



Driver adherence to recommendations from support systems improves if the systems explain why they are given: A simulator study



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ABSTRACT

This paper presents a large-scale simulator study on driver adherence to recommendations given by driver support systems, specifically eco-driving support and navigation support. 123 participants took part in this study, and drove a vehicle simulator through a pre-defined environment for a duration of approximately 10 min. Depending on the experimental condition, participants were either given no eco-driving recommendations, or a system whose provided support was either basic (recommendations were given in the form of an icon displayed in a manner that simulates a heads-up display) or informative (the system additionally displayed a line of text justifying its recommendations). A navigation system that likewise provided either basic or informative support, depending on the condition, was also provided.

Effects are measured in terms of estimated simulated fuel savings as well as engine braking/coasting behaviour and gear change efficiency. Results indicate improvements in all variables. In particular, participants who had the support of an eco-driving system spent a significantly higher proportion of the time coasting. Participants also changed gears at lower engine RPM when using an eco-driving support system, and significantly more so when the system provided justifications. Overall, the results support the notion that providing reasons why a support system puts forward a certain recommendation improves adherence to it over mere presentation of the recommendation.

Finally, results indicate that participants' driving style was less eco-friendly if the navigation system provided justifications but the eco-system did not. This may be due to participants considering the two systems as one whole rather than separate entities with individual merits. This has implications for how to design and evaluate a given driver support system since its effectiveness may depend on the performance of other systems in the vehicle.

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1. Introduction

Eco-friendly driving is based on the concept of adapting one's driving style to reduce fuel consumption of a vehicle and, by extension, the emission of noxious particles such as CO₂. The European project ECOWILL, for example, states that:

Eco-driving means smarter and more fuel-efficient driving. Eco-driving represents a new driving culture that makes best use of advanced vehicle technologies, while improving road safety. (www.ecodrive.org).

Several studies estimate that present-day fuel consumption can be reduced by 10 to 15% (Barkenbus, 2010; Gonder, Earleywine, & Sparks, 2011; Rakotonirainy, Haworth, Saint-Pierre, & Delhomme, 2011); Japan, for instance, has reduced CO₂ emissions by 31Mt compared to 2011 levels by encouraging fuel-efficient driving (Rakotonirainy et al., 2011) while it has been estimated that the US could achieve a reduction of 33Mt CO₂ emissions if one third of its drivers were to drive more economically (Gonder et al., 2011).

A straightforward approach to achieve a reduction of fuel consumption is the direct encouragement of drivers to operate their vehicle in an eco-friendly manner. This can be achieved in several ways. Typical strategies include prior education, in-vehicle feedback while driving, or post-drive statistics (see Hof et al. (2014), for a review of various strategies, and Manser, Rakauskas, Graving, & Jenness (2010), for examples). In particular, real-time feedback given while driving has been found to work well. For example, instantaneous acceleration information outperformed overall feedback on fuel economy (Gravin, Manser, & Becic, 2010; Hof et al., 2014; Rakauskas, Graving, Manser, & Jenness, 2010). That said, there is currently no consensus on how eco-driving feedback should be presented to drivers (Barkenbus, 2010).

Some of us have discussed in previous work – and based on work by others studying interaction between humans and artificial cognitive systems – that, in general terms, a driver's propensity to follow the recommendations of a given system may depend on the cognitive capabilities the driver attributes to this system (Thill, Hemeren, & Nilsson, 2014; Thill & Riveiro, 2015). In particular, we previously found that *system awareness* – that is, an awareness of the inner working of a system that one might interact with (more largely studied in the context of situation awareness, see Matthews, Bryant, Webb, & Harbluk, 2001) – played a role in whether or not drivers followed a navigation system's recommendations: drivers preferentially followed the system if the system presented a justification as to *why* it made a particular recommendation. Human perception of a recommendation system's inner workings (and the cognitive processes underlying this perception) may therefore shape adherence to the system's suggestions. When it comes to eco-driving systems, several types of recommendation systems have been tested (see, for example, Manser et al., 2010; Meschtscherjakov, Wilfinger, Scherndl, & Tscheligi, 2009) but few have taken into consideration such processes explicitly (Stillwater, 2011).

The present paper presents a simulator study investigating the effect such system awareness might have on adherence to system recommendations in the context of eco-driving. This is measured through (estimated simulated) fuel consumption and driver behaviours that directly pertain to the recommendations given by the system in this study. The specific manipulation in this study concerns the informativeness of both an eco-driving and a navigation system, and in both cases the hypothesis that drivers are more likely to follow recommendations of a system if they have a higher system awareness holds. Interestingly, it was also found that when the navigation system is more informative than the eco-driving system, the participants' driving style was *less* eco-friendly than in other experimental conditions in which an eco-driving system was present. This suggests that the two systems were not perceived as separate systems in their own right, which has implications for the design of future systems. We return to this point below; first, however, relevant related work is presented.

2. Related work

2.1. Driving support systems and system awareness

Although it happened relatively late compared to other domains (such as, for example, aviation), driver support systems have slowly been introduced in the vehicle market (Onken & Schulte, 2010). Early examples include cruise control and anti-lock braking system, later followed by, for example, parking aids, adaptive cruise control (ACC), forward collision warning and lane keeping aids; most of which can normally be activated/deactivated by the driver. New sensor technologies (such as novel camera technologies, infrared, or radar) have contributed to the emergence of further driving guiding systems.

It has also been shown that providing specific feedback and information related to the inner-workings of driving support systems (thereby increasing the system awareness of the driver) appear to have positive effects on driving performance. For example, Seppelt and Lee (2007) showed that a visual representation of ACC behaviour promoted appropriate reliance and support effective transitions between manual and ACC control and suggest that providing drivers with continuous information about the state of the system is a promising alternative to providing warnings. Similarly, Verberne, Ham, and Midden (2012) showed that ACCs were perceived as more trustworthy if they provided information regarding their driving goals when they took over driving tasks. Thill et al. (2014) found that participants were more likely to follow the recommendations of a navigation system (in an environment in which multiple routes to the goal were possible) if the navigation system provided a justification for its choices. Interviews with the participants confirmed that this was simply because they appreciated knowing *why* a decision was made.

System awareness can also include information about the confidence a system has in its abilities to function. Beller, Heesen, and Vollrath (2013), for example, found that providing drivers with such information in the context of an automated car led to an increased situation awareness and higher trust ratings. Similarly, Helldin, Falkman, Riveiro, and Davidsson (2013) carried out a simulator study of an automated drive during snowy conditions. Some participants were given a visual indication of the vehicle's confidence to continue driving while others were not. The results showed that drivers who were provided with information tended to take control of the car faster when needed while simultaneously spending less time overall looking at the road ahead (and were thus able to, to a higher degree, perform tasks other than driving without compromising driving safety).

2.2. Current eco-driving systems

Fuel savings can essentially be achieved through less aggressive driving, avoiding (for instance) rapid accelerations, and avoiding gear changes at high engine RPM. Several car manufacturers already integrate eco-driving recommendation systems to this effect.

