Correlation between reaction time, multi-modal feedback and take-over requests for level 3 automated vehicles

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***Abstract*—We are currently experiencing a paradigm shift towards fully automated vehicles (AVs). On the way towards fully AVs, we will experience an increase in numbers of automated vehicles on our roads, requiring the human driver to take back control in situations, which cannot be handled by the vehicle. These human-robot take-over requests (TORs) can lead to safety risks, in particular in scenarios when the driver fails to understand the TOR and, hence, lacks situational awareness (SA).**

In this paper, the correlation between reaction time, multi-modal feedback, informing the human driver of a transition in automation level, and success of transfer of control has been investigated. Nineteen human drivers have participated in experiments in a full-sized driving simulator: First, the driver was engaged in a secondary reading task while the car was in self-driving mode. Then, a TOR indicated to the driver to take back control. Seven different feedback modalities for the TORs have been created consisting of an audio chime, a visual cue or a static mechano-tactile haptic feedback, or a combination of these. The mechano-tactile feedback is hereby given through soft pneumatic actuators embedded into a novel soft robotic driver's seat. After the driver experienced the TOR, they were given seven seconds to regain SA, retake the driving task and react to a road incident ahead. Based on the results, it can be concluded that reaction times below 2.6 seconds and above 6 seconds result in an unsuccessful transfer of control. Additionally, we have found that haptic feedback results in a timely and safe transfer of control within a shorter time frame, when added to currently commercially available auditory and visual feedback.

I. INTRODUCTION

The mobility sector is currently undergoing a shift toward fully automated vehicles (AVs) [1]. In May 2022, the first vehicle's assistive technology became commercially available with level 3 automation [2]. The fundamental difference between vehicles with level 2 and 3 automation is that the liability of any incidents is with the car manufacturer rather than the human driver [3]. Level 3 legally allows the driver to hand over the driving task to the vehicle within certain constraints (when driving max. 60 km/h on a multi-lane carriageway with a median barrier, e.g., in highly congested traffic) [2]. In these situations, the driver can focus on non-driving related tasks (NDRTs), decreasing the level of their situational awareness (SA) with regards to the actual driving task [4]. When the

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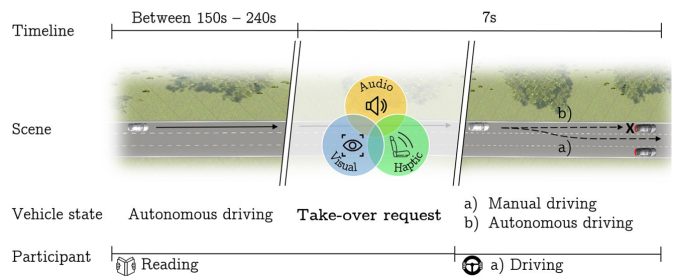

Fig. 1. Experimental protocol to compare multi-modal feedback for TORs in AVs: In the beginning, the vehicle is in self-driving mode for a time between 150 and 240 seconds. During this time, the driver is asked to read in a magazine. Once a stationary vehicle in the same lane is 7 seconds ahead, the driver of the automated vehicle is asked to take back control through an audio, visual or haptic cue or a combination of these. The driver is either required (a) to steer and avoid a crash or a hazardous situation or (b) to brake and come to a full stop.

vehicle is unable to handle a driving task (e.g., because of faded lane markings) or reaches the programmatic constraints of the system (e.g., through the increase in traffic flow), the driver must take over the driving task. The shift in automation (e.g., from level 3 automation to manual driving) can be very challenging as the driver is required to increase their SA level shortly after the take-over request (TOR) is issued [5], though the driver might be fully disengaged from the driving task.

Previous studies show that giving multi-modal feedback to alert drivers of upcoming transfers of control is more effective than unimodal feedback [6]. In particular, adding vibro-tactile haptic feedback may result in quicker reaction times [6], while reporting high satisfaction and usefulness scores [7].

