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# A vibrotactile interface to support the driver during the take-over process

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– Bastiaan

# Abstract

Slowly but surely more driving tasks are allocated to automated systems and it is only a matter of time before conditional automation will enter the commercial market. When a conditionally automated system is active, the driver is allowed to perform other non-driving tasks, but the automation requires the driver to be the fall-back option when the system's limits are reached. The automation will then present a request to intervene and the driver needs to perform a takeover. Traditional visual and auditory displays might not be effective warnings, when a driver is engaged in visually or auditory loading non-driving tasks, like reading or talking on the phone. Vibrotactile displays are expected to be effective as a take-over request and could potentially be used to direct the attention of the driver or convey more complex messages. The aim of this thesis if to evaluate how a vibrotactile interface can support the driver during the take-over process and how to incorporate such an display in a multimodal interface.

Two literature reviews were performed to investigate how vibrotactile displays could be used to support the driver during the different stages of the take-over process. A vibrotactile seat was analysed and designed in a full design cycle. Four empirical studies were conducted to evaluate the application of the display during the take-over process. The first experiment evaluated the driver's reaction time to visual, auditory, and vibrotactile take-over requests while they were reading, making a phone call, or watching a video. The second investigated unimodal and bimodal (auditory and vibrotactile) take-over requests, as well as the spontaneous driver response to a directional cue embedded in stimulus. The third study compared the recognition rate and driver response to directional cues embedded in static and dynamic vibration patterns under three cognitive loads. The fourth and final study evaluated three approaches to a visual interface, which supports the driver's decision making process.

Auditory and vibrotactile take-over requests yield faster reaction times than visual ones. Bimodal auditory and vibrotactile take-over requests yield slightly faster reaction times than the unimodal constituents. Directional cues embedded in the take-over requests did not evoke a spontaneous ipsi- or contra-lateral response. Moverover, directional cues could not be reliably recognized by the driver when they were under a cognitive load. A take-over request that was complemented by a visual interface, providing information on the traffic situation or suggesting an appropriate action yielded faster and more correct driver responses, compared to simple take-over requests.

The main conclusion of the thesis is that vibrotactile displays can be effectively and efficiently used to convey take-over requests, but their capability to support the driver during the remainder of the take-over process is limited. It is recommended to implement a cascading warning strategy, that withholds vibrotactile stimuli for urgent scenarios. In order to validate the results of the studies on-road tests should be performed to investigate how well the driver perceives vibrotactile warnings when natural engine and road vibrations are present.

# Zusammenfassung

Langsam aber sicher werden zunehmend mehr Fahraufgaben automatisierten Systemen übertragen, und es ist nur eine Frage der Zeit, bis Konditionale Fahrzeuge den kommerziellen Markt betreten. Während ein Konditionale System aktiv ist, steht es dem Fahrer frei, fahrfremde Tätigkeiten ausüben. Dennoch erfordert die Automatisierung, dass der Fahrer als sicherheitskritische Rückfallebene fungiert, wenn die Systemgrenzen erreicht werden. In diesem Fall gibt das System eine Übernahmeaufforderung aus, woraufhin der Fahrer die Fahraufgabe übernehmen muss. Traditionelle visuelle und auditive Warnungen sind möglicherweise nicht effektiv, wenn der Fahrer eine auditiv oder visuell beanspruchende Nebentätigkeit, beispielsweise Lesen oder Telefonieren, ausübt. Es wird erwartet, dass vibrotaktile Anzeigen eine effektive Übernahmeaufforderung darstellen und potenziell verwendet werden können, um die Aufmerksamkeit des Fahrers zu lenken oder komplexere Nachrichten zu vermitteln. Ziel dieser Dissertation ist zu evaluieren, wie eine vibrotaktile Anzeige den Fahrer während des ÃIJbernahmeprozesses unterstÃijtzen und wie eine derartige Anzeige in eine multimodale Schnittstelle integriert werden kann.

Anhand von zwei Literaturrecherchen wurde untersucht, wie eine vibrotaktile Anzeige während der verschiedenen Phasen des Übernahmeprozesses verwendet werden kann. In einem vollständigen Designzyklus wurde ein vibrotaktiler Sitz analysiert und entworfen. Vier empirische Studien wurden zur Bewertung der Anzeige durchgeführt. Der erste Versuch betraf die Geschwindigkeit von Reaktionen auf visuelle, auditive, und vibrotaktileÜbernahmeaufforderungen, während derer die Fahrer lasen, telefonierten oder einen Film sahen. Der zweite Versuch untersuchte die spontane Fahrerreaktion, wenn die uni- oder bimodale (auditive und vibrotaktile) Übernahmeaufforderung einen Richtungshinweis enthielt. Die dritte Studie verglich Erkennensrate und Fahrerreaktion auf Richtungshinweise in statischen und dynamischen Vibrationsmustern unter drei Abstufungen kognitiver Beanspruchung. Die vierte und letzte Studie evaluierte drei Ansätze zur Gestaltung einer visuellen Schnittstelle um den Entscheidungsfindungsprozess des Fahrers zu unterstützen.

Vibrotaktile und auditive Übernahmeaufforderungen bedingen schnellere Reaktionszeiten als visuelle Reize. Bimodale auditive und vibrotaktile Übernahmeaufforderungen führen dabei zu geringfügig schnelleren Reaktionen als ihre unimodalen Bestandteile. Richtungshinweise verursachen keine spontane, weder ipsi- noch kontralaterale, Fahrerreaktion. Darüber hinaus können Richtungshinweise unter kognitiver Beanspruchung nicht zuverlässig erkannt werden. Wenn eine Übernahmeaufforderung durch eine visuelle Schnittstelle ergänzt wird, die Information über die Verkehrssituation bereitstellt oder eine entsprechende Reaktion vorschlägt, bedingt dies schnellere und bessere Fahrerreaktionen im Vergleich zu einfachen Übernahmeaufforderungen.

Zentrale Schlussfolgerung dieser Dissertation ist, dass vibrotaktile Anzeigen als effektive und effiziente Übernahmeaufforderung genutzt werden können, wobei jedoch

ihre Eignung den Fahrer während des Übernahmeprozesses zu unterstützen limitiert ist. Es wird eine kaskadenförmige Warnstrategie empfohlen, in der vibrotaktile Stimuli für dringliche Szenarien reserviert sind. Zur Validierung der Ergebnisse sind Studien auf realen StraÃ§en erforderlich, welche die Wirksamkeit vibrotaktiler Reize im Beisein natürlich vorkommender Vibrationen untersuchen.

# Contents

# 1 | Introduction

*"There is nothing worse than a smart-ass automobile"*
– K.I.T.T., The Knight Rider 2000

## 1.1 Background

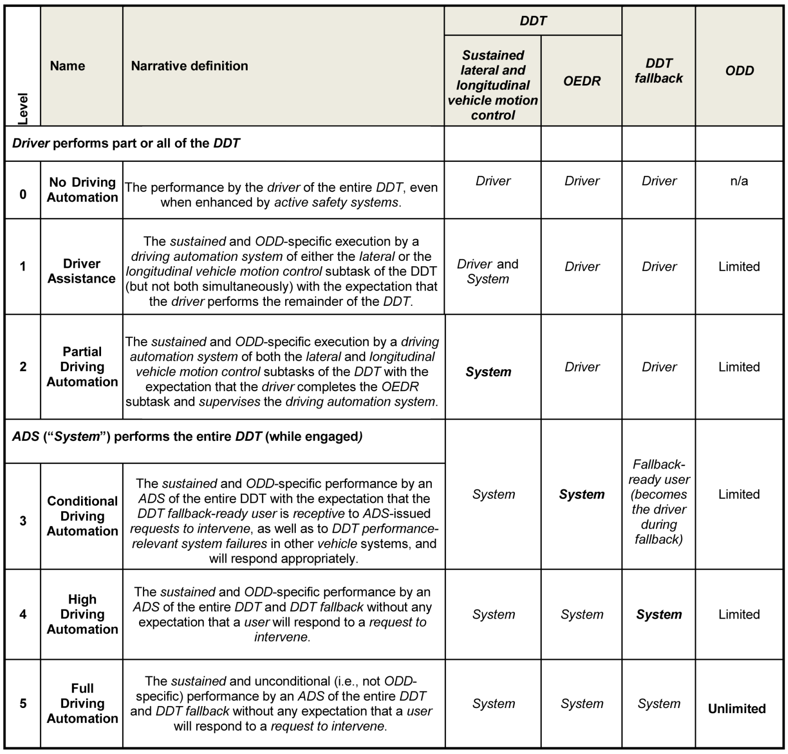
Ever since the invention of the 'Motorwagen' by Karl Benz in 1886 (Akamatsu et al., 2013), developments in the car industry have been aimed at making driving easier, more comfortable, and above all safer. The starter motor, electronic windscreen wipers, power steering, automatic gear shifts, and Anti-lock Braking Systems are only a few examples of the ever increasing amount of automated systems in our vehicles. Nonetheless, these features did not fundamentally change the task of the driver, until the cruise control system was invented in 1950 (Akamatsu et al., 2013; Teetor, 1950). This feature, introduced to the market by Chrysler and aptly named 'Autopilot' (Chrysler, 1958) kept a constant speed. More recent developments have led to the introduction of so-called active lane keeping assistance systems, which automate the steering task. When such a system is combined with an adaptive cruise control, which keeps a safe gap to a vehicle ahead, it forms a basic automated system for highway driving. It has been predicted that automated system will incrementally take over the driving task (Davies, 2015). Ultimately, fully autonomous cars drive us from A to B while we keep ourselves otherwise occupied, without worry in the world. The future looms, but that time has yet to come.

## 1.2 Conditionally automated driving systems

The state-of-the-art automated driving systems currently on the road are SAE level 2 (cf. figure 1.1; SAE International, 2016), which requires the driver to permanently monitor the automation and be ready to take over when it does not perform correctly. It is widely recognized that humans have difficulties monitoring a system for prolonged periods of time, leading to reduced vigilance, overreliance, and loss of situation awareness (Bainbride, 1983; Endsley, 1995). Indeed, in a recent fatal accident, involving a Tesla Model S, the driver was watching a movie and probably did not monitor the system actively (Levin & Woolf, 2016).

The next generation of automated driving system (i.e., SAE-level 3 or conditional driving automation) is believed to mitigate at least part of these problems, since the driver is no longer required to actively monitor the system. According to many key actors within the automotive domain, conditionally automated driving will make its introduction in the next 5 to 10 years (Viereckl et al., 2016; ERTRAC, 2015; VDA, 2015).