Present-day eco-driving recommendations are mainly given to drivers through visual displays (Hof et al., 2014; Jamson, Hibberd, & Merat, 2015a), although sound- and haptic-based solutions have been also suggested (such as vibrotactile pedals, see the examples by Meschtscherjakov et al. (2009) and Gonder et al. (2011)). Eco-driving systems can be incorporated in the dashboards or screens of the vehicle or in nomadic devices, such as tablets and smart phones.

Meschtscherjakov et al. (2009) present a technology acceptance online survey with 57 participants who evaluated five prototypes based on commercial solutions for supporting eco-driving behaviour. The best acceptance results were obtained by a display that made use of various colours (green-yellow) around the speedometer, followed by one which showed a summary of the total fuel saved. Additionally, it was found that the propensity to accept and intend to use a system was affected by individual expectations of the systems' disturbance and risk factors.

Manser et al. (2010) compared several visual displays, and found, for example, that participants scored representative or symbolic forms of fuel economy information, such as horizontal bars or iconic images highest (as compared to text displays). This is in line with several other studies, including our own (Thill et al., 2014): drivers appreciate information conveyed but prefer not to receive it in textual form.

Gonder et al. (2011) compared various methods currently available, including smart phone applications, navigation systems, systems that provide feedback offline, and built-in systems. They found that efficiency feedback from an original system built into the dashboard of the vehicle was one of the most effective approaches while two of the most promising aftermarket solutions were feedback from a smart phone app and a dedicated additional device connected to the vehicle's on-board diagnostic port.

Birrell, Fowkes, and Jennings (2014) are one of the few to evaluate a smart driving system – one that provides both safety and fuel-efficient driving advice – in a real-world road test during which 40 participants drove an instrumented vehicle over 50 min in a mixed-route driving scenario. The key findings were a 4.1% improvement in fuel efficiency when using the smart driving aid, with neither increase in journey time nor reduction in average speed. Fuel savings were made possible by limiting the use of lower gears (facilitated by planning ahead to avoid unnecessary stops) and an increased use of the fifth gear (advised by the in-vehicle system).

Finally, several papers – as part of a recent special issue of Transportation Research Part C (2015) – tackle challenges associated to the provision of guidance for eco-driving and their effects on fuel consumption. Customisable user interfaces for eco-driving support systems are recommended by Fors, Kircher, and Ahlström (2015) for truck drivers. Most participants in their study preferred simple and clear information; the eco-driving constituents that were rated as most useful were advice on gas pedal pressure, speed guidance, feedback on manoeuvres, fuel consumption information and simple statistics. In a simulator study, Jamson, Hibberd, and Jamson (2015b) found that any type of eco-driving advice improved fuel efficiency performance and whilst continuous real-time visual feedback proved to be the most effective, this modality reduces attention to the forward view and increases subjective workload. A follow up driving simulator study presented by Hibberd, Jamson, and Jamson (2015) showed that a haptic accelerator pedal was most effective for preventing over-acceleration, and induced lower perceived workload than a visual-auditory interface. Finally, Jamson et al. (2015a) compared different advice modalities and concluded that visual distraction could be reduced by using well-timed auditory feedback.

To sum up, eco-friendly feedback tends to be best received when it is simple (Manser et al., 2010; Fors et al., 2015). Research on other driver support systems also suggests that providing increased system awareness is appreciated and might contribute to improved adherence to recommendations. Here, we therefore explore a possible connection between the two in a simulator study that primarily manipulates the “informativeness” of driver support systems. While we are interested in the degree to which drivers adhere to the recommendations, designing an optimal system is not our main aim. For the present purposes, especially given that at least some research indicates that any type of recommendation is going to have an impact (Jamson et al., 2015b), we therefore limit ourselves to a simple system which recommends gear changes and engine braking/coasting whenever such behaviours are relevant. In particular, we omit a haptic throttle since such a device does not provide explicit recommendations for actions.

3. Methods

3.1. Participants

The necessary number of participants was estimated using a power analysis, assuming the use of ANOVA for significance tests (we will however rely on confidence intervals for reporting statistics in the remainder of the paper since these are more informative). We used the *pwr.anova.test* function provided by the R statistical computing environment, specifying the level of significance (0.05), the desired power (0.8), and a desired effect size of 0.4 (the effect size is chosen based on Cohen, 1977). The analysis suggested around 120 participants would be necessary. 133 participants were thus recruited (including a safety margin). Six participants had to be excluded from further analysis due to a deviation in the experimental setup. Another two were excluded for treating the experiment as a racing game and a final two were unable to complete the experiment due to self-reported simulator sickness. As a result, 123 participants were included in the analysis (89 male, 34 female). Age data was collected in the form of age groups (see Table 1).

Participants were recruited from the University of Skövde's students and staff (not otherwise associated with the project or similar research), as well as co-located private companies. A valid driver's license and fluency in Swedish was required. Participants were given a cinema ticket worth 120SEK (\approx 14USD). Participants were informed about the ticket in advance and were free to withdraw from the experiment at any time without needing to give a reason and without losing the cinema ticket. The entire experiment was conducted in accordance with applicable ethical guidelines.

Participants were balanced across conditions for both gender and whether or not they wore glasses.¹ Participants were only assigned to conditions once they appeared at the experiment to ensure a randomised but balanced assignment to the different groups. The following procedure was adopted: Four sequences of random permutations of the numbers 1–6 were generated (one sequence per possible combination of gender and glasses). The test leader assigned each participant to the condition corresponding to the first number of the relevant sequence upon arrival of the participant, then removed that number from the sequence.

The main advantages of this approach are that there is no need for advance information about the participants and it is robust to drop-outs. It also ensures that participants are distributed approximately evenly across conditions while maintaining the desired balances.

3.2. Simulator

3.2.1. Physical simulator and software

The driving simulator used in the present study consists of a real Volvo S80 with complete interior and exterior (see Fig. 1). The front of the car is surrounded by five projection screens, which together cover most of the driver's and the passengers' fields of vision FOV; the minimal and maximal values for the FOV, which varies as a function of the position of the eye plane, are 205 and 240 degrees. Another two projection surfaces are placed behind the car in such a way that they are visible both through the car's rear-view mirrors and when looking over the shoulder. Each of the seven projection surfaces is controlled by a standard PC running a Windows OS. These computers act as clients to an eighth computer, the server (also a standard Windows PC), which coordinates the part of the virtual world to be displayed by the client any given moment. The server's interface to the car is implemented as a game controller, making it easy to use arbitrary simulation environments and games. For the present experiment, the UnityCar 2.2 Pro vehicle simulation package,² which uses the Unity 3D game engine³ was used. Engine, road and wind noise are played back in the car using the car's original sound system. To increase the feeling of immersion, a vibration unit is mounted on the vehicle body. It is controlled by the server (as are the vehicle's speed- and rpm meters).

3.2.2. Environment

The environment was designed to be easy to navigate but not monotonous so as to ensure that participants remain engaged during the study. Some of the notable features include changing speed limits and red traffic lights, which motivate some of the recommendations given by the eco-driving system (see Section 3.2.3), and several routes to the destination. In particular, there were two instances where the navigation system's recommendation was in conflict with information on road signs, but avoided undesirable events (a traffic jam or the scene of an accident). Fig. 2 provides a map with details of the various features and events.