In this paper, we investigate the correlation between the type of feedback given to the driver during take-over requests (TORs) in level 3 automated vehicles, the driver's reaction times to these alerts, and the success of transfer of control, when giving static mechano-tactile feedback (below 5 Hz), as opposed to the previously employed vibro-tactile feedback (above 5 Hz) [8], [9]. In particular, we inform the driver through audio, visual, and static mechano-tactile haptic feedback as well as a combinations of these. Static mechano-tactile feedback is introduced through a novel haptic seat with embedded soft robotic structures. Seven highway scenarios have been designed (Figure 1). At the very beginning, the vehicle starts in self-driving mode, e.g., level 3 automation. Participants were asked to engage by reading in a magazine until the vehicle triggers a TOR. The participants then had to regain situational awareness (SA) and react to a road incident ahead. If no action was taken, the vehicle would crash into the back of a stationary car in the same lane within seven seconds.

We analysed the correlation of the alternating feedback type (independent variable) and resulting success of the transfer of control as well as reaction times (dependent variables).

This paper addresses the following research questions:

- How do the distributions of reaction times differ between successful and unsuccessful transfers of control?
- Which feedback mode triggers reaction times, which resembles the distribution of reaction times observed during successful transfers of control?
- Does haptic feedback in addition to visual and audio feedback provide any benefit?

The novelty of this study lies particularly in understanding a driver's reaction after a transfer of control alert using soft robots embedded in the driver's seat. This provides empirical evidence on how static mechano-tactile feedback influences driver reaction times and control transfer success rates.

Section 2 introduces related work in literature. Section 3 provides an overview of the equipment used in this study, including a description of the haptic feedback seat, and reports on the involved participants. The experimental procedure is outlined in Section 4. Section 5 introduces the variables and processing techniques utilised in this paper. Section 6 presents the obtained results, which are subsequently discussed in Section 7. Finally, Section 8 concludes with closing remarks and provides an outlook for future work.

II. Related works

In commercially available cars, a number of feedback systems inform the driver of a TOR. These systems include visual cues (e.g., on the dashboard [10], [11], [2], [12], steering wheel [11], centre console [13], or head-up display [12]) and non-vocal auditory cues (e.g., audio chimes [10], [13]). Current accident statistics from the Department of Motor Vehicles in California involving automated vehicles [14] show that although the take-over periods only take up a fraction of the overall operating time, more than 15% of accidents happen during the shift of automation from vehicle to driver. To address the aforementioned challenges and mitigate the emerging safety issues, researchers have explored and compared multi-modal feedback for TORs. For instance, Yoon et al. [15] compare visual, auditory and vibro-tactile cues as well as a combination of them and their effect on the mean take-over reaction time. It is reported that the feedback type can have an influence on the driver's time to react to an alert. In fact, multi-modal TORs seem to be effective in reducing the driver's reaction time. This finding aligns well with previous studies that have highlighted the effectiveness of multi-modal alerts during attention demanding tasks [16], [17]. However, visual cues, on the one hand, might be unnoticed by the driver when engaged in a NDRT (e.g., by an interaction with a smartphone or watching a video). On the other hand, audio feedback might be missed by the driver when superimposed by other sources of sound inside the vehicle (e.g., by the radio) or outside the vehicle emerging from the environment.

To explore sensing modalities beyond visual and audio cues, Fels et al. [18] introduced a tilting driver's seat. They showed that stimulation through the haptic seat improved the drivers' performance. Other researchers focused on implementing vibro-tactile actuators into seats. Experimental results concluded that the driver reacts quicker to a TOR compared to text based [19] and auditory cues [20], while observing low frustration [19]. Telpaz et al. [21] found that giving vibro-tactile feedback resulted in a thorough understanding of the environment in the seconds after issuing the TOR compared to not giving any feedback, resulting in a high level of SA. Fitch et al. [22] highlighted that providing multiple stimuli using vibro-tactile feedback is suitable for directional cues. However, overloading the driver with feedback cues (more than three haptic cues at a time) might lead to performance degradation. This is in line with the findings of Bazilinskyy et al. [7], who show that giving directional cues through vibro-tactile feedback only has limited success. They understood that giving vibro-tactile feedback yields higher satisfaction levels than audio or visual feedback and higher usefulness scores than visual feedback. In particular, unimodal vibro-tactile feedback reaches highest satisfaction scores, which led to the conclusion that more research is required to determine satisfactory integration of haptic feedback with audio and visual feedback. In contrast to these findings, while observing overall high satisfaction levels, Chang et al. [20] discovered that their vibro-tactile seat resulted in lower satisfaction levels compared to auditory systems, and Nukarinen et al. [19] reported a startling effect of vibro-tactile feedback on the participants. In a push for within-modality comparison [6], contrary to vibro-tactile feedback, another way of transmitting haptic feedback is through static mechano-tactile feedback. Peters et al. [8] show that giving static mechano-tactile feedback through a novel haptic driver's seat yields an average satisfaction score of 1.5 on a 5-point Likert scale from -2 to 2 (compared to 1.1 and below in [7]). In fact, a number of car manufacturers have utilised pneumatic air cushions in the driver's seat to increase comfort for the driver in recent years [23], [24]. Albeit so far not used as guidance systems to alert the driver, these actuated, soft material structures show potential of transmitting static mechano-tactile haptic feedback for TORs, informing the driver to take back control from a self-driving mode.

