Design concept for a visual, vibrotactile and acoustic take-over request in a conditional automated vehicle during non-driving-related tasks

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Abstract: Automated cars will be able to control themselves, but there will still be a need for take-over requests in critical situations that the automation system cannot handle on its own. In this paper a development and evaluation of three different take-over requests was performed. For this purpose, a total of 70 subjects took part in three independent studies conducted in a driving simulator mock-up. Within the studies three different critical scenarios with either a visual, a vibrotactile or a multimodal (combination of visual, vibrotactile and acoustic) take-over request were examined. During the automated ride, the test subjects were asked to engage in two different non-driving related tasks. The results show that all three take-over requests serve their purpose and all subjects switched from automated driving mode back to manual driving by using the steering wheel or pedals to intervene into the driving situation. Based on the results published here, a multimodal take-over request should be preferred, as it has the fastest reaction times in critical and non-critical traffic situations and consistently received good ratings within the questionnaires. A vibrotactile take-over request scored the worst in the questionnaires and participants stated that vibration as single stimulus is not being associated enough with a warning signal.

1. Introduction

Automated driving is currently one of the most discussed topics in the automotive industry. The technical development proceeds progressively and first automation systems are already available in certain driving conditions. Nevertheless, there will be situations where such systems reach their limits in conditional automated mode and will not be able to work reliably. In these cases, the driver must intervene and take over control of the vehicle as quickly as possible and with a high take-over quality.

In this manuscript, the analyzed investigation context of automated driving is based on the automation levels of SAE [20]. In addition to Manual Driving (Level 0) Assisted Driving (Level 1) exists since the adaptive cruise control system was introduced in 1998. In Partial Automation (Level 2) the vehicle autonomously assumes stabilization and the driver monitors the system at the track guidance level [6]. In Conditional Automation (Level 3) it is assumed that the driver can face away from active driving for a certain period of time and devote himself or herself entirely to non-driving related tasks (NDRT). According to the definition of SAE [20] and the NHTSA [14], the driver still has a duty in Conditional Automation to take over vehicle control within a certain period of time as requested by means of a take-over request (TOR). In this case, humans act as a fallback for the automation system.

1.1. *Take-over process after automated driving*

A TOR intends to generate an adequately timed response of the driver. Consequently, the driver must perceive this request explicitly. In the first step, the perception of stimuli themselves needs to be examined.

Former studies already dealt with few factors that are affecting the driver's take-over in automated driving. Radlmayr et al. [19] already proved that traffic density has a significant impact when driving in a motorway situation. Furthermore, the authors reached the conclusion that the exertion of NDRT, just as using a smartphone, worsens take-over quality in situations with heavy traffic and increases the likelihood for collisions. When showing the participants of an online survey pictures of different complex traffic situations, Eriksson et al. [7] found out that orientation occurred faster in less complex situations and when being pressed for time. Merat et al. [13] ascertained the similarity of reactions to critical incidents during automated driving without NDRT to reactions in situations during manual driving. Within the scope of a driving simulator study, Carsten et al. [3] examined the impact of three different automation levels (manual, semi-automated and highly automated) on the driver's ability to concentrate his attention on the street in association with his engagement during NDRT. Referring to this, the authors came to the conclusion that engagement in NDRT grows with a higher automation level, resulting at the same time in a decrease of the diver's focus on the street. Strand et al. [21] confirmed the negative influence of a high automation level on the driving performance after a take-over through comparing semi-automated with highly automated driving in critical situations, which occurred due to errors in the automation system. Happee et al. [9] conducted a driving simulator study that aimed on examining passing maneuvers on a motorway with blocked lanes. In the context of their research, they were able to prove a negative influence of higher automation levels on the driver's take-over as his steering and brake input occurred delayed in autonomous driving compared to manual driving. Damböck et al. [5] studied the required time needed for a take-over from autonomous driving back to manual driving in order to enable a comfortable take-over process for the driver. Based on their results the authors suggest a timeframe of at least six seconds needed for a comfortable take-over. Other studies focus on researching different sensory channels involved in a TOR during highly automated driving. Naujoks et al. [15] examined the effects of visual-auditive compared to visual-only TORs on the driver. The response time „Hands on Steering Wheel“[1] was found to be significantly shorter after a visual-auditive TOR. Petermeijer et al. [16] revealed positive functions of a vibrotactile feedback compared to an auditive TOR and the combination of both. The experiments were conducted on a simulated straightaway three-lane motorway without traffic and a driving speed of 120km/h. Within the study the drivers' response times while being involved in NDRT were evaluated. The results show that an intervention in the means of steering can be executed the fastest in a combined TOR situation. The direction of the evasive after a TOR is independent of whether the warning sound and/or the vibration was played from left or right. Petermeijer et al. [17] examined the effect of different variations of a vibrotactile TOR in a driving simulator study. The driving route was a three-lane motorway without traffic. Based on the results the participants' response times were faster when vibration was perceptible over the whole pad instead of single vibration patterns being noticeable. Telpaz et al. [22] conducted experiments with vibrotactile feedback after participants were asked to send a text message from a cell phone during autonomous driving. Within the scope of the TOR vibration was an indication for traffic. Driving took place on a simulated five-lane motorway. Response times were found to be faster for a vibrotactile TOR compared to an acoustic TOR. In summary, former studies dealt with response times dependent on the automation level, the traffic situation, NDRT and variations of a TOR.

1.2. Scope of this paper

Based on the literature, the following research question emerges: Is a unimodal TOR sufficient enough to ensure a fast reaction time between the TOR activation and the driver's intervention or does a simultaneous multimodal addressing of different sensory channels lead to better reaction times? In addition, it will be investigated whether there is a direct call to action after different TOR modalities and how disturbing the visual and acoustic TOR in particular is perceived by passengers.

For this purpose, three different TORs were developed and evaluated in three independent subject studies in this paper, see Table 1. Furthermore, reaction times between a visual, a vibrotactile and a multimodal (combination of visual, vibrotactile and acoustic) TOR will be compared.

The background for the development and evaluation is the selection of a supposedly optimal TOR. This is necessary in order to rebuild the driver's situation awareness as quickly as possible in critical driving situations. For this purpose, three realistic traffic situations, which differ from previous studies found in the literature, were developed and implemented in a driving simulator mock-up.

In Study (1) the perceived vibration intensity was examined. The scope was to identify the ideal vibration strength of a vibrotactile TOR.

In Study (2), a visual TOR was tested within three different scenarios. Test persons were asked to use their smartphones as a NDRT during the automated drive.