3.2.3. Recommendation systems design

Two recommendation systems were created: one for eco-friendly driving, and one for navigation. Both systems come in two versions, *basic informative*. Basic systems simply provide accurate recommendations for actions by displaying icons corresponding to the relevant actions (see Fig. 3 for a complete list). Informative systems additionally provide a brief

¹ As part of the wider methodology, eye-tracking data was collected using lightweight Tobii glasses 1. These are however not used in the present paper and mentioned here only for completeness.

² <http://unitypackages.net/unitycar/joomla/index.php>.

³ <http://unity3d.com/>.

Table 1
Number of participants per age group.

Age group	n participants
18–20	12
21–29	63
30–39	21
40–49	14
>50	13
Total	123

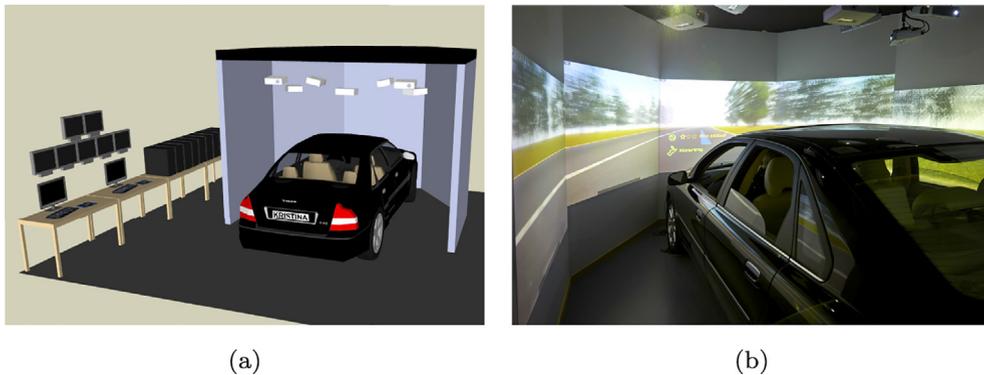


Fig. 1. (a) Schematic of the vehicle simulator at the University of Skövde: a complete, real car is surrounded by seven screens (two screens behind the vehicle – visible in rear-view mirrors – are not shown on the schematic) on which the environment is projected, creating an immersive experience. (b) Photo of the simulator and environment with the eco-driving system visible on-screen.

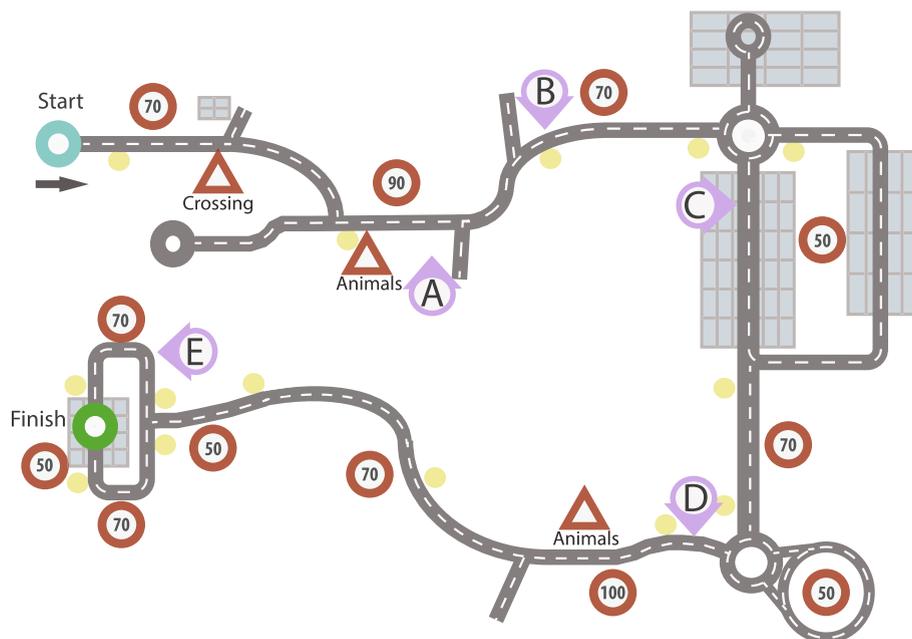


Fig. 2. Overview of the track driven by the participants. Events during the drive: (A) animals on the road side, (B) truck waiting to enter the main road – once in, it follows the participant until the round about, (C) accident and traffic jam, (D) car parked on the side, after the participant passes it starts and follows for a while and (E) second accident, crashed cars on the side. Blue and gray grids mark urban areas; yellow pale circles marked where road signs were placed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

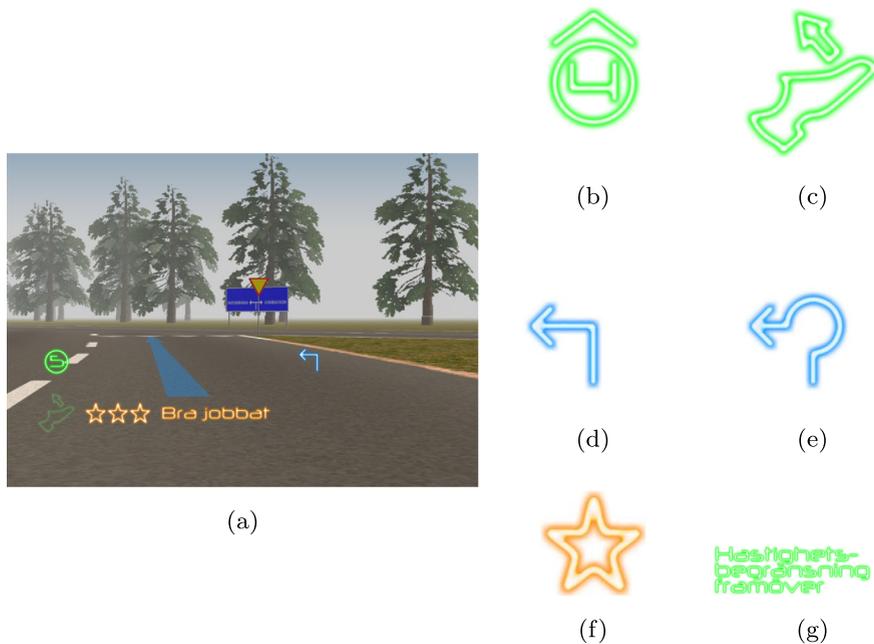


Fig. 3. (a) An example of the interface displayed on the HUD. The large blue arrow is always present and its orientation continuously updated to indicate the preferred direction to the destination. The gear change recommendation symbol (b) and the symbol for recommending to release the throttle (c) are the essential eco-driving recommendations given. The navigation recommendations for junctions (d) and roundabouts (e), in addition to the larger blue arrow, are the navigation aids given. For informative conditions, the system also provides reward feedback from 1 to 3 stars (f); and adds a justifying text (g; see also Table 2) to the recommendation icons (b–e). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
List of the textual justifications used by informative system.

