Autonomous Driving: Investigating the Feasibility of Car-Driver Handover Assistance

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ABSTRACT
Self-driving vehicles are able to drive on their own as long as the requirements of their autonomous systems are met. If the system reaches the boundary of its capabilities, the system has to de-escalate (e.g. emergency braking) or hand over control to the human driver. Accordingly, the design of a functional handover assistant requires that it enable drivers to both take over control and feel comfortable while doing so – even when they were "out of the loop" with other tasks. We introduce a process to hand over control from a full self-driving system to manual driving, and propose a number of handover implementation strategies. Moreover, we designed and implemented a handover assistant based on users' preferences and conducted a user study with 30 participants, whose distraction was ensured by a realistic distractor task. Our evaluation shows that car-driver handovers prompted by multimodal (auditory and visual) warnings are a promising strategy to compensate for system boundaries of autonomous vehicles. The insights we gained from the take-over behavior of drivers led us to formulate recommendations for more realistic evaluation settings and the design of future handover assistants.

ACM Classification Keywords
H.1.2 User/Machine Systems: Human factors; H.5.2 User Interfaces: Evaluation/methodology, Graphical user interfaces (GUI), Prototyping, Screen design (e.g., text, graphics, color), User-centered design

Author Keywords
Car-driver handover; Autonomous driving; User study; Driving simulator; Human-computer-interaction; Human factors; Multimodal interface

INTRODUCTION
Many advanced driver assistance systems have emerged in the past decades, for example collision avoidance, lane departure warnings, and even automated systems such as adaptive cruise control (ACC), full speed range ACC, lane centering, and automatic lane changing. Prototypes of self-driving cars have already been presented and tested on public roads. For instance the media has discussed at length the self-driving car of Google that is equipped with neither a steering wheel nor an accelerator or a brake pedal. However, it is not likely that we will move directly from manual driving to fully autonomous driving. Initially, it is more probable that there will be highly automated vehicles on our roads that provide the opportunity of being manually controlled in critical situations.

Even if the automated systems are improved constantly, some situations that today's systems cannot handle in daily usage scenarios may remain an issue for the foreseeable future. Therefore, highly automated vehicles have to provide mechanisms that allow drivers to take over control.

This paper adresses such handover situations that govern the transition from full automation to manual driving. First, related work is discussed. Next, the design of a handover assistant is presented. Subsequently, we report the execution and results of an in-lab study that investigated different warning designs and varying situations after the take-over. Finally, we provide a conclusion and recommendations for the design and implementation of future handover assistants.

RELATED WORK
As both reasearch and industry progresses towards *Full Self-Driving Automation* [1] public roads may be filled with a great number of vehicles that are capable of driving autonomously as long as certain circumstances are given, i.e. scenarios that allow the sensors to work properly. As a consequence, vehicles that support *Limited Self-Driving Automation* [1] have to hand over control to the driver if the required conditions are not met. Gold and Bengler [5] defined a generic procedure for take-over situations: If the autonomous system detects that a system boundary currently applies, it requests the driver to take-over via a *Take-Over Request* (TOR). As soon as the driver gazes on the traffic scene, the self-driving automation is shifted to manual driving within a *transition area* that begins when the driver starts to steer. The time period between the TOR and the moment when the vehicle reaches its system boundary is called *time budget*.

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As a consequence of autonomous driving drivers may engage in non-driving related tasks. Thus, drivers should be considered to be “out of the loop” [11]. It has been shown that distracted drivers are capable of taking over control within a time budget of 4 to 8 seconds, depending on the complexity of the situation [3]. If drivers are provided with a longer time budget, they brake less and intervene later [6]. Furthermore, the length of the time budget has an impact on the error rate – drivers make less errors in take-overs with a larger time budget [3]. A study of Damböck et al. [3] also discovered an impact of the varying time budgets on the drivers’ perceived comfort during the take-overs.

Another human-computer interaction issue in autonomous driving is the impact of the automation on the post-automation behavior of drivers. Brandenburg and Skottke [2] investigated the effect of platooning. After 33 km of platooning (20 minutes), their participants decreased their distance to the lead vehicle (for up to 8 km (≈ 5 minutes)), increased their speed partly and deviated further from the middle of their lane (for up to 10 km (≈ 6 minutes)) compared to their pre-automation driving behavior. They concluded that highly automated driving has a critical impact on the post-automation behavior of drivers.

