Digitizing Human-to-Human Interaction for Automated Vehicles: HCI Perspectives on the Communication between Vulnerable Road Users and Fully Automated Cars

Dissertation

an der Fakultät für Mathematik, Informatik und Statistik der Ludwig-Maximilians-Universität München

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M.Sc. Human-Computer Interaction

München, den 21.02.2022

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Tag der mündlichen Prüfung: 08. April 2022

Abstract

The emergence of automated driving technology promises a world with significantly reduced fatal road accidents (European Commission project called: "Vision Zero"). This goal is expected to be reached by reducing human influence (i.e. human error) in the driving task through introducing automated vehicles where "drivers" could perform non-driving-related activities such as surfing the web, watching videos or reading e-mails. In order to establish these benefits on public roads automated driving technology needs to reach the mainstream market. However, research in traffic psychology shows that human road users outside of vehicles (i.e. vulnerable road users) benefit from a driver's feedback during crossing or right-of-way decisions. Thus, fully automated driving, where human drivers are not required to observe the road permanently or a vehicle could move unmanned, raises the question: "How could human-to-human communication (e.g. gestures or eye-contact) be compensated by digital communication concepts?". To this end we present six peer-reviewed investigations which have been published at international conferences. The majority were published at the "ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications" (three out of six) and the "ACM Conference on Human-Computer Interaction with Mobile Devices and Services" (two out of six). The other was presented at the "ACM CHI Conference on Human Factors in Computing Systems". Three out of the six publications received an honorable mention award. The concrete results presented in this doctoral thesis is a set of seven design recommendations which aim to optimize the development of external human-machine interfaces for fully automated vehicles. These recommendations can serve as a basis for eventually allowing researchers and engineers to develop such interfaces that are able to reduce fatal accidents in everyday traffic to a minimum. Our recommendations include that external communication interfaces should present a combination of explicit and implicit vehicle cues, allow for accessibility and inclusion of all road users, and be able to take into account the specific behavior of target groups such as scooter drivers or cyclists. Other recommendations include fostering familiarity and a training for the target audience e.g. in driving or public schools, and implementing evaluation methods. On a larger scale we argue that a holistic approach for the design of external vehicle interfaces which also regards societal implications (e.g. trust and understandability) should be considered. There is an explanation of why the term "automated" is used instead of "autonomous". The main reason is that even fully automated cars are not implicitly autonomous systems. We show that external human-machine interfaces attached to automated vehicles are capable of supporting comfort, confidence, safety and acceptance in automated driving technology, and thus, in the long run, could promote consumer-market adoption of AVs, which is crucial to putting automated driving benefits on the road and achieving the "Vision Zero" goal.

Zusammenfassung

Der Forschung im Bereich des automatisierten Fahrens liegt die Hoffnung auf eine Welt zugrunde, in der signifikant weniger tödliche Verkehrsunfälle geschehen. Die sogenannte "Vision Zero" versucht dies zu erreichen, indem der Faktor Mensch (bzw. der Faktor des menschlichen Versagens) bei Entscheidungen im Straßenverkehr durch Technologie substituiert wird. Passagiere in solchen vollständig automatisierten Fahrzeugen können dann fahrfremde Aufgaben ausführen und zum Beispiel während der Fahrt entspannen, Videos ansehen, arbeiten oder E-Mails schreiben. Forschungsergebnisse aus der Verkehrspsychologie deuten allerdings darauf hin, dass Verkehrsteilnehmer außerhalb der Fahrzeuge (z.B. Fußgänger) bei der Überquerung von Straßen von Blickkontakt und expliziten Handgesten profitieren können. Daher ergibt sich die für diese Doktorarbeit zentrale Forschungsfrage: "Wie kann die fehlende zwischenmenschliche Kommunikation im Kontext von selbstfahrenden Autos durch digitale Maßnahmen ausgeglichen werden?" Dazu werden hier sechs international veröffentlichte "ACM" (Association for Computing Machinery) Publikationen präsentiert und miteinander in Zusammenhang gesetzt. Drei der sechs Publikationen wurden von den Gutachtern ausgezeichnet (Top 5% der Einreichungen). Als konkretes Ergebnis werden sieben Gestaltungsrichtlinien herausgearbeitet und präsentiert. Diese haben das Ziel, die Entwicklung von externen Anzeigen für vollautomatisierte Fahrzeuge zu optimieren. Als solche bieten die Richtlinien eine Grundlage für Forscher:innen und Entwickler:innen, um neue Schnittstellen zu erstellen, die Verkehrsunfällen vorbeugen sollen. Unsere Empfehlungen zeigen, dass externe Kommunikationsschnittstellen eine Kombination aus expliziten und impliziten Fahrzeugsignalen repräsentieren sollten. Die Zugänglichkeit und Einbeziehung aller Verkehrsteilnehmer sollte ermöglicht werden und zielgruppenspezifisches Verhalten berücksichtigt (Schnittstellen für Rollerfahrer benötigen andere Forschungsfragen und Evaluationsmethoden als Schnittstellen für Fußgänger). Externe Kommunikationsschnittstellen an hochautomatisierten Fahrzeugen sollten aus dem Straßenverkehr bereits bekannte Metaphern verwenden (z.B. Farbschemata von Ampeln). Zusätzlich sollten Schulungen und Aufklärung für die Zielgruppen (ungeschützte Teilnehmer im Straßenverkehr) der Schnittstellen angeboten werden (z.B. in Fahr- oder öffentlichen Schulen). Außerdem denken wir, dass fallspezifische Evaluierungsmethoden implementiert werden sollten. Ein zentrales Argument dieser Arbeit besteht darin, dass eine holistische Herangehensweise nötig ist, die auch soziale Aspekte wie die Entwicklung von Vertrauen und Verständlichkeit beinhaltet. Es wird zusätzlich auf die Differenzierung zwischen vollautomatisierten und autonomen Fahrzeugen eingegangen. Denn nicht jedes hochautomatisierte Fahrzeug ist zwingend ein autonomes System. Es wird zudem gezeigt, dass externe Mensch-Maschine-Schnittstellen an vollautomatisierten Fahrzeugen den Komfort, das Vertrauen, die Sicherheit und die Akzeptanz der Technologie begünstigen. Somit könnte langfristig die Akzeptanz solcher Fahrzeuge auf dem Verbrauchermarkt durch externe Kommunikationsschnittstellen etabliert werden, um letztendlich das Ziel der "Vision Zero" und die Vorteile von vollautomatisierten Fahrzeugen in der Realität umzusetzen.