System	Swedish original	English translation
Eco-driving	Lågt varvtal	Low engine speed
	Högt varvtal	High engine speed
	Hastighetsbegränsning framöver	Speed limit ahead
	Rött trafikljus	Red traffic light
	Släpp gasen nu för att slippa bromsa sen	Release throttle now to avoid breaking later
Navigation	Bra jobbat	Well done
	Undvik olycksplats	Avoid traffic accident
	Undvik kö	Avoid queue

justification in the form of a short text explaining why the recommendation was given (see Table 2 for a complete list of the justifications used), displayed next to the icon, followed by performance feedback consisting of 1 to 3 stars (calculated based on reaction times). In other words, informative systems were designed to provide the driver with a greater *system awareness* (Matthews et al., 2001).

The recommendations were given using a simulated heads-up display (HUD) displayed on the central screen of the simulator, visible through the wind shield, essentially simulating an advanced version of informative displays available in some modern vehicles while reducing the likelihood that participants miss recommendations given to them. Participants were also told only that the purpose of the experiment was to test future HUDs to avoid priming an artificial adherence to the recommendation systems, see Section 3.5. The eco-driving system recommended two types of behaviour (gear change and engine coasting) while the navigation system recommended directions to take at junctions.

These recommendations were triggered in different ways: navigation-related recommendations are triggered by proximity to the relevant places on the map (junctions or roundabouts). The engine brake/coasting recommendation was similarly triggered by location; specifically when approaching either a red traffic light, or an upcoming speed reduction, and timed so that adherence to the recommendation would result in an appropriate speed at these events.

Gear recommendations, meanwhile, were primarily based on engine revolution (recommending a change up at high rpm and down at low rpm), but also on fuel injection rate and current speed compared to the current speed limit to anticipate the

likelihood that a driver might currently want to accelerate. Gear recommendations were never triggered while coasting, while inside a crossroad, or if the previous gear change happened less than one second ago.

3.3. Experimental design

Since the main hypothesis is that providing informative systems will encourage adherence to the recommendations to a higher degree than basic ones a between-participants design has been chosen that allows us to test combinations of systems and their informativeness while avoiding, for example, learning effects one might expect in a within-participant design.

There are thus two independent variables: the degree of informativeness of the eco-driving and the navigation systems respectively, while the dependent variables (estimated fuel savings, gear change behaviour, coasting behaviour) measure the eco-friendliness of the driving behaviour. Hence, for the eco-driving system, the possible values are “none” (to provide a baseline estimated simulated fuel consumption), “basic”, or “informative” (as defined above) while they are “basic” or “informative” for the navigation system. [Table 3](#) summarises the experimental conditions.

3.4. Data

3.4.1. Simulator logs

For every session, the full state of the Unity simulation was logged at a frequency of 10 Hz, and it is possible to replay each participant’s session from these files. The state of the physical car, in particular the position of the steering wheel, pedals, and gear lever (but not aspects unrelated to behaviour, such as the position of the driver’s seat or that of the mirrors) was similarly logged. Fuel consumption was calculated using the fuel model provided by the simulation environment, itself based on the models described by [Genta \(1997\)](#).

3.4.2. Questionnaire and interviews

Participants were given two questionnaires, one prior to the simulator drive and one after. The first questionnaire focused on participants’ background, driving experience, and experience of driver support systems including navigation and eco-driving systems, while the second questionnaire addressed the participants’ experience of the simulator drive and the interfaces tested.

The second (post) questionnaire was similar to the one used by [Thill et al. \(2014\)](#), and is based on several previous studies ([Endsley, 1995](#); [Jian, Bisantz, & Drury, 2000](#); [Lund, 2001](#)). It covered the following topics: perception of trust and intelligence (trust in a system may lead to the association of a higher level of intelligence to it, see [Jian et al. \(2000\)](#), while perceived intelligence was previously identified as a factor modulating system awareness, see [Thill et al. \(2014\)](#), three levels of situation awareness) (level I: perception of pre-defined aspects, level II: comprehension of the relation between these aspects and the task, and level III: ability to project future states, see [Endsley \(1995\)](#)) and usability ([Lund, 2001](#)). For each subject, participants were asked to evaluate a number of statements on a 5-point Likert scale (without a neutral option – the five options were (translated from Swedish): *disagree*, *agree a little*, *agree somewhat*, *mostly agree*, *agree entirely*). A “cannot answer” option was also given as the final option on the list. A list of statements used is given in [supplementary Table S1](#).

Following completion of the main experiment and the post questionnaire, a semi-structured interview was conducted with 46 randomly selected participants balanced across conditions (4 male and 4 female participants per condition, except two, for which only 3 females were interviewed) to capture their experiences and opinion in more detail. We did not interview every participant because experience from previous studies suggests that the likelihood of finding previously uncaptured insights diminishes rapidly (according to [Nielsen & Landauer, 1993](#), [about 85 % of usability issues can be discovered by conducting 6 evaluations](#)).

As with the questionnaire, the focus was on topics such as trust in the system, and its (perceived) intelligence and usability. Each interview took about 10 min and was conducted by the test leader in Swedish. It was audio recorded and then transcribed by a third-party. The transcripts were imported into the ATLAS.ti qualitative research software. This was followed by a data reduction process in which the identified expressions were translated into English, and grouped to identify common themes and motives (*cf.* grounded theory and “open coding” [Strauss & Corbin, 1998](#)). To avoid possible biases, researchers involved in this process had no access to the quantitative results until after completion of this task.

3.5. Procedure

The experimental environment consisted of two rooms ([Fig. 4](#)) one containing the simulator itself (see [Fig. 1](#)) and one containing two chairs, a table, a coat rack and free drinks and snacks for the participants. Participants were in the first room only during the simulation while all other activities took place in the second room. Refreshments were provided for the participants.

Upon arrival, participants were greeted, informed that the car simulator was located in the second room, and that the session would start with some information and questions. In particular, participants were informed of the expected duration of the experiment, that they may experience simulator sickness, and that they were free to withdraw from the experiment at any time, without needing to provide a reason. They were also informed that the purpose of the experiment was to test future HUDs (mentions of eco-driving or navigation support systems were avoided at this point to not prime an artificial

Table 3

The experimental design of the study with the number of participants in each condition after removal of invalid data, and the shorthands used to refer to the conditions in text.

Nav sys	Basic Informative	Eco-driving system		
		None	Basic	Informative
		BN (20)	BB (19)	BI (20)
		IN (22)	IB (21)	II (21)