Taking these issues into account, there are special requirements for in-vehicle interfaces in this domain. Martens and van den Beukel [11] outlined a number of design recommendations, e.g. to interrupt secondary tasks and to use force feedback to achieve fast information transmission. A lot of work was conducted to investigate different modalities (auditory, visual, and tactile) to alert drivers (e.g. [4, 9, 14]). In fact, multimodal combinations thereof are promising [7, 13]. The use of warning cues is not limited to alerting drivers; they can also guide spatial attention [8], encode urgency [12, 13] or provide further information (e.g. verbal messages). For critical situations, it is recommended to communicate the reason for imminent system behavior (i.e. *why* something is going to happen) as well as the behavior itself (i.e. *how* the system is going to react), whereas for uncritical situations the reason alone is sufficient [10].

DESIGN OF A CAR-DRIVER HANDOVER ASSISTANT

In order to investigate the behavior of drivers during and directly after a take-over, respectively, we developed a car-driver handover assistant. The following subsection describes a generic handover process for the transition from full self-driving automation to manual driving. The remainder of this paper addresses a concrete handover assistant prototype implemented regarding a concrete scenario: approaching screens of fog. The assumption of this scenario is that the autonomous system is not able to work properly in dense fog. As a result, the system hands over the control to the driver when it detects a screen of fog. This scenario is fictional, i.e. it is not based on the capabilities of real world sensors which may well function despite adverse weather conditions. However, even for the average driver, this scenario is easy to comprehend. As such it is qualified to simulate a complete handover in a predictable situation.

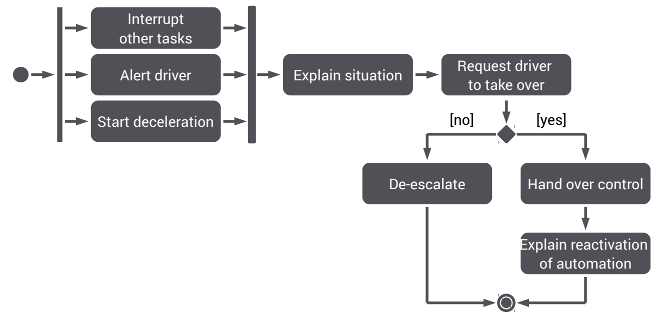


Figure 1: Procedure of a generic handover process from full self-driving automation to manual driving.

Handover Procedure

Fully self-driving vehicles have to alert drivers prior to requesting them to take over. Figure 1 shows the procedure of a generic handover process from full automation to manual driving. In parallel to the alert, the system should interrupt secondary tasks and start deceleration. If the alert did not already provide the reason for the system behavior, the reason should be communicated right after the alerting cue. After the system has gained the driver’s attention it can request them to take over. Finally, the handover of control can proceed. It may also be useful to explain to the drivers how they reactivate automation. If the driver does not take over, the autonomous system has to manage the situation on its own. There may be different de-escalation strategies depending on the situation, e.g. driving at a lower speed, or an emergency stop on the side of the road.

There are different possibilities for the implementation of the actual handover of control. We propose that the following handover procedures be taken into consideration, as well as some suitable combinations thereof:

Immediate Handover Complete shift of control from one second to the other, e.g. when drivers grasp the steering wheel.

Stepwise Handover Control is handed over step by step, e.g. first longitudinal control followed by lateral control, or vice versa.

Driver Monitored Handover Drivers monitor the system behavior, e.g. by grasping the steering wheel (force feedback). After a certain period of time (countdown), the control is handed over.

System Monitored Handover The system monitors the inputs of the driver for a certain period after the handover. In cases wherein the driver input may result in an unsafe situation, e.g. too harsh braking that threatens to result in a rear-end collision, the system can adjust the inputs.

As a first step in the investigation whether drivers are able to take over full control immediately, and moreover, to observe the full spectrum of drivers’ behavior during a take-over, the prototype presented in this paper implements an *immediate*

(a) “Caution: Fog” alert.

