Presenting system uncertainty in automotive UIs for supporting trust calibration in autonomous driving

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ABSTRACT
To investigate the impact of visualizing car uncertainty on drivers’ trust during an automated driving scenario, a simulator study was conducted. A between-group design experiment with 59 Swedish drivers was carried out where a continuous representation of the uncertainty of the car’s ability to autonomously drive during snow conditions was displayed to one of the groups, whereas omitted for the control group. The results show that, on average, the group of drivers who were provided with the uncertainty representation took control of the car faster when needed, while they were, at the same time, the ones who spent more time looking at other things than on the road ahead. Thus, drivers provided with the uncertainty information could, to a higher degree, perform tasks other than driving without compromising with driving safety. The analysis of trust shows that the participants who were provided with the uncertainty information trusted the automated system less than those who did not receive such information, which indicates a more proper trust calibration than in the control group.

Categories and Subject Descriptors
H.1.2 [User/Machine Systems]: Human factors

General Terms
Design, Human Factors, Experimentation

Keywords
Uncertainty visualization, trust, automation, driving, acceptance.

1. INTRODUCTION
Technological advances have led to the development of numerous driver assistance systems such as adaptive cruise control, lane departure warning, collision avoidance, automatic parking and driver drowsiness detection systems. Experiments with fully autonomous cars have also been carried out, which provides us with a glimpse of what the future might hold. The purposes of developing such support systems are to make driving safer, easier, more relaxing and more enjoyable. However, such goals can only be achieved if the driver feels comfortable enough to hand over control to the automation and if a good cooperation between the driver and the automation can be achieved. Studies from other domains, such as the aviation domain, have shown that the anticipated positive effects of automation might be diminished due to human-automation cooperation related problems, such as automation misuse and disuse [1, 2], automation surprises and mode confusion [3, 4], reduced situation awareness [5], complacency as well as over reliance on the automation [6]. To reduce the possible negative effects of automation, while at the same time reinforce the positive ones and promote a safe and appropriate usage of the automation, several researchers have highlighted the importance of informing the human operators of the strengths and limitations of the automated systems used, as well as the continuous state of the automation (see for instance [7-11]). For example, in the study by Stanton and McCaulder [12], it became evident that the drivers had insufficient knowledge of the limitations of the adaptive cruise control system, resulting in collisions due to the drivers’ inappropriate levels of trust in the automated system. This finding is in line with the research reported by Dzindolet et al. [13] and McGuirl and Sarter [7] where it was found that operators who were provided with continuous feedback regarding the performance of the automated aid had more appropriate trust in the aid than operators who were not given such information.

We argue that more research is needed to evaluate the effectiveness of providing feedback on changes in the automated system’s capability during autonomous driving. To the authors’ knowledge, no research has addressed how to convey the limits and performance of automatically driven cars to their drivers as a means to achieve appropriate trust. As such, the objective of this study was to evaluate the effects of visualizing a continuous representation of car uncertainty on the drivers’ trust in the automatic support system used. First, we wanted to assess if such visualization would make the drivers able to more appropriately calibrate their trust in the system while at the same time making them aware of the limitations of the system. Secondly, due to one of the motivations for introducing automation in cars, namely to
enable drivers to feel more relaxed while driving and even to perform other things while travelling, we also wanted to investigate if displaying the uncertainty representation would result in a higher number of drivers performing other tasks than driving during the test scenario. Finally, we also wanted to test if the drivers being presented with the uncertainty information would look away more from the road than the drivers not being provided with this information, while at the same time being better prepared to take control over the car when/if needed (i.e. requiring less time to take manual control over the car).

The paper is structured as follows: section 2 provides information regarding advances within the area of uncertainty and system reliability visualization. Section 3 presents the study setup, whereas section 4 reports on the study findings and section 5 presents a brief analysis of the results. Section 6 discusses the results obtained whereas the conclusions and ideas for future work are found in section 7.