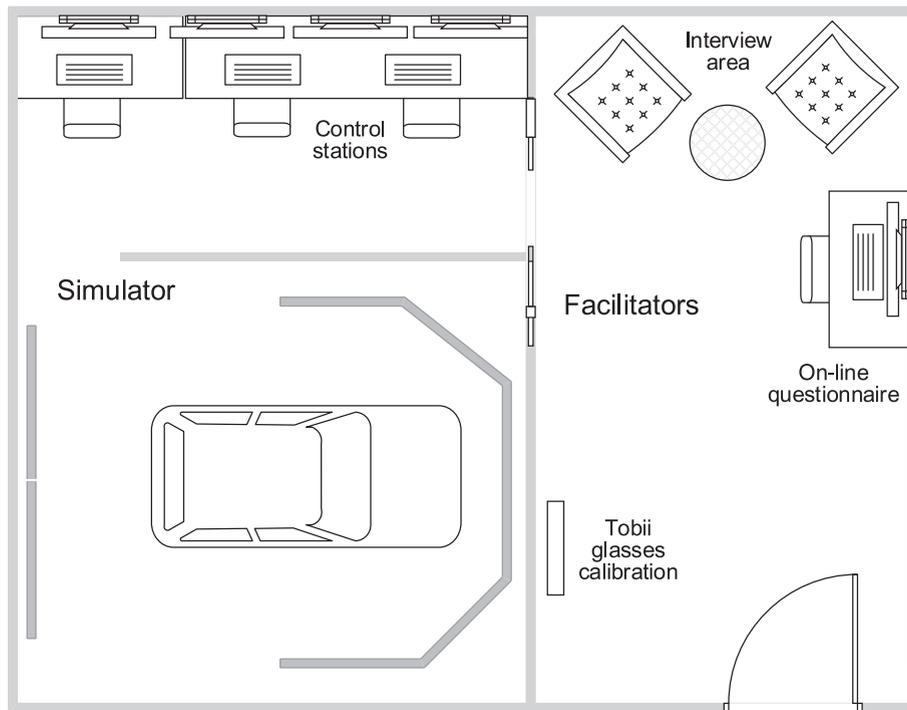


Fig. 4. A sketch of the full experimental environment including the simulator itself and the interview room.

adherence to the system) and of the overall session design, namely that it would start with a questionnaire followed by driving the simulator and concluding with another questionnaire. Participants selected for an interview were additionally informed that there would be an interview while participants without glasses were additionally briefed regarding the eye-tracking. This information was provided in a printed document as well as verbally by the test leader.

Participants were then handed a Samsung Galaxy Note 10.1" (2014 edition) tablet on which the first questionnaire was displayed after participants gave their explicit informed consent to participate in the study. Once the questionnaire was filled in, and after calibrating the eye-tracking equipment if applicable, the participant was invited into the simulator. Participants took a seat in the car and the test leader made sure the participants wore the seat belt, were comfortable, and familiar with operating the vehicle.

Participants were then informed that the simulation had two parts. The first one was a tutorial in which they would be given a series of pre-recorded instructions to allow the participants to familiarise themselves with the handling of the simulator. Participants were allowed to drive freely until they felt comfortable following the pre-recorded instructions. They were allowed to ask questions during this part of the simulation, and the test leader was always present (but out of sight).

The pre-recorded instructions asked that participants adjust mirrors, press the pedals, and change gear. The instructions then went on to describe the head-up display (HUD). The final instruction was to turn on the ignition, and to drive around until participants felt ready to start the second part of the simulation. The HUD was not used during this part of the simulation and the environment consisted merely of a long, wide, straight and empty road.

Once happy with the handling of the vehicle, participants turned off the ignition and the second simulation was loaded while the test leader answered any questions participants might have.

The second part of the simulation started with an instruction, displayed on-screen, to drive to a fictional location (Nusseboda, see Fig. 2). The text disappeared after the participants turned on the ignition again, and the main experiment began.

Overall, the drive took roughly ten minutes, after which participants left the simulator and returned to the other room. Here, participants were again offered refreshments, asked to finish the questionnaire, and interviewed if applicable.

4. Results

Throughout the results and discussion, the different groups of participants are referred to by the shorthand listed in Table 3: each group is denoted by a two-letter code, the first of which denotes the type of navigation system (Basic or Informative) while the second denotes the type of eco-driving system (None, Basic or Informative).

4.1. Fuel consumption

Table 4 summarises the average estimated fuel consumption for participants in the different groups. It is immediately apparent that groups BN and IB display the worst performance. This is expected for the BN group but not the IB group, which we will return to later.

For participants with basic navigation, the availability of any type of eco-system is accompanied by a significant difference in fuel consumption compared to the condition with no eco-system, as determined by the one-sided⁴ 95% CIs for the difference between means (one-sided Δm 95% CI) of the groups (BN and BB: [0.07, 0.54]; BN and BI: [0.07, 0.55]). Interestingly, a similar effect is not observed when the navigation system is informative. Ignoring the somewhat special case of group IB for the time being, one-sided Δm 95% CI between groups IN and II was found to be [−0.03, 0.31], which includes zero and therefore does not allow a conclusion. While one could postulate that the informative navigation system itself has an effect on fuel consumption, the same observation applies for comparing BN and IN (one-sided Δm 95% CI: [−0.003, 0.504]), thus preventing us from conclusions to that effect. Finally, the difference between groups BN and II, the two extremes on our set-up, does appear significant (one-sided Δm 95% CI: [0.17, 0.61]).

Overall, the fuel consumption analysis therefore reveals mixed results and it is not trivial to paint a clear picture. In general terms, it is important to approach results based on fuel consumption with some caution since they are estimated using, and thus will depend on, the fuel model used (or, in real-life equivalent, on the vehicle used). The main take-home message from this part of the analysis is thus that there appears to be a significant difference in fuel consumed between the two extremes in our design, BN and II. Given the one-sided Δm 95% CIs reported, this fuel saving corresponds to a plausible range between 3.08% and 10.72%, which is in line with the effects reported in other literature (for example, previous findings include 4.1% (Birrell et al., 2014, in a real world environment), 5.45% (Zhao, Wu, Rong, & Zhang, 2015), 17% (Sullman, Dorn, & Niemi, 2015) and 20% (Gonder et al., 2011)).

The fuel consumption behaviour of our participants can be understood in more detail by considering the distribution of mean fuel consumption across all participants, depicted in the top graph of Fig. 5. This distribution suggests that values are drawn from two separate, roughly normally distributed random variables, and that our participants are divided into two distinct populations, one of which tends to drive more economically than the other. To verify, a model of the following form can be fitted to the curve:

$$Y = p\Phi_1^{\mu_1, \sigma_1} + (1 - p)\Phi_2^{\mu_2, \sigma_2}$$

where the two Φ s are used to indicate two normal distributions with their corresponding means μ and standard deviations σ , and p is the probability that a particular data point is sampled from the first distribution. Such a model fits the observed distribution well ($p = 0.91$, $\mu_1 = 5.30$, $\sigma_1 = 0.30$, $\mu_2 = 6.35$, $\sigma_2 = 0.25$, adjusted R-square: 0.9925, RMSE: 0.034).

Next, the same model is applied to each of the six conditions, whose overall fuel consumption distribution can be seen in the six graphs on the bottom of Fig. 5. Table 5 summarises the fit for each condition. The general trend apparent here is that for the groups that had an eco-driving system, the probability p of a point being sampled from the first distribution is higher, and that this effect is stronger when the system is informative. This is not readily apparent for group BI since the best fit uses a relatively low p value; however, μ_2 is also rather close to μ_1 , collapsing the distinction between the two populations into one. For all other models, $\mu_2 \approx 6.3$, as one would expect from the top figure in Fig. 5.

These results can be interpreted as follows: in each of the groups, a subset of the participants already drive at near-optimal levels. The eco-driving system is therefore going to be most effective only for the subset that does not. The reduced sampling from a distribution with a mean around 6.3 l/100 km whenever an eco-driving system is present supports this as it indicates that a larger number of participants drive at near-optimal levels in those groups. It also supports previous findings that any system will have an effect (Jamson et al., 2015b), although, in our case, the effect is nonetheless most clearly seen for group II.