The vibrotactile TOR and multimodal (visual, vibrotactile and acoustic) TOR were tested for reaction times in Study (3). A tablet was offered to the subjects as a NDRT.

The aim of the NDRT is to distract the test persons as much as possible from the actual driving events and to create uniform test conditions. In addition to the objective driving data from the simulator, subjective data was collected in all studies using questionnaires. The data from Study (2) and Study (3) are compared and a design recommendation for an optimized TOR is derived from this comparison.

Table 1 Overview of the three studies used to evaluate a take-over request

Applied studies		TOR	Test environment	NDRT	Participants	Scope of analysis
1	Vibration mat		Vehicle mockup without driving simulation	-	N = 21	Perceived Vibration
2	LED light strip	Visual	Vehicle mockup with driving simulation	Smartphone	N =19	Reaction time & subjective ratings
3	Vibration mat	Vibrotactile	Vehicle mockup with driving simulation	Tablet	N = 30	Reaction time & subjective ratings
	Vibration mat, LED light strip & acoustic warning sound	Multimodal				

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[1] The Hands on Steering Wheel response time is defined as the time between the TOR entry and the first contact of hands with the steering wheel.

2. Developed take-over requests

Automated cars (Level 3 and Level 4) will be able to control themselves on different roads and in different traffic situations. However, there will still be a need for TORs in situations that the automated car cannot handle on its own as well as in planned changes of control. The TOR aims at bringing back the driver from autonomous to manual driving. Those TORs can be communicated to the driver via different modalities, as already being discussed in the introduction of this paper. Kayser et al. [12] rated the importance of different sensory channels for the vehicle guidance. For this reason, the development was reduced to a visual, acoustic and vibrotactile TOR. Within the frame of the following research, three different TORs were developed and evaluated in subject studies at the Institute of Ergonomics & Human Factors at the Technische Universität Darmstadt.

2.1. Visual take-over request via LED light strips

Research experiments have shown that LED batten luminaires have great potential as a visual warning signal compared to classic visual ADAS. Utesch [23] showed that fewer gaze averting from the road occurred, since warnings are also perceived in the peripheral field of vision. This leads to better reaction times due to selective attention theory, which says that a person can react faster to larger stimuli than to smaller ones. The LED arrangement around the driver can also be used to provide spatially oriented warnings. Common display elements used in series production, such as the combination, head-up and multimedia display cannot offer this feature.

Therefore, a visual information and warning system was developed. For this purpose, three LED light strips (LPD8806) were installed at the driving simulator mock-up, adding up to 97 individually selectable LEDs. One attached to each driver and passenger door and a third one attached to the dashboard at the height of the windscreen, see Figure 1. It was ensured that these were mounted in the driver's field of vision. The field of view of 180-200° presents a considerably greater vertical than binocular expansion (ca. 130°). Within the development and construction special attention was payed to the visibility of the LED light strips when turning away from the current street situation due to NDRTs. With the help of an Arduino microcontroller the LED light strips were dynamically controlled regarding their brightness, colour and blinking frequency and they were connected to the simulation software. In the course of the visual TOR the LEDs gave light in red and pulsated in a frequency of 2,6 Hz.

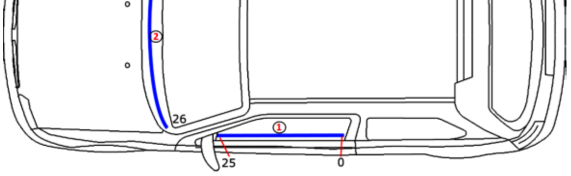

Fig. 1. *Visual LED arrangement layout with 97 LEDs*

2.2. Acoustic take-over request via loudspeakers

Acoustic signals are sensible independently of the driver's direction of view and therefore play a significant role when executing a NDRT. Furthermore, they are omnidirectional and can be perceived from every direction. Referring to Wicken's [24], theory of multiple resources, further advantages can be identified since a parallel processing of acoustic signals and visual information is possible. Regarding the selection of a suitable signal tone a study of Färber [8] was used as reference. In this study participants had to evaluate different tone frequencies in terms of urgency and amenity. Based on the results a 75 dB(A) 440Hz sinusoidal tone with a duration of one second, played every two seconds, was selected as acoustic TOR. This acoustic warning signal aims at alerting the driver without directional indication in case of a dangerous driving situation.

2.3. Vibrotactile take-over request via vibration mat

Typical visual or auditory interfaces have the disadvantage of being possibly ignored. For example, acoustic warning systems run the risk of being covered by an ambient noise or sounds of the NDRT.

The information content of vibrotactile signals is limited compared to visual or acoustic signals. However, information can be passed on to the driver independently from his field of vision and ambient sounds and will be only perceptible for himself or herself. Possible areas of application within a vehicle are the driver's seat, the back rest, the seat belt and the steering wheel. Since physical contact between the driver and the vibrating surface is essential for an information intake, certain areas of application can be classified as unsuitable. As the driver can be involved in NDRTs in autonomous driving and does not have to steer the car himself or herself, hands can be taken off the steering wheel. Petermeijer et al. [16] explained that seat belts and seats themselves are the only parts within a car that present a suitable area of application for vibrotactile feedback devices as the driver is always physically connected to them. Therefore, a vibration mat, usable within the IAD Driving Simulator as well as in non-simulators, was constructed for this research. The most useful publication to support this approach is the work of Ji et al. [11]. The authors conduct different studies, all of them referring to the intensity area of vibrotactile actuators being appropriate for human drivers and to the space needed between two actuators to feel their different localizations.

Vibration actuators that have a similar characteristic as suggested by Ji et al. [11] were used. Also, an unbalanced motor of Precision Microdrives Ltd was chosen. The relevant actuator characteristic curve of frequency and amplitude dependent on the applied voltage can be found in Figure 2. A vibration mat including 21 eccentric mass rotation actuators (Precision Microdrives 320-105) in a 7x3 arrangement was developed, see Figure 3. The mat is able to transmit both dynamic and static vibration patterns and can be used on the driver's seat in a driving simulator or in field tests. Each of the actuators can be controlled separately. Electronics and actuators were designed with focus on a wide vibration intensity spectrum. The control of each actuator is realized by means of another Arduino microcontroller with a self-developed software to ensure the connection with the simulation software.