III. Experimental setup in the IM@UCL driving simulator

This research was carried out in the Intelligent Mobility at UCL (IM@UCL) driving simulator, which is introduced in Section III-A. Multi-modal feedback is provided to participants including audio, visual and haptic feedback as explained in Sections III-B and III-C, respectively.

A. Driving simulation of a highway VR environment

The IM@UCL driving simulators includes a static full-size sports utility vehicle in front of a curved screen. A virtual reality (VR) simulation environment can be projected onto the 180° curved screen by three projectors. A human driver is then able to navigate within the VR scene from the driver seat of the vehicle using the pedals and steering wheel. A view from the middle rear seats inside the vehicle of the driving simulator is shown in Figure 2. The highway VR environment used for this study is built in Unity software. Three mirrors (replaced with LCD screens) on the left and right hand side as well as in the centre provide the driver with simulated rear views. The digital dashboard is fully integrated and informs the driver of the current vehicle speed. A screen in the middle console is utilised to provide additional information (see Section III-B) to the human. Vehicular sound is added by an 8.1 sound system with four speakers and a subwoofer inside the car and four speakers outside the car. The sound files are provided by the Unity module NWH Vehicle Physics 2.

To analyse the visual response of the driver during our experiments and to have a recording of the scene from their point of view, each participant was asked to wear eye-tracking glasses (Tobii Pro Glasses 3). This equipment records the position of the participant's pupils and overlays them onto a video recording of the scene captured by an integrated camera pointing to the front.

B. Audio and visual feedback

The vehicle communicates a TOR to the driver via three ways: visually, through auditory signals and via haptic feedback. Three distinct audio chimes have been synthesised. One type of sound informs the driver that the automated mode is activated. Another type indicates that the automated mode is deactivated, transitioning the car into manual mode. A continuous beeping chime serves as a TOR alert. All three sounds are designed in line with the sound provided by a Tesla Model 3 [25], [26]. All alerts are played at a volume level of 70dBA with the engine noise being played at 65dBA.

Visual feedback is given through a 7-inch screen mounted to the centre console of the driving simulator (see Figure 3). While driving in automated mode, the entire screen displayed a green colour with black letters indicating "Autonomous Driving Active". During the TOR alert, the screen would switch to a red colour with black letters displaying the message "Take Over Immediately". Once the driver intervened and drives manually, the screen would turn white showing the words "Manual Driving Enabled".

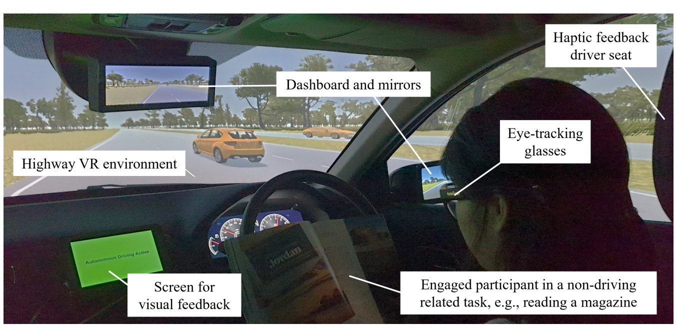

Fig. 2. A participant sits on a haptic feedback driver seat in the IM@UCL full-size driving simulator. A highway virtual reality environment is projected onto a 180° curved screen. Mirrors have been replaced with LCD screens to provide rear views. The person wears eye-tracking glasses and is engaged in a non-driving related tasks, i.e., reading a magazine, while the vehicle is in self-driving mode, as indicated on the screen mounted to the centre console through visual feedback. Speakers provide auditory feedback.