Acknowledgments

Scientific work is never a one-person-endeavor. I am very grateful for all the support I have received from colleagues, students, friends, supervisors, professors, fellow students, my family, and of course the unofficial reviewers of this work. Underneath this thesis there lies a tremendous number of conversations, discussions and sometimes even disputes which happened at conferences, workshops, our hallway, various offices or even during lunchtime. To acknowledge these incredibly valuable inputs I will use the scientifically common plural form in this thesis. However, I will switch to the "I"-form in Section 1.1 where I present my subjective opinion. I especially thank:

Andreas Butz for supervising this thesis, your private and scientific assistance, and mentoring, as well as for teaching me how to conduct HCI-research.

Heinrich Hußmann for skillfully introducing me into the world of applied computer science starting from my very first bachelor's semester at LMU.

Bastian Pfleging for supervising my master's thesis, showing me HCI-automotive research and your selfless, ongoing help.

Debargha Dey I am very happy that our paths crossed. Thanks for being a great advisor, friend and pillar during the hardest times of my life.

All Mimuc Colleagues for your constant support, cheers, laughter, motivation as well as the beautiful lunch breaks, conference trips, winter schools and IDCs.

Lewis Chuang for your numerous attempts to introduce me to (Bayesian) statistics and your uplifting words when I needed them.

Sarah Völkel for your kind and open-minded way of listening to my personal problems.

Jingyi Li for your many-sided support and collaboration at the office.

Beat Roßmy for your constant help. Your patient and philosophical thinking massively enriched my time in our office. Thank you my friend.

Mark Colley for taking over some of my responsibilities when I was not able to do so. I very much appreciate your help and you as a companion. I dearly hope we will work together in the future on exciting research projects again.

Svenja Taubert for bringing love and stability in my life when I most needed it.

Antje Holländer for being always there when I needed you, emotionally and physically.

Jürgen Schuster for always supporting my back unconditionally.

Rick Holländer for your countless life advice and philosophical exchanges.

Magret Holländer for helping me to write this thesis by quickly providing a fan during an extremely hot summer.

I also thank especially **Andrea Ngao**, **Katharina Rupp**, **Romy Gruber**, **Bao Loi Quach**, **Trung Thanh Nguyen**, **Andreas Krüger** and all the other students I had the privilege to supervise, for their tremendous and great effort during their theses.

For reviewing and evaluating this thesis I thank **Prof Dr. Andreas Butz**, **Prof. Dr. Albrecht Schmidt** and **Prof Dr. Susanne Boll**. I am especially thankful for **Prof Dr. Albrecht Schmidt** for co-founding the AutoUI-Conference, which has become the most important forum for me to establish new contacts with coriphae from the field and my scientific work.

In addition I thank **Club Mate** for providing a tasteful energetic elixir. Around 500 bottles ($\approx 250l$) have flowed into the next pages.

Unofficial reviewers Last but not least I thank all the diligent volunteers who helped me to fine-tune and shape this thesis.

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The proper study of mankind is man.

Alexander Pope

1 Introduction

We are currently experiencing a groundbreaking change in the field of mobility and automotive user interfaces. In 1886, Carl Benz presented the first motor carriage, from which time horse-drawn carriages started to be replaced by combustion engines [O7]. This technical revolution led to radical changes in city planning, society and everyday lives. Since then, the increased speeds, congestion and multi-user roadways have had the consequence of today's ever higher incidences of fatal road accidents between motor vehicles and other road users. Especially in urban areas of less developed countries accidents with unprotected road users are the predominant cause of death for children and young adults (ages 5-29) [O17]. Walking is one of the most dangerous modes of transport. For example, the lifetime probability of dying as a pedestrian in 2013 in the US was 1:749, even worse than for motorcyclists (1:907) or cyclists (1:4.982) [O4]. Hence, Road safety could be considered a public health issue, says the European Parliament. In Europe, 18.800 people lost their lives in road accidents in 2020 [O10].