2. RELATED WORK

The visualization of uncertainty in the context of automatic driving has been recently studied by Beller et al. [14]. The aim of this study was to evaluate whether communicating when the car was uncertain using a symbol (a face with an uncertain expression) improved the driver-automation interaction. A driving simulator experiment varying the level of uncertainty with 28 participants was conducted. The results show that the presentation of uncertainty information increased the time to collision in cases of automation failure, that situation awareness was improved and that automation with the uncertainty symbol received increased acceptance and higher trust ratings. These positive results regarding the visualization of information related to smart systems in cars seem to coincide with two previous studies, i.e., Verberne et al. [15] and Seppelt and Lee [8].

Seppelt and Lee [8] investigated if a visual representation of the adaptive cruise control (ACC) behavior promote appropriate reliance and support effective transitions between manual and ACC control. Twenty-four participants were recruited to drive in two different situations, with different failure types. In traffic conditions, the participants relied more appropriately on ACC when the information about the ACC was present. Moreover, it promoted faster and more consistent braking responses and show additional positive effects in other traffic situations. The authors suggest that providing drivers with continuous information about the state of the automation is a promising alternative to providing warnings.

The work presented by Verberne et al. [15] focuses on investigating if representations of descriptors of three ACCs with different automation levels that either shared their driving goals or not affected trustworthiness and acceptability of those systems. A driving experiment with 57 participants was carried out. The results show that ACCs that took over driving tasks while providing information were more trustworthy and acceptable than ACCs that did not provide information.

Several relevant works regarding the influence of uncertainty visualization on decision-making can be found in other research areas, such as the military domain. For example, Finger and Bisantz [16] studied the use of blended and degraded icons to represent uncertainty regarding the identity of a radar contact as hostile or friendly. The first part of the study showed that participants could sort, order and rank five different sets of icons conveying different levels of uncertainty. In the second part of the study, three of the pairs of icons were used in an application in which participants should identify the status of contacts as friendly or hostile. Three conditions were studied: with degraded icons and probabilities, with non-degraded icons and probabilities and with degraded icons only. The results demonstrate that participants using displays with only degraded icons performed better on some measures and as well on other measures, than the other tested conditions. Thus, the use of distorted or degraded images may be a viable alternative to convey situational uncertainty.

Wang et al. [17] examined the effects of presenting the aid reliability on trust and reliance on a combat identification (CID) scenario. Twenty-four participants carried out a simulated CID task, half of whom were told the reliability level. The results show that response bias varied more appropriately with the aid reliability when it was disclosed than when not, and that trust in aid feedback correlated with belief in aid reliability. The authors highlight that to engender appropriate reliance on CID systems, users should be made aware of system reliability.

3. METHOD

3.1 Participants

A total of 59 participants (31 male, 28 female) between 28 and 58 years old (4 between 21–30 years, 22 between 31–40, 25 between 41–50 and 8 between 51–60) with an average age of 41.2 years took part in the simulator experiment. The participants were selected from a population of 488 Volvo employees, mostly non-technical personnel of whom none is involved in the development of functionality for autonomous driving or the implementation of the driver’s information module (DIM). The only prerequisite for taking part in the study was that the participant had a driver’s license.

Each participant was randomly assigned to a display condition. A balanced latin square design was used in order to minimize the effects of participants driving early in the morning, directly after lunch and late in the afternoon. This led to 30 participants (16 males and 14 females) driving with the added uncertainty information and 29 participants in the control group.

3.2 The DIM

Two interfaces were designed – one with and one without the uncertainty representation. Figure 1 shows a sketch of the DIM design including: the speedometer, the engine speed, the fuel level, the outside temperature, the current time, the current gear used, the placement of the steering wheel during the autonomous drive as well as the ability of the automation to maneuver the car. During the experiments performed together with the control group, the information regarding the automation ability was taken away. Figure 2 depicts two states of the ability of the automation, from high ability (left figure) to low ability (right figure) as indicated by the color/transparency of the 7 levels, as well as the red arrow, representing the threshold where the ability of the automation no longer can be guaranteed.
Figure 1 - Sketch of the DIM used during the experiments (including the representation of uncertainty).

Figure 2 - Graphical representation of the ability of the car to drive autonomously, ranging from 7 (very high ability, left figure), to 1 (no ability, right figure). The red marking indicates the threshold for when the performance of the automated driving system no longer can be guaranteed.