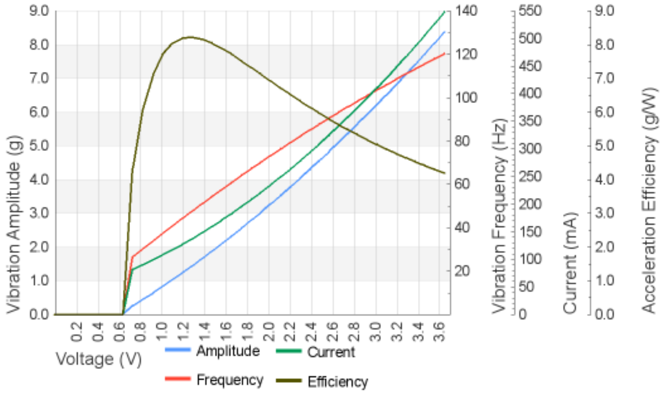

Fig. 2. *Vibration motor performance of actuator type 320-105 (Precision Microdrives [18])*

The portable vibrotactile mat consists of 2,5 cm thick foam material. Twelve cutouts in the seat back and nine cutouts in the seat cushion are made for the actuators. The actuators are situated in protecting plastic pipes which then were placed within the cutouts. The foam material features a high degree of hardness to prevent the user from sinking in and to enable a comfortable sitting. In addition to the 2,5 cm thick foam material mat with the embedded actuators, two 1 cm thick pads consisting of foam material as well and with the same degree of hardness were attached, one on top of the seat back and the other on top of the seat cushion. Those two additional pads aim at preventing the user of the vibration mat from feeling the actuators and increase the comfort of the mat.

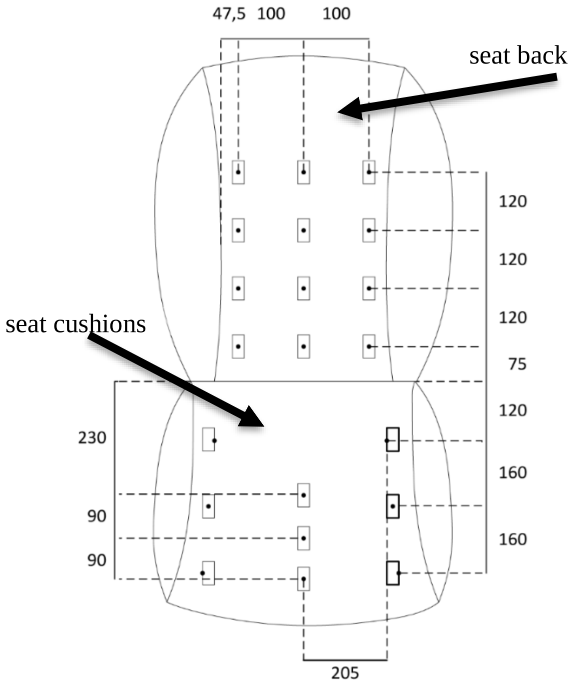

Fig. 3. *Vibrotactile mat arrangement layout with 21 (7x3) vibration motors (eccentric mass rotation). All distances are given in millimetres*

3. Method

3.1. *Experimental Set-Up*

Experiments were conducted in a high fidelity static driving simulator mock-up at the Institute of Ergonomics & Human Factors at the Technische Universität Darmstadt. The driving simulator consists of a full vehicle mockup (Chevrolet Aveo), a field of view of 180° front projection and a representation of all driving mirrors due to three rear projections. The simulation is realized with Silab 5.1 (WIVW) and a self-developed automation controller based on the definition of SAE [4] Level 3 Conditional Automation.

For Study (1), only the vibrotactile vibration mat was tested independently from a simulated driving task. For a realistic test environment, a total of three different critical scenarios were created which are used in Study (2) and Study (3):

3.1.1 Scenario 1 – city exit: Complete breakdown of the automation system at 50 km/h at the city exit after 110 sec of autonomous driving. As a result, the car drifts off to the right grass verge. A non-intervention of the driver leads to a collision after 3.5 sec with a street sign.

3.1.2 Scenario 2 – tunnel exit: Complete breakdown of the automation system at 100 km/h (street out of town) at the exit of a tunnel after 210 sec of autonomous driving. A non-intervention of the driver first leads to a cut into the oncoming lane and after 2.85 sec to a collision with a reflector post and a couple of trees.

3.1.2 Scenario 3 – broken-down vehicle: TOR during an inner-city left turn at 50 km/h after 350 sec of autonomous driving due to a broken down vehicle on the same lane. Breakdown of the longitudinal control, lane and speed stay constant. A non-intervention of the driver leads to an accident after 5.8 seconds.

Overall, three different TORs will be analyzed within this paper: a visual TOR, a vibrotactile TOR and a multimodal (combination of visual, vibrotactile and acoustic) TOR. The three different scenarios and TORs form a 3x3 experimental design. Between the vibrotactile TOR and the multimodal TOR as well as between a visual TOR and a vibrotactile TOR a within-subject design was chosen. Between a visual TOR and a multimodal TOR, a between-group design was set. In order to minimize the positive effect of learning on the driver's take-over reaction, the subject group tested the respective scenarios and TORs in permuted order in conditional automation mode according to SAE [20] Level 3. In all scenarios, the driver has to switch from the NDRT to traditional manual driving. 20 sec after the successful take-over the simulation paused and participants had to answer a questionnaire. Afterwards the next scenario followed. Altogether the driving simulator experiment had a duration of 30 min in Study (2) and 60 min in Study (3).

3.2. *Examined parameters*

A questionnaire regarding an evaluation on a 7-Point Likert Scale (very pleasant – very unpleasant) of the perceived vibration was given to the participants of Study (1). Questionnaires were originally written in German and have been translated afterwards into English for the purpose of this paper. The participants had to evaluate twelve different vibration strengths, given in permuted order for 5 sec each, one after another.

In order to compare the different TORs in Study (2) and Study (3) with each other, subjective and objective measures were collected during each of the studies. Objective driving data from the simulator was recorded.

The subject's reaction time to a TOR is characterized as the period of time from the moment the simulation software started the TOR to the moment the driver reacts to it and intervenes into driving. Intervention could happen in the form of actuating at least one of the classic vehicle controls steering wheel and pedal. Intervention through the steering wheel is captured starting at a change in angle of 2°. Intervention through operating the gas or brake pedal is detected when the pedal position changes by more than 10% from its initial position. The intervention, which was first made by the driver, will be considered as a minimum reaction time in the further process. A self-developed questionnaire was distributed to the subjects after every TOR. With the questionnaire subjects assessed the perceived urgency, usability, distraction and comfort transmitted by the TOR. All questions were asked in German and the participants were able to rate the TOR on a 7-Point Likert Scale.

