Usefulness and satisfaction of take-over requests for highly automated driving

Pavlo Bazilinskyy[1], Alexander Eriksson[2], Bastiaan Petermeijer[3], Joost de Winter[1]

1. Department of Biomechanical Engineering, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Delft, The Netherlands, p.bazilinskyy@tudelft.nl, j.c.f.dewinter@tudelft.nl

2. Transportation Research Group, Faculty of Engineering and Environment, University of Southampton, Boldrewood Campus, Southampton SO16 7QF, UK.

3. Lehrstuhl für Ergonomie, Fakultät für Maschinenwesen, Technische Universität München, Boltzmannstraße 15, 85747, Garching, Germany.

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Abstract

This paper summarizes our results from survey research and driving simulator experiments on auditory, vibrotactile, and visual take-over requests in highly automated driving. Results showed that vibrotactile take-over requests in the driver's seat yielded relatively high ratings of self-reported usefulness and satisfaction. Auditory take-over requests in the form of beeps were regarded as useful but not satisfactory, and it was found that an increase of beep rate yields an increase of self-reported urgency. Visual-only feedback in the form of LEDs was regarded by participants as neither useful nor satisfactory. Augmented visual feedback was found to support effective steering and braking actions, and may be a valuable complement to vibrotactile take-over requests. The present findings may be useful in the design of take-over requests.

Keywords

Highly Automated Driving; Human Machine Interfaces; Human Factors; Multi-modal feedback

1. Introduction

Automated driving is being pursued at a large scale by various vehicle manufacturers. However, fully automated driving, in which the driver never has to intervene, does not exist yet on public roads. Between September 2014 to December 2016, 2,616 disengagements of control were recorded in on-road automated test vehicles. These were due to a human factor (e.g., driver discomfort with the vehicle's behaviour) in 30% of the cases, 52% were due to system failures (e.g., software discrepancy), and 11% were due to external conditions (e.g., poorly marked lanes) (Favarò et al., 2018).

When an automated car reaches its operational limits, the driver has a certain time buffer to reclaim control. This type of automated driving is also called 'highly automated driving' according to BASt (Gasser & Westhoff, 2012) or 'conditionally automated driving' according to SAE International (2018). This time buffer (also called lead time, transition time, or time budget) may range from long (for non-urgent situations) to short (for high-urgent situations, such as an impending collision) (Bazilinskyy et al., 2017). Prior research has measured drivers' behaviour in take-over situations involving time buffers ranging between 2 and about 10 seconds (e.g. Gold et al., 2013, for a review see Eriksson & Stanton, 2017).

The design of take-over requests (TORs) is a crucial factor in the safety of automated driving systems, because a late or wrong response may lead to incidents and accidents. If the time buffer is short, the driver could benefit from receiving a take-over request (a warning) that conveys a high level of urgency. On the other hand, if the automated vehicle can anticipate when a transition to manual control will be needed, a take-over request can be issued long in advance in a discretionary manner.

New types of in-vehicle feedback, such as take-over requests, can be rated along two dimensions: (1) usefulness (quality) and (2) satisfaction (pleasure) (Van der Laan et al., 2016). Both dimensions are regarded as important. That is, the feedback should be useful in that it supports drivers in making a safe and timely response, and it should be satisfactory: if it is not, then drivers may become annoyed and disable the feedback system altogether (Parasuraman & Riley, 1997).

Within the project HFauto (Human Factors of Automated Driving), we have investigated how drivers perceive and respond to different auditory, vibrotactile, and visual take-over requests for automated driving. The aim of the present paper is to summarize our contributions regarding the effects of take-over request modality on drivers' self-reported usefulness and satisfaction, as well as their response.

2. Auditory take-over requests

Beeps are a commonly used type of auditory feedback in automated driving. In a crowdsourcing study with 1,692 participants, we replicated previous experimental results by showing that there exists a clear monotonic relationship between self-reported urgency and inter-beep duration (Bazilinskyy et al., 2018), see Figure 1.