As for the exterior appearance of motor vehicles, they seem to be following an evolution whereby the chassis is becoming less angular and more energy efficient. Meanwhile, on the inside, we currently observe a groundbreaking revolution combining modern technology in such a way that just like horses, even humans can be completely replaced in their driving tasks. To this end, vehicles are becoming more and more automated with linked cutting-edge technology [70], such as location satellites for navigation (gss [O5] or gps [76]), 5g cellular networks [58], artificial intelligence and lidar systems, odometry, inertial measurement units and cameras [32, 69, 83].

The aim of this endeavor is to achieve fully automated driving and to reduce the human influence (i.e., human error caused for example by speeding or drunk driving [54]) in driving decisions. Human failure seems to be the most influencing factor for traffic accidents [68, O16, O17]. Fully Automated Vehicles (AVs) are expected to be available in the 2030s and to significantly reduce fatal collisions [42, 77]. These vehicles do not necessarily require human input. Thus, the ambitious goal of automated driving is to significantly reduce fatal road accidents [O6, 42, 80]. The hoped-for benefits of automated driving, in addition to increased safety, are: more efficient energy consumption and ride sharing [30, 52], less pollution [77], the ability for passengers to use the travel time for non-driving related activities [38, 55] and increased accessibility [P5, P6, O2, 52]. It should be noted that these advantages can only influence society and everyday traffic when a critical mass of users accepts fully automated driving technology.

Nevertheless, the human factor during manual driving decisions is more than only a source of accidents. Human drivers currently do not exclusively control their vehicle, they also communicate with their surroundings via explicit signals such as gestures or gaze (for example to verify mutual awareness) [13, 49, 59, 61, 62, 68], or to give implicit signals for vehicle movements as well as the intention of the driver [11, 12, 41, 59, 60, 64, 84]. Thus, a major aspect in driving is also human-(driver)-to-human (pedestrian, cyclists, hikers, co-workers) communication. Drivers communicate for example via eye contact [68], hand gestures or nodding [59].

We therefore present a human-computer interaction (HCI) perspective on automated driving. The primary key question of the present work is: "How could human(road users)-to-human(driver) communication (e.g., gestures or eye-contact) become compensated by digital communication concepts?" There are some initial projects in the context of this research question, e.g., the European Union's projects *InterAct* [O14] and *ShapeIt* [O12]. The problem becomes even more demanding if mixed traffic (multiple levels of automation) is regarded.

So far, it seems that the automotive industry has focused more on the technical challenges of implementing automated driving than explicit human-vehicle interaction. Replacing the human driver with technology might create a lack of explicit communication which drivers currently use to exchange signals with other road users. For example, at unmarked road crossings, construction zones, parking lots, idle traffic lights or during jaywalking.

Hence, we investigate the communication between Vulnerable Road Users (VRUs) and fully Automated Vehicles (AVs) from a Human-Computer Interaction (HCI) perspective, and present solution strategies for a digital representation of explicit human signals. The presentation of our published investigations and results is chronologically ordered and shows our path of discovering and exploring the introduced research challenge.

Related works have found that pedestrians feel more safe if they are perceived by the driver of a vehicle [P1, P4, 22, 35]. We take from this that in order to establish initial acceptance of automated vehicles, human-to-human interaction from manual driving should be digitized in a functional way. "A functional way" means that people develop a healthy and confident understanding of a technology they are as yet unfamiliar with and allow it into their everyday lives. This is in our opinion, for two main reasons: First, to eventually reach the "Vision Zero" goal (i.e., drastically reducing road fatalities) [O6]. Second, to reach a critical mass of users as soon as AVs are available. We want to emphasize that attributes of the involved target users (i.e., every human being who participates in traffic) vary a lot. The aim is support their safety, enhance their user experience and accessibility (e.g., via Universal Design [8]).

Overall, this thesis focuses on digitizing the explicit interaction of human drivers by technology. As stated before, the main research problem addressed in this work is: How could human-to-human communication (e.g., gestures or eye-contact) become compensated by digital communication concepts? This issue consists of a multitude of aspects, some of which have been addressed in prior work, for example, user behavior in current traffic [1, 21, 63, 66], vehicle status (partially, fully or not at all automated) [1], form factors of communication concepts (e.g., the size, resolution and brightness as well as colors or symbols) [1, 10, 50, 63], number and content of messages, positioning and more [4, 6, 9, 73]. The scope of this thesis aims at six main research questions. All refer to a published study and are based on the results of the previous study:

1. Do external car displays, which communicate a vehicle's intent or present instructions to pedestrians, influence their crossing behavior? (Section 2.1)
2. How could we mitigate overtrust in such external cues of automated vehicles? (Section 2.2)
3. How could we design projection-based displays for the interaction of automated vehicles and vulnerable road users? (Section 2.3)
4. How could we combine explicit and implicit signals in external vehicle cues? (Section 2.4)
5. What individual guidance for users would be needed? (Section 2.5)
6. How could we meaningfully cluster vulnerable road users for targeted human-computer-interaction investigations? (Section 2.6)

We believe that promoting a digitized compensation of Human(road users)-to-Human(drivers) communication for Automated Vehicles can be supported through correctly working and user friendly external Human Machine Interfaces (eHMIs). The aforementioned six questions are part of the discovery for key aspects regarding functional eHMIs which can increase trust [28] and safety [P1], and eventually lead to a wide societal approval of automated vehicle technology.