3.3. Execution of non-driving related tasks before take-over request

During the automated ride, the subjects were asked to engage in NDRTs. In advance of the actual test execution participants were given an explanation of the functional principles of an automatized driving car. Thereby, the subjects were also given the information that a focus of one's attention on the driving situation was not necessary anymore and that an occupation in a NDRT was possible instead.

In order to attain an equal degree of distraction and a consistent experimental design across all participants, possible NDRTs were selected in advance. When investigating the visual TOR (Study 2), the subjects were asked to actively distract themselves from the driving activity and to interact with their own smartphone.

As the participants of Study (2) did not use their smartphone during the entire automated ride, participants of Study (3) (vibrotactile and multimodal TOR) were asked to complete a cognitively demanding test on a tablet (Huawai MateBookE). For this purpose the Brain Workshop program was installed on the tablet [2]. This program is based on a n-back test, used as a dual 2-back test within the study. Hereof, a blue visual stimulus is presented in random order in a 3x3 matrix. At the same time a letter is announced acoustically with every new presentation of the blue stimulus. With every new presentation and announcement, the subject has to identify if the forelast (2-back) stimulus and letter combination is congruent to the current one. If a repetition is detected correctly, a button on the tablet must be tapped accordingly, depending on the stimulus. The test's goal is to identify as many congruent pairs as possible and the study's participants have therefore been motivated to perform best possible. A more precise explanation of the n-back task can be found in [10].

3.4. Subject studies

The results of this paper are based on three independent subject studies. Participants have been acquired via notices at the TU Darmstadt and a subject database. In Study (1) (evaluation of the vibration intensity) 21 people, six of them women, participated. The subjects‘ average age was 27.3 years (SD 9.5 years). In Study (2) (visual TOR) 19 people, five of them women, participated (MN = 24.7 years, SD = 5.7 years). 30 people, eight of them women, participated in Study (3) (vibrotactile and multimodal TOR) The subjects‘ average age was 33.2 years (SD 6.8 years). In all three studies participants did not have any former experience with highly automated driving simulator mock-ups.

3.5. Statistical Evaluation

The parameters examined are displayed in a BoxPlot diagram, indicating the arithmetic mean [1]. Different test procedures are used for the statistical evaluation. The significance level is set to $\alpha = 0.05$. For the testing for standard distribution the Shapiro-Wilk test is used. As far as a standard distribution of the two samples is present, a T-test for dependent samples is performed in Study (3). For comparing Study (2) and Study (3) with each other a T-test for independent samples is used. Thereby, homogeneity of variance is examined with the Levene-test. As a result of the mean value comparison, a prediction can be made as to whether the considered mean values differ significantly from each other ($p \leqslant 0.05$) or not. If the results differ significantly, the effect strength is calculated according to Cohen [4].

4. Results

The results of the studies are presented in the following section. The descriptive data as well as the interference statistics will be mentioned as well.

4.1. Perceived Vibration

The aim of the first study was to adjust the constructed and built vibration mat to an optimized vibration intensity. The structure of the study and the number of required participants is based on Ji et al. [11]. Twelve different vibration intensities were transmitted in permuted order to the subjects in the simulator mock-up. The subject then had to evaluate each level on a Likert scale from one (very unpleasant) to seven (very pleasant). Any level of vibration intensity is held for five sec. Between each level there is a pause of five sec for the participant to complete the questionnaire.

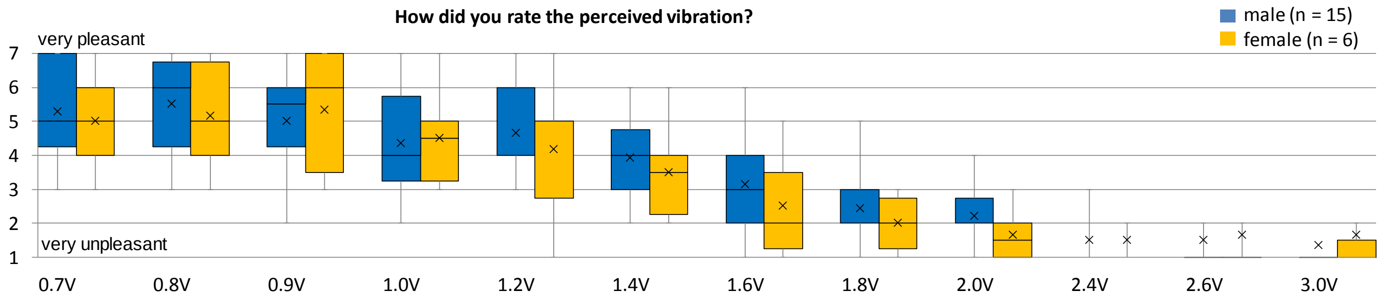

Fig. 4. *Rated vibration intensity as a function of gender and applied voltage*

Table 2 *Dataset: rated vibration intensity as a function of gender and applied voltage*

Voltage [V]	MN ♂ / ♀	SD ♂ / ♀	Voltage [V]	MN ♂ / ♀	SD ♂ / ♀
0.7	5.29 / 5.00	1.49 / 1.55	1.6	3.14 / 2.50	1.41 / 1.64
0.8	5.50 / 5.17	1.34 / 1.72	1.8	2.43 / 2.00	1.22 / 0.89
0.9	5.00 / 5.33	1.66 / 1.97	2.0	2.21 / 1.67	0.80 / 0.82
1.0	4.36 / 4.50	1.74 / 1.52	2.4	1.50 / 1.50	0.94 / 0.84
1.2	4.64 / 4.17	1.34 / 2.23	2.8	1.50 / 1.67	0.65 / 0.82
1.4	3.93 / 2.50	1.41 / 1.64	3.0	1.36 / 1.67	0.50 / 1.03

As seen in Figure 4 and Table 2, the feeling of pleasure decreases with increasing vibration intensity. Low vibration levels (0.7 V / 30 Hz / 0.3g) are rated as pleasant and high vibration levels (3V / 105 Hz / 6g) as very unpleasant. As also described in Ji et al. [11] a gender dependence on the perceived sensation of vibration was observed. Female test subjects rated the vibration intensity in the range of 1.2 V to 2.0 V as more unpleasant compared to male test subjects. With low and high vibration intensities, there are hardly any gender differences. Due to the low number of test persons, interference statistics were dispensed. According to the results of Study (1), a value of 1.4 V was chosen for the selection of the optimal vibration intensity, as this was evaluated by the test persons as the average between very pleasant and very unpleasant. Based on this, the conclusion can be drawn that in further studies subjects neither will not notice the vibration due to a too low intensity nor will they be distracted too much by an excessively vibration intensity set.