The SAE's technical report J3016 (SAE International, 2016) describes an automated driving system as a system that performs "the entire DDT [Dynamic Driving Task] on a sustained basis" (p.3). The Dynamic Driving Task (DDT) is defined as "all of the real-time operational and tactical functions required to operate a vehicle in on-road traffic, excluding the strategic functions such as trip scheduling and selection of destinations and waypoints" (SAE International, 2016, p.5). This includes controlling the lateral and longitudinal motion of the vehicle, monitoring the surrounding traffic, Object and Event Detection and Response (OEDR), but also maneuver planning and enhancing the conspicuity of the vehicle via, for example, signalling. Note that the DDT comprises of the operational (i.e., longitudinal and lateral motion) and tactical driving tasks (e.g., maneuver planning), but excludes strategic functions (e.g., destination and route planning). See Michon (1985) for a taxonomy on operational, tactical, and strategic driving tasks.



| **Level** | **Name** | **Narrative definition** | ***DDT*** | | ***DDT fallback*** | ***ODD*** |
|---|---|---|---|---|---|---|
| | | | ***Sustained lateral and longitudinal vehicle motion control*** | ***OEDR*** | | |
| ***Driver* performs part or all of the *DDT*** | | | | | | |
| **0** | **No Driving Automation** | The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems*. | *Driver* | *Driver* | *Driver* | n/a |
| **1** | **Driver Assistance** | The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*. | *Driver* and *System* | *Driver* | *Driver* | Limited |
| **2** | **Partial Driving Automation** | The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the *DDT* with the expectation that the *driver* completes the *OEDR* subtask and *supervises* the *driving automation system*. | ***System*** | *Driver* | *Driver* | Limited |
| ***ADS* ("*System*") performs the entire *DDT* (while engaged*)*** | | | *System* | ***System*** | *Fallback-ready user (becomes the driver during fallback)* | Limited |
| **3** | **Conditional Driving Automation** | The *sustained* and *ODD*-specific performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user* is *receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle* systems, and will respond appropriately. | | | | |
| **4** | **High Driving Automation** | The *sustained* and *ODD*-specific performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*. | *System* | *System* | ***System*** | Limited |
| **5** | **Full Driving Automation** | The *sustained* and unconditional (i.e., not *ODD*-specific) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*. | *System* | *System* | *System* | **Unlimited** |

Figure 1.1: Overview of the levels of driving automation, as specified by the SAE. The following abbreviation are used: Dynamic Driving Task (DDT), Operational Driving Domain (ODD) Object and Event Detection and Response (OEDR), Automated Driving System (ADS). Figure taken from SAE International (2016, p.17).

A closer look at the SAE taxonomy (Figure 1.1) reveals that there is distinct difference between level 2 and level 3 automation regarding the roll of the driver. Level 2 requires the driver to supervise the system actively, whereas a level 3 system does not required the driver to be actively engaged in the DDT as long as the system active. In other words, the driver is allowed to take the hands/feet of the steering wheel/pedals and can engage in non-driving related tasks, such as reading or making a phone call.

However, a level 3 automation still requires the driver to be a fall-back option when the system reaches the limits of its Operational Design Domain. The SAE defines conditional driving automation a "the sustained and ODD-specific [Operational Design Domain] performance by an ADS [Automated Driving Systems] of the entire DDT with the expectation that the DDT fallback-ready user is receptive to ADS-issued requests to intervene, as well as the DDT performance relevant system failures in other vehicle systems, and will respond appropriately" (SAE International, 2016, p.23). The Operational Design Domain is broadly defined as the specific conditions in which the system was designed to function correctly (SAE International, 2016). Depending on the state of the technology, these conditions include roadway, traffic, speed, but also time of day or weather conditions.

The request to intervene[1] is a safety critical moment, because the system will no longer perform the DDT and if the driver does not respond in a timely and appropriate manner the vehicle might crash. That is, the driver needs to promptly resume the DDT, which may include performing a minimal risk maneuver, such as an emergency stop. Interface designers face the challenge to develop an interface that provides an unambiguous take-over request and, if possible, that assists the driver to make a rapid and appropriate response.

### 1.2.1 Take-over scenario

The take-over scenario is defined as the driving conditions at the moment a take-over request is presented to the driver (Gold, 2016). For example, a take-over request could be issued because the vehicle is about to leave the highway and the system's operational domain is limited to the highway. Damböck et al. (2012) were among the first to investigate the take-over scenario in the automotive domain. This study investigated take-overs with a time budget of 4, 6, and 8 seconds and found that, given 4 or 6 seconds to respond, drivers made significantly more lane change errors (i.e., performed too late or in the wrong direction) compared to a baseline condition. Gold et al., (Gold et al., 2013) studied the topic further in a series of studies. It was found that shorter time budgets yield faster take-over times (Gold et al., 2013), the characteristic of the secondary task had no large effect on the take-over performance, and the mere presence of traffic not so much the density seems to decrease the take-over performance of the driver (Radlmayr et al., 2014; Gold et al., 2015).

### 1.2.2 Take-over process

Within this thesis the take-over process is defined as actions a driver has to perform during the transition of DDT, from automated system back to the driver, and the driver's response to the take-over scenario. Zeeb et al. (2015) and Kerschbaum et al. (2015) argued

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[1] Throughout this theses the term 'request to intervene' is interchangeable with 'take-over request'

that the driver has to take several actions to resume the driving task, namely shift the attention to the road, get physically ready to start driving, interpret the traffic situation, and select an action to implement.

The driver's actions during the take-over process, could be categorized according to Kahneman's (2003) two system approach to cognition. The shift of attention and grabbing the steering wheel seem to be intuitive (system 1) responses, which are fast, automatic, and require almost no effort. Indeed, gaze and hands-on reaction times have been shown to be fast (Gold et al., 2013; Lorenz et al., 2014). Alternatively, the interpretation of the traffic situation and action selection are could be labelled system 2 processes, which are slower, rule-governed, and require cognitive effort (Zeeb et al., 2016). An interface that assist the driver should be designed with this distinction in mind.

During a take-over the driver essentially switches from non-driving related activity to actively controlling the car. Previous research on task switching has shown that there are several factors that affect the efficiency and effectiveness of the switch. In their book Wickens et al. (2012) stated that a highly engaging or perceptually loading task resist interruption, which could delay the switch (see also Horrey et al., 2009; Lavie, 2010). Alternatively, an interrupting task with high salience facilitates fast and reliable switching performance (Trafton et al., 2003). Hence, a well-designed interface should present a salient take-over request in order to facilitate a rapid and reliable switch. In that light, the driver's take-over performance has often been measured by reaction time (Gold et al., 2013; Eriksson & Stanton, 2017) and (correct) response (Lorenz et al., 2014; Louw et al., 2015), which will be referred to as efficiency and effectiveness, respectively.

## 1.3 Tactile stimuli to assist drivers during a take-over

### 1.3.1 Tactile take-over requests

Previous take-over studies mainly used auditory warnings and visual indicators to inform the driver of a take-over request (Gold et al., 2013; Radlmayr et al., 2014; Damböck et al., 2012; Zeeb et al., 2015; Mok et al., 2015; Feldhütter et al., 2016). However, visual and auditory displays might be less suited to convey a take-over request, since the driver will probably perform non-driving tasks, which employ the visual and auditory senses. Drivers could, for example, be engaged in a phone call, making an auditory warning less effective. Alternatively, when drivers are reading a book or checking their email, it is more probable that they will miss a visual warning, because it needs to be in field of view to be perceived.

Therefore, tactile stimuli are expected to be effective take-over requests, since they are considered hard to ignore (Van Erp, 2002) and "less central to the driving task" (Meng & Spence, 2015). That is, tactile warnings are salient and employ a sensory modality that is not used by the non-driving related task. Which, according to task switching paradigms, should enhance switching performance (Wickens et al., 2012).

Moreover, tactile stimuli might be able to elicit an intuitive gaze reaction towards a certain direction. Previous studies suggested that, by embedding a directional cue in tactile stimuli, it might be possible to direct the driver's attention towards a certain direction (Van Erp & Self, 2008; Ho & Spence, 2009; Spence & Ho, 2008). However, Spence & Santangelo (2009) also argued that most benefits have been shown in laboratory conditions, with limited concurrent perceptual load, and it remains to be investigated whether directing attention can be done efficiently and effectively in a driving scenario.

### 1.3.2 Tactile stimuli to convey information

In order to assist the driver in selecting an appropriate action during a take-over an interface needs to communicate information with higher levels of semantics. Traditionally, messages to the driver are conveyed by visual and auditory displays and there has been little attention for the tactile modality as an information channel. Actually, Wickens' original multiple resource model included only the visual and auditory modalities as the human's information processing channels (Wickens, 2002). Though recently, Wickens called the tactile perception "the new member to the team" (Technion, 2012) and it has recently been included in the latest version of the multiple resource theory (Wickens et al., 2012).

Accordingly, tactile displays have been proposed as a potential alternative to visual and auditory interfaces in driving (Meng & Spence, 2015) and there is a growing interest in the tactile modality to convey more complex information (Van Erp & Self, 2008). For example, BMW's Lane Departure Warning uses vibrations on the steering wheel (BMW, 2008), or Nissan's Distance Control Assist System produces a counter force on the gas pedal when the gap with a lead vehicle becomes to small (Nissan, 2007). Moreover, Fitch et al. (2011), found that vibration patterns can be used to instruct the driver to make a certain action, like 'brake' or 'steer left'. However, these systems support manual driving and it remains to be investigated how effective and efficient vibrotactile stimuli can convey messages in a take-over scenario. Moreover, it is likely that an interface to support the driver during the take-over process will be implemented in a multimodal approach. Since, a well designed multimodal interface would profit from the principle of redundancy gain and the principle of multiple resources (Wickens et al., 2004).

## 1.4 Research goal and approach

The goal of this thesis is to evaluate how a tactile display can support the driver during the stages of a take-over process and how to incorporate such an interface in a multimodal approach. In order to accomplish this goal, this thesis aims to:

1. Review existing literature in order to investigate how tactile interfaces have been previously applied in the automotive domain and how tactile stimuli can be applied to convey more semantic messages during the take-over process.

2. Use a full design cycle to analyse, design, and evaluate a tactile display that conveys a take-over request and assists the driver to resume the dynamic driving task.

3. Provide recommendations on the integration of a tactile display in a multimodal approach to support the driver in the take-over process.