The DIM was placed in the instrument cluster of the car in front of the driver. The design of the interfaces was carried out in collaboration with an expert HMI designer at Volvo cars. As such, we argue that its design is similar to other interfaces used in Volvo cars.

3.3 Procedure and questionnaire
The participants were first informed of the purpose and setup of the study. Thereafter, all participants were allowed to drive the car simulator in manual mode for about 3–5 minutes so as to get acquainted with the simulator. Directly after the training session, the participants were informed of the prerequisites of the test session: that the car could drive autonomously, but that the performance of the automatic driving system was coupled to the weather conditions. The participants were also informed that they could at any time take control over the car by steering/braking/giving gas to the car in accordance with their own assessment of the appropriateness of using the system. The DIM was explained to both of the groups; however, the uncertainty representation (see Figure 1) was presented and explained to only one of the groups (hereafter “with uncertainty information group”). Before the start of the test session, the participants were informed that there were newspaper and sweets at their disposal in the passenger seat if they so pleased. Thereafter, the 9-minute test session started.

After the test session, the participants were asked to fill out a questionnaire about their trust in the system, using a modified version of the trust in automation scale [18]. The participants answered seven questions such as “I am confident in the system” and “I can trust the system” using a seven point Likert scale ranging from 1 (fully disagree) to 7 (fully agree). The instructions given to the drivers and the questionnaire can be found in the appendix.

3.4 Simulator
The experiments were carried out at the Human Machine Interaction (HMI) laboratory at Volvo Car Corporation, Gothenburg, Sweden. The laboratory contains several integrated systems: a driving simulator and a fully functioning cockpit (see Figures 3 and 4).

Figure 3 - Driving simulator, Volvo Car Cooperation HMI lab.

Figure 4 - Overview of HMI lab

The participants drove the car simulator through a snowed two-lane country-side road, with a number of sharp turns, but with no other traffic (see Figure 5). Due to the weather conditions, the intensity of snowing varied from 0% to 100% where the maximum amount of snowing is illustrated in Figure 6, and the minimum amount (0%) corresponds to a clear sky with full visibility. The snowing intensity varied according to Figure 7. The direction and speed of the car were controlled by the automation. The speed of the car was independent of the snowing intensity (see Figure 7), but did change at times according to road conditions (sharp turns and hilltops). When the visibility was the worst, the car simulator could no longer maneuver the car. At this event, the automation stopped working.
completely, meaning that no gas or steering was provided, without giving any warning to the driver (apart from the graphical representation in Figure 2 and switching to the manual DIM).

3.5 Collected data
Logs from each simulator session were recorded. The quantitative data thus collected corresponds to values from steering angle, brake, acceleration, look away time and weather conditions. Cameras were used to record all the sessions.

In addition to the quantitative data, qualitative data was collected through observing the participants. The data collected included to which extent the driver had his/her hands on the steering wheel, if the participant stayed on the road after take-over and if the participant read the newspapers or ate the sweets provided. Time to take-over (TTO) was calculated by analyzing the logged data, measuring the time between the snowing intensity reaching its maximum (1.0) and a significant change in either braking or steering (indicating that the driver had taken control over the vehicle).

4. RESULTS
Regarding time to take-over, the group provided with the uncertainty representation needed 1.9 seconds to take control of the car on average while the control group needed 3.2 seconds. The individual results are shown in Figure 8 below.

The differences between the two groups are summarized in Figure 9 below.

The results were submitted to a one-way ANOVA analysis. The analysis showed that, with a 95% certainty, there is a statistically significant difference between the two groups \([F(1, 57)]= 5.62, p=0.02\). Regarding looking away from the road, the group provided with the uncertainty representation, on average spent 18% of the driving time looking at other things but the road, while the control group was looking at other things 12% of the time on average. The individual results are shown in Figure 10 below.
The differences between the two groups are summarized in Figure 11 below.

A one-way ANOVA analysis showed that, with a 95% certainty there is a statistically significant difference between the two groups \(F(1, 57) = 4.81, p = 0.03\).

In addition to the proportion of the total time spent on looking at other things than the road ahead, the number of times drivers looked away for more than 2 seconds were counted, since this is regarded as the limit for how long a driver can look away while maintaining awareness of the situation ahead [19]. The group provided with the uncertainty representation looked away for more than 2 seconds 8.0 times on average, while the control group looked away 5.0 times on average (see Figure 12 below).