Auditory take-over requests can also be provided in the form of speech (Gold et al., 2015; Politis et al., 2015). In the same large-scale international online survey, we found that the female and male voice ("Please take over!") were rated as more preferred than beeps (Bazilinskyy et al., 2018). In another large-sample crowdsourcing study (Bazilinskyy & De Winter, 2017), 2,669 participants from 95 countries listened to a random 10 out of 140 take-over requests and rated each take-over request on urgency, commandingness, pleasantness, and ease of understanding. We found that differences in speech intelligibility and self-reported urgency between take-over requests in male versus female voice are generally small. Additionally, in agreement with earlier findings by Hellier et al., 2002, we found that the spoken phrase (e.g., "Note, take over" versus "Take over now") affects self-reported urgency. Furthermore, it was shown that an increase in speech rate yielded increased self-reported urgency (Figure 1).

In an experiment in a driving simulator (Experiment 1), we found that drivers responded effectively (i.e., average steer initiation times of about 2.0 s, which was well within the 7 s time buffer) to an auditory take-over request (double beep) (Petermeijer et al., 2017a). However, *directional* auditory feedback provided via the car's speakers on either the left or the right was not noticed by drivers. Drivers who received directional feedback almost always steered to the left in a scenario where a stationary car blocked the middle lane (Figure 2), just as did drivers who received non-directional feedback (i.e., TOR provided via the left and right speakers simultaneously).

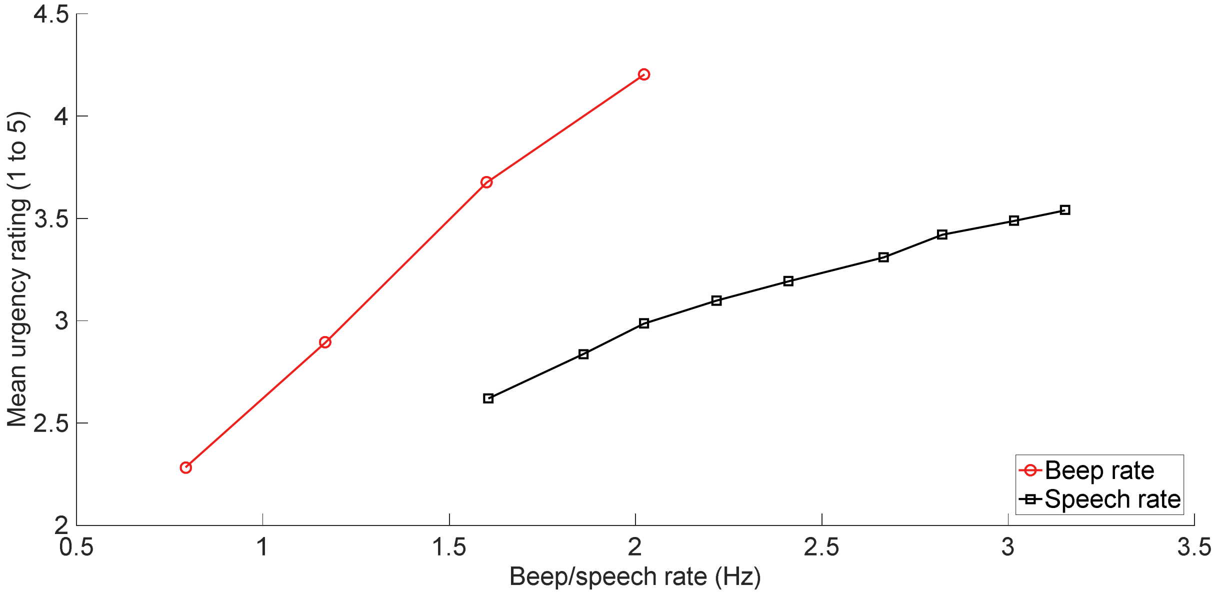

Figure 1. Relationship between self-reported urgency and beep rate/speech rate (Bazilinskyy et al., 2018; Bazilinskyy & De Winter, 2017). The beep rate is the number of beeps per second (beeps were presented in pairs, with a 0.11 s pause in between); speech rate is expressed in syllabi per second for the uttered phrase "*take over please*" (i.e., 4 syllabi). Participants responded to the statement 'I consider such a sound as urgent' or 'The message is urgent' on a scale from 1 = Disagree strongly, 5 = Agree strongly.