As before, results for group IB, whose fit most resembles group BN, is at odds with the rest. This suggests that, for this group, the eco-driving system had no discernible effect. Again, this will be discussed more thoroughly in the discussion.

⁴ One-sided CIs for the difference between means are used throughout since the prediction is that the addition of basic and informative systems will improve (rather than merely change) performance.

Table 4
Mean estimated fuel consumption (l/100km) per condition and corresponding 95% confidence intervals.

			Eco-driving system		
			None	Basic	Informative
Nav sys	Basic	<i>m</i>	5.66	5.35	5.34
		CI	[5.41, 5.91]	[5.20, 5.50]	[5.19, 5.50]
	Inf.	<i>m</i>	5.41	5.54	5.27
		CI	[5.22, 5.60]	[5.25, 5.82]	[5.18, 5.36]

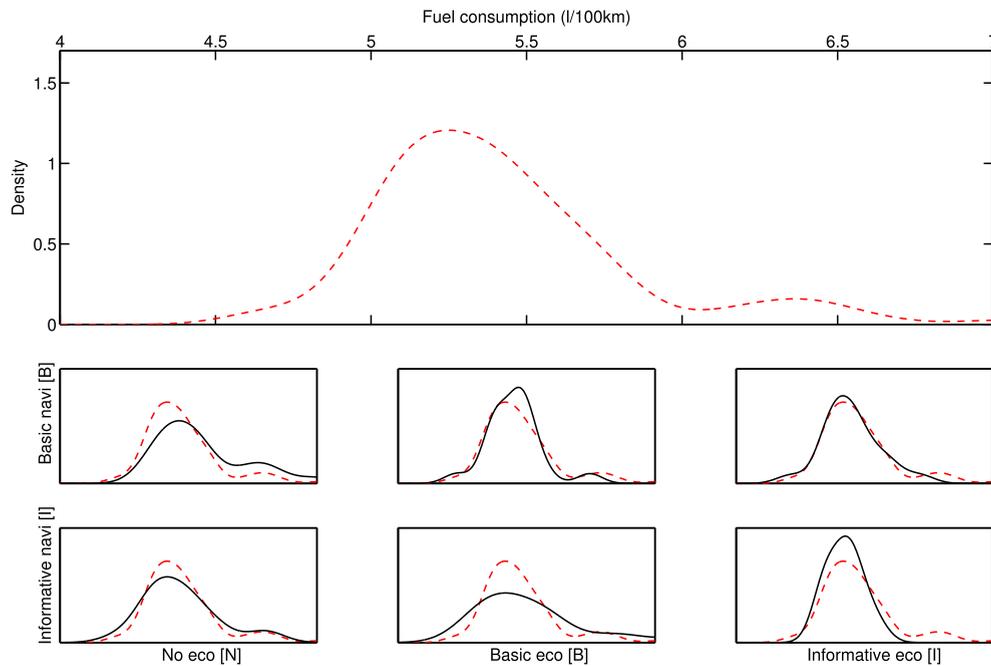


Fig. 5. Distribution of the mean fuel consumption for all participants (top) and split by condition (bottom group of graphs with dashed line reproducing the top graph).

Table 5
Model values and goodness-of-fit estimates for the distributions shown in Fig. 5.

	<i>p</i>	μ_1	σ_1	μ_2	σ_2	adj. R-square	RMSE
II	1	5.26	0.25			0.997	0.028
IB	0.78	5.27	0.44	6.34	0.71	0.996	0.016
IN	0.89	5.30	0.36	6.34	0.28	0.997	0.016
BI	0.38	5.23	0.19	5.42	0.42	0.998	0.017
BB	0.95	5.34	0.26	6.26	0.13	0.990	0.047
BN	0.75	5.28	0.32	6.36	0.35	0.997	0.016

4.2. Participant behaviour and adherence to system recommendations

4.2.1. Navigation system

The map in the present experiment featured two instances in which the navigation system's recommendation differed from the signposted roads: once in a roundabout, and once at a T-junction (see Fig. 2), allowing a brief validation of previous work on informative navigation systems (Thill et al., 2014).

In the present study, regardless of experimental condition, only very few participants would follow the road signs at the roundabout. At the T-junction, however, driving behaviour differed substantially as a function of whether or not they drove with a basic or informative navigation system. Overall, approximately 75% of the drivers followed the basic system while the informative system was obeyed by over 95% (see Table 6 for a summary of the results), in line with previous results.

We speculate that the main reason participants nearly always followed the system in the roundabout was because traffic signs were only placed outside the roundabout but not inside. There was thus no possibility to compare the system recom-

Table 6

The proportion of drivers that followed the road signs rather than the navigation system's recommendations.

Nav sys Eco sys	Basic			Informative		
	None	Bas	Inf	None	Bas	Inf
Roundabout	0.05	0	0.05	0.09	0.05	0
T-junction	0.3	0.26	0.2	0	0.09	0.04

mentation with a traffic sign if one had not remembered the previous sign. In general, interviews indicated that whenever the system recommendation was in conflict with road signs, drivers who followed the system did so because they believed that there was an underlying reason for the recommendation, and because they were themselves not familiar with the road. Previous positive experience with navigation systems also influenced this decision (the converse could also be observed: some participants who used the basic navigation system stated they did not trust the system because of previous negative experiences with (real) navigation systems). However, the decision to follow the system was facilitated when justifications (listed in Table 2) for the choices were given. As discussed in Section 2, however, it is not necessarily desirable to maximise such adherence: rather care has to be given to ensure that the system is designed so as to promote a level of trust in line with its abilities.

4.2.2. Eco-driving system

Driver behaviour is analysed in terms of gear changes and coasting as these were the two behaviours targeted by the recommendation system (see Table 7 for a summary of the number of recommendations given and adhered to).

Gear change behaviour was characterised by determining at what engine rpm state (defined as the state immediately preceding a press of the clutch) drivers switched to a higher gear. The results are shown in the left graph of Fig. 6. It can be observed that, with the recurring exception of group IB's behaviour, the presence of an eco-driving system encourages earlier gear changes, and this effect is more pronounced when the system is informative than when it is not. The significance of the effect is shown, as before, through one-sided Δm 95% CIs (BN and BB: [16.32, 197.98]; BN and BI: [217.4, 391.52]; BB and BI: [126.95, 267.67]; IN and II: [267.88, 443.05]). It can also be observed that group IB performed significantly worse (Δm 95% CI, IN and IB: [-323.12, -115.39]).

Similarly, coasting/engine brake behaviour was assessed by measuring the proportion of time that drivers spent *not* pressing down on any of the pedals. This is plotted in the right graph of Fig. 6 and it is apparent that groups which have an eco-driving system spend more time coasting (significantly so; one-sided Δm 95% CIs for BN and BB: [-0.05, -0.015]; BN and BI: [-0.05, -0.02]; IN and IB: [-0.07, -0.03]; IN and II: [-0.04, -0.01]). It is also apparent that there is no difference between basic and informative displays and, interestingly, this is the only measure in which the behaviour of group IB does not seem to be at odds with the general trend.