A one-way ANOVA analysis \((\alpha = 0.05)\) showed that there is no statistically significant difference between the two groups with respect to looking away from the road ahead for longer periods of time \(F(1, 57) = 2.54, p = 0.12\).

Trust was assessed using the scale for trust in automated systems developed by Jian et al. [18]. Participants of both groups answered the questions after the driving exercise, using a seven point Likert scale ranging from 1 (fully disagree) to 7 (fully agree). The questions are listed in the appendix. The results are shown in figures 13-14. The mean of the scores was used as an overall trust score (as presented by Beggiato and Krems [10]). The average trust value for the control group was 5.30, while the group with uncertainty representation shows an average trustworthiness of 4.89.

Reliability was measured using Cronbach’s alpha values. The values obtained, 0.87 (with uncertainty representation) and 0.85 (control group) show a good internal consistency \((0.8 \leq \alpha < 0.9)\).
The analysis of the participants’ responses regarding system’s trustworthiness (see questions in the appendix) show that, on average, the control group perceives the car without information about uncertainty more trustworthy (mean=5.30 vs. mean =4.89).

5. ANALYSIS

The results show that presenting (un)certainty information results in better prepared drivers in take-over situations. The difference in look away times between the two groups manifested itself in that of the 33 drivers that stayed on the road after take-over, 20 (61%) were drivers provided with the uncertainty information.

Furthermore, the results show that drivers presented with (un)certainty information look away from the road to a higher degree. Although looking away more in terms of total time compared to the control group, the drivers who were presented with the uncertainty information did not look away for longer periods of time more often.

Lastly, the collected qualitative data indicate that drivers who were presented with the uncertainty information would perform other tasks than driving during the test scenario. Of the 15 drivers that read the newspapers, 9 (60%) were from the test group. Of the 21 drivers that ate of the sweets, 11 (52%) were from the test group. More important, of the drivers that read the papers and drove off the road at take-over, only 20% were from the test group. Of the 28 drivers that, to a lesser or greater extent, kept their hand on the steering wheel during the test, 12 (43%) were drivers provided with the uncertainty information. More important, of the drivers that kept their hands on the wheel and drove off the road at take-over, only 20% were from the test group.

To summarize, the results show that drivers provided with the uncertainty information performed better in take-over situations and they were also more comfortable with performing other tasks while driving, as compared to drivers without this information.

6. DISCUSSION

Results from the study show that the drivers who were informed of the car uncertainty were better prepared in take-over situations. Also, these drivers had better calibrated their trust in the automatic driving system, whereas the control group reported on higher trust ratings despite the needed manual take-over in the scenario used in the training sessions. These findings are in line with the work presented by McGuril and Sarter [7] where the participants who were informed of the system confidence were better able to more appropriately calibrate their trust in the decision aid.

Even though the drivers with certainty information were better prepared to take control of the car while, on average, spending more time doing other activities, the results show that the trust scores for this group were worse than the group without aid. The findings reported in this paper are in contrast to the ones reported by Beller et al. [14] and Seppelt and Lee [8], that recommend that providing drivers with continuous information about automation is preferable to providing warnings, and that information about automation increase trust and acceptance. A possible explanation for interpreting our results can be found in Dzindolet et al. [13], where the role of trust in automation reliance is studied. Their findings suggest that participants initially considered automated decision aids trustworthy and reliable, but, after observing the automated aid make errors, participants distrusted even reliable aids, unless an explanation was provided regarding why the aid might err. Knowing why the aid might err increased trust in the decision aid and increased automation reliance, even when the trust was unwarranted. Thus, it should be further investigated if the visual representation of the car uncertainty used in our study should be complemented with additional information regarding why the level of uncertainty used was high.

Another representation of the car’s ability to autonomously drive could have generated different results than the ones obtained. According to Seppelt and Lee [8], not just any representation of continuous information will enhance driving performance. In the experiment presented in [8], it was concluded that the use of color dilution to represent sensor degradation in a rain condition was not an effective cue. Further, to combine a graphical representation of uncertainty together with a haptic and/or sound etc. could result in better performance regarding time to take over times and longer look away times.