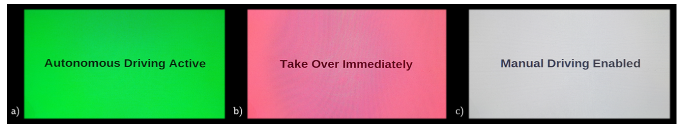

Fig. 3. The screen in the centre console displays visual feedback informing the driver if the vehicle a) is in self-driving mode, e.g., level 3 automation, b) issues a TOR or c) drives manually, i.e., in level 0.

C. Embedded static mechano-tactile haptic feedback

To provide static mechano-tactile haptic feedback to the driver, we created a soft robotic, haptic feedback driver seat [8]. A number of soft robotic actuators are placed in the foam under the leather seat cover (see Figure 4(a)). Each robot consists of multiple layers of Ecoflex 00-30 silicone material and fibre/fabric reinforcement. In particular, the outer wall of the chamber is lined with a two-way stretch fabric. An inextensible fabric is incorporated along with an additional layer of stiffer silicone, Dragon Skin 30 silicone. This combination enhances the actuator's shape stability. Air pressure is supplied to the soft actuator through a pipe inlet located at the bottom. Soft robotic actuators are integrated into two designated haptic feedback areas (HFA), as shown in Figure 4(a). Within the bottom side bolsters (HFA 1), there are a total of eight actuators, with four actuators labeled LLX on the left side and four actuators labeled LRX on the right side, where $[X = 1, ..., 4]$. To regulate the pressure of all HFA 1 actuators, four pressure regulators are employed. Each LLX/LRX pair of actuators is pressurised by a single regulator. In the area HFA 2, the two actuators on each side are pressurised by one valve each.

The control system for actuating the soft pneumatic actuators within the haptic feedback seat is shown in Figure 4(b). This system incorporates a programmable logic controller (PLC, Controllino Maxi Automation) from Conelcom GmbH. Connectivity is established through an I2C-bus and an analogue output module. The control system interfaces with two

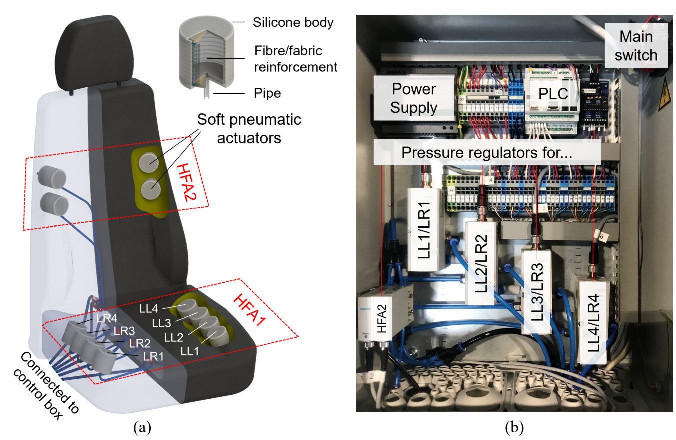

Fig. 4. (a) The soft robotic, haptic feedback seat with twelve integrated pneumatic actuators. In the area HFA 1, eight soft robots are embedded, four on each side labelled LLX on the left and LRX with $[X = 1, ..., 4]$ on the right side. In the area HFA 2, two actuators are placed on each side. (b) The actuators are connected to a control box with a programmable logic controller (PLC) connected to pressure regulators. The pressure of all HFA 1 actuators are controlled by four pressure regulators, where an LLX/LRX pair is pressurised by one regulator. The pressure for HFA 2 is controlled by another two regulators in the same way [8].

distinct types of proportional pressure regulators employed in this research. For the actuators situated in the lower section of the seat (LR1-4, LL1-4), they are driven by VPPM-type proportional pressure regulators, specifically the Festo VPPM-6L-L-1-G18-0L2H-V1P-S1. The actuators located in the upper part of the seat are actuated using smaller proportional pressure regulators, specifically the Festo VEAB-L-26-D2-Q4-V1-1R1.

The eight actuators installed in HFA 1 are used to generate wave-like signals within the driver seat bottom. Starting with actuator LR4/LL4, they are pressurised with 230 mbar of air (full inflation). After 150 milliseconds, they are deflated to a pressure of 115 mbar with the adjacent chambers LR3/LL3 inflating to a full 230 mbar pressure. After another 150ms, LR4/LL4 deflate, with LR3/LL3 deflating to 115 mbar and LR2/LL2 being fully actuated (230 mbar) and so on. This pattern creates a wave-like effect, repeated every 600 milliseconds to provide a TOR alert to the driver. The soft actuators in the area HFA 2 are repeatedly inflated by an air pressure of 200 mbar of air, followed after 600 milliseconds by a deflation.