(b) “Caution: Take over the wheel” take-over request.

Figure 2: Screenshots of the “Caution Fog” alert and the take-over request. Along with both visual cues, an abstract earcon was played followed by a verbal message that gives the same text as displayed visually.

handover procedure. Thus, the control is shifted as soon as the driver grasps the steering wheel.

Alerting the Driver

The related work shows that multimodal alerts are particularly promising. Thus, the combination of auditory and visual messages should be used for the alert and take-over request in the handover assistant. The design space is manifold, for instance the auditory cues could be abstract earcons, real world sounds, or spoken messages – or combinations thereof. A visual cue could be iconographic and textual. An online survey on the personal preferences of 25 participants was conducted to tailor the large design space down for the implementation of a concrete prototype. Figure 2 shows screenshots of the resulting prototype[1]. Simultaneously to the visual alert and take-over request, abstract earcons are played followed by a verbal message that gives the same information as the visual cue: “caution fog” and “caution take over the wheel”.

STUDY

An explorative in-lab user study was conducted to gain deeper insights into the take-over behavior of drivers. With the help of this study, the proposed and implemented *immediate* handover assistant was evaluated. This study intended to reveal whether drivers that are distracted by a realistic distractor task are able to take over the control from one moment to the other, and if they feel comfortable with such handovers. The study was conducted with the implemented prototype and the *approaching screens of fog* scenario.

[1]The survey and the study was conducted in Germany, thus the auditory and visual cues were presented in German: “Achtung Nebel” and “Achtung übernehmen Sie das Steuer”.

Figure 3: This driving simulator of the Institute of Media Informatics at Ulm University was used for the evaluation. The image shows a participant watching a video to her right (distractor task) while automation is enabled.

Apparatus

The user study was conducted in the driving simulator of the Institute of Media Informatics at Ulm University (see Figure 3). The driving scene was presented on three 40-inch displays positioned in front of the driver’s seat. Drivers were able to steer, brake and accelerate from a RaceRoom Game Seat equipped with a Logitech G27 Racing Wheel. In addition, a copper wire was coiled around the steering wheel in order to function as a hands-on sensor. Moreover, a 7-inch display, positioned to the right of the steering wheel, enabled multimedia presentations of videos and alerts while driving. The prototype under discussion was implemented using an adapted version of the OpenDS simulation software.

Participants

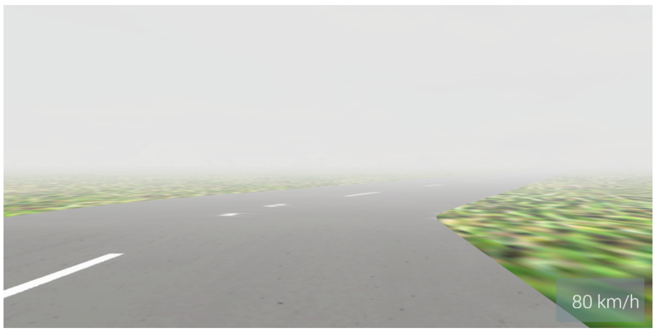
Thirty participants (9 women) participated in the study. The ages ranged from 20 to 36 years ($M = 24.9$, $SD = 3.42$). All participants had owned a driving licence for 3.25 - 18 years ($M = 7.45$, $SD = 3.04$) and reportedly drove between 20 and 50,000 km in the past twelve months. All participants owned at least a higher education entrance qualification.

Procedure

Participants were provided with three different warning conditions that varied the information content and the time budget:

- **ALERT&TOR** The combination of a “caution fog” alert followed by a take-over request displayed 6 seconds prior to the vehicle reaching the screen of fog.
- **TOR4SECONDS** The take-over request displayed 4 seconds prior to the vehicle reaching the screen of fog.

(a) A broken-down car in the CARHAZARD Situation.



(b) A sharp curve in the CURVEHAZARD Situation. There were two left turns (119° and 130°) and one right turn (148°).

Figure 4: The hazardous situations with which the participants were challenged. These hazards were positioned 50 m after the start of the fog.