## 1.5 Outline of this thesis

This thesis consists of three parts. The first part consists of two theoretical studies (chapter 2 and 3), reviewing previous literature to provide the background and motivation and define the research questions for this thesis. The second part (chapter 4) describes the requirements and design of a tactile seat. The third part (chapter 5, 6, 7, and 8) consists of four empirical studies evaluating the tactile seat in combination with auditory and visual interfaces. Chapter 2 through 8 of this thesis are (pre)published articles and each chapter summarises the study and includes a reference to the specific paper.

**Chapter 2** is a survey regarding previous scientific work on haptic interfaces in the automotive domain. **Chapter 3** is a literature survey that investigates the psychophysics of vibrotactile stimuli, their potential application in SAE-level 3 driving automation, and proposes a framework for the take-over process that is used to discuss the results. **Chapter 4**, describes the requirements and design of the vibrotactile seat, based on the findings of chapter 3. **Chapter 5** compares reaction times to visual, auditory, and vibrotactile take-over requests while the drivers were reading, calling, or watching a video. **Chapter 6** investigates the effectiveness and efficiency of the vibrotactile seat, an auditory display, and a bimodal combination of both to convey a take-over request. Additionally, it investigates whether drivers yield a spontaneous response when there is a directional cue (left/ right) embedded in the take-over request. **Chapter 7** studies spatially static and dynamic vibration patterns to instruct the driver to make a lane change to the left or right, as well as the effect of cognitive load on the vibration patterns' recognition rate. **Chapter 8** evaluates a visual interface with three levels of semantics (i.e., indication, information, and suggestion), that assist the driver in their take-over process. **Chapter 9** summarizes two student theses completed within the scope of this thesis, as their results will be elaborated on in the discussion. Finally, **chapter 10** elaborates on the conclusions of the experiments, discusses the limitations, and provides recommendations for the integration of tactile interfaces in a multimodal approach, as well as future research.

# 2 Haptic assistance systems in driving

*Petermeijer, S. M., Abbink, D. A., Mulder, M., & De Winter, J. C. F. (2015). The effect of haptic support systems on driver performance: A literature survey.* IEEE Transactions on Haptics, 8(4), *467–479.*

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> *"If I have seen further it is by standing on the shoulders of giants"*
> – Isaac Newton

This study provides an overview of previous research that has been done on haptic assistance systems in driving. 70 studies were included, in which the participants had to drive a real or simulated vehicle, control the heading and/or speed, and a haptic signal was provided to them to support a specific driving task. The studies were evaluated using three questions:

*What haptic support systems are currently available or being developed?* A clear distinction between two system functions was found, namely to guide and warn drivers. Guidance systems provide continuous feedback to assist the driving task, by, for example, providing a counter force based on time to collision. On the other hand, warning systems activate when a certain threshold of a parameter is exceeded, such as crossing a lane boundary. Moreover, guidance forces are inherently presented on the control inputs of the vehicle (i.e., steering wheel and gas pedal), whereas vibrations can be presented on a multitude of locations (e.g., steering wheel, seat belt, or seat bottom).

*How are these haptic system evaluated?* The studies differed widely in experimental design and evaluation methods. However, warning systems were usually evaluated using reaction time measures and/or driver behaviour post warning. Studies involving guidance systems generally evaluated the performance of the supported task (e.g., lateral error to the lane center for a lane keeping assistance system). Few studies involved the evaluation of high level driving behaviour, such as gaze behaviour.

*What are the effects of these haptic systems on driver performance?* Compared to no-feedback conditions, a well-functioning warning system decreases the driver's reaction time and guidance system improves performance. Though, on the downside warnings systems might evoke annoyance and guidance systems could suffer from long-term automation issues.

# 3 Vibrotactile displays in the take-over process

*Petermeijer, S. M. , De Winter, J. C. F., and Bengler. K. J. (2015). Vibrotactile displays: A survey with a view on highly automated driving.* IEEE Transactions on Intelligent Transportation Systems, 99*, 897–907.*

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*"Dare to strike out and find new ground"*
– John Keating, Dead Poets Society

This study reviews existing literature on the perception and psychophysics of vibrotactile feedback, and it provides a framework on the take-over process in order to identify how vibrotactile feedback could support the driver during a takeover.

Humans sense vibrotactile stimuli through mechanoreptors in the skin, which connect via nerves to the central nervous system. Vibrotactile stimuli have the benefit that they are hard to ignore and can be privately conveyed. Four dimensions for vibrotactile information coding are distinguished, namely 1) frequency, 2) amplitude, 3) timing, and 4) location. These dimensions can be presented either static (i.e., not changing over time) or dynamic (i.e,. changing over time). It appears that, of those four, humans are able to discriminate timing and location more effectively than the remaining two dimensions.

Previous research has shown that vibrotactile stimuli are effective warnings signals. Recently, there has been a growing research interest into the potential of vibrotactile displays to direct a human's attention or convey more complex messages. For example, vibrotactile feedback was successfully used to draw the attention of the driver towards the rear-view mirror or reduce lateral drift in helicopter pilots. However, it remains to be investigated whether similar approaches are effective during the take-over process.

When the automated driving system presents a take-over request the driver has to 1) shift visual attention to the road, 2) *cognitively process* and evaluate the traffic situation and *select* an appropriate maneuver, like stabilizing the vehicle or evading an obstacle, 3) *reposition* himself, so that the dynamic driving task can be resumed (i.e., hands and feet on control inputs), and 4) *implement* the selected maneuver via the control inputs.

Directional cues could potentially assist the driver during the *shift of attention* phase, by directing the attention towards a certain direction. Alternatively, more complex spatially dynamic patterns could support the driver in the *cognitive processing and action selection* phase, by mapping the vibration location to surrounding traffic. Finally, it is recommended that vibrotactile feedback is not used in isolation, but in a multimodal approach to assist the driver in the take-over process.

# 4 | Design of a vibrotactile seat

*Petermeijer, S. M., Hornberger, P., Ganotis, I., De Winter, J. C. F., and Bengler, K. J. (2017). The design of a vibrotactile seat as a human-machine interface to convey take-over requests in automated driving.* Proceedings of the 8th International Conference on Applied Human Factors and Ergonomics (AHFE).

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> *"Look what we've made; started from nothing, building"*
> – Newton Faulkner, Brick by Brick

Conditional automated driving systems will allow the driver to have his hands/feet of the steering wheel/pedals, as a result the seat is the only part of the car that is in constant contact with the driver. Moreover, the seat is in contact with a large area of the drivers body, making it very suitable to convey spatial vibration patterns. This article presents the design of a vibrotactile seat. See Appendix A for a manual or the tactile seat and a technical drawing of the printed circuit board.

In order to build a vibrotactile display that can provide spatially and temporally dynamic patterns, the following requirements were defined:

- The matrix of motors covers most of the contact area between the driver and the seat.
- The timing and intensity of the motors are controllable for each vibration motor.

The seat consists of three main parts, namely:

- 48 eccentric rotating mass vibration motors (type Pico Vibe, model: 307-100) located in 2 matrices of 6x4, secured in a mat (using a series of Velcro strips), that is placed on the driver seat.
- An microcomputer (Arduino Mega 2560), that controls three Pulse Width Modulation (PWM) drivers (Texas Instruments, TLC5940NT), which in turn control the DC-voltage (i.e. rotational speed) to the vibrations motors.
- Software that facilitates communication between the Arduino and the simulation environment SILAB (WIVW, 2016), so that the seat can be controlled based on certain simulation parameters (e.g., TTC to vehicle ahead).

# 5 | Comparing visual, auditory, and vibrotactile take-over requests

*Petermeijer, S. M., Doubek F., and De Winter, J. C. F. (2017). Driver response times to auditory, visual, and tactile take-over requests: A simulator study with a 101 participants.* Submitted to: IEEE International Conference on Systems, Man, and Cybernetics

> *"Your assumptions are your windows on the world.*
> *Scrub them off every once in a while, or the light won't come in "*
> – Isaac Asimov

Auditory or visual take-over requests might not be optimally effective or efficient when drivers are engaged in non-driving tasks that employ the visual or auditory senses. This study investigated the interaction between take-over request modality and the type of non-driving task, regarding the driver's reaction time. It was hypothesized that tasks which predominantly use a certain perceptual modality would yield increased reaction times when the take-over request was presented in that same modality. For example, auditory take-over requests were expected to be relatively ineffective in situations in which the driver is making a phone call.

101 participants, divided into three groups, performed one of three non-driving tasks, namely reading (i.e., visual task), calling (auditory task), or watching a video (visual/ auditory task). Each participant experienced six take-over requests (i.e., two visual, two auditory, and two vibrotactile) in a counterbalanced order. Eyes-on road, steer initiation, and steer turn reaction time were recorded, as well as a subjective assessment of the usefulness and satisfaction.

Results showed that tactile and auditory take-over requests yielded faster (approximately 0.3 s) reactions than visual take-over requests. Calling seemed to yield slightly faster reaction times, but no significant difference between the non-driving related tasks was found. The expected interaction between take-over modality and the dominant modality of the non-driving task was not found. As for self-reported usefulness and satisfaction, tactile take-over requests outperformed the auditory and visual ones.

In conclusion, visual take-over requests do not seem efficient compared to auditory and tactile ones. Moreover auditory and tactile stimuli yielded equal initial reaction times, regardless of the non-driving task.

# 6 | Directional cues in vibrotactile and auditory take-over requests

*Petermeijer, S. M., Bazilinskyy, P.*[1]*, De Winter, J. C. F., and Bengler, K. J. (2015). Take-over again: Investigating multimodal and directional TORs to get the driver back into the loop.* Applied Ergonomics, *62, 204–215.*

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*"The greatest danger is always the one we are ignorant of"*
– Robin Hobb, Fool's Fate

This empirical study evaluated the reaction time and driver response to auditory and vibrotactile take-over requests, as well as the bimodal combination of both. Furthermore, the study investigated whether a directional cue embedded in the take-over request (i.e., stimulus coming from the left or right) evokes a spontaneous ipsi- or contra-lateral response in drivers.

Twenty-four participants (8 female) drove three trials (i.e., auditory, vibrotactile, bimodal) in the driving simulator at the Lehrstuhl für Ergonomie, TU Munich. The simulated vehicle drove highly automated, and the participants were asked to perform a, visually distracting, Surrogate Reference Task (ISO/DTS 14198, 2012). Participants were presented with directional (i.e., left/right) or non-directional take-over requests and had to change lane left or right to avoid a collision with a stationary vehicle ahead. In order to study the spontaneous response to directional stimuli, the participants were not instructed that a directional cue was intermittently embedded in the take-over request.