IV. Experimental protocol

Nineteen subjects participated in the experiments (six female, thirteen male). Their age distribution ranges between 20 and 67 years old (mean=31.42, SD=12.0). All participants were in possession of a valid driver's license, reported being in good health, successfully completed the experiments and did not experience any drowsiness during the experiment.

Before the start of the experiments, all participants were given an opportunity to drive the vehicle in the manual mode to familiarise themselves with the driving simulator and VR environment. Then, the procedure illustrated in Figure 1 was followed: Participants took a seat in the driver's seat (the haptic feedback driver seat described in Section III-C) of the driving simulator. They were asked to engage in a non-driving related task, i.e, reading a magazine, while the vehicle (the ego car) was in self-driving mode. After a randomised time interval between 150 and 240 seconds, the car alerted the driver to take back control of the driving task (return to manual driving) due to an upcoming situation that the vehicle is unable to handle. The participants then had to get back in the driving loop, perceive, comprehend, and project the situation, to react to the road incident ahead and avoid crashing into a stationary car positioned in the same lane. The only inputs a participant needed to provide were accelerating using the right hand side pedal, braking with the pedal to the left of the throttle, and steering via the steering wheel. All other potential inputs were disabled for this experiment.

Based on accident reports involving self-driving vehicles [14], the following parameters were chosen for the scenario: The car was driving on a three-lane highway with sparse traffic. There were no adverse weather conditions; it was sunny and well lit; the road surface was dry. The ego car remained in the slow lane on the very left. Other road users on the fast lanes (middle or right lanes) were able to overtake. However, no vehicle changed lanes at any time. When the TOR was activated, a stationary vehicle obstructed the lane, the ego car was travelling in, within a distance of 220 metres. This distance is inspired by the capability of radars used in commercially available AVs. At a speed of 70mph, the driver is given about 7 seconds to take back control and avoid crashing into the stationary vehicle in the same lane. In some trials, an additional car in the middle or right lane appeared, which is also stationary. This difference in simulation introduced a level of variety in the experimental protocol.

Seven combinations of TOR alerts were provided to the driver: Either a single feedback modality, i.e., visual (v), audio (a), or haptic (h) feedback alone, or a combination of two feedback modalities (visual & audio (v&a), visual & haptic (v&h), or audio & haptic (a&h)) or all three feedback modalities at the same time (visual & audio & haptic (v&a&h)) were activated. Each participant repeated the scenario seven times, hence experiencing each combination of TOR alerts once. The order of the alerts was randomised.

V. Data collection and processing

To understand the impact of the feedback modality on the reaction time and a successful transfer of control, several variables (e.g., engagement of the participant in the NDRT or driving task) have been extracted from the recordings of the eye-tracking glasses and input through the pedals and steering wheel, executed by the participants. In this paper, reaction time is defined as the delay between the onset of the TOR alert and the driver's first input — either through the pedals or steering wheel — that significantly reduces speed or initiates a lane change. A lane change occurs when the ego vehicle's centre crosses the lane markings to the next faster lane, while significant braking is defined as applying more than 40% of maximum brake force for over 0.5 seconds. All driver inputs were extracted from the driving simulator data.

The video recordings from the camera integrated in the eye-tracking glasses, pointing to the front, were used to manually examine if participants (a) were fully engaged in the reading task in the 15 seconds prior to receiving the TOR alert and (b) managed to react safely to the road incident. Results were classified into two categories, which were defined as follows:

- Unsuccessful transfer of control: The participant either crashed into an obstacle or left the three-lane highway. If the participant managed to avoid the obstacles and stayed on the road, but they did not check their mirrors, in particular when introducing a lane change, the transfer of control was considered unsuccessful. This category also includes sudden full stops with the onset of the TOR alert, even if no obstacle was in sight.
- Successful transfer of control: The participant managed to avoid the obstacles, stayed on the road, and checked the mirrors accordingly before changing lanes.

In order to determine whether there are variations in reaction times across the aforementioned categories of transfer of control, the statistical significance is determined. The two categories of reaction times are treated as non-parametric independent datasets, leading to the utilisation of the Kruskal-Wallis one-way analysis of variance to test for significance [27], [28].