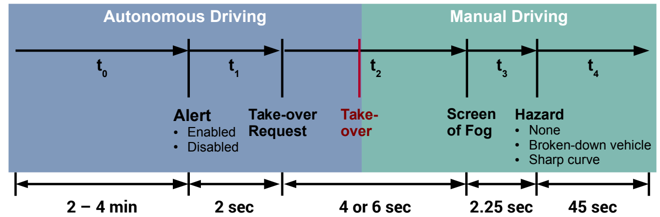


Figure 5: Procedure of a trial: Autonomous driving until the system asks the driver to take-over. In some cases, a hazard appears 50 m behind the screen of fog. The autonomous system drives at a speed of 80 km/h; as soon as the participants took over, they could adjust the speed (up to 100 km/h). The reported durations in the graphic are based on a continous speed of 80 km/h.

TOR6SECONDS The take-over request displayed 6 seconds prior to the vehicle reaching the screen of fog.

The “caution fog” alert as well as the TORs were displayed visually on the front scene and the multimedia display, as well as auditively, for two seconds each. This resulted in a presentation duration of four seconds in the ALERT&TOR condition and two seconds in the two pure take-over request conditions.

Besides the different warning conditions, the participants were challenged with three different situations. In two of them there was a hazardous circumstance 50 m beyond the screen of fog: a broken-down car (CARHAZARD) or a sharp curve (CURVEHAZARD). The screenshots in Figure 4 show these hazardous situations. In the third situation there was no hazard at all (NOHAZARD).

As a result, each participant had to pass 3 (warning conditions) x 3 (situations) = 9 trials. These trials were presented in randomized order with the constraint that the first trial contained one of the NOHAZARD situations. In order to avoid learning effects, each trial was passed only once. Every trial started with an autonomous driving part that lasted two to four minutes at a speed of 80 km/h before the alert or TOR was presented (see procedure in Figure 5). The duration of autonomous driving varied among the trials to prevent temporal predictability of the handover.

The screen of fog was positioned at a fixed point. Depending on the time budget, the warning appeared four or six seconds before the vehicle would pass the screen of fog. From that point onwards, the drivers were confronted with dense fog. The broken-down car was perceivable as a pixel on the flat horizon from a distance of about 650 m; from a distance of 190 m it could be recognized as a vehicle (shortly before the warnings appeared). In contrast, the sharp curve became visible only from a distance of around 30 m.

At the end of each trial the participants were asked to rate the take-over on a 7- point Likert scale (see [3]) that ranged from *very stressful* to *very comfortable*.

While the automation was active, the participants were engaged in a realistic distractor task. They were instructed to watch a video on a screen to the right of the center console. To ensure that the participants focused on the video they were informed that they would have to answer three questions at the end of each trial regarding mainly visual attributes of the videos. The videos originated from German public service broadcasting, and included genres such as travel, science, nature and talk shows. Furthermore, participants were motivated to focus on the videos by a 10 Euro Amazon voucher for the participant with the most correctly given answers.

Each session lasted about 70 minutes and started with a short introduction and the collection of demographic data. Next, the participants were introduced to the driving simulator and had to pass a manual driving training for about 8 km. The training track also contained a broken-down car and a sharp curve. This manual driving training was intended to familiarize the participants with the driving simulator. Afterwards, the full self-driving automation and the handover concept was introduced followed by two training runs. After these training phases the nine trials were executed. The participants had to answer a questionnaire on their take-over behavior and strategy at the end of the session, and were subsequently rewarded with 10 Euros.

In summary, we conducted a 3x3 repeated measures within-subject design with the factors *situation* and *warning*. The take-over time, the first brake application, the perceived comfort, as well as several subjective ratings on the ease of tak-