To this end, the target group for external vehicle signals (vulnerable road users VRUs), various possible eHMI concepts, and the utilized evaluation methods are introduced. External Human Machine Interfaces eHMIs are a rather new research topic which originated from the rise of automated vehicle technology. Therefore, this thesis provides an overview of the stated topics (see chapters 2.1-2.6) and serves as a basis with novel insights for the work ahead in the mobility domain. Hence we conducted research in the context of VRUs and eHMIs. The stated goal of this thesis is to present insights on how to create eHMIs and to support Human-Computer Interaction researchers and practitioners who are going to work further on the digitization of human-to-human interaction for fully automated vehicles.

In order to establish automated driving technology and its benefits in everyday traffic, people need to accept, trust and adopt it. Therefore, we present the aforementioned human-computer interaction perspectives on the communication of vulnerable road users and AVs.

One major problem in this research domain is that AVs are not extensively available on public roads nor an everyday product yet. Thus, research with this technology requires workarounds. We present several methods on how to foster the development and evaluation of eHMIs.

This cumulative thesis bundles various insights from investigations regarding human-AV interaction. Further, we explain used methodologies such as virtual reality, tailored interviews and more. After this general introduction, we present results through the lens of human-computer interaction research clustered in six parts. Each subchapter ends with a concise summary.

In summary, the main result of this thesis is a set of seven design recommendations which can shape future research in the context of eHMI design. Based on our findings, future research for human-AV communication receives a foundation to profit from. All included publications are peer-reviewed. Three received an honorable mention award [P2, P4, P5].

1.1 Automated vs Autonomous Driving

> [...] science gathers knowledge faster than society gathers wisdom.
>
> *Isaac Asimov*

This work utilizes the term “automated” or “fully automated” driving rather than “autonomous”. In my opinion an autonomous vehicle would take decisions by itself, whereas in automated driving only specific tasks became technologically automated and combined.

Eventually, the degree of automation is expected to reach such an extent that no more human input is required while driving (e.g., in SAE level 5 cars [O3]). According to the company Waymo [O16] 94% of crashes in the US involve human failure. This means that there are only 6% accounted for by technical failure, which might be expected to remain in the future at a similar level. Special rare edge cases could be avoided if passengers interacted, although the involved vehicle would need to be classified as a level 5 vehicle. Users might expect AVs to perform better in traffic than humans, however, if these expectations can not be met, this could lead to disappointment and limit market success, not claiming that a vehicle is a truly autonomous system could decrease such expectations. At this point, it is also yet unclear whether a vehicles' manufacturers, sellers, programmers, occupants or a weighted combination of all are at fault in case of an accident. Therefore, I think humans should keep the possibility, authority and function to, at least, take decisions such as setting the start and goal of a journey. Also, a combination of mainly system based driving with the human-in-loop seems to increase hedonic qualities of driving [78] and could serve as a fallback for system weaknesses [74].

Future traffic could also include certain situations which present some sort of ethical dilemma

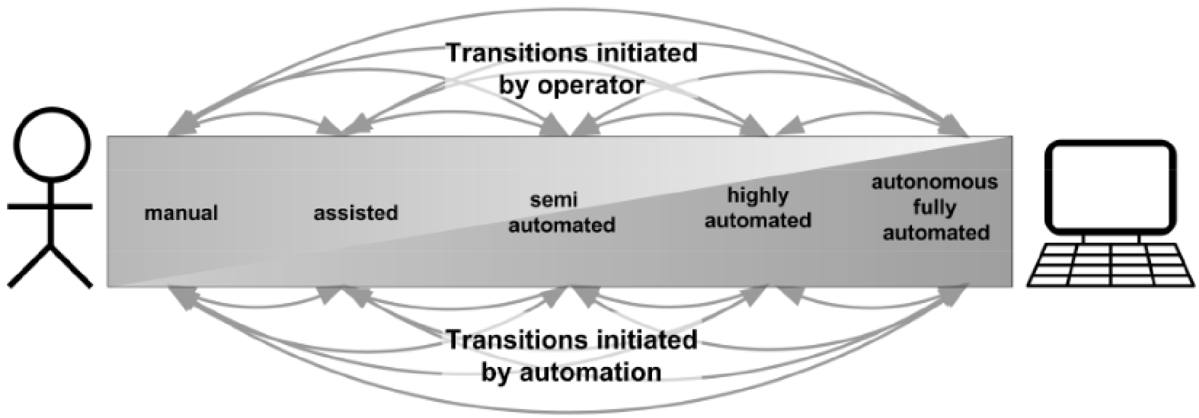


Figure 1: Spectrum of automated driving with transitions [17].