It is possible that the more efficient gear changes were simply a result of the larger visual stimulus given that an icon with justifying text will take up more space than the icon alone priming a faster response. However, Δm 95% CIs for the precise reaction times of the different groups (as measured as the time between the onset of the stimulus and the next clutch press within the previously mentioned time window) showed no significant differences. This casts doubt on the likelihood that the size of the visual stimulus had an influence on the efficiency of gear changes.

4.3. Categorical background effects

We also verified whether aspects of the participants' background (particularly those not balanced for) had a direct effect on the results. Group IB, for example, was found to contain both a larger proportion of younger drivers (those aged 29 or younger) and of drivers with previous experience of eco-driving systems than the other groups, which may be a contributing factor to their observed behaviours.

However, no consistent effect on either fuel consumption or coasting behaviour was found. Regarding gear changes, there were small but significant differences only between males and females: males changed gears on average at 3084.1 rpm (95% CI: [3048.43, 3119.76]) while females did at 2894.83 rpm (95% CI: [2834.28, 2955.39]), yielding a Δm 95% CI of [130.33, 248.19].

It is therefore unlikely that the results reported here, in particular the unexpected behaviour of group IB, can be explained by the participants' background.

4.4. Driver perception of informative systems

Overall, our results so far are in line with expectations that system awareness modulates adherence to the system recommendations. The questionnaires and interviews further support these results, indicating, for example, that participants trust informative systems more than basic ones and that justifying decisions appears to be a deciding factor. Several participants who used basic systems even suggested adding such justifications as a possible improvement to the system. For the navigation system specifically, participant responses also indicate that informative systems are perceived as more pre-

Table 7

Summary of the number of recommendations given per type (gear change or coasting/engine braking) as well as the proportion of recommendations followed. This adherence was defined as whether or not participants carried out an action compliant with the recommendation within a reaction time window based around the commonly assigned value of 2.5 s, from 0 to 3 s (following Chang et al., 1985; Sivak et al., 1982).

		Nav sys	Basic		Informative	
		Eco sys	Bas	Inf	Bas	Inf
Recommendation	Gear	n given ($m \pm s$)	10.95 \pm 4.21	6.50 \pm 3.62	10.14 \pm 3.48	6.72 \pm 4.25
		followed (%)	94.45	93.83	97.03	97.75
	Coast	n given ($m \pm s$)	9.89 \pm 3.19	10.85 \pm 4.17	12.05 \pm 2.86	10.27 \pm 3.63
		followed (%)	96.43	97.45	97.47	95.34

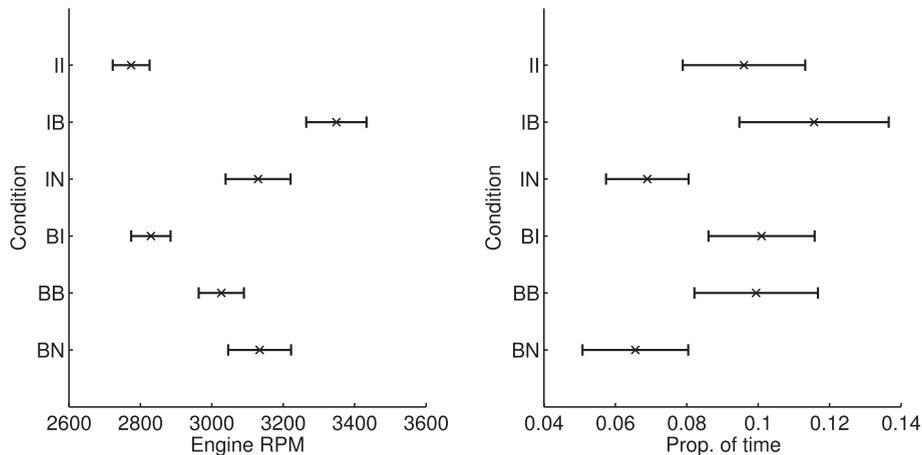


Fig. 6. Mean and 95% confidence intervals for (left) the engine rpm at which participants in the different groups (y-axis) change gears and for (right) the proportion of time that participants in the different groups spend engine braking.

dictable than basic systems, which may be another factor influencing trust. Finally, a contributor to trust in the system was that drivers could verify justifications by the system (since, for example, the traffic jam that the system mentioned was visible).

4.4.1. Situation and system awareness

In general, it appears that the justifications contributed to improved situation awareness at the higher level (projection, see Section 3.4.2 and Endsley, 1995). More specifically, several participants stated – in interviews – that information about upcoming events (such as speed limit changes, traffic light states, or events that require re-routing such as the traffic jam; see Table 2) allowed them to foresee required actions before they could see the event in question. Interviews also confirm that providing the additional information increased the participants' system awareness, as participants indicate that the justifications helped them understand how the system operates.

For the lower levels of SA, the majority of the participants in BN (about 90%) reported in the questionnaire that they were fully aware of what was going on in the traffic environment in their surroundings. This number was somewhat reduced for the other groups, especially for the II-group (55 %) indicating that the additional information could have a negative effect on the participants (subjective) perception of the situation (SA level I, see Endsley, 1995), although the better results at the higher SA level also indicate that a well-designed system might in fact reduce the need for lower-level SA. Support for this interpretation comes from results relating to questions about animals that were placed at several locations along the route (see Fig. 2): while only 55% of participants in group BN stated they perceived these as a safety hazard, the proportion was higher in the other groups, in particular group II (around 80%), which could indicate that having at least one informative system allowed the participants to focus more on relevant aspects of the surroundings. Interestingly, some of the events during the drive that had no clear relevance to safety (such as a truck waiting to merge with the road, see Fig. 2), were missed by the majority of participants across all groups). Supplementary Fig. S1 summarises the responses to the main lower-level SA-related questions in our study.

4.4.2. Usability of the system

Although it is not a main focus of this paper, it is interesting to briefly investigate how participants judge the usability of driver support systems such as used in this study. First, although participants appreciate the informative systems more than basic ones, those who experienced the informative eco-driving system in particular also reported it as distracting, possibly

due to the amount of text. Interviews indicated, for example, that participants appreciated the simple and minimalistic design of the systems. The amount of the information that they were provided with was in general viewed as appropriate, although opinions about the eco-driving system in particular varied. In general, however, interviews indicated an overall request to reduce the amount of information. It therefore appears, as also noticed elsewhere (see Thill et al., 2014), that there is a conflict between a desire for relevant information and a reluctance to invest additional effort into obtaining it.

Nonetheless, the reported intention to use the system(s) in the future was relatively high over all conditions (75% or more). Interestingly, it was lowest for group II (75%). This may indicate that participants already felt that they drove in an eco-friendly manner and therefore had no need for systems to promote this explicitly. This is further reflected in reports on the usefulness of the system, which indicated that participants across all groups found the navigation system useful, but that the eco-driving system's main utility was seen to assist drivers who wanted to learn how to drive in a more eco-friendly manner. Both systems were generally perceived as easy to use, with the navigation system (whose lowest score came from group BI in which 74% of the participants found it easy to use) more so than the eco-driving system (where the lowest values around 65% were found for groups BI and IB).