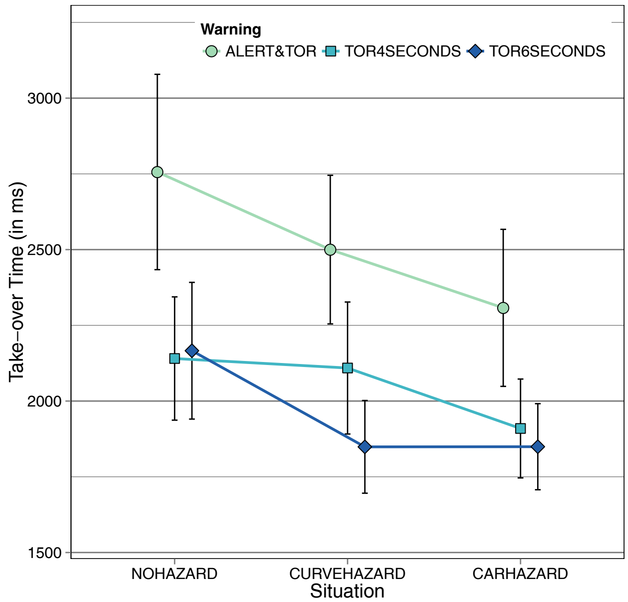


Figure 6: Take-over time: The duration from the appearance of the warning until the participants touched the steering wheel. The error bars show the standard errors.

ing over and the take-over performance were measured as dependent variables. Furthermore, we asked the participants to describe their take-over strategy and to state their preference regarding the different warning conditions.

Results

We executed the driving simulator study with 30 participants and collected both quantitative and qualitative data. The analysis of the collected data is reported in the following.

Take-Over Time

The control shift from the autonomous system to the driver was executed as soon as the participants touched the steering wheel. The duration between the appearance of the warning and this event is the take-over time, on average the participants needed on average 1746 ms to take over (see Figure 6). Due to technical drop out and violation of task demands (leaving the hands on the steering wheel), two subjects had to be excluded. A two-way repeated measures ANOVA was calculated ($N = 28$), but the assumption of sphericity was violated (Mauchly test was significant), hence the degrees of freedom were adjusted by using Greenhouse-Geisser correction. A significant difference was revealed for both the warning conditions ($F(1.36, 36.79) = 15.64$, $p < .001$, $\eta^2 = .37$) and the situation conditions ($F(1.64, 44.22) = 4.73$, $p < .05$, $\eta^2 = .15$). Post-hoc tests using Bonferroni correction indicated that the ALERT&TOR warning resulted in significantly longer take-over times than TOR4SECONDS ($p < .01$) and TOR6SECONDS ($p < .001$), but showed no difference between TOR4SECONDS and TOR6SECONDS (see Figure 6). Regarding the situation conditions, more time is needed to grasp the steering wheel in the NOHAZARD situation compared to the CARHAZARD situation ($p < .05$). The take-over times of NOHAZARD and CURVEHAZARD, as well as CURVEHAZARD and CARHAZARD, did not differ significantly. With regard to the interaction of warning and situation, results indicated no significant interaction of take-over time ($F(2.97, 80.11) = 0.53$, $p > .05$, $\eta^2 = .02$), which shows that the type of warning presentation was not affected by the type of situation.

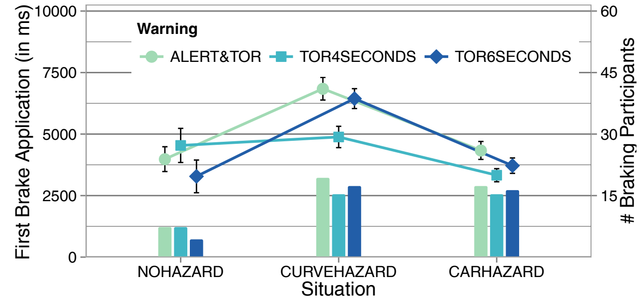


Figure 7: First brake application after the appearance of the warning. The bars indicate the number of braking participants and correspond to the right y-axis. The line graph shows the mean duration between appearance of the warning and the brake application, and the standard errors corresponding to the left y-axis.

	NOHAZARD	CURVEHAZARD	CARHAZARD
ALERT&TOR	23.3 %	63.3 %	56.7 %
TOR4SECONDS	23.3 %	50.0 %	50.0 %
TOR6SECONDS	13.3 %	56.7 %	53.3 %

Table 1: Percentage of participants that applied the brakes within 10 seconds after a warning appeared.