The results yielded no significant difference between vibrotactile and auditory take-over requests. However, bimodal take-over requests yielded faster initial reaction times (i.e, first steer/ brake touch and steering initiation) compared to vibrotactile ones. There seemed to be no spontaneous response to the directional cues embedded in the take-over requests, since most participants overtook the stationary vehicle on the left side (which is in line with German driving regulations). The final questionnaire revealed that the majority of the participants had not perceived the directional cues.

Vibrotactile take-over requests are equally effective as auditory ones. Though, bimodal take-over seemed to convey a more urgent warning, because the drivers' initial response was approximately 0.2 s faster. It could be that instructions and more salient directional cues might be needed to make attention direction possible.

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[1] S. M. Petermeijer and P. Bazilinskyy contributed equally to this study and are joined first authors on this publication

# 7 | Spatially static and dynamic vibrotactile patterns

*Petermeijer, S. M., Cieler, S., and De Winter, J. C. F. (2017). Comparing spatially and dynamic vibrotactile take-over requests in the driver seat.* Accident Analysis & Prevention, 99*, 218–227.*

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*"Whoo! Scratch four!"*
– Maverick, Top Gun

This empirical study aimed to evaluate how accurately instructed drivers can distinguish spatially static and dynamic directional cues embedded in a take-over request. Moreover, the effect of cognitive load on driver reaction time, response, and recognition rate was investigated.

Eighteen participants (5 female) experienced three experimental sessions. During the first baseline session participants were presented eight vibrations patterns (4 static and 4 dynamic) and were asked to distinguish the direction of the vibration (i.e., no cognitive load). During the second session, the participants drove conditionally automated and had to evade a stationary car ahead when a take-over request was issued (i.e., medium cognitive load). They were asked to change lane according to the directional cue embedded in the vibration pattern. The third session was the same as the second, but the participants performed a additional memory task (2-back as in Mehler et al., 2011) in order to induce a high cognitive load.

With a recognition rate of 91%, the participants were very capable of distinguishing the direction of the vibration patterns in the baseline condition. However, the recognition rate dropped to 83% and 77% when the cognitive load increased, though not significantly. Static patterns seemed to be recognized slightly better than dynamic patterns, but there was no significant differences to be found. The static patterns yielded slightly faster initial response times (i.e., steer touch and steer turn), which is in line with the other driving parameters. Namely, steering wheel angle and the head heading angle showed an earlier reaction for static patterns compared to dynamic ones.

Vibrotactile patterns are effective as an initial take-over request, but the directional cue embedded in the signal cannot be reliably detected when the driver is under cognitive load. It is therefore recommended not to use vibration stimuli to direct the attention of the driver during the take-over process.

# 8 A visual interface to support decision making

*Eriksson, A., Petermeijer, S. M.*[1]*, Zimmermann, M., De Winter, J. C. F., Bengler, K. J., and Stanton, N. A. (2017). Rolling out the red (and green) carpet: Supporting driver decision making in automation to manual transitions.* submitted to: IEEE Transactions on Man-Machine Systems.

*"Alone we can do so little; together we can do so much"*
– Helen Keller

This chapter investigated how a visual augmented reality interface could support the driver in the *cognitive processing and action selection* phase of the take-over process. The visual interface support the driver on three levels, based on the stages of automation, as proposed by Parasuraman et al. (2000).

Twenty-five participants (11 female) performed four sessions in a static drivings simulator. When a slow moving vehicle appeared ahead in right lane of a two-lane highway, a take-over request was issued to alert the driver. At the moment of take-over request the left lane would be either blocked (i.e., braking scenario) or free (i.e., steering scenario). During a session the participant experienced 1) no additional visual support (baseline) or support based one of three automation stages namely, 2) *acquisition* (sphere), 3) *analysis* (carpet), and 4) *decision selection* (arrow), to assist the driving during the take-over process.

Higher levels of semantics (i.e., carpet and arrow) yielded higher success rates compared to the baseline and sphere conditions. Moreover, the sphere actually seemed to worsen the decision making of the driver in the steering scenario. The carpet scored significantly higher compared to sphere on a subjective usefulness and satisfaction score. Eye-tracking data revealed that the gaze behavior of the driver was attracted to the position of the visual overlay.

Support with higher level semantics is more effective than low-level support, but seems to have a ceiling effect. Furthermore, it seems automation bias can be mitigated by presenting visual overlays in the appropriate location, but presenting an ambiguous interface might be detrimental for the take-over procedure.

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[1] A. Eriksson and S. M. Petermeijer contributed equally to this study and are joined first authors on this publication

# 9 | Complementary studies

*"A scientist's aim in a discussion with his colleagues is not to persuade, but to clarify"*
– Leo Szilard

Two student theses were completed within the scope of this thesis. A short summary is of the two studies is given.

*Inform or instruct – How can we support the driver in take-overs during conditional automation?* This semester thesis (Sippl, 2016) aimed to investigate the effect of three visual displays on the driver's response time and behaviour. The visual interface consisted of a written message that provided either 1) a simple warning, 2) information about the take-over scenario, or 3) a suggested action. Thirty-four participants drove three sessions and experienced 4 take-over scenarios (i.e., 2 easy and 2 complex) per session. The results showed that information or suggestions yielded faster response times in complex scenarios and drivers braked less often.

*Vibrotactile displays in HAD: Guidance to help the driver back into the loop.* This thesis (Liu, 2016) investigated the use of tactons to direct the attention of the driver towards a certain area of interest (i.e., windscreen, side mirror, or cluster instrument). Three temporally dynamic vibration patterns were used to indicate the area of interest the driver was supposed to look at. Twenty-six participants (10 female) drove 2 sessions, one in which only simple warnings were presented and one with tactons to direct attention. Results showed that drivers assisted by tactons had slightly higher success rates, but response times did not improve. It seemed that the time it took to interpret the tactons mitigated the efficiency.

# 10 | Discussion and conclusion

> *"I may not have gone where I intended to go,*
> *but I think I have ended up where I needed to be"*
> – Douglas Adams

This chapter will provide the a general discussion of the results and limitations of the studies performed, as well as recommendations for future research. The goals of this thesis were to evaluate a tactile display supporting the driver during the take-over process and to investigate how to incorporate such a display in a multimodal approach.

Chapter 2 found, based on previous research, that haptic assistance systems could generally be divided in two categories, namely guidance and warning systems. Chapter 3 reviewed the literature on vibrotactile perception, proposed a framework for the take-over process, and argued that directional feedback could potentially be used to direct the attention of the driver or to convey more complex messages. Chapter 4 describes the design of a vibrotactile display that is able to convey spatially, temporally, and intensity dynamic vibrations in the driver seat. Chapter 5 showed that vibrotactile and auditory take-over request yielded faster initial reaction times than visual take-over requests, regardless of the non-driving related task. Chapter 6 revealed that bimodal take-over requests yielded slightly faster initial reaction times and that drivers did not show a spontaneous response to a directional cue embedded in the take-over request. Chapter 7 demonstrated that the recognition rate of vibration patterns decreased when driver experienced an increasing cognitive load. Nonetheless, spatially static patterns seemed to be recognized slightly better than dynamic ones. Chapter 8 found that visual displays, that conveyed a high level of semantics yielded a slight increase in correct responses and decreased lane change response times.

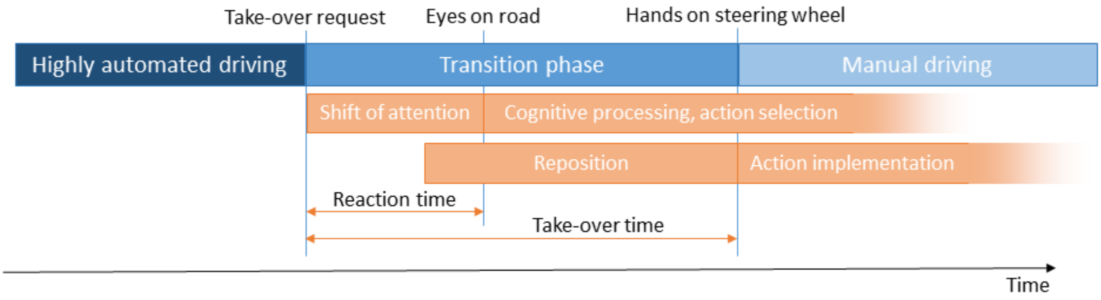

Figure 10.1: The take-over process with the four stages as presented in Petermeijer et al. (2016).

## 10.1 Discussion

### 10.1.1 The take-over process

A successful takeover consists, from a driver's perspective, of two aspects, namely a timely and appropriate response. In recent years, the timing aspect of the take-over process has been well-researched. Relatively short take-over times (i.e., between 2 and 3 seconds) are reported when the driver is required to make an evasive maneuver within a certain time (e.g., 3, 5, or 7 s in Louw et al. (2015); Gold et al. (2014); Radlmayr et al. (2014), respectively). Gold (2016) developed a quantitative model to predict driver reaction time and performance, which was reasonably accurate within the limits of the model. It appears that drivers are quiet capable of performing a rapid take-over when the situation demands it. However, Eriksson & Stanton (2017) reported large variances in take-over times during a non-urgent scenario. In their study, take-over times yielded a median of 4.6 s when there was no immediate risk of an accident, which increased to 6.0 s when the driver was also engaged in a non-driving task (i.e., reading). Moreover, the study reported that drivers occasionally required more than 20 s to take back control.

Alternatively, the driver's appropriate response to the scenario, is difficult to quantify, because it is highly dependent on the specific take-over scenario. Studies evaluated lateral and longitudinal accelerations (Feldhütter et al., 2016; Lorenz et al., 2014), time-to-collision with surrounding vehicles (Radlmayr et al., 2014), or safety checks (e.g., Gold et al., 2013). However, such variables provide limited information whether drivers performed appropriately and safely. For example, a small time-to-collision can be interpreted as unsafe, but could also mean that the driver took more time to perform safety checks before deciding what to do.

As such, the framework (chapter 3) deliberately describes the take-over process in a qualitative manner and it serves to frame the discussion of results within the literature. Initially, it was specified for transitions from conditional automation to manual driving that are initiated by the automated driving system, but could also be used in a more general way for all transitions that require the driver to switch from 'passive passenger' to 'active driver' (see Lu et al. (2016) for a taxonomy on control transitions in automated driving).