Figure 2. A take-over scenario. Participants could avoid the stationary car by steering left or right (Petermeijer et al., 2017a; Experiment 1).

3. Vibrotactile take-over requests

Vibrotactile messages can be perceived even in the presence of auditory distractions such as a phone call or radio music (Petermeijer et al., 2016). In a driving simulator experiment involving take-over situations with 7 s time buffer, we found that vibrotactile-only warnings in the driver seat are effective for ensuring that drivers reclaim control of the steering wheel in time (Experiment 1) (Petermeijer et al., 2017a). However, *directional* vibrotactile cues embedded in the take-over request did not elicit a directional response in uninstructed drivers (Petermeijer et al., 2017a). In a follow-up study (Experiment 2) (Petermeijer et al., 2017b), it was evaluated how well drivers recognized directional cues presented via the vibrotactile seat when they were explicitly instructed about the meaning of the directional cues. Here, the participants received a static (i.e., left or right) or dynamic (i.e., moving left or right) take-over request and were asked to change lane according to the directional cue. Results showed that participants did not accurately detect the directional vibrotactile cues (correct response rates of about 80%). Furthermore, it was found that static take-over requests yielded faster reaction times than dynamic ones. In summary, vibrotactile take-over requests are useful for alerting a driver, but the amount of information that can be communicated via a vibrotactile seat may be limited (Petermeijer et al., 2016).