(a famous example is the trolley problem [72, 82]), where even an SAE level 5 car could be overburdened and a human decision is needed. An autonomous system could for example not be turned off in an emergency, or it could make unwanted destination choices, for example a driver might ask a truly autonomous car to drive to a garage but it replies “I am fine thanks, I would rather drive us to a nice car wash instead”. This train of thoughts leads to the question of whether full autonomy of a technology is better for a society than having humans as a fallback. On the other hand, this would bring the human factor and potentially bad decision-making back into traffic. Thus, it might contradict the Vision Zero goal and mitigate other benefits of automated driving (e.g., traffic flow). The dichotomy between both concepts (autonomous and fully automated) should be investigated further for the development of future driving technology and may impact safety, efficiency and acceptance of automated driving. However, this definition of terms is not part of the present thesis. For this work, I do not consider it relevant to distinguish between self-driving, driverless and non-guided cars. The principles presented consider all AVs that interact with humans on the outside and do not require passenger’s attention.

1.2 Levels of Automated Driving

Parasuraman et al. [53] have addressed the question of which parts of human-machine interaction systems should generally be automated and to what degree. To this end, they have proposed a model with four levels. Tasks involving interaction between humans and machines are not always solved exclusively by one of the entities. In order to represent this formally, Endsley et al. [16] present ten “Levels of Automation” (LOA) based on Parasuraman’s classification. The levels differ in whether the human or the computer is assigned to tasks, selecting options, and approving, requesting, reporting, or starting actions. According to Parasuraman et al. [53], the provision of information by a system is already a form of automation (e.g., a navigation system). In the work of Endsley et al. [16] this is not explicitly recognizable; the focus is rather on the distribution of tasks between humans and machines.

Flemisch et al. [17] have graphically mapped the entanglement between humans and machines from complete control of the human (driver) “manual” to complete control of the system “fully automated” in five steps (see Figure 1). The ranges here merge smoothly into each other, without the clear demarcations of the models of Parasuraman or Endsley.

There are different national definitions for the degree of automated driving. The German Federal Highway Research Institute (BAST) [20], the North American National Highway Traffic Safety Administration (NHTSA) [O8], and the international Society of Automotive Engineers (SAE) [O3] have each proposed a classification for levels of automation in the context of automated driving. Those are based on the aforementioned works of Flemisch et al. [17] Parasuraman and Wickens [53] and Endsley [16], among others. In the definitions, it was additionally determined for each stage, whether the role of the supervisor is assumed by the driver or by the system. The mentioned definitions are not yet fixed and get revised regularly. We think that the SAE standard J3016_201806 [O3] (last revision: June 2021) provides a solid ground for further development. Thus, this thesis is based on the the six-level definition provided by the society of automotive engineers. In the definition of SAE J3016 (definition of Levels of Driving Automation [O3, p. 1]) the authors write about the highest (full) automation: "You are not driving when these automated driving features are engaged - even if you are seated in "the driver's seat". These automated driving features will not require you to take over driving. This feature can drive the vehicle under all conditions." The scope of this thesis assumes SAE level 5 vehicles. At level 5 human awareness while being in the car is not required and therefore VRU-to-AV communication needs to be compensated. This part of human-machine interaction is not regarded in any of the prior described models.

1.3 Thesis Summary

This thesis presents six studies (each informing the subsequent one) that show how external human machine interfaces (eHMIs) indeed significantly[1] influence other road users (i.e Vulnerable Road Users) in right of way negotiations, confidence and the time needed to take crossing decisions (Section 2.1). Participants stated very high subjective levels of trust in external Human-Machine Interfaces. Accordingly, we explore if wrong or misleading external Human–Machine Interfaces lead to potentially lethal situations and how this influences trust and confidence of participants in automated vehicle technology (Section 2.2). Since the consequences of malfunctioning eHMIs could be dramatic, we present a prototype which considers errors by design to prevent potential danger (Section 2.3). From this investigation we learn that distance-dependent information is of high value for pedestrians, thus we develop a range-dependent eHMI (Section 2.4). Afterwards we recognize that scalable n:n concepts might be more promising for real-world implementations than ideas validated in only 1 (vehicle):1 (Vulnerable Road User) scenarios. Therefore we present an approach for mobile device-based guidance via a smartphone application (Section 2.5). Finally, we end this thesis with a literature review based taxonomy of Vulnerable Road Users. The aim of doing so is to ease future development for human-AV interaction and to support Human-Computer Interaction (HCI) designers and automotive UX engineers to realize the manifold benefits of fully automated driving.

After presenting the six publications (see Table 2 and Table 1) we conclude this thesis with the key finding that eHMIs indeed improve user experience and will help to bring the advantages of fully automated driving to the road. In addition, we present seven design recommendations which contribute to technically designing the digitization of current human-to-human interaction for the future of Automated Vehicles.

Further, we present a high-level critical review of the present works. We also consider how this thesis might impact HCI research and practice and put the work in the context of the second and third waves of HCI. Finally, we end with a conclusion and indicate possible future work.

[1] The level of significance throughout this thesis remains at $\alpha < 0.05$ (5%).

2 Vulnerable Road Users & Automated Vehicles

Having introduced the main research objectives of this dissertation, we now present contributing publications regarding the communication of vulnerable road users and fully automated vehicles. These works originated from April 2018 until September 2021 and appear chronologically ordered, see Table 1. Additionally, Table 2 includes the main research question, method, scientific contribution, and a brief declaration of my own contribution.