Braking Behavior

The participants were not forced to adopt a specific behavior after the TOR, except that they had to grasp the steering wheel. As a result, only some participants applied the brakes while taking over (see Table 1) in the NOHAZARD situation, whereas at least 50% braked in the CARHAZARD and CURVEHAZARD conditions within 10 seconds after the warning. Regarding the time until first brake, Figure 7 shows that the fastest braking behavior was performed in critical situations when a car appeared in front of the scene, obviously independent of the type of warning. Apparently the NOHAZARD situation and the CURVEHAZARD seemed less critical to participants, resulting braking later. Due to the intraindividual variability and small amount of within data these assumptions can only be explained descriptively.

Comfort of Take-Over

Participants had to rate how comfortable they perceived each take-over on a Likert scale ranging from *very stressful* (1) to *very comfortable* (7). Figure 8 shows the means and standard errors of the estimated comfort in different types of warning and situation conditions indicating a more comfortable take-over in the NOHAZARD situation. This assumption was

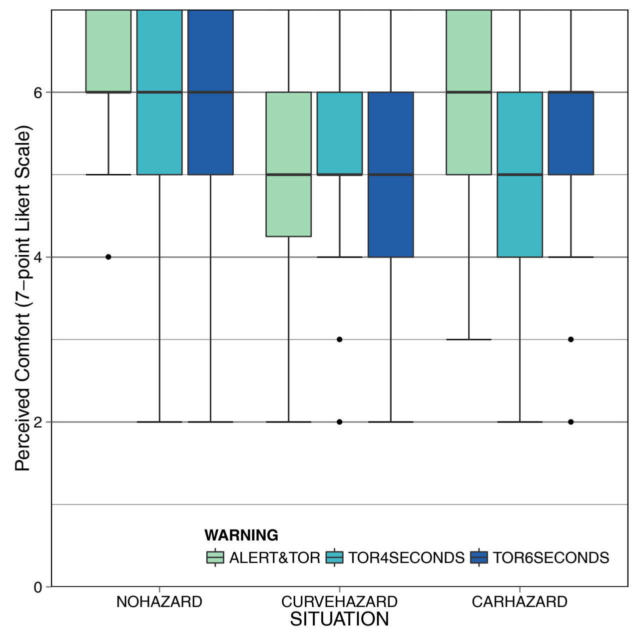


Figure 8: Boxplot of the perceived comfort.

supported by a two-way repeated measures ANOVA revealing a main effect of situation (Greenhouse-Geisser corrected $F(1.67, 46.71) = 7.31$, $p < .01$, $\eta^2 = .21$), and post-hoc analyses (Bonferroni corrected) that showed the higher estimation of comfort for NOHAZARD compared to CURVEHAZARD ($p < .05$) and CARHAZARD (marginally significant $p = .06$). There was no significant interaction ($F(4, 112) = 17.80$, $p < .001$, $\eta^2 = .47$), nor a main effect of warning (Greenhouse-Geisser corrected $F(1.62, 45.39) = 1.74$, $p > .05$, $\eta^2 = .06$), although Figure 8 descriptively indicates a higher rating of ALERT&TOR over all situations.

Ease of Taking Over

Besides the comfort, the ease of the take-overs in general was also assessed. For this purpose, the participants had to rate their agreement to three statements on 7-point Likert scales (*strongly disagree* (1) – *strongly agree* (7)) at the end of the test session. Their ratings – whether they found it easy ($M = 5.73$, $SD = 1.015$) or stressful ($M = 2.87$, $SD = 1.279$) to take over and if they were overwhelmed ($M = 2.43$, $SD = 1.006$) – are depicted in Figure 9.

Take-Over Performance

Moreover, the participants had to reflect on their take-over performance regarding the hazardous situations. They were asked whether they were able to handle the situations in a safe manner. Their ratings on a 7-point Likert scale (*strongly disagree* (1) – *strongly agree* (7)) are plotted in Figure 10. Participants' ratings to these statements were significantly higher when they were asked whether they were able to handle CARHAZARD situations ($M = 5.47$, $SD = 1.224$) compared to situations with a CURVEHAZARD ($M = 3.90$, $SD = 1.494$), $T = 6.50$, $p < .001$, $r = -0.56$.