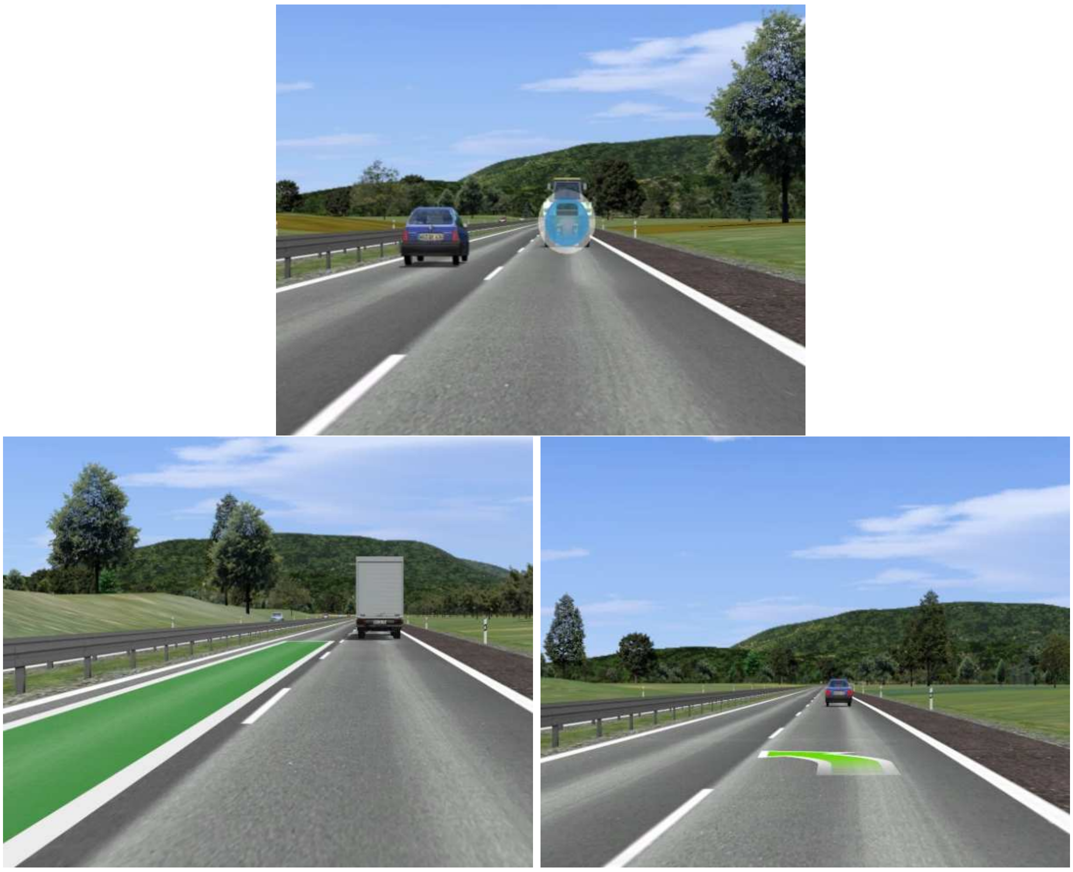

Figure 3. Examples of the visual interfaces used in Eriksson et al. (2017; Experiment 3). Top middle (sphere): a sphere highlighting the slow-moving vehicle ahead in both scenarios. Bottom left (carpet): a green carpet in the left lane for the lane change scenario. Bottom right (arrow): a green arrow pointing left for the lane change scenario.

4. Visual augmented feedback and visual take-over requests

In a driving simulator study (Experiment 3, Eriksson et al., 2017) we assessed the effectiveness of visual augmented feedback for supporting vibrotactile take-over requests. This study involved a highly automated driving scenario in which the automated driving system has awareness of the surrounding environment, but requests the driver to implement a braking or lane-change decision. Four types of visual feedback were evaluated during lane change and braking take-over scenarios: (1) a baseline condition without visual support, (2) a sphere highlighting a slow-moving vehicle ahead (Fig. 3, top middle), (3) a green carpet in the left lane for the lane change scenario (Fig. 3, bottom left) and a red barrier covering the lane markings for the braking scenario, and (4) a green arrow pointing left for the lane change scenario (Fig. 3, bottom right) and red arrow pointing backwards, for the braking scenario. We found that the carpet feedback and arrow feedback facilitated accurate braking and lane changing behaviour compared to the baseline condition, whereas the sphere feedback appeared to cause confusion as drivers showed unnecessary braking in a scenario in which they only had to change lanes.

In another driving simulator study (Experiment 4, Petermeijer et al., 2017c), we measured driver response times to take-over requests provided via (1) a vibrotactile seat, (2) auditory beeps, and (3) visual LEDs surrounding the secondary task display and above the steering wheel, while drivers were performing different types of secondary tasks (watching a video on the display, reading on the display, or performing a simulated hands-free phone task). The results of this study showed that the initial steering response times were about 0.6 s slower for the visual take-over requests than for the vibrotactile and auditory take-over requests. It was concluded that visual warnings convey a low sense of urgency or may go unnoticed even when in the driver's visual field of view. In summary, visual messages are prone to be overlooked, especially during highly automated driving in which drivers will be allowed to take their eyes off the road and engage in non-driving tasks.

5. Comparing auditory, visual, and vibrotactile take-over requests

Figure 4 summarizes the results of the same usefulness and satisfaction questionnaire (Van der Laan et al., 1997), for all four driving simulator experiments reviewed above. All experiments were performed with the same driving simulator software (SILAB) and with equivalent simulator hardware (i.e., full passenger vehicle with surround projection).

Several findings stand out: visual-only take-over requests (i.e., the LEDs) was not regarded as useful by participants (Experiment 4, Petermeijer et al., 2017c). These subjective findings mirror the objective take-over response times for visual-only take-over requests, which were found to be slower than the response times to vibrations-only and auditory-only take-over requests (Petermeijer et al., 2017c). Furthermore, auditory-only feedback (Experiments 1 & 4; Petermeijer et al., 2017a and Petermeijer et al., 2017c) was useful, but not satisfactory. In our experiments, the auditory take-over request consisted of loud beeps. Vibrations were overall regarded as both useful and satisfactory (Experiments 1–4). However, vibrations combined with ambiguous visual information (Sphere) reduced overall usefulness and satisfaction as compared to vibrations-only take-over requests (Experiment 3, Eriksson et al., 2017).