### 10.1.2 Shift of attention

Vibrotactile stimuli are a more efficient and effective approach to present a take-over request, than visual ones. Chapter 5 showed that vibrotactile stimuli yield faster gaze reaction times than visual ones, which in line with previous research (Prewett et al., 2012).

Furthermore, auditory and vibrotactile take-over requests performed equally, regardless of the non-driving related task. Indeed, chapter 5 and 6 found that auditory and vibrotactile stimuli elicit similar eyes-on-road reaction times. Moreover, it seems that the eyes-on-road reaction time is not only independent of the type of task (Zeeb et al., 2016; Petermeijer et al., 2017), but also driver distraction (Zeeb et al., 2015) and time budget (Gold et al., 2013). Gold et al. (2013) also found no difference in the gaze reaction times for driver that performed the non-driving related task on a hand-held device or on the center console.

These results strengthen the argument that the *shift of attention* in the take-over process is a system 1 response (Kahneman, 2003). Zeeb et al. (2016) argued similarly, that the driver's initial responses "are carried out almost reflexively, with little influence of the driver's mental state"(p. 239). Indeed, eye tracking data from chapter 7 and 8 showed that the driver's first gaze reaction is towards the road ahead before they start to scan the surroundings. Similar behaviour has been found in several studies, which investigated driver gaze behaviour to forward collision warnings (Morando et al., 2016; Tivesten et al., 2015).

Directional cues embedded in the vibrotactile take-over request did not elicit a spontaneous ipsi- or contra-lateral gaze reaction in naive drivers (Chapter 6). Moreover, instructing the driver about the directional cues did not result in a fast gaze reaction towards the intended direction (chapter 7). Drivers still focused on the road ahead first, before directing their visual attention towards the lane they were intending to change to. Kahneman (2003) explained that "some attributes of a stimulus are automatically perceived, while others must be computed" (p. 702). It seems that the directional cues that were used during the experiments were not automatically perceived, which inhibited a directed intuitive response.

### 10.1.3 Repositioning

Chapter 6, 7, and 8 reported average hands-on reaction times around 2 s, which is in line with studies that investigated similar scenarios (Gold et al., 2016; Radlmayr et al., 2014; Naujoks et al., 2014; Feldhütter et al., 2016). Nevertheless, a slight decrease in hands-on reaction time can be accomplished by tuning the parameters of the warning stimulus so that they are more salient. For example, chapter 6 showed that bimodal auditory and vibrotactile take-over requests yielded a decrease of approximately 0.2 s for the hands-on reaction times. Moreover, static vibration patterns yielded slightly faster reaction times compared to dynamic ones (chapter 7). Although the reductions in reaction times are minor, they are still substantial in a driving context.

Similar to the initial gaze reaction, repositioning seems effortless as long as the driver does not have to dispose of any hand-held objects. Studies showed that the hands-on reaction times do not seem affected by type of hands-free secondary task (Zeeb et al., 2015; Körber et al., 2016), driver distraction (Zeeb et al., 2016), age (Körber et al., 2016), or urgency of the scenario (Naujoks et al., 2014; Sippl, 2016). Even so, there seems to be a limit to the improvement a well-designed warning signal can yield in the initial response of the driver. There are probably other factors that are more important determinants for hands on reaction time. When non-driving tasks involves hand-held objects, the *repositioning* stage will require more physical and cognitive effort, which will be detrimental to the reaction time. Indeed, several studies (Befelein et al., 2016; Eriksson & Stanton, 2017) reported increased hands-on reaction times when drivers were playing a game, watching a video on a mobile phone, or reading a book compared to hands-free tasks.

### 10.1.4 Cognitive processing and action selection

The *cognitive processing and action selection* stage seems indeed a system 2 process (Kahneman, 2003), which is effortful, rule-governed, and (relatively) slow. Regardless whether the take-over scenario requires immediate action (e.g., perform an evasive maneuver), the driver needs to perceive and interpret the traffic situation, and select an appropriate course of action. In order for an interface to assist the driver during this stage it needs to be able to communicate more complex information and convey in such a way that does not interfere with the driver's cognitive process.

It was shown that, with instruction, vibrotactile patterns could be used to convey simple messages, but it is not likely that they can assist the driver to make faster decisions. For example, in chapter 7 drivers changed lane to the left/right, depending on the spatial vibration pattern. Unfortunately, in terms of absolute correct response rate directional cues were not reliably interpreted when participants were cognitively loaded. Moreover, Liu (2016) showed that temporal patterns can be used to instruct the driver where to look, but they took longer to be interpreted than simple warnings. Especially if one takes into account that the participants experienced frequent take-over requests in a relatively short period of time. It is expected that correct response rates will decrease even further when take-overs become more rare. Hence, interpreting vibrotactile patterns seemed to cost time, cognitive effort, and were not reliably recognized, during a take-over.

Therefore, conveying complex messages to the driver, like the suggestion to change lane, should be done using auditory or visual displays instead of vibrotactile stimuli. Visual and auditory messages are considered easier to interpret than vibration patterns (Meng & Spence, 2015; Baldwin et al., 2012), resulting in a faster and more reliable response. Chapter 8 showed that an augmented reality display can not only assist the driver in making the correct decision, but also improve the time the driver needed to make that decision, although these beneficial effects were modest. Moreover, results still showed a considerable number of unsafe lane changes in the condition were a brake response was preferred. Lorenz et al. (2014) and Zimmermann et al. (2014) showed similar improvements using comparable interfaces. Unfortunately, the state-of-the-art head-up displays have a limited operational surface and are not yet able to cover the entire windscreen. Nonetheless, written suggestions, presented via a standard head-up display, also improve the correct response rate and time in complex take-over scenarios (Sippl, 2016). Written instructions have the advantage of being very explicit, but might take more time to be interpreted (i.e., read) than symbols. Another option would be to communicate via verbal messages, which is not uncommon in the aviation domain. For example, pilots are warned to 'pull up' when they fly to close to terrain (see Noyes et al. (2006) for an overview on speech warnings and Wickens et al. (2012) for an general overview on visual and auditory communication).

Nevertheless, the implementation of visual and auditory displays to support the driver should be carefully considered. They need to be designed to support the driver where needed and not interfere with the cognitive process. For example, auditory and specifically speech interfaces can be very disruptive for visual tasks (Wickens & Colcombe, 2007). Visual interfaces can also be distracting (Gish & Staplin, 1995) or obscure objects

(Werneke & Vollrath, 2013). Indeed, chapter 8 showed that the driver's attention is drawn towards the visual overlays, and can have detrimental effects when they are present ambiguously. Moreover, Pfannmüller (2017) showed that drivers yielded decreased lane keeping performance when an imprecise ACC signal was presented in a head-up display. Hence, if a display cannot reliably present information, it might be preferred to provide no support at all, since drivers are capable of making fast decisions when the scenario demands it (Gold et al., 2013; Radlmayr et al., 2014)

### 10.1.5 Action implementation

Once the driver has repositioned him/herself and the automated driving system has been deactivated the take-over process is essentially completed (i.e., the driver is back in manual control). It is expected that the majority of the take-over scenarios will be non-urgent (Eriksson & Stanton, 2017) and that the driver does not need to take immediate action. Nonetheless, if the automation deactivated because it could not handle the oncoming situation, the driver might have to implement an evasive maneuver.

In most studies of this thesis, the driver had to avoid a collision with a vehicle ahead by either changing lane or braking. However, none of the investigated interfaces were meant to supported the driver in the implementation of a maneuver. Evidently, there were no meaningful differences concerning the results of the evasive maneuver (e.g., lateral position or steering wheel angle). Nonetheless, during this stage the driver could be assisted by a haptic interface that provides forces on the steering wheel or pedals. Previous studies (Flemisch et al., 2008; Mulder et al., 2010; Abbink et al., 2011) have shown that such approaches can improve driver performance (i.e., lane keeping or distance to lead vehicle), though considerably less literature can be found on haptic support during evasive maneuvers. One of the few examples is Della Penna et al. (2010), who assisted drivers to evade a vehicle ahead by inverting the steering wheel stiffness. Another is Katzourakis et al. (2014), who prevented lane departures during evasive maneuver, by providing a corrective torque on the steering wheel.

## 10.2 Limitations

### 10.2.1 Methodical limitations

All studies in this thesis were performed in driving simulators, which have well-known benefits and disadvantages as a research tool (De Winter et al., 2012). Simulators provide good controllability, reproducibility, and the participants are not physically at risk of injury. Ironically, the latter also reduces the behavioral fidelity of the simulator, especially in urgent take-over scenarios that might lead to a crash. In real-life take-over scenarios the driver might be startled and brake hard or serve out of the lane as a response.

Furthermore, during the studies participants experienced a high number of take-overs with a short time period (i.e, approximately every 2 minutes). Participants probably expected a take-over request to be issued, which is known to be beneficial for their reaction times (Warm et al., 2008). Therefore, it can be argued that the take-over reaction times reflect the driver's optimal response to an expected take-over request.

Moreover, the proposed framework (chapter 3) did not include the non-driving related activity as a part of the take-over process. It seems that two aspects of the non-driving related task affect the driver's take-over performance. First, whether or not the non-driving related task involves any nomadic devices. As discussed before it seems that hand-held devices are detrimental to the *repositioning* stage. Second, the level of engagement of the non-driving task. Previous studies on task switching have shown that engaging tasks are harder to interrupt (Horrey et al., 2009; Matthews et al., 2010; Montgomery et al., 2004). In all studies involved in this thesis the driver was asked to perform a specific non-driving related task, which might not have been as engaging as a task that is voluntarily chosen.

### 10.2.2 Limitations of the vibrotactile seat

The vibrotactile seat was used in static based simulators. In a real car, vibrotactile stimuli might be masked by vibrations produced by the engine or road, possibly reducing their effectiveness as warning signals. On-road studies are needed to discover an effective signal-to-noise ratio in order to prevent spatial masking (cf. chapter 3). The challenge lies in choosing the stimulus frequency and amplitude (signal), so that they are not in the range of the natural road and engine vibrations felt at the seat (noise), but also mitigate annoyance.