4.2. Reaction times between a take-over request and the driver’s intervention

In the following, the reaction times from Study (2) and Study (3) between the initiated TOR and the driver’s intervention are summarized and explained.

In scenario 1, after the vehicle has been driven through a city in a conditional automated mode for 110 sec, the automation controller fails at the city exit and the TOR is activated. In this scenario, there were no significant differences between the three different developed TORs. However, it turns out that in the case of the visual TOR participants require the longest period of time ($MN_{visual,S1}$ = 1.55 sec, $SD_{visual,S1}$ = 0.87 sec, n = 14) to intervene after the TOR activation. The fastest response times were observed with the multimodal TOR ($MN_{multimodal,S1}$ = 1.12 sec; $SD_{multimodal,S1}$ = 0.21 sec, n = 10), followed by the vibrotactile TOR ($MN_{vibrotactile,S1}$ = 1.36 sec, $SD_{vibrotactile,S1}$ = 0.43 sec, n = 25). Participants who were requested to resume to manual driving by a vibrotactile TOR ($MN_{vibrotactile,S2}$ = 1.35 sec; $SD_{vibrotactile,S2}$ = 0.39 sec, n = 22) in scenario 2 (omission of road markings), took over significantly faster compared to when the TOR was transmitted visually ($MN_{visual,S2}$ = 2.05 sec; $SD_{visual,S2}$ = 0.81 sec, n = 18, t(23,406) = 3.389, p = .002). The effect strength according to Cohen [4] is d = .57 and corresponds to a medium effect. An even greater effect strength can be seen when comparing the visual TOR with the multimodal TOR ($MN_{multimodal,S2}$ = 1.14 sec; $SD_{multimodal,S2}$ = 0.22 sec, n = 23, t(18.932) = 4.644, p = .000, d = .73.

In scenario 3, where the automation controller does not clearly recognize a broken down vehicle in the city and starts the TOR approximately six sec before the imminent collision, similar results compared to those in scenario 2 can be found. In the case of a visual TOR ($MN_{visual,S3}$ = 1.95 sec, $SD_{visual,S3}$ = 0.62 sec, n = 18) the subjects intervene significantly later than in the case of a vibrotactile TOR ($MN_{vibrotactile,S3}$ = 1.46 sec, $SD_{vibrotactile,S3}$ = 0.36 sec, n = 21, t(37) = 3.024, p = .005, d = .45). Response times for a multimodal TOR ($MN_{multimodal,S3}$ = 1.22 sec, $SD_{multimodal,S3}$ = 0.23 sec, n = 20) prove to be significantly faster than for the visual TOR, t(21.070) = 4.729, p = .000, d = .72, and significantly faster in comparison to the vibrotactile TOR, t(14) = 2.446, p = .028, d = .55.

At the end, the reaction times between the start of the TOR and the first measurable driver intervention were averaged over all three scenarios. Similar to the results of scenario 3, significant differences between the visual TOR ($MN_{visual,av.}$ = 1.89 sec, $SD_{visual,av.}$ = 0.60 sec, n = 19) and the vibrotactile TOR ($MN_{vibrotactile,av.}$ = 1.39 sec, $SD_{vibrotactile,av.}$ = 0.27 sec, n = 29, t(22.962) = 3.451, p = .002, d = .58) can be observed. Response times for the multimodal TOR ($MN_{multimodal,av.}$ = 1.17 sec, $SD_{multimodal,av.}$ = 0.20 sec, n = 27) prove to be significantly faster on average than for the visual TOR, t(20.835) = 5.055, p = .000, d = .74, and significantly faster

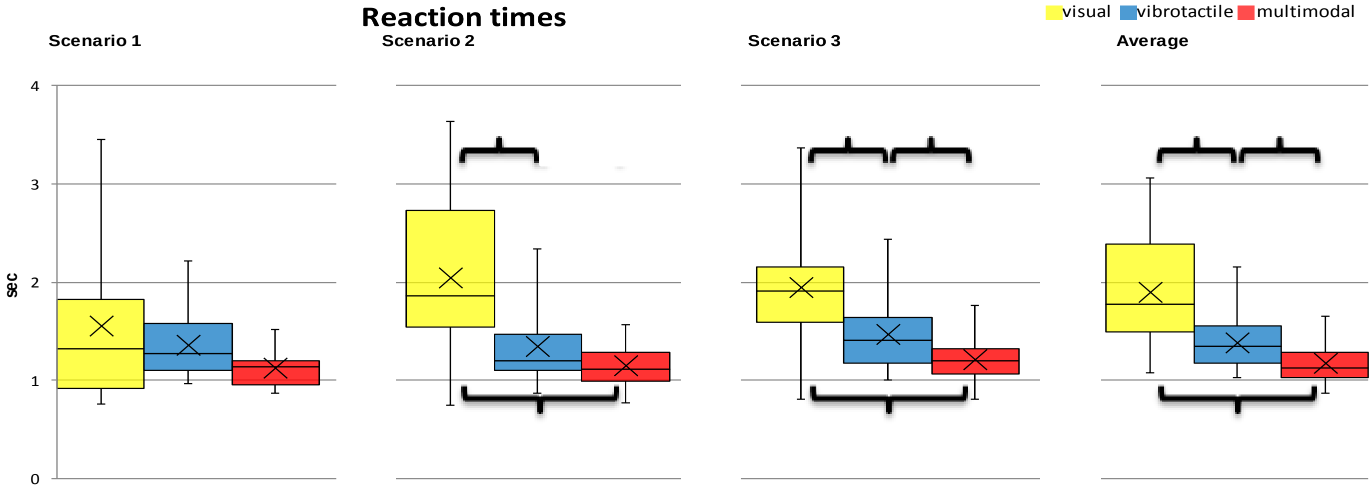

Fig. 5. Reaction times between the examined TOR and the driver intervention depending on the scenario

Table 3 Dataset: Reaction times between the examined TOR and the driver intervention depending on the scenario

TOR	Scenario 1 MN / SD [sec]	Scenario 2 MN / SD [sec]	Scenario 3 MN / SD [sec]	Average MN / SD [sec]
Visual	1.55 / 0.87	2.05 / 0.81	1.95 / 0 62	1.89 / 0.60
Vibrotatcile	1.36 / 0.34	1.35 / 0.39	1.46 / 0.37	1.39 / 0.27
Multimodal	1.12 / 0.21	1.14 / 0.22	1.22 / 0.23	1.17 / 0.20

than for the vibrotactile TOR, t (26) = 5.215, p = .000, d = .72. The results of the reaction times are shown in Table 3 and Figure 5 using box plots.