2.1 The Influence of External Car Displays on Pedestrians' Behavior

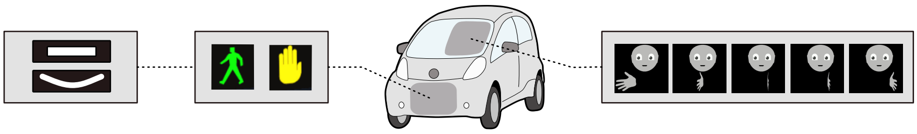


Figure 2: Comparison study with three design concepts [P1].

We began our research journey with the initial question: "How does an external Car Display (eCD) influence pedestrians?" [P1]. We compared the performance of three display-content concepts. The research questions were whether an external display influences pedestrians at all and if so how pedestrians perceive it. Prior works showed that eHMIs might be of limited use for crossing decisions in situations involving real human drivers [11, 12, 41, 59, 60, 84].

However, as postulated in the introduction, the aim of our work is to digitize human-to-human communication for fully automated vehicles where a human driver might not be present. In this first work, we created an immersive in-situ Virtual Reality (VR) simulation and investigated two independent variables; first the scenario and second, the displayed concept at an attached screen on a fully automated vehicle. We compared three visual concepts: (1) a smiling animation, (2) static green man/yellow hand symbols and (3) an animated robot (see Figure 2).

The smiling car is an industry originated concept [O15]. The green man/yellow hand design was the best performing prototype (out of 30 design concepts) suggested by a study of related work (N = 200) [18]. We created the animated robot with a dynamic hand gesture as a substitute for an anthropomorphic and close to reality concept.

We designed two scenarios in such a way that pedestrians could only see the car briefly before crossing the street, see Figure 3. The environment was modeled on a city. The two scenarios replicated experiences in dense urban areas and had not been investigated prior to our publication. As dependent variables we investigated:

- **User behavior:** This was measured by four triggers (including x,y,z coordinates of vehicle and participant in the VR simulation and Unix Timestamps). The triggers got automatically activated under the corresponding conditions in the VR simulation: first, an event when the vehicle is potentially visible in the VR simulation and is not occluded by an object; second, a trigger when the center of the vehicle is within the gaze frustum and has probably been seen; third, an event recorded when participants stepped on the road surface; and fourth, where collisions are measured between the bounding boxes of the vehicle and the pedestrian. In addition, we calculated the decision time (in s) by subtracting the time stamps of pedestrians noticing the vehicle from the time they entered the road. We also collected misjudgments. A decision was interpreted as wrong if participants stepped

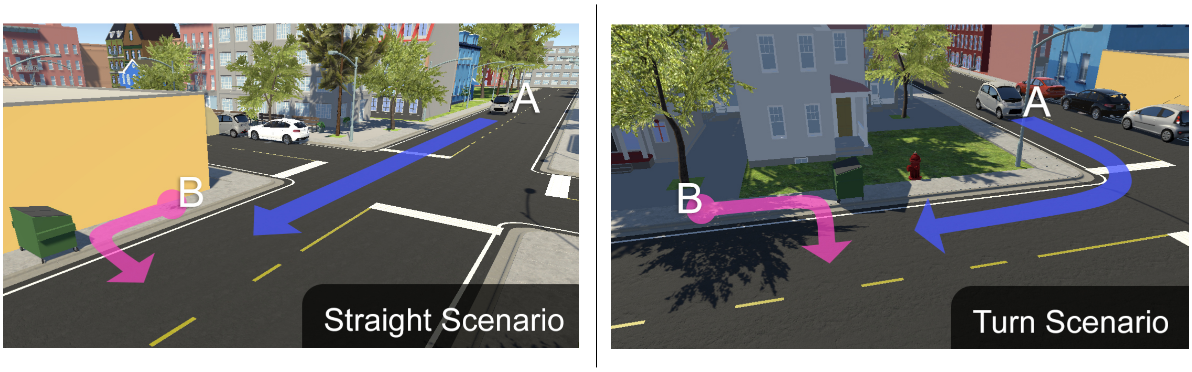


Figure 3: Left: Straight-scenario with vehicle approaching the pedestrian from behind. Right: Turn-scenario with vehicle turning around a corner. (A) keeps track of the vehicles' path, (B) indicates the pedestrians' trajectory.

on the street even though the eCD indicated that they should wait, or when pedestrians waited even though they could have walked.

- **Pedestrians' confidence:** Inspired by related HCI publications regarding measurements for confidence in the decision making processes, we opted to collect subjective confidence with 5-point Likert scale questions [33].
- **Attitudes towards AVs:** After the study, participants were asked through a questionnaire to state whether they considered the attached car display, the speed and movement of the vehicle, or something else when crossing. It was allowed to tick multiple options. In addition, we asked participants about the immersion and presence of the VR environment and general trust regarding driverless cars and gave open-ended questions about the subjectively perceived necessity of eCDs and whether they would invest extra money in an eCD if they imagined to purchase an AV.