When examining the distribution of reaction times of different feedback modes, it is most advantageous to have a distribution similar to that of successful transfer of control. Two distributions are compared using cumulative distribution functions (CDFs) [29]. The two-sample Kolmogorov-Smirnov test is then employed to compare two CDFs [30]. It assesses the dissimilarity between the CDFs by calculating the maximum difference between them, referred to as the Kolmogorov-Smirnov test statistic. Put simply, a lower test statistic indicates that the two data sets are more equally distributed.

It is worth mentioning that no input was made to the vehicle if participants did not react to any TOR alert. Hence, the reaction time has been set manually to seven seconds, i.e., the time between onset of the TOR alert and the car crashing into the obstacle ahead (TTC).

VI. Experimental results

Figure 5 presents the distribution of reaction times in seconds for the two categories defining the success of transfer of control. The reaction times for unsuccessful transfers of control range from 1.87 seconds to 7 seconds. When the driver did not react to the TOR, the trial was assigned a reaction time of 7 seconds. Also, when the reaction time yielded a value greater than 7 seconds, it was capped at this value. Successful transfers range from 1.77 to 6.07 seconds. Except for the lowest reaction time observed in successful transfers of control, the distributions of unsuccessful transfers are more spread out compared to that of successful transfers. Furthermore, the median reaction time is lower for successful transfers of control (4.34 seconds) compared to unsuccessful transfers (5.09 seconds). The Kruskal-Wallis test results in a p-value of 0.021, indicating that the two distributions are statistically significantly different.

Table I shows the two-sample Kolmogorov-Smirnov test statistic (KS) when comparing the CDFs of the reaction times of each of the seven feedback modalities (FB) with the reaction times of all successful transfers. A high test statistic shows that the CDFs are further apart, hence the reaction times are more unequally distributed. For the single feedback modes, auditory feedback has the highest test statistic (0.390), followed by visual (0.296) and haptic (0.237). The lowest overall test statistic is achieved for visual & haptic feedback (0.149), followed by all three feedback modalities combined (0.181).

The violin plot in Figure 6 shows the distribution of reaction times for each feedback modality. The highest maxima are

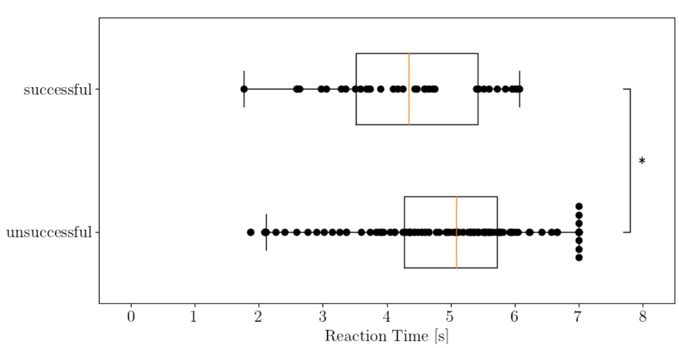

Fig. 5. Boxplot of reaction times clustered into successful (top) and unsuccessful transfers of control (bottom), as described in Section 5. Black dots depict individual data points.

TABLE I

Two-sample Kolmogorov-Smirnov test statistics (KS) and p-value, comparing the cumulative distribution functions of reaction times of successful transfers of control with the seven combinations of feedback, and mean and standard deviation (SD) of reaction times of the respective feedback.

FB	v	a	h	v&a	v&h	a&h	v&a& h
KS	0.296	0.390	0.237	0.237	0.149	0.277	0.181
p-value	0.191	0.035	0.423	0.423	0.905	0.250	0.737
Mean	5.223	5.035	4.835	4.643	4.586	4.814	4.157
SD	1.237	0.749	1.048	1.265	1.331	1.150	1.502

reported for visual, visual & haptic and visual & audio & haptic at 7 seconds, followed by audio & haptic (6.65s), haptic (6.23s), visual & audio (6.07s) and audio feedback (5.95s). The minima range from 3.50s (visual feedback) to 1.77s (visual & audio & haptic feedback). The highest median reaction time is observed for audio feedback (5.35s), followed by visual & audio (5.09s), visual (4.95s), audio & haptic (4.92s), haptic (4.82s), visual & haptic (4.33s) and visual & audio & haptic feedback (4.12s). No two of the distributions of reaction times are statistically significantly different from each other when calculating p-values using the Wilcoxon signed-rank test and Bonferroni correction for multiple comparisons.