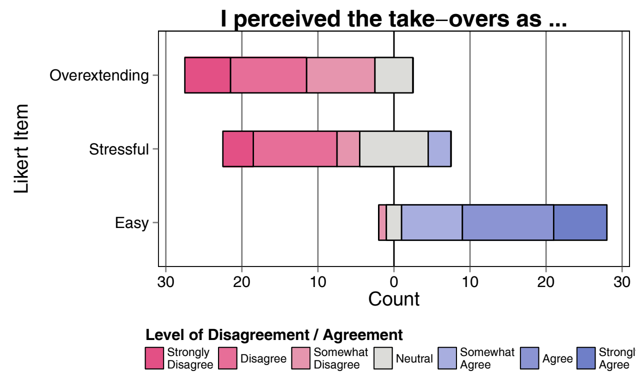


Figure 9: Level of agreement / disagreement of participants on a 7-point Likert scale on statements targeting several aspects of the ease of use.

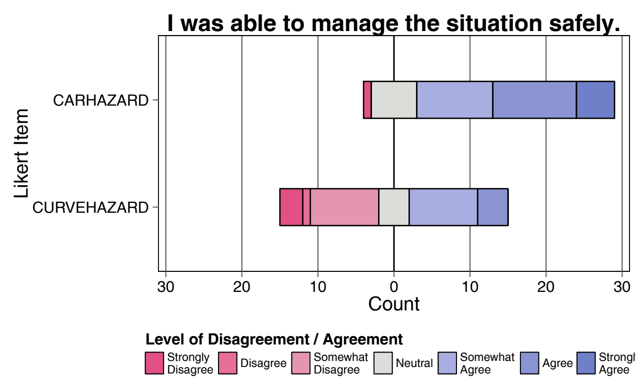


Figure 10: Participants' level of agreement / disagreement (7-point Likert scale) on the statement that they were able to manage the hazardous situations safely.

Take-Over Strategy

Another question the participants had to answer after the nine trials targeted their take-over strategy. Most participants reported that they grasped the steering wheel right away and started to brake instantly. A third tried to perceive the situation before intervening. Generally, most participants decreased the speed (automation drove at a speed of 80 km/h).

Participant Preference: "Caution Fog" & TOR vs. Pure TORs

At the end of each session, the participants were asked if they preferred the combination of the "caution fog" alert and the take-over request, or the pure take-over requests. The combination was preferred by 58.67 %, while 20 % chose the pure take-over requests. The remaining 23.33 % did not report any preference.

Performance in the Distractor Task

At the end of each trial, the participants had to answer three questions about the video they saw while the automation was active. On average, they answered 81.87 % of the questions correctly. Furthermore, most participants reported that they focused entirely on the video, but glanced up to the street from time to time.

DISCUSSION

In the questionnaire at the end of each session, participants described the take-over of control as very comfortable, regardless of the warning condition or the situational circumstances. Due to findings of Koo et al. [10], we expected to find an advantage in the presentation of the reason of a TOR (ALERT&TOR condition) in critical situations. However, the study showed no significant effect of the warning situation conditions. A suitable explanation for this may be that the warning about upcoming fog was redundant, as the participants could already see the fog ahead. Nevertheless, the results show that the participants preferred the combination of an alert that gives the reason for a take-over, followed by the take-over request. The subjective rating of the ALERT&TOR condition was higher than for the pure TOR conditions. Yet it also led to longer take-over times, which may be fatal in critical situations. The ALERT&TOR interfered with the participants' vision within the traffic scene in front of them for four seconds: the "Caution Fog" alert followed by the take-over request, each lasting for two seconds. In contrast, the pure take-over requests were displayed for two seconds in total.

Our generic handover process suggests that the vehicle should start deceleration as soon as the system alerts the driver, but this feature was not implemented in the evaluated prototype. Participants reportedly decelerated after the take-over, but less than 25 % applied the brake if there was no visible hazard. In contrast, about half of the participants applied the brake if there was a hazard. Thus, if the system starts to decrease the speed on its own, drivers might perceive this behavior as natural, especially in case of a hazardous situation. Only a third of participants reported that they tried to perceive the traffic scene before they intervened. Further research is necessary to investigate whether drivers generally tend to intervene before they are back "in the loop", in which case *grasping the steering wheel* is not a suitable trigger for a take-over.