Supplementary Fig. S2 summarises the responses to the main usability-related questions. Overall, however, the focus of this study was not on usability as such, and it would require a more dedicated study to understand in detail what aspects contribute to or impede the perceived usability of systems such as those used here.

4.4.3. Perception of the systems as a whole

An important final insight from the interviews was that, when asked about how they perceived the systems, participants tended to compare them with each other. Thus, the eco-driving system was perceived as less predictable by participants in group IB than those in any other group. Similarly, about 75% of the participants in this group indicated in the post questionnaire that the navigation system performed according to expectations compared to 55% who found that the eco-driving system did. Interestingly, this trend was reversed for group BI, where most participants found the eco-driving system performed according to expectations (80% compared to 65% for the navigation system).

5. Discussion

5.1. Main results

In terms of fuel consumption, a significant difference between the most basic and the most informative systems (BN and II) was found. Further analysis of the distribution of fuel consumption performance revealed that providing an eco-driving system reduced or eliminated a sub-population of participants with a fuel consumption higher than that of the main population (see Fig. 5 and Table 5). This is in line with other studies: Jamson et al. (2015b), for example, found that any type of eco-driving advice has a noticeable result, and that real-time visual feedback is most effective.

In behavioural terms, the results suggest that the effect of system recommendations on driver behaviour is, in general, larger if the system is informative. The exception is the coasting recommendation, for which the informative version had no added effect. Since there are multiple possible reasons (for example, the full potential for coasting might already have been reached or the textual description (Table 2) in the informative case may have failed to convey the appropriate system awareness), we did not investigate this further here. However, interviews indicate that participants did not always see the need for the justifications provided by the eco-driving systems. For example, one participant remarked that he did not see the need to explain that shifting gears up was necessary due to high engine rpm. It may thus be possible that, to be most effective, justifications need to address aspects that are not obvious to the driver (which, in turn, may depend on the driver themselves).

It is worth pointing out that fuel saving should not necessarily be the primary variable of interest, in particular in simulator studies, (although it may obviously be that when the primary interest is in building a fuel saving system) when measuring eco-friendly driving behaviour. Fuel usage is an estimate that heavily depends on the fuel model used, and represents a nonlinear transformation of actual driver behaviours. It may therefore be more informative to measure those behaviours directly, as done in the present study.

In this context, it is also worth briefly highlighting limitations arising from the fact that, like many others, the present study was carried out in simulation. For example, several participants (across all groups) stated that they found it difficult to get a good feeling for the car dynamics, and they may have been following the eco-system in order to compensate for that. Others stated that they adhered to the system more or less automatically given that they were in a study, but that they might behave differently in real circumstances. While such an adherence to the system (whether due to unfamiliarity with the vehicle or due to automatic responses) cannot explain the observed differences between basic and informative systems, there is nonetheless a need to further validate these results in a real vehicle.

Another aspect we did not address in the present study is the effect that displaying eco-driving information may have on workload and, consequently, on driver distraction, awareness and overall safety. In general, how different in-vehicle information systems' interfaces and various modalities of feedback influence driver workload has been an important matter of study in this domain (see, e.g. Carsten & Brookhuis, 2005; Chen, Lin, & Doong, 2005; Engström, Johansson, & Östlund, 2005). For eco-driving in particular, several studies have evaluated the effect of displaying eco-driving information on

subjective workload. Most of these show an increase in workload (e.g. Hibberd et al., 2015; Rouzikhah, King, & Rakotonirainy, 2013), but it is not trivial to come to a general conclusion since many aspects play a role in this, such as the modality of feedback (visual, auditory, haptic, or others), the novelty of the task, type of interaction, and so on. For example, Jamson et al. (2015a) found that any type of eco-driving advice improved fuel-efficient driving, but while continuous visual feedback proved to be the most effective, this modality reduced attention to the forward view and reported higher subjective workload. Conversely, the haptic force system had little effect on reported workload, but was less effective than the visual system. There is certainly a need to further study the effects that systems such as the one used here (which, unlike most other studies, used a heads-up display), as well as a need to disambiguate between drivers' subjective workload and actual impact on relevant behavioural factors. This remains an interesting and an important topic for further research.

5.2. Conflicts in system performance

A recurring theme in the results was that group IB – the group with an informative navigation system, but only a basic eco-driving system – nearly always seemed at odds with the pattern of results observed across all others. We found no indication that this could have been due to some selection bias in that group. Our current hypothesis is that the discrepancy in informativeness between the navigation and eco-driving system – that one justified its recommendations and the other did not – may have led to a disregard of eco-driving recommendations.

Circumstantial evidence that this may be the case includes that, when participants were asked how “intelligent” they thought the vehicle was, the answers indicated that both systems (and their respective level of informativeness) were considered as a whole. Similarly, participants listed a number of possible improvements for the navigation system, including requests for more information ahead of events (such as a countdown to intersections, distance to a change in speed limit, advance warnings of upcoming turns, upcoming red lights). Although participants were discussing navigation systems, this type of information has bearings on eco-driving as well, and some of it is in fact in line with the justifications used by the eco-driving system (see Table 2). This further supports the idea that participants may not have treated the two systems as distinct, which may further have led to a preferential following of the justified recommendations only.

More work is needed to verify this, and we are not aware of other studies that investigate such an effect explicitly; but if replicated, it has consequences for the design of driver aids: their effectiveness may not just depend on their own performance, but also on their performance of other systems. It might, for example, not be valid to evaluate them in isolation, and effectiveness in one context (such as a specific vehicle design) may not necessarily transfer to a different one.

It is also worth pointing out that we did not find any evidence for a possible symmetry one might have expected between groups IB and BI. For example, while BI participants suggested that the navigation system could justify its recommendations, the converse was not true for the eco-system in group IB. However, this may simply be due to the different nature of the systems – even if their distinction was not always clear to the participants – and that, as interviews indicated, there simply was less of a consciously perceived need for the justifications attached to the recommendations by the eco-system.

6. Conclusions

We presented a simulator study on the effect of system awareness on adherence to recommendations by eco-driving and navigation support systems, finding that participants tend to follow recommendations more if systems additionally provide justifications for them.

Our study provides two main insights of relevance to the design of eco-driving support systems (and driver support systems in general). The first is that providing justifications for why recommendations are given appears to increase the effectiveness of the system. This is particularly interesting in the case of systems such as eco-driving systems, whose recommendations are in a sense entirely optional for the driver. We further found indications that drivers appreciate information about aspects that were not obvious to them more. Interestingly, however, the effectiveness on the system may not depend on that, given for example our results on gear change behaviour.

The second insight pertains to the evidence indicating that the effectiveness of one system may depend on the performance of other systems within the vehicle. This has implications for both the design and the evaluation of such systems. The next step would be to validate the results further in real vehicles.

7. Author contributions

ST: overall research design, experimental design, quantitative analysis, manuscript writing. **MR:** experimental design, user interface design, quantitative analysis. **EL:** simulator programming, experiment lead, participant interviews, quantitative analysis. **ML:** simulator programming, experiment support, simulator data visualisation tools. **PH:** experimental design. **AH:** user interface design, qualitative analysis. **MK:** overall research design, experimental design, user interface design.

All authors contributed to the preparation of the manuscript.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.trf.2018.05.009>.

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