4.3. Questionnaires

In addition to the objective driving data, a questionnaire was handed out to the subjects after each TOR. The results of the subjective survey are shown in Figure 6 and Table 4. According to this, most subjects from Study (2) perceived the visual TOR to be urgent, but not very urgent ($MN_{visual,Q1}$ = 4.89 , $SD_{visual,Q1}$ = 1.28, n = 19). There is a difference in the ratings of the vibrotactile feedback ($MN_{vibrotactile,Q1}$ = 4.03 , $SD_{vibrotactile,Q1}$ = 1.17, n = 30). This was evaluated significantly less urgently than the visual TOR, t(47) = 2.44, p = .019, d = .34. The multimodal TOR was most urgently assessed by the subjects ($MN_{multimodal,Q1}$ = 5.02, $SD_{multimodal,Q1}$ = 0.96, n = 30) and differs significantly from the vibrotactile TOR, t(29) = -4.05, p = .000, d = .60.

Regarding the second question, subjects assessed the different TORs according to their usefulness. The visual TOR ($MN_{visual,Q2}$ = 5.21 , $SD_{visual,Q2}$ = 1.28, n = 19) tended to be more useful than the vibrotactile TOR ($MN_{vibrotactile,Q2}$ = 4.69 , $SD_{vibrotactile,Q2}$ = 1.36, n = 30). However, a significant difference in usefulness evaluation could only be determined between the vibrotactile TOR and the multimodal TOR ($MN_{multimodal,Q2}$ = 5.25, $SD_{multimodal,Q2}$ = 1.33, n = 30), t(29) = -2.446, p = .021, d = .41.

It can be seen that the majority of the test persons did not perceive the warning system as disturbing. Between the visual ($MN_{visual,Q3}$ = 5.74 , $SD_{visual,Q3}$ = 1.29, n = 19), the vibrotactile ($MN_{vibrotactile,Q3}$ = 5.63 , $SD_{vibrotactile,Q3}$ = 1.18, n = 30) and the multimodal TOR ($MN_{multimodal,Q3}$ = 5.41, $SD_{multimodal,Q3}$ = 1.40, n = 30) were no significant differences.

The perceived comfort is tending to be the highest with the visual TOR ($MN_{visual,Q4}$ = 5.08 , $SD_{visual,Q4}$ = 1.25, n = 18) but no significant differences can be found between the different variants ($MN_{vibrotactile,Q4}$ = 4.79 , $SD_{vibrotactile,Q4}$ = 1.13, n = 30; $MN_{multimodal,Q4}$ = 4.53, $SD_{multimodal,Q4}$ = 1.22, n = 30.).

Finally, all three TORs were generally judged on a 7-Point Likert Scale (recommend - not recommend). The visual TOR ($MN_{visual,Q5}$ = 5.63 , $SD_{visual,Q5}$ = 1.09, n = 16) was recommended significantly more often than the vibrotactile TOR ($MN_{vibrotactile,Q5}$ = 4.57 , $SD_{vibrotactile,Q5}$ = 1.91, n = 30, t(43.716) = 2.396, p = .021, d = .34). On average, the visual and the multimodal TOR ($MN_{multimodal,Q5}$ = 5.60, $SD_{multimodal,Q5}$ = 1.90, n = 30) hardly differ from each other and no significant difference to the vibrotactile TOR was found.

5. Discussion

The discussion is divided into three sections. First, the design of the individual TORs is critically questioned and frequently mentioned statements by the study's participants are mentioned. In the further course of the discussion, the determined reaction times are compared with each other and with different literature references. Furthermore, the questionnaire data will be discussed. Finally, the research questions from chapter 1.2 will be discussed and answered as well.

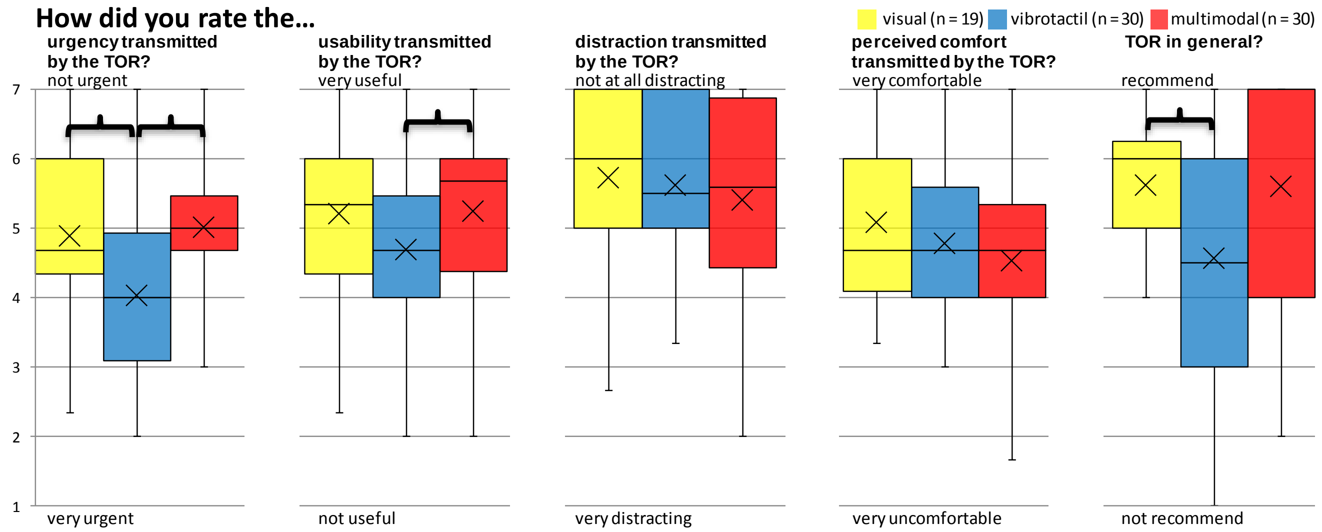

Fig. 6. *Subjective ratings of examined TOR*

Table 4 *Dataset: Subjective ratings of examined TOR*

TOR	Urgency MN/SD	Usability MN/SD	Distraction MN/SD	Comfort MN/SD	In General MN/SD
Visual	4.89 / 1.28	5.21 / 1.28	5.74 / 1.29	5.08 / 1.25	5.63 / 1.09
Vibrotatcile	4.03 / 1.17	4.69 / 1.36	5.63 / 1.18	4.79 / 1.13	4.57 / 1.91
Multimodal	5.02 / 0.96	5.25 / 1.33	5.41 / 1.40	4.53 / 1.22	5.60 / 1.90