VII. Discussion

Figure 5 illustrates that both extremely short and long reaction times are strongly associated with an increased likelihood of crashes. In cases of very short reaction times, drivers may lack SA, as they likely have not fully perceived, understood, or anticipated the dynamics of their environment. For instance, a driver may initiate a lane change without checking their mirrors, leading to premature actions that result in hazardous manoeuvres or collisions. Conversely, when reaction times are excessively long, drivers may not have sufficient time to execute a safe lane change, further increasing the risk of an accident. Only one very fast reaction time resulted in a successful transfer of control. An in-depth analysis of this outlier concludes that this participant looked up to monitor the environment for several seconds less than 15 seconds prior to the car issuing the TOR. Hence, they built up a significant level of SA before the TOR requested to intervene, resulting

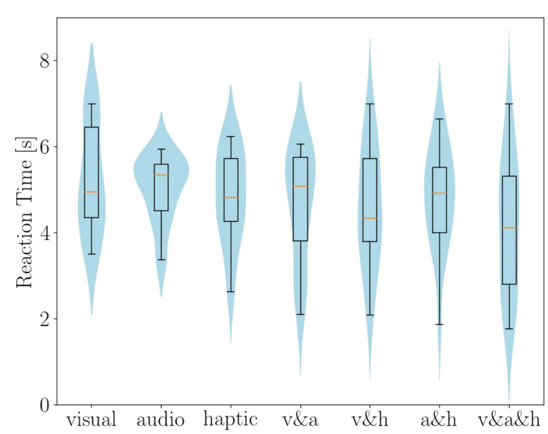

Fig. 6. Violin plot with overlaid box plot showing the distribution of reaction times for each feedback modality, i.e., visual, audio, and haptic feedback as well as a combination of them.

in a quick and successful transfer of control. This outlier, being the only trial where the participant shifted attention from the NDRT just before receiving the TOR alert, supports the hypothesis that in-depth knowledge about the surrounding dynamics and hence a good level of SA is of great importance to take over the driving task in a safe way. It therefore can be noted that when being engaged in a NDRT and not having any SA at the moment the TOR is issued, there might be an ideal window for the reaction time of between 2.6 seconds and 6.0 seconds (mean: 4.39 seconds).

Next, the distribution of reaction times for each of the seven feedback modes is compared to the reaction times of only the successful transfers of control. The premise hereby is that the potential for a safe transfer of control is higher if a feedback mode triggers reaction times within the time window described above across different participants. On the other hand, if a feedback mode is so alerting that the participant immediately reacts without having built up enough SA prior to reacting or if it is easily missed, resulting in a very late reaction, the take-over is more likely to result in a hazardous situation or in a crash. The Kolmogorov-Smirnov test statistic (see Table 1) shows the biggest discrepancy between two CDFs. It can be seen that the CDF of the haptic feedback most resembles the CDF of the reaction times of all successful transfers of control if only one feedback modality is used. With the exception of audio and haptic feedback, all multi-modal feedback mechanisms result in a lower statistic compared to single-modal feedback modalities. Although solely the distribution for auditory feedback reaches statistical significance, these observations suggest a trend that multi-modal feedback is more effective to achieve a timely and safe transfer of control. When adding haptics to any given feedback mode, the test statistic decreases, indicating that the haptic feedback seat is a valuable addition to current feedback modes.

The value of haptic feedback is further supported when comparing reaction times across feedback modes. Figure 6 shows a decline in median reaction times with multimodal feedback. Although not statistically significant, reaction times are notably lower with haptic feedback than without. This phenomenon may be attributed to the unique nature of haptic feedback, as it engages a sensory channel that in this experiment otherwise remains undistracted. Some participants might overlook visual cues when they are engaged in the reading NDRT, diverting their visual attention. Similarly, audio cues, as they are superimposed onto the car noise, could be easily missed as the participant's brain filters out the ambient sounds. However, there is no other haptic feedback given through the seat to the participant prior to the TOR. The most impressive reduction in reaction times is observed when all three feedback modalities are combined. This effect may be explained by the comprehensive sensory stimulation: even if one of the cues is missed, the participants are still promptly alerted by additional cues, enabling them to swiftly return to the driving task.