Qualitative data were collected through a questionnaire at the end of each session and show that the participants think that taking over control was easy and not very stressful. They believed that they were able to take over safely if there was a broken-down car. In cases where there was a sharp curve, the opinions of the participants on whether or not they took over safely were more diverse. Overall, they did not feel overwhelmed by the take-over mechanism. It is important to note that this applies to the simulated fog scenario, whereas real-world traffic situations may present more complex take-over situations.

Related research used very artificial tasks to distract their participants in order to ensure that they were "out of the loop". In contrast, we challenged the participants with a realistic distractor task – watching videos. The participants performed well in the task and reported that they focused on the videos while the automation was activated. Nevertheless, they succeeded in taking over control.

The participants reported that they were able to handle the CARHAZARD situations more safely than the CURVEHAZARD situations. The reason for the difference between these two hazards might be the fact that the car became recognizable very early (even through the visual overlays), whereas the sharp curves did become visible later, as the terrain was flat and there were no signs indicating the curve.

Our study was conducted under laboratory conditions; as a consequence, the periods of autonomous driving were shorter than they might be in everyday usage scenarios. Furthermore, there were frequent take-over situations to trade off the amount of collected take-over data against the strain of participants. One participant reported at the end of the session that he was bored by the provided videos of the distractor task. In consequence, he was not as distracted as desired. Even if only one participant reported this issue, there might be others that were also not completely "out of the loop". We recommend that participants should choose media on their own in future studies to accomplish that participants are distracted with a realistic task they are interested in. Another problem in driving simulator studies is that there is no threat for the participants' physical safety and there is no financial risk. The latter could be simulated in simulator studies if the financial reward of the participants was linked to the integrity of their vehicle. Moreover, the participants in our study had to expect only two different hazards and no other traffic participants. Future work is necessary to investigate car-driver handovers in more realistic or even real traffic situations where participants have to react to a larger variety of situations.

CONCLUSION & FUTURE WORK

We proposed a generic handover process to achieve the shift of control from a full self-driving vehicle to manual driving. To gain deeper insights into the handover behavior of drivers, a prototype of a handover assistant was implemented using the exemplary *approaching screens of fog* scenario. The design of the visual and auditory cues was based on an online survey. With the help of the implemented prototype we ran a user study with 30 participants. Our results indicate that drivers that are focused on videos are able to take over control within three seconds, and that they feel comfortable while doing so. Furthermore, the participants reported that they were able to overtake a broken-down car. When challenged with a sharp curve, the data is less clear.

The majority of our participants took over as soon as they were alerted, and did not report trying to perceive the situation before they intervened. In consequence, we suggest an evaluation regarding whether the implementation of system-monitored handover procedures prevent drivers from performing dangerous maneuvers, and whether this variant is accepted by the users.

The sharp curve that appeared in a third of the trials was not as obvious as the broken-down car, and became visible later than the car. If drivers have to take over within a short distance before such an unforeseeable circumstance occurs, the car could include further information in the take-over request (e.g. from maps or sensors) to enrich the user's mental model of the traffic situation. However, further research is necessary to validate this assumption.

Participants preferred the combination of an alert that gave the reason for the impending handover, and the take-over request. The longer display duration of this warning condition resulted in longer take-over times. To compromise between the participants' preference and the risk that the driver might take over too late, future implementations could dismiss the warning as soon as the participants intervene. At least the visual component of the warning should be dismissed. Maybe a handover assistant could even function without any visual component. Furthermore, in the case of the broken-down car, the participants saw the hazard even while the warning was displayed and intervened even earlier. In such cases, a mechanism that clears the view of the participants would be even more useful.

Further research should be conducted in the area of car-driver handovers, for instance to explore whether these results also apply to other situations (e.g. with the presence of other traffic participants, or more menacing circumstances) or real traffic. Beside the technical issues, liability issues also have to be taken into account: Who is responsible for accidents that occur in the transition phase from self-driving automation to manual driving. Our results suggest that car-driver handovers cued by a combination of auditory (i.e. earcons and speech) and visual (i.e. icons and text) warnings are a promising approach to compensate for situations wherein a fully self-driving vehicle reaches the boundary of its capabilities.

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