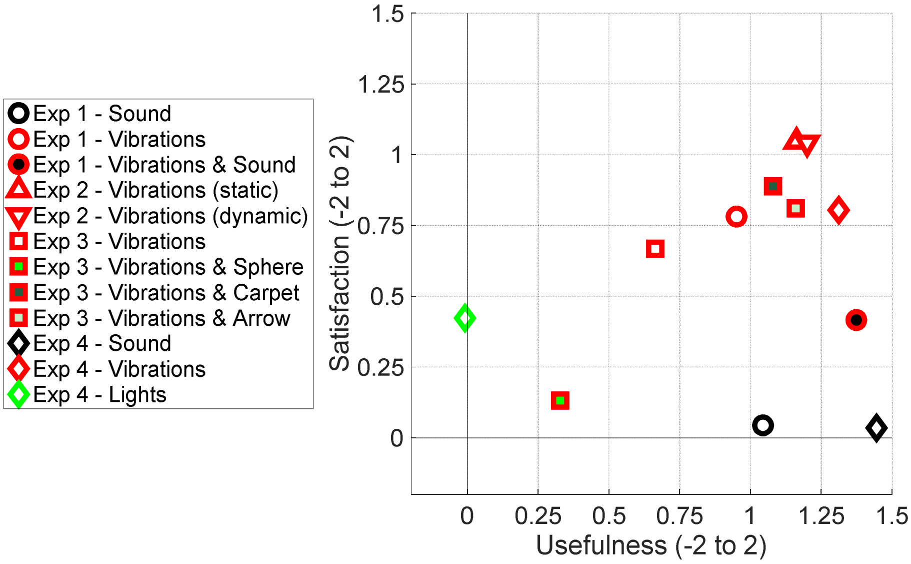

Figure 4. Self-reported satisfaction and usefulness for take-over requests tested in four driving simulator experiments.

6. Discussion

We designed and evaluated various auditory, visual, and vibrotactile take-over requests. Results showed that visual-only take-over requests in the form of LEDs yielded low ratings of usefulness and high steer-touch response times compared to sound-only and vibration-only take-over requests. Augmented visual feedback (Carpet, Arrow) has the potential to enhance decision making (e.g., whether the driver appropriately implements a steering or braking action), but should be implemented with care. Visual feedback tends to be dominant over feedback in other modalities, and if augmented visual feedback does not provide semantically meaningful information (cf. Sphere), then the driver may respond inappropriately, and self-report ratings of usefulness may be impaired. It should be noted that the present results do not necessarily generalize to all types of visual feedback. For example, recently the use of ambient light was found to be promising as a take-over request (Borojeni et al., 2016).

Vibrotactile take-over requests were found to be useful for getting the driver back into the loop, even when presented in isolation. However, the effectiveness of directional (left vs. right) vibrations in the driver seat may be limited as compared to non-directional vibrations. Another limitation of vibrotactile feedback is that the driver and the source of vibrations have to be in physical contact with each other (Petermeijer et al., 2016).

The beeps yielded low satisfaction ratings and were rated as less satisfactory than speech-based take-over requests. However, beeps may be a useful channel for conveying a sense of urgency, and the inter-beep interval is a critical moderator variable in this regard (see Figure 1, cf. parking sensors). Our results may be specific to the type of beeps used in the driving simulator experiments. It is possible that other types of beeps, earcons, or speech-based take-over requests would yield high satisfaction ratings (for more research into speech-based take-over requests, see Bazilinskyy & De Winter, 2017; Gold et al., 2015; Politis et al., 2015; Walch et al., 2016; Mok et al., 2015).

In order to counteract the limitations of unimodal take-over requests, the use of multimodal take-over requests may be promising. Multimodal feedback increases the redundancy of the warning and consequently reduces the probability of misses, as compared to unimodal feedback. By means of a crowdsourced online questionnaire, we asked the opinion of 1,692 people on auditory, visual, and vibrotactile take-over requests in highly automated driving (Bazilinskyy et al., 2018). The survey included recordings of auditory messages and illustrations of visual and vibrational messages. The results of the survey showed, consistent with the literature, that multimodal take-over requests were the most preferred option in high urgency scenarios. Furthermore, in a driving simulator experiment (Petermeijer et al., 2017a), we found that drivers showed a faster initial response to multimodal (i.e., auditory and vibrotactile) than vibrotactile-only take-over requests.

Future research should seek ways to maximize the usefulness and satisfaction of take-over requests by finding the right combination of auditory, vibrotactile, and visual feedback. Here attention should be paid to temporal and semantic congruence.

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Supplementary material for this paper is accessible online: https://www.dropbox.com/sh/sb2180f8t27hw3x/AAAMIuifV7NlVv6T3xqpXW8ja?dl=0

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