A wider mat could have made larger travelling distance for dynamic patterns possible, which are easier to recognize. Kahneman (2003) that a central concept in intuitive thoughts and responses is "*accessibility* – the ease (or effort) with which particular mental content come to mind" (p. 699). He argues that accessibility can be affected by the presentation of the stimulus. Consequently, directional cues might be easier recognized when the are presented further apart. Indeed, Schwalk et al. (2015) showed that dynamic spatial patterns with a larger travelling distance were better recognized. The current design of the vibrotactile seat only allowed for a maximum lateral distance of 210 mm between two stimuli. A wider mat would also allow for the static patterns to be presented further apart. The static patterns activated the one half of the seat, which could have led to tactile clutter (cf. chapter 3) if the stimuli were too close to the center of the torso. In another study of Schwalk et al. (2016) it appears that directionality of the vibrotactile signal on a single location at the extremes (left/right) of the seat are better recognized than larger areas towards the center. Further investigation is needed to uncover how vibrotactile stimuli, in terms of dimensions like location and timing, can be optimized to convey a directional cue or more complex information.

Even though it is doubtful that directional cues will be effective during the take-over process, they still might be a viable communication channel in other domains or applications, like aviation or navigational tasks. Future research should investigate in which applications directional vibrotactile feedback can be effective. After which, a structural investigation how to present vibrotactile patterns, in terms of the stimulus dimensions (cf. chapter 3) in order to optimize directional feedback is needed.

## 10.3 Conclusion

### 10.3.1 Main conclusion

The main conclusion of this thesis is that vibrotactile displays can be effectively and efficiently used to convey take-over requests, but their capability to support the driver effectively during the take-over process is limited. Drivers did not yield a intuitive response to a directional cue embedded in the stimuli, nor were they able to reliably recognize them when they were under the cognitive load of a non-driving related task. Visual head-up displays seem a more effective approach to direct attention of drivers and can support them in the *cognitive processing and action selection* stage of the take-over process, by providing information about surrounding traffic or suggest an appropriate action.

### 10.3.2 Recommendations for the interface supporting the take-over process

Apart from slight reaction time improvements, little could be gained during the *shift of attention* stage, because the initial response of the driver seemed to be almost automatic. Indeed, Zeeb et al. (2015) stated "it seems clear that cognitive and not motor processes determine take-over performance" (p.221). Alternatively, the *cognitive processing and action selection* stage of the take-over process is a system 2 process and therefore probably yields the most potential for improvement of the take-over performance (i.e., a timely and appropriate response to the take-over request). Visual or auditory displays could potentially be used to assist the driver by providing additional information or suggesting an action. . Though, more research is warranted to improve the effectiveness of such interfaces. Also, such interfaces could also have a disrupting effect, which is detrimental to performance. Consequently, more research into driver behavior and how to assist them during the *cognitive processing and action selection* stage is needed.

For the take-over request, it is advised to use a cascading warning strategy depending on the urgency of the scenario. A take-over request needs to convey a salient and unambiguous warning. Based on the results in this thesis, both auditory and vibrotactile stimuli are effective take-over requests and even more so in a bimodal approach. However, annoyance could be an issue when the driver is frequently exposed to vibrotactile stimuli. A cascading strategy would, for example, during a non-urgent scenario present an auditory take-over request. If the driver does not respond and the scenario becomes urgent, the take-over request escalates accordingly. More urgently perceived warnings can be accomplished by presenting multimodal stimuli as well as an increased signal rate (i.e., shorter inter-stimulus intervals and stimulus duration; see Van Erp et al., 2015).

Implementing vibrotactile displays should be done with careful consideration of the annoyance thresholds of the human, especially concerning the amplitude, duration, and location of the stimulus. Strong vibrations can evoke the sensation of pain (Van Erp, 2002), long vibrotactile patterns should be avoided, as well as densely innervated areas of the body. Moreover, the intensity of the stimuli should be adaptable, since vibrotactile sensation shows large variance across age and gender (Geschneider et al., 1994; Ji et al., 2010).

## 10.4 The future of automated driving

Developers of future automated systems will have to take well-known human factors issues into account. Overreliance, complacency, mode confusion, or loss of skills are just a couple of the issues that developers should consider. One of the major problems with these constructs is that they are hard to capture in standardized tests, which puts pressure on the safety authorities. Car manufacturers and scientists have the social duty to protect consumers from the dangers that accompany driving automation even if that means holding off on introducing a system on the market. The most important goal of automating driving should always be safety.

There is no doubt that one day cars will be fully autonomous and able to transport us from A to B without human intervention, though the technology is not there yet. The main issue for the automotive domain is how to fill the time until we arrive at a point were an automated system drives safer than a human. Development is incremental and presently the technological push for driving automation is in full swing. One wonders if the consumer should be exposed to all intermittent development steps. For example, current automated driving systems (SAE level 2) require the driver to monitor the system permanently. Decades of human factor research have shown that humans are notoriously bad at passively monitoring a system and exposing drivers to such systems seem to be a clear case of automation abuse (Parasuraman & Riley, 1997).

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# A | Manual vibrotactile seat

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## A.1 General description

The tactile seat has been developed at the TU München, by Bastiaan Petermeijer. The tactile seat has been developed as a human-machine interface that provides vibrotactile stimuli to drivers via a matrix of vibration motors in the driving seat.

### A.1.1 Functional description

The seat consists of 48 Direct Current (DC) vibration motors. DC to the motors (PicoVibe -âĂŞ 25 mm) is controlled by three PWM-drivers (Texas instruments TLC5940NT), which in turn are controlled by a microcontroller (Arduino Mega 2560). Power to the Arduino and motors is supplied by a 100W AC/DC converter (230V AC/3.3V DC). See Figure A.1 for a functional diagram of the components.

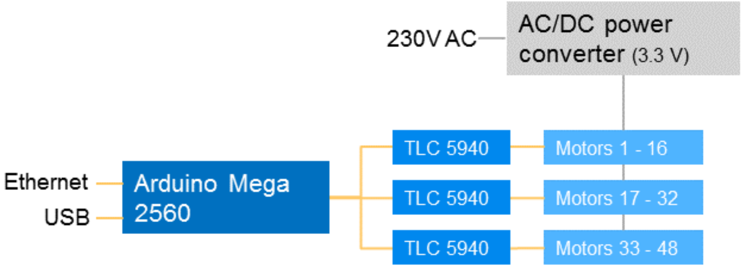
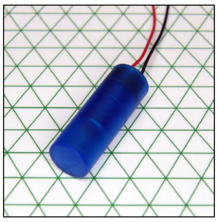


Figure A.1: Functional diagram of the tactile seat

### A.1.2 Hardware

**Motors:** Eccentric rotating mass (ERM) motors produce vibrations by rotating a mass outside a rotation axis and are generally low-cost. The rotational speed of the motor is controlled by the voltage to the motor. The rotational speed determines the frequency and amplitude of the vibration, which are thus not independently controllable. The motors that were used in this prototype were Precision Microdrives™(type: Pico Vibe, model: 307-100). See below for the specifications of the ERM motor.



| | |
|---|---|
| Rate operating voltage | DC 3 V |
| Body dimensions | 8.8 mm x 24.9 mm |
| Eccentric weight | 4.9 g |
| Maximum frequency | 225 Hz |
| Range of amplitude | 0.25 g – 8 g |
| Typical rise/stop time | 22.5 ms/56.5 ms |

**Motor matrix:** A series of Velcro strips were used to create a mat, which could be placed in the driver's seat. The vibration motors were placed between the Velcro strips so that the motors formed two 6 x 4 matrices (i.e., 48 motors in total). One matrix was located in the seat pan, and the other in the seat back. Due to this design, the configuration of motors can be changed if needed, and the seat mat is interchangeable between simulators or real vehicles.

**Control unit:** The motors are controlled by three Pulse Width Modulation (PWM)-drivers (Texas Instruments, TLC5940NT), which are connected to an Arduino microcontroller (Arduino Mega 2560). The PWMs control the motors by a series of on/off pulses, which vary the duty cycle (i.e., percentage of time that the signal is on per cycle). The pulses (de)activate the transistor and consequently control the average DC voltage to the vibration motor. The Arduino in turn can connect to the software environment through a USB or Ethernet connection.

**Electrical circuit:** The DC-voltage to the motors is controlled by a PWM signal to a transistor (Figure A.2). The resistor (R1, 100 Ohm) is connected to the base of a PNP transistor (Q1, 2N5401). The emitter and collector of the transistor are connected to the ground and a motor (M), respectively. A diode (D1, 1N4001) is connected in parallel with the motor to prevent inductive motor spikes flowing back to the transistor. Power to the Arduino, TLCs, and motors is provided by an AC/DC converter (TracoPower, TXL 100-3.3S), which converts 230 V AC from the power network to 3.3 V DC.

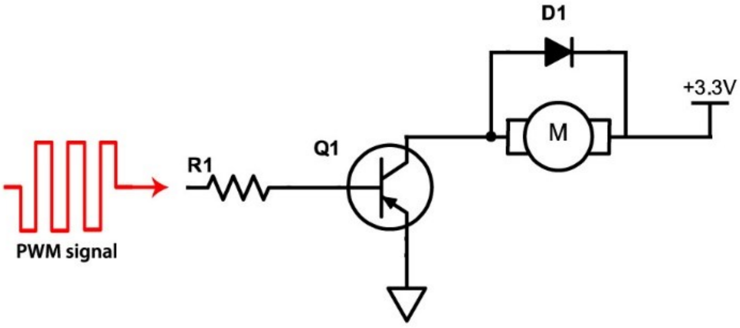


Figure A.2: Functional diagram of the tactile seat

## A.2 First time use of the seat

### IMPORANT FOR FIRST TIME USE OF THE SEAT

1. Install Arduino software on your computer. https://www.arduino.cc/en/Main/Software

2. Copy the folder TLC5940 (Software > Configuration Files) to the library folder of Arduino (default Windows: `C:\Users\Username\Documents\Arduino\libraries`)

### A.2.1 Starting up the tactile seat

1. Connect the power cables to the box
2. Plug the power transformer into a wall socket
3. Connect a laptop to the Arduino via the USB-cable
4. Load the script `Skeleton_version.ino` to the Arduino
5. Switch on the control box (switch on the back of the box)

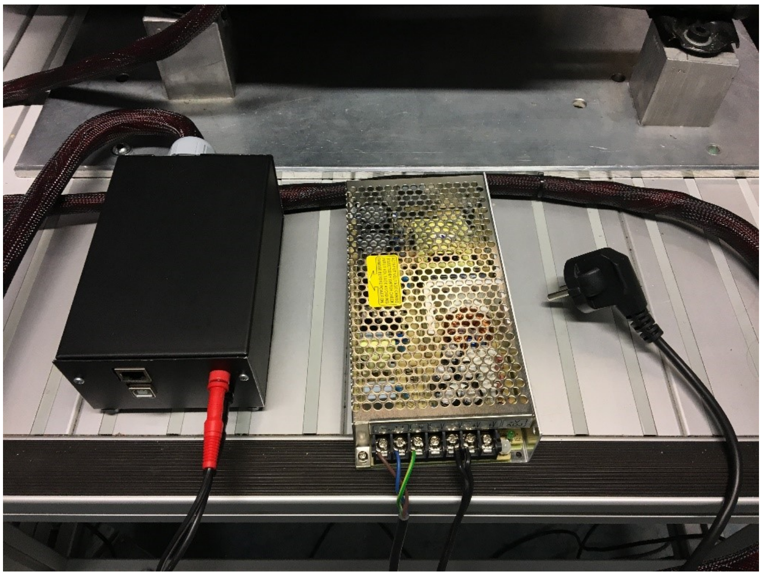


Figure A.3: Control box and power supply

### A.2.2 Ways to communicate with the Arduino

#### USB (serial monitor)

Generally, used to load scripts from computer to Arduino. The serial monitor (Arduino function) can be used to control the Arduino directly. This function can be useful for development of scripts. More information on the Serial library can be found at https://www.arduino.cc/en/Reference/Serial

#### Ethernet (UDP)

Generally used to facilitate communication between simulator network and Arduino. More information on the Ethernet library can be found at https://www.arduino.cc/en/Reference/Ethernet.