Several studies confirm low reaction times for feedback issued through a haptic (vibro-tactile) seat compared to visual cues [19], visual and auditory feedback [20], and a control group with no feedback given [21]. Comparing the same seven feedback modality combinations as in our paper, Yun et al. [6] concluded that a combination of all three modalities yields lower reaction times. Their reported mean reaction times however differs from the mean reaction times in our experiments. While Nukarinen et al. [19] and Chang et al. [20] report mean reaction times between 1 and 1.5 seconds, Telpaz et al. [21] measured reaction times of 8.5 to 10 seconds for haptic feedback. This is due to the different nature of their task, with the two first studies asking the participants to react as quickly as possible with a potential hazard immediately in front of them and the latter study not having any obstacle in the way. Thus, absolute times might not be comparable.

In a literature review, Eriksson et al. listed the resulting reaction times reported in 25 papers and concluded a mean of 3.04 ± 1.6 seconds [31]. In this study, we report on a mean reaction time of 4.75 ± 1.24 seconds. The slightly higher mean reaction time in our paper is due to the different definition of the reaction time: We defined the reaction time as the time difference between the onset of the alarm and the first *meaningful* input, leading to a significant reduction in velocity or the intiation of a lane change, rather than reporting on the first input. When only taking into account the first input of the participants we get a first touch reaction time of 3.21 ± 1.35 seconds, which closely resembles the difference between the mean reaction times in [31] and our results. In their own experiment, performed on a highway with a reading NDRT, they achieved a mean reaction time of 6.06 ± 2.39 seconds, explaining the discrepancies with the non-criticality (e.g. no immediate hazard or obstacle) in their scenario. Naujoks et al., for their three lane highway study with a reading NDRT, report a mean reaction time for a visual alert of 6.19 seconds and 2.29 seconds for a visual & auditory feedback [32]. Because of the occurring crash we capped the reaction time to 7 seconds, resulting in a lower mean reaction time for visual feedback, however our results correlate for the visual & auditory feedback mean first touch reaction time (2.86 seconds). In a very similar study, equally a three lane highway scenario with a TTC of 10 seconds, Vogelpohl et al. report on mean reaction times of 4.10 ± 2.51 seconds to 4.94 ± 1.23 seconds for different scenarios when the driver was engaged in a reading NDRT before the TOR [33]. The higher mean reaction time compared to our findings can be explained with the higher time budget for the TTC. Mean reaction times in the literature being in the same region as in our study validates our findings and hence supports the plausibility of the results involving the novel mechano-tactile feedback seat.

When adding haptic feedback to audio and visual feedback, reaction times decrease for successful transfers of control. In this experiment, the time budget was 7 seconds for every trial, which is the maximum time budget at a speed of 70mph within capabilities of current technical equipment. In the real world, a hazardous situation can evolve right in front of the automated vehicle, only allowing for a shorter time budget. Then, having a driver who can build up SA to a level rapidly where they feel confident to perform an evasive manoeuvre is of paramount importance. This again shows the potential of haptic feedback in addition to visual and audio feedback to convey take-over requests from automated vehicles to the driver.

VIII. Conclusions

Drivers can now engage in non-driving tasks when vehicles operate at Level 3 automation. Thus, it is crucial for drivers to regain control when the automated system reaches its design limit and the driver has to resume manual driving. This study examined reaction times and the success of transfers of control from car to driver when giving distinct take-over alerts: State-of-the-art visual and auditory feedback and haptic feedback through a novel mechano-tactile driver's seat and all possible combinations. The findings suggest multi-modal feedback alerts improve reaction times for successful transfers. Among single-modal feedback, static mechano-tactile feedback elicits faster, more successful responses than visual or audio cues. Adding haptic feedback to the state-of-the-art visual and audio feedback results in shorter reaction times for successful transfers of control.

Future work includes increasing the number of participants, with an aim of a total of 40 participants. A larger cohort will enable the investigation of whether specific personal factors, such as height or weight, impact the detection quality of mechano-tactile cues. Environmental factors, such as uneven roads, might likewise change the perception of the haptic feedback, which could be determined in a real-world study. Incorporating subjective measures or driver preferences may help explain the lack of statistical significance in the current results. If the patterns observed in the current study persist, a compelling argument may emerge for the incorporation of haptic driver's seats in automated cars to mitigate unsuccessful transfers of control from the vehicle to the driver.

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