5.1. *TOR design concept*

It turns out that the visual TOR, due to its alarming red pulse frequency, is intuitively understandable and is well suited as a warning system. Despite carrying out a NDRT and therefore turning eyes away from the road the system with the visual TOR is still well visible in the driver's peripheral field of vision. Test subjects from Study (2) testified that they would support an audible warning in addition to the visual stimulus. In principle, the test persons did not find the system disturbing. Only reflection effects on the mock-up's windscreen were noted negatively.

The acoustic TOR was positively perceived by the subjects in Study (3). The warning tone of 440 Hz was noticed by all participants, despite simulated traffic and wind noise. Overhearing of the warning signal, even when a NDRT is executed, did not occur due to the volume of 75 db (A). In the performed study, the acoustic signal was only tested in combination with the vibrotactile and the visual TOR. Whether an acoustic TOR leads to different reaction times should be investigated in another study.

Since hardly any results about the required vibration intensity were available in the literature, a vibration intensity recommendation was determined based on the results of Study (1). For the used actuators (Precision Dynamics 320-105), this is a vibration frequency of approx. 50 Hz and a vibration amplitude of 1.5 g at an applied voltage of 1.4 V. This value was chosen because it presents the average between "very pleasant" and "very unpleasant" rated by the test persons.

It can be assumed that in further tests, subjects neither will not perceive the vibration due to a too low vibration intensity nor will they be frightened by a too high vibration intensity, which would lead to a poorer take-over quality.

It is also noteworthy that there were differences at the perceived vibration intensity in terms of gender. Female subjects evaluated the perceived vibration intensity more unpleasant than male subjects, especially in the medium voltage range (1,2 – 2,0 V). Similar results were shown in Ji et al. [11] and can be confirmed by this study. Whether this effect actually depends on gender or body weight should however be examined in further studies. Individual test persons point out that various areas of vibration were perceived as very unpleasant. The entries vary from subject to subject, so that no generally valid statement can be made. Nevertheless, the back area in general and the kidney area in particular are more frequently mentioned.

Furthermore, based on the test person's evaluations the visual red light bar and the loud warning tones appear threatening and can also alarm and frighten the passengers. The vibrotactile feedback, on the other hand, is very private and can only be perceived by the contact person.

5.2. *Reaction times*

One of the most important criteria for the evaluation of a TOR are the reaction times, which need to be as short as possible in critical real driving situations.

The experiments within this study show that under the same scenarios, the fastest reaction times are caused by the multimodal TOR, followed by the vibrotactile and the visual TOR. Especially in scenarios 2 and 3 these differences are significant and show high effect strengths.

A possible reason why the visual TOR led to delayed reaction times could be due to the fact that the subjects were occupied by a visual NDRT. A visual stimulus right before the activation of a visual TOR could therefore result in a delay of information processing and ultimately in the execution of an action. This also speaks for the multiple resource theory according to Wickens [24]. Whether similar effects occur in the case of an acoustic NDRT being performed right before the activation of an acoustic TOR should be further investigated.

Furthermore, the different response times may have been caused by the different NDRTs used in Study (2) and Study (3). In Study (2) subjects held their private smartphone in their hands with the incitement to do everyday things. Since not all subjects operated the smartphone continuously during the experiment, a tablet was attached to the central information display position in Study (3) and a cognitively highly demanding dual 2-back test needed to be executed by the subjects. Despite the supposedly higher cognitive demand, the reaction times are significantly shorter. One possible cause could be that in the case of a TOR the test persons did not want to drop their smartphone directly out of their hands and tried to put it down safely.

The influencing factor of the time budget and indirectly of the take-over situation's criticality as well, which has already been investigated by Damböck [5], could also be found in this study. In this case, scenario 3 was the most uncritical, as it specified a time budget of approximately six secs before a collision with a broken down vehicle occurs. The results show that in scenario 3 the reaction times were longer than in scenario 2, where the time budget amounts for only approximately 3.5 sec. Furthermore, scenarios 2 and 3 differ from the failure of the automation controller. While in scenario 2 (and 1 as well) the automation system fails completely, in scenario 3 only the longitudinal controller was deactivated. Scenario 3 is therefore less critical, as the vehicle does not drift off the road. Ultimately, it can be concluded that the less critical the situation, the longer the reaction times.

A comparison of reaction times with literature data shows that the take-over times after a vibrotactile TOR found by Petermeijer et al. [16] and Petermeijer et al. [17] are approximately 2.67 sec and 1.97 sec respectively. These values are considerably slower than the results of this study ($MN_{visual,av.}$ = 1.89 sec, $MN_{vibrotactile,av.}$ = 1.39 sec, $MN_{multimodal,av.}$ = 1.17 sec).

5.3. Questionnaires

The subjective data from the questionnaires reinforce the previously described results from chapter 5.2. The subjects expressed that the visual TOR effectively informs about the need for intervention since a direct call to action regarding the relevant area is established, in this case the windscreen and thus the external traffic events. In the case of the vibrotactile TOR, the vibration stimulus is not associated with an operational intent and test persons often did not know exactly what to do. A warning effect by a vibrotactile TOR is therefore not guaranteed; this can also be confirmed by the question of urgency.

The results regarding the question about the perceived usability confirms the aforementioned thesis that a vibrotactile signal may perceived as unhelpful. The perceived distraction does not differ from the three variants and is not perceived as disturbing by the majority of the subjects.

Although Study (1) determined a trade-off for the best vibration intensity, the questionnaire results show that the perceived comfort for a vibrotactile stimulation was rated lower than for a visual TOR.

6. Conclusion

The results show that all three TORs serve their purpose and all participants switched from automated driving mode back to manual driving by using the steering wheel or pedals again. For further investigations, in cases where the time aspect of the TOR is decisive, a TOR should be used, that causes the shortest reaction times. Three different TOR variants were developed based on existing literature results. Furthermore, the TORs were tested for their reaction times in three different critical scenarios and were subjectively evaluated using questionnaires. A total of 70 subjects took part in the three independent studies.