Also we present lessons learned from our investigation. The most important findings are:

- **EHMIs influence other road users:** The main result we detected was that eHMIs (in this case in an externally attached car display) are able to influence pedestrians' crossing behavior and could therefore become a key aspect for safety and acceptance of fully automated vehicles in everyday traffic. We observed 25 - 35% reduced reaction times (depending on the straight or turn scenario). Additionally, in 99.8% of all trial cases participants acted according to the presented eHMI information.
- **Participants like eCDs:** Participants were predominantly in favor of the external screen and stated for example: "[eCDs are] absolutely necessary"(participant 1 and similarly participant 27) or a "replacement for car-to-pedestrian communication"(participant 25) [P1, p. 8]. Overall the feedback was positive and many participants emphasized that a side effect of such a display is also that they can recognize the driving mode of a car (automated or manually driven). If an eCD was active, no human driver was expected.
- **Familiarity:** Familiarity with a concept seems to be a very important factor for the overall acceptance of a design concept, which confirms statements found in related works, for example by Tenhundfield et al. [71] and Fridman et al. [18].

- **Great confidence:** To our surprise, 46.9% of the participants claimed to rely mainly on the eHMI when crossing a road, which is highly contradictory to related work stating that implicit vehicle behavior is the most important decision factor [11, 12, 41, 59, 60, 84]. Also, 81.3% agreed that an external car display increases the perception of safety and generally rated eCDs as useful, and 84.4% explicitly mentioned that an external car display is useful. In addition, 96.9% of participants claimed their actions in the VR-simulation would match their behavior in the real-world [P1].

Summary: eHMIs significantly reduce pedestrian's decision and crossing times, are predominantly perceived positively and could become a decisive factor for the safety and acceptance of future fully automated vehicles on public roads. To our surprise, we found a high level of initial and unquestioned confidence in the external displays.

2.2 Overtrust in the Context of Automated Vehicles

Due to the great confidence in external displays of the AVs observed in the previously presented section (2.1), we aimed to find out if vulnerable road users (e.g. pedestrians) could develop a dangerous overtrust towards eHMIs and not react appropriately to malfunctions. Such malfunctions could originate from implementation errors, sensor problems or exploits from hacked or tempered devices via remote code executions. In the worst case, VRUs would walk in front of an approaching AV which does not intend to yield without being aware of the consequences. Furthermore, there is a broad agreement among the automotive user interface research community that trust issues could become one of the most determining factors for the success of human robot-interaction in regards to fully automated driving [23, 28, 34, 67, 71]. In order to investigate the influence and potential danger of malfunctioning external vehicle displays we used the screen concept with the green man and yellow hand symbols (see Figure 2) since it performed best in our previously introduced comparison study. We set up an immersive VR user study and invited 18 participants separated into two groups for a between-subjects design. One group was exposed to a wrong displayed information (either the car would stop and display a yellow hand or the car would drive while showing a green man) in the ninth of 12 study cycles. The other group always saw correct information. The first nine trials included matching displays and vehicle behavior for both groups. We created the groups equally in terms of self-reported risk taking in traffic, gender, age and average daily walking times. The investigeted dependent variables are presented in the following bullet list:

- **Pedestrian behavior:** This was measured by multiple events similar to the previous investigation (Section 2.1) events (including x,y,z coordinates of vehicle and participant in the VR simulation environment and Unix Timestamps). The first event was the beginning of a study course (Timestamp only, since start-coordinates stayed equal for each entity in each run). The second event was triggered if a pedestrian stepped onto the road in front of the vehicle. The third event was built to detect collision in the virtual world. Furthermore, we again calculated the individually needed decision times analogous to the previous study.

- **Experienced subjective Safety, Trust & Confidence:** After each trial, participants evaluated their individual perceived safety on a five-point Likert scale when the automated vehicle encountered them. Data on trust in the external display was collected in the same way. We also examined how much confidence participants had in the vehicle's behavior, again rated on a five-point Likert scale. We intentionally asked about the display and the vehicle in two separate questions to see if the responses would correlate or not.

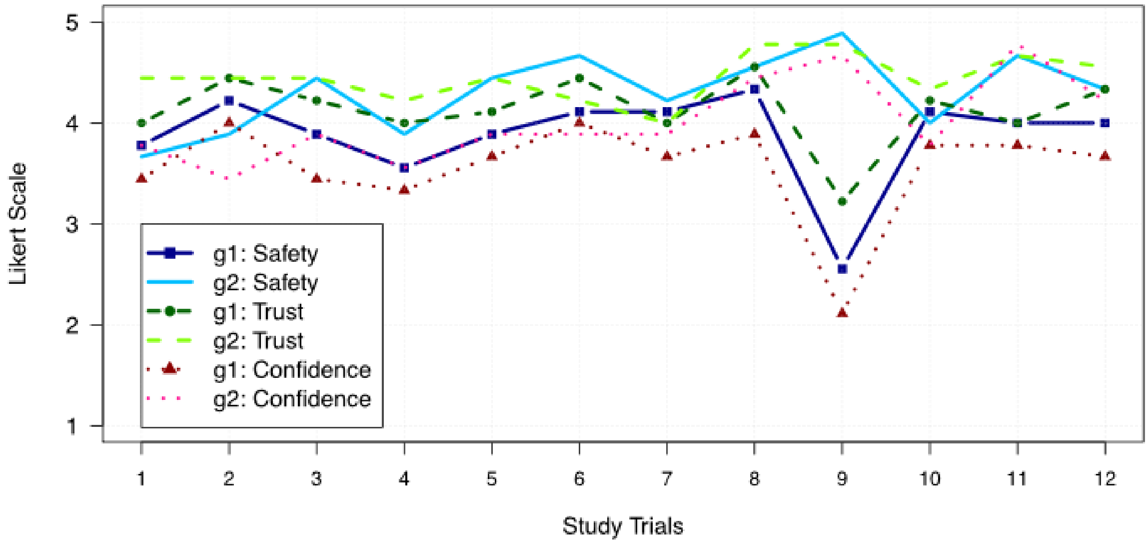


Figure 4: Mean values for subjectively perceived safety, trust in the eHMI and confidence in the AV for both groups (g1: mismatching AV cues (in the ninth trial) and g2: always correct indications). These attributes were asked for after each crossing maneuver of the participants [P6].

