT or FP=AT)
DC- Driver in Control. The values are: Yes, No, NA (no information available), -- (not applicable, e.g. if FP=BT or FP=AT)
Persuasive requirements:
PTS – Primary Task Support. The values are: R (reduction), Tu (tunnelling),Ta (tailoring), P (personalisation),SM (self-monitoring),S (simulation),-- (not applicable), NA (no information available)
DS – Dialogue Support. The values are: P (praise),R (reward),S (suggestion), Rem (reminders), SR (social role), Sim (similarity), -- (not applicable), NA (no information available)
SCS – System Credibility Support. The values are: T (trustworthiness), E(expertise),SC (surface credibility),V (verifiability),RWF(real-world feel), A (authority), TE (third-party endorsement),-- (not applicable), NA (no information available)
SS – Social support. The values are: SL (social learning), SC (social comparison), Nor (normative influence), SF (social facilitation),C (cooperation), Com (competition),R (recognition),No (no social support),-- (not applicable), NA (no information available)
Other:
? – Means that the system could have certain feature, however its presence is not clearly described in the article
(*) I, E from face to face workshops; I, A, S from e-learning part; I,S from on-board system. Note: some of the off-line (e-learning) instruction comes from an expert driver
(**) System could be manually tuned by the efficient driving expert to determine how sensitive are alarms informing about certain behavioural aspects
(***) System proposes two versions, therefore the values are: “--“ for driver support system, “No” for autonomous vehicle.