The vibrotactile TOR scored the worst in the questionnaires, since the vibration stimulus appears to be not associated enough with a warning signal. The different NDRT or parallel processing of the visual channel can explain the higher response times of the visual warning system.

Based on the results published here, a multimodal TOR should be preferred as it implies the fastest reaction times in critical and non-critical traffic situations as well as it has consistently good ratings from the questionnaires. Future studies should continue with the parameterization of individual factors of the multimodal TOR and optimize them with a uniform test design.

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8. References

[1] Bortz, J. and Weber, R. Heidelberg : Springer Berlin Heidelberg, 2005. *Statistik. Für Human- und Sozialwissenschaftler von Jürgen Bortz, René Weber*. Springer-Lehrbuch. Springer Berlin Heidelberg, Berlin, Heidelberg.

[2] *Brain Workshop. Dual N-Back game. http://brainworkshop.sourceforge.net/*.

[3] Carsten, O., Lai, F. C. H., Barnard, Y., Jamson, A. H., and Merat, N. 2012. Control task substitution in semiautomated driving. Does it matter what aspects are automated? *Human Factors: The Journal of the Human Factors and Ergonomics Society* 54, 5, 747–761.

[4] Cohen, J. 1988. *Statistical Power Analysis for the Behavioral Sciences*. Taylor and Francis, Hoboken.

[5] Damböck, D., Farid, M., Tönert, L., and Bengler, K. 2012. Übernahmezeiten beim hochautomatisierten Fahren. *Tagung Fahrerassistenz. München*.

[6] Donges, E. 1982. Aspekte der aktiven Sicherheit bei der Führung von Personenkraftwagen. *AUTOMOB-IND* 27, 2.

[7] Eriksson, A., Marcos, I. S., Kircher, K., Västfjäll, D., and Stanton, N. A. 2015. The Development of a Method to Assess the Effects of Traffic Situation and Time Pressure on Driver Information Preferences. In *Engineering Psychology and Cognitive Ergonomics*, D. Harris, Ed. Lecture Notes in Computer Science. Springer International Publishing, Cham, 3–12. DOI=10.1007/978-3-319-20373-7_1.

[8] Färber, B. 1987. *Geteilte Aufmerksamkeit. Grundlagen und Anwendung im motorisierten Strassenverkehr*. Mensch, Fahrzeug, Umwelt 20. Verl. TÜV Rheinland, Köln.

[9] Happee, R., Gold, C., Radlmayr, J., Hergeth, S., and Bengler, K. 2017. Take-over performance in evasive manoeuvres. *Accident; analysis and prevention* 106, 211–222.

[10] Jaeggi, S. M., Buschkuehl, M., Jonides, J., and Perrig, W. J. 2008. Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences of the United States of America* 105, 19, 6829–6833.

[11] Ji, Y. G., Lee, K., and Hwang, W. 2011. Haptic perceptions in the vehicle seat. *Hum. Factors Man.* 21, 3, 305–325.

[12] Kayser, H. J., Sanders, A. F., Hess, M., Spijkers, W. A. C., and Bartmann. 1989. *Das Wahrnehmungsverhalten des Kraftfahrers in Abhängigkeit von der gefahrenen Geschwindigkeit und der Straßenraumgestaltung :Forschungsbericht aus dem Forschungsprogramm des Bundesministers für Verkehr und der Forschungsgesellschaft für Straßen- und Verkehrswesen E.V.* Bundesminister für Verkehr, Bonn-Bad Godesberg.

[13] Merat, N., Jamson, H., Lai, F., and Carsten, O. 2012. Highly Automated Driving, Secondary Task Performance, and Driver State. *Human Factors: The Journal of the Human Factors and Ergonomics Society* 54, 5, 762–771.

[14] National Highway Traffic Safety Administration. 2012. *Visual-Manual NHTSA Driver Distraction Guidelines for In-Vehicle Electronic Devices* NHTSA-2010-0053. NHTSA.

[15] Naujoks, F., Mai, C., and Neukum, A. 2014. The effect of urgency of take-over requestsduring highly automated driving underdistraction conditions. In *Advances in human factors and ergonomics 2014. 5th International Conference on Applied Human Factors and Ergonomics : 20 volume set: proceedings of the 5th AHFE Conference, 19 - 23 July 2014*, R.-L. Jang and T. Ahram, Eds. AHFE Conference.

[16] Petermeijer, S., Bazilinskyy, P., Bengler, K., and Winter, J. de. 2017. Take-over again. Investigating multimodal and directional TORs to get the driver back into the loop. *Applied ergonomics* 62, 204–215.

[17] Petermeijer, S. M., Cieler, S., and Winter, J. C. F. de. 2017. Comparing spatially static and dynamic vibrotactile take-over requests in the driver seat. *Accident; analysis and prevention* 99, Pt A, 218–227.

[18] Precision Microdrives TM. 2018. *vibriation motor performance type 320-105*. https://www.precisionmicrodrives.com/product/320-105-20mm-vibration-motor-25mm-type. Accessed 14 May 2018.

[19] Radlmayr, J., Gold, C., Lorenz, L., Farid, M., and Bengler, K. 2014. How Traffic Situations and Non-Driving Related Tasks Affect the Take-Over Quality in Highly Automated Driving. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 58, 1, 2063–2067.

[20] SAE J3016. 2014. *Automated Driving. Levels of driving automation are defined in new SAE International Standard J3016*.

[21] Strand, N., Nilsson, J., Karlsson, I. M., and Nilsson, L. 2014. Semi-automated versus highly automated driving in critical situations caused by automation failures. *Transportation Research Part F: Traffic Psychology and Behaviour* 27, 218–228.

[22] Telpaz, A., Rhindress, B., Zelman, I., and Tsimhoni, O. 2017. Using a Vibrotactile Seat for Facilitating the Handover of Control during Automated Driving. *International Journal of Mobile Human Computer Interaction* 9, 3, 17–33.

[23] Utesch, F. *Unscharfe Warnungen im Kraftfahrzeug. Eignet sich eine LED-Leiste als Anzeige für Fahrerassistenzsysteme?* Dissertation. Technische Universität Carolo-Wilhelmina. Braunschweig.

[24] Wickens, C. D. 2008. Multiple resources and mental workload. *Human Factors: The Journal of the Human Factors and Ergonomics Society* 50, 3, 449–455.