Individual differences in trust in automation and automation reliance should be further explored. Lee and Moray [20, 21] found strong individual differences in automation use – some participants were prone to use manual control, others were prone to use automation. As such, future work should include a further analysis of the results in relation to the participants’ estimated locus of control and driving styles.

Several limitations of the study should be mentioned. The driving scenario and exercise might be considered very simple, but it was designed to analyze the effect of uncertainty visualization on trust and how the drivers would take over the control of the car when automation could no longer guarantee a safe drive, thus, we tried to minimized other experimental variables that could affect the driving task and affect our analysis on trust and automation reliance. It might be that the simplicity of the scenario made some of the participants in the test group neglect the uncertainty representation and concentrated on the weather conditions instead. Moreover, the uncertainty of the automation could have been
associated with additional parameters than the weather, such as other contextual information, e.g. the traffic situation.

Regarding the validity of the study here presented we would like to highlight that during the design of the experiment we ruled out extraneous variables that could affect our study on trust issues and automation making as simple scenario as possible (e.g. avoiding dense traffic or overtaking situations) guaranteeing, thus, internal validity. An experiment has external validity (generalizability) if the results are not unique to a particular set of circumstances, but generalizable. We are confident that the large number of participants in this study, as well as the selection criteria applied, make the results presented generalizable.

7. CONCLUSIONS
This paper has reported on an empirical study performed together with 59 drivers in a simulator experiment, were the effects of displaying continuous support system uncertainty during an automated driving scenario was evaluated. The results indicate that drivers who were informed of the car uncertainty were better prepared to switch to manual control when required than the control group. Further, the control group showed tendencies of automation bias, resulting in inappropriate calibrations of trust, which is also in line with research presented by [13], where it was concluded that people generally have positive expectations of unfamiliar automated decision aids.

Future work will include additional data collection regarding the participants in the study so as to associate the results with information regarding the drivers’ driving style and their perceived subjective locus of control. Future work will also explore other driver-automation forms of collaboration. As discussed by Inagaki [22], for the human-automation collaboration to progress, the automation might need to implement some control actions when it determines that the human is in a condition where he/she is unable to give directives to the automation, resulting in automated technologies that are able to understand the human’s psychological and physiological conditions, intentions and actions in relation to the situation. In a driving scenario, such cooperation could be based on the automated car’s understanding of the current status of the driver (alert, sleeping, texting etc.) and adapt the level of automation and the frequency of warnings accordingly.

The transition of control is also a topic which needs further structuring and investigation [23]. According to Flemisch et al. [11], there are many questions that need to be investigated regarding the proper balance between the driver and the automated systems, special about the authority of the assistance and automated systems in emergency situations. How to design such driver-automation handovers must also be further explored.

APPENDIX
A1: Listed below are the questions for measuring trust answered after the driving exercise:

- Q1: I understand how the system works – its goals, actions and output
- Q2: I would like to use the system if it was available in my own car
- Q3: I think that the actions of the system will have a positive effect on my own driving
- Q4: I put my faith in the system
- Q5: I think that the system provides safety during driving
- Q6: I think that the system is reliable
- Q7: I can trust the system

A2: Below follows the instructions given to the drivers provided with the uncertainty information (the same instructions were given to the control group, with the exception of the information regarding the uncertainty representation):

- You will first practice to drive the car manually in the simulator for about 5 minutes. Thereafter, the test session will begin, which runs for about 10 minutes and is performed fully autonomously, that is, the automation maneuvers the car as good as it can, based on, amongst other variables, the prevailing sight conditions.
- In the instrument cluster for autonomous driving the following is displayed: the speed, the engine speed, the current gear used, the outside temperature, the current time, the fuel level, the position of the steering wheel during the autonomous drive, and how confident the car is about its ability to drive autonomously. The red arrow indicates the limit for when the automation no longer can maneuver the car.
- To start the test session, put the gear in driving mode. The car starts to drive autonomously when you press the gas pedal, thereafter you can let go of the pedal. You can take control over the car again if you so please at any time by steering/braking/giving gas at any time.

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