When the Ethernet shield is used to communicate with a network you need to assign an Mac and IP-address to the shield in the Arduino script. The Mac Address is hardware relevant and is given on a sticker on the back of the Ethernet shield (it is also stated in skeleton_version.ino). As an alternative you could invent a random Mac address. The IP-address needs to be within the IP network boundaries of the network that it is connect to.

**NOTE:** The Ethernet shield uses SPI mode to communicate with the Arduino. This has consequences for the connection between Arduino and the PWM-drivers. Please see the section TLC5940 library (below) for more information.

### TLC5940 library

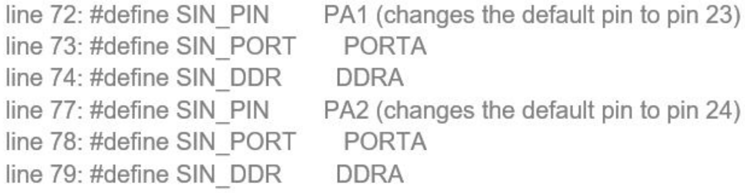
Arduino uses a library to control the three PMW-drivers. This library consists of 3 basic functions:

1. `Tlc.set`(*pin_number, PWM_value*): Sets the *pin_number* (ranging: 0 – 47) to the *PWM_value* (ranging: 0 – 4095), which translate into a voltage to that particular motor of 0 to 3.3V
2. `Tlc.clear`(): Sets all pins of all TLCs to zero.
3. `Tlc.update`(): Sends the set values to the TLCs. This is the moment the PWM-ouputs of the PWM-drivers change. `Tlc.set` and `Tlc.clear` only set the values, but do not update them.

As a default Arduino communicates with the PWM-driver via SPI, but since that mode is used by the Ethernet shield as well the BITBANG mode is used. This is accomplished by changing the file `tlc5940_config.h` in the TLC5940-library. The following lines have been changed:

```
line 71: DATA_TRANSFER_MODE == TLC_BITBANG (to change from SPI to BITBANG
communication
```

Defines the communication mode to `BITBANG`.



```
line 72: #define SIN_PIN       PA1 (changes the default pin to pin 23)
line 73: #define SIN_PORT       PORTA
line 74: #define SIN_DDR       DDRA
line 77: #define SIN_PIN       PA2 (changes the default pin to pin 24)
line 78: #define SIN_PORT       PORTA
line 79: #define SIN_DDR       DDRA
```

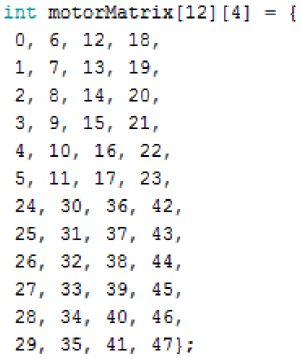
Defines pins 23 and 24 of the Arduino to be used as SIN and SCLK ports to the TLCs. For more info on how the TLC is operated consult the specification sheets of the TLC 5940 in the folder hardware specifications.

## A.3 Defining vibration patterns

The Arduino code is used to create vibrations patterns. To define a pattern each individual motor has to be controlled by using the commands in TLC library (see section TLC library). You can activate a motor by addressing it directly or make use of the `motorMatrix`. The `motorMatrix` can be used to activate specific rows and/or columns of the seat (see Figure A.4).

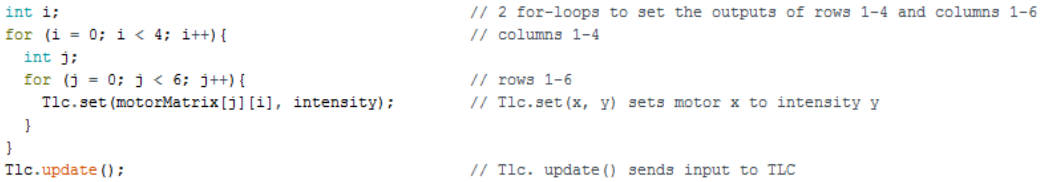
`Motor matrix`: This is a 12x4 matrix of all the motors in the current configuration of the tactile seat. The 4 columns represent the 4 columns of motors from top to bottom in the seat.The rows are orientated from right to left, when you are sitting in the seat. This matrix can be used to easy set multiple motors. For example (see Figure A.5), by using two for-loops you can set half the motors to a certain intensity.

**NOTE:** Columns and rows in Arduino start at zero. so `motorMatrix[0][0]` activates TLC output pin 0, which corresponds to physical motor 1 or in other words top right motor in the seat).



```
int motorMatrix[12][4] = {
 0, 6, 12, 18,
 1, 7, 13, 19,
 2, 8, 14, 20,
 3, 9, 15, 21,
 4, 10, 16, 22,
 5, 11, 17, 23,
 24, 30, 36, 42,
 25, 31, 37, 43,
 26, 32, 38, 44,
 27, 33, 39, 45,
 28, 34, 40, 46,
 29, 35, 41, 47};
```

Figure A.4: Motor matrix as it is defined in Arduino

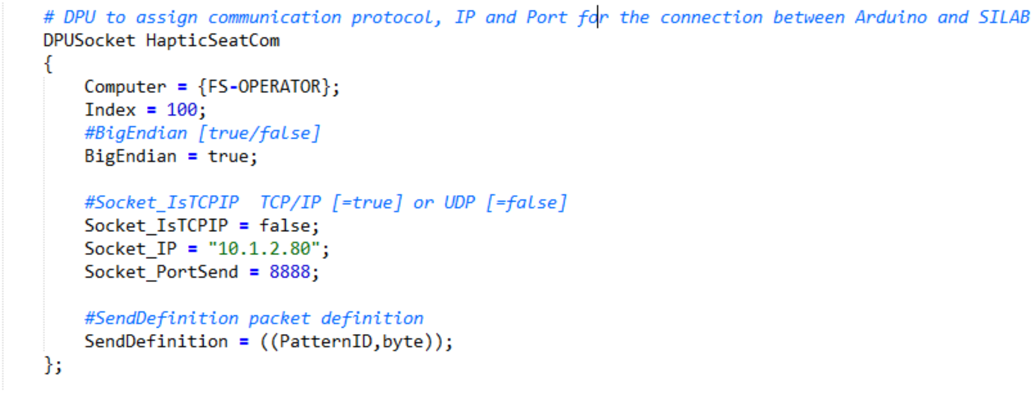


```
int i;                                       // 2 for-loops to set the outputs of rows 1-4 and columns 1-6
for (i = 0; i < 4; i++){                     // columns 1-4
  int j;
  for (j = 0; j < 6; j++){                   // rows 1-6
    Tlc.set(motorMatrix[j][i], intensity);   // Tlc.set(x, y) sets motor x to intensity y
  }
}
Tlc.update();                                // Tlc. update() sends input to TLC
```

Figure A.5: For-loop that sets columns 0-3 and rows 0-5 of the seat matrix motor, which translate all the motors in the seat back (rows 1-6 and columns 1-4).

## A.4 SILAB implementation

In order to let SILAB communicate with the Arduino we make use of the DPUSocket, which enables UDP communication between devices. The `Socket_IP` needs to be the same as the one specified in the Arduino code and within the IP-range of the network.



```
# DPU to assign communication protocol, IP and Port for the connection between Arduino and SILAB
DPUSocket HapticSeatCom
{
    Computer = {FS-OPERATOR};
    Index = 100;
    #BigEndian [true/false]
    BigEndian = true;

    #Socket_IsTCPIP  TCP/IP [=true] or UDP [=false]
    Socket_IsTCPIP = false;
    Socket_IP = "10.1.2.80";
    Socket_PortSend = 8888;

    #SendDefinition packet definition
    SendDefinition = ((PatternID,byte));
};
```

Figure A.6: Arduino code of the DPUSocket that facilitates UPD communication between SILAB and Arduino.