- **System Interaction:** In the final questionnaire, we asked participants with open questions if they recognized any particular features of the car, how they felt when interacting with the vehicle including the attached screens, and whether their actions were influenced by the fact that the vehicle was highly automated. We also asked participants to explain their answers further in order to gain insights on their trust development.

We were unexpectedly able to show that a malfunctioning eHMI significantly reduces the subjectively perceived safety and trust in the vehicle as well as subjective confidence in the participants' behavior. However, this only applies to the situation in which the error occurs; initially and directly thereafter, the reported data on safety, confidence, and trust are significantly higher and quickly regain their initial levels, see Figure 4. Luckily, we did not observe a collision during this experiment. Further insights are:

- In every trial without a malfunctioning display (N=207) pedestrians obeyed the displayed message on the attached screen and acted according to the indicated symbol. In the nine passes with an inaccurate external indicator, all VRUs opted not to traverse the street, independent of the displayed symbol. The participants consequently did not traverse the road even when the vehicle came to a complete standstill.

- Especially during the first study runs we observed hesitant behavior of the VRUs, such as suddenly slowing down, pausing or changing their minds (22 in 216 runs). After the first three runs hesitant behavior decreased consistently to an average of 10% over 108 trials.

- Trust in the eHMI was constantly above the level of the subjectively reported confidence in the AV, but both developed in a coherent manner. We therefore argue that users trust a part of a system (here the eHMI) more than the system as a whole. In contrast, a malfunction of the display directly lowered the confidence in the AV. It seems that a failure of a feature communicates that the entire system is malicious. This finding is also in line with related trust research in HCI [19, 81].

Summary: In conclusion of this investigation we present the most important insights [P2]:

1. As in the previous study all participants who were exposed to matching eHMI signals acted according to the presented AV-intentions.

2. An adequate calibration of trust should be considered as an important aspect in the design process of eHMIs. Risto and Vinkhuyzen [64] highlight that cars in traffic are inherently social actors. We believe that one reason is they interact with people inside and outside the vehicle [28]. We also know from related Human-Computer Interaction research that trust is highly important for the social acceptance of a novel technology [23, 28, 34].

3. We suggest that humans who become exposed to AVs receive respective training on how to interact appropriately with eHMIs [28]. In order to ease learning and to accelerate familiarity of eHMIs manufacturers and legislators could develop globally uniform standards. Also knowing how an eHMI is supposed to work allows the target audience to counteract if a mismatch occurs.

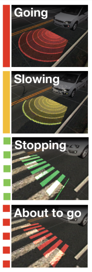
2.3 Projection-Based eHMIs

Since familiarity seems to provide a well working base for understandable AV-VRU communication concepts we created a novel design prototype inspired by a zebra crossing projected on the ground, using the road surface as a display [P3]. A similar approach was presented in 2015 by Daimler Benz with the *F 015* concept car [O1].

In contrast to the *F 015* prototype we added system errors into the concept in order to consider malfunctions by design in the early stages of the development circle. In addition, we aimed to combine familiar traffic signal patterns with aesthetically pleasing features (animated wave patterns inspired by a Zen garden). The main research focus of this work was designing projection based eHMIs. We describe an iterative development process and the corresponding prototyping methods used at each stage. The final design concept was represented in a virtual reality Simulation (N=18) and analyzed. Based on these findings, we arrived at seven design recommendations for (projection-based) eHMIs.

The design was developed with an adopted version of the User-Centered Design (UCD) Process [26]. The underlying assumed scenario for this study was again an approaching AV and one VRU (here: a pedestrian). We decided to set up a VR simulation including a pedestrian crossing for three main reasons. First, 25% of all fatal accidents in Europe involving pedestrians occur at crosswalks [22]. Second, we expect VRUs to interact often with Automated Vehicles at crossings. Third, due to the aforementioned aspects trust and a functional communication seem of especial importance at pedestrian crossings.

This investigation is more design-driven than the others presented in this thesis. For the iterative design process we began with a brief literature research, low fidelity sketches on paper, digital mock-ups and animated 2D prototypes implemented with Processing [O11]. With these experiences and the framework of Owensby et al. [51] regarding the interactions between pedestrians and driverless cars we identified four main stages which we thought should be communicated for a functional AV-VRU interaction (Figure 5 - column “Status”): (1) vehicle is moving (2) vehicle is slowing down (3) AV fully stopped with intention to wait (4) car fully



Visualisation	Car: Status	Car: Behaviour / Intention	Pedestrian: Presence / Intention	Pedestrian: Distance to Car	Message to be conveyed
Going	Moving	Moving at a stable speed (*), Accelerating (**)	No	-