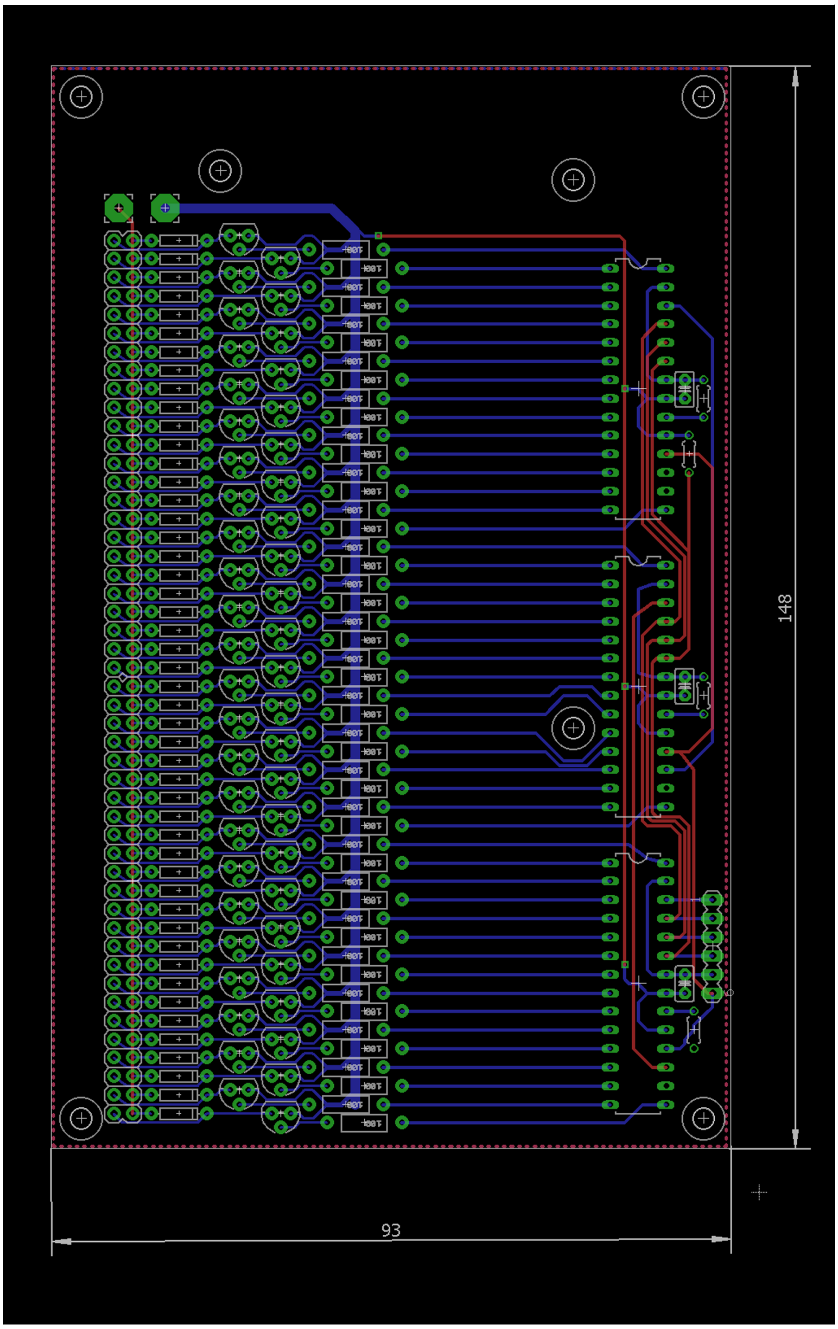


Figure A.7: Technical drawing of the printed circuit board

# B | Curriculum Vitae (English)

## Sebastianus Martinus Petermeijer

Date of birth: May 15th, 1987
Place of birth: Delft, the Netherlands
Nationality: Dutch

Address: Paulus Potterstraat 2
2526 TC, The Hague
The Netherlands
Telephone: +31 6 2005 1956
E-mail address: Bastiaanpetermeijer@gmail.com

## Education

Sep 2012 – March 2014

**Master of Science Mechanical Engineering, Delft University of Technology (Cum Laude)**
Specialization: Biomechanical Engineering (Automotive)
Gaduation topic: Haptically supporting car driving: Optimizing or satisficing?

Sep 2005 – Jan 2012

**Bachelor of Science Mechanical Engineering, Delft University of Technology**
Thesis subject: The effect of tyre grip on learning car racing
Minor: Management of Technology at the faculty of Technology, Policy and Management

Sep 2000 – May 2005

**High school, Stanislas College Delft, Gymnasium**
Profile Nature & Technology
(Mathematics, Physics, Chemistry)
Additional courses: English, German, Ancient Greek, Economics

## Additional courses

April 2014 – Sep 2016

**Early Stage Research Training (80 hours)**
Topics:
- Highly automated vehicles simulator studies
- Naturalistic data analysis
- Visual attention
- HMI design and evaluation
- Driver state estimation
- EEG and ERP in driving research

| | |
|---|---|
| | – Cognitive Work Analysis<br>– Scientific writing<br>– Eyetracking |
| May 2015 | **Argumentation and negotiation skills (14 hours)**<br>Negotiating without giving in |
| Oct 2016 – Jan 2017 | **Improving your statistical inferences (21 hours)**<br>Coursera online course<br>Educator: Daniel Lakens |

## Extra curricular activities

| | |
|---|---|
| Sep 2005 – April 2014 | **Hockey Trainer/Coach**<br>– Trainer/coach of youth and senior teams<br>– Member of the Technical Committee Youth (2010-2013)<br>*Supervising all trainers/coaches of the girls under 16 and 18 teams* |
| Jan 2007 – Jun 2009 | **Student committee work at 'Gezelschap Leeghwater'**<br>– President of the case committee (2008 – 2009)<br>*Organizing bimonthly cases at companies for bachelor and master students*<br>– Member of the excursion committee (2007 – 2008) *Organizing bimonthly study trips for bachelor students to companies and a week long study trip visiting companies in Switzerland and Germany*<br>– Editor of the yearbook (2006 – 2007) |

# C | Curriculum Vitae (Deutsch)

## Sebastianus Martinus Petermeijer

| | |
|---|---|
| Geburtsdatum: | 15 Mai, 1987 |
| Geburtsort: | Delft, die Niederlande |
| Nationality: | Niederländisch |
| Adresse: | Paulus Potterstraat 2<br>2526 TC, Den Haag<br>Die Niederlande |
| Telefone: | +31 6 2005 1956 |
| E-mail adresse: | Bastiaanpetermeijer@gmail.com |

## Bildung

Sep 2012 – März 2014

**Master of Science Maschinenwesen, Delft University of Technology (Cum Laude)**

| | |
|---|---|
| Spezialisierung: | Biomechanik (Automotive) |
| Masterarbeitthema: | Haptically supporting car driving: Optimizing or satisficing? |

Sep 2005 – Jan 2012

**Bachelor of Science Mechanical Engineering, Delft University of Technology**

| | |
|---|---|
| Bachelorarbeitthema: | The effect of tyre grip on learning car racing |
| Minor: | Management of Technology at the faculty of Technology, Policy and Management |

Sep 2000 – Mai 2005

**Gymnasium, Stanislas College Delft**

| | |
|---|---|
| Profil: | Natur & Technologie<br>(Mathematik, Physik, Chemie) |
| Zusätzliche Facher: | Englisch, Deutsch, Alt Griechisch, Wirtschaft |

## Zusätzliche Kurze

April 2014 – Sep 2016

**Early Stage Research Training (80 Stunde)**

Themen:
- Simulator Versuche für Hoch Automatisiertes Fahren
- Naturalistische Daten Analyse
- Visuelle Aufmerksamkeit
- Entwurf und Evaluation von MMI
- Messung des Fahrerzustands
- EEG and ERP in Fahrerversuche

| | |
|---|---|
| | – Kognitive Arbeit Analyse<br>– Wissenschaftliches Schreiben<br>– Blickerfassung |
| Mai 2015 | **Argumentation and Verhandlung Fähigkeiten (14 Stunde)**<br>Verhandlungen ohne Zugeben |
| Okt 2016 – Jan 2017 | **Improving your statistical inferences (21 Stunde)**<br>Coursera online Kurz<br>Lehrer: Daniel Lakens |

## Außerschulische Aktivitäten

| | |
|---|---|
| Sep 2005 – April 2014 | **Feldhockey Trainer**<br>– Trainer of jugend and senior Mannschaften<br>– Mitglied of the Technischer Ausschuss Jugend (2010-2013)<br>*Aufsicht Trainers aller Jugendliche Mädchenmannschaften* |
| Jan 2007 – Jun 2009 | **Studierendeausschuss bei 'Gezelschap Leeghwater'**<br>– Vorsitzende der Fallstudienausschuss (2008 – 2009)<br>*Organisierung von Fallstudien bei Firmen für Studenten*<br>– Mitglied der Exkursionausschuss (2007 – 2008)<br>*Organisierung von Studentenexkursionen nach Firmen und ein wochenlänge Ausflugreise nach Firmen in Deutschland und der Schweiz*<br>– Jahrbuchredakteur (2006 – 2007) |

# Overview of published papers

## Published

Petermeijer, S. M., Abbink, D. A., and De Winter, J. C. F. (2015). Should drivers be operating within an automation free bandwidth? Evaluating haptic steering support systems with different levels of authority. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 57*(1), 5–20.

Petermeijer, S. M., Abbink, D. A., Mulder, M., and De Winter, J. C. F. (2015). The effect of haptic systems on driver performance and behaviour: A literature review. *IEEE Transactions on Haptics, 8*(4), 467–479.

Petermeijer, S. M., De Winter, J. C. F., and Bengler, K. J. (2016). Vibrotactile displays – A survey with a view on highly automated driving. *IEEE Transactions on Intelligent Transportation Systems, 17*(4), 879–907.

Petermeijer, S. M., Bazilinskyy, P., Bengler, K. J., De Winter, J. C. F. (2017). Take-over again: Investigating multimodal and directional TORs to get the driver back into the loop. *Applied Ergonomics, 62*, 204–215.

Petermeijer, S. M., Cieler, S., De Winter, J. C. F., and Bengler, K. J. (2017). Comparing spatial static and dynamic vibrotactile take-over request in a driver seat. *Accident Analysis & Prevention, 99*, 218–227.

Petermeijer, S. M., Hornberger, P., Ganotis, I., and De Winter, J. C. F. (2017). The design of a vibrotactile seat for highly automated driving. *8th International Conference on Applied Human Factors and Ergonomics (AHFE2017).*

## Under review

Eriksson, A., Petermeijer, S. M., De Winter, J. C. F., Bengler, K. J. and Stanton, N. A. (2017). Assisting the driver in decision making according to the stage of automation. *IEEE Transactions on Man-Machine Systems, under review.*

Petermeijer, S. M., Doubek, F., and De Winter, J. C. F. (2017). Driver response times to visual, auditory, and tactile take-over requests: A simulator study with 101 participants. *Submitted to IEEE International Conference on Systems, Man, and Cybernetics.*

## Co-authored

Bazilinskyy, P., Petermeijer, S. M., De Winter, J. C. F. (2015). Use of auditory interfaces for take-over requests in highly automated driving: A proposed driving simulator study. *Workshop on In-Vehicle Auditory Interactions at the 21$^{st}$ International Conference on Auditory Displays*, 1–3.

Bazilinskyy, P., Petermeijer S.M., Petrovych, V., Dodou, D., and De Winter, J. C. F. (2017). Take-over request in highly automated driving: A crowdsourcing survey on auditory, vibrotactile, and visual displays. *Applied Ergonomics, under review*.

Bazilinskyy, P., Eriksson, A., Petermeijer, S. M., Happee, R., and De Winter, J. (2017). Recent findings regarding the design of take-over requests for highly automated driving. *Road Safety & Simulation International Conference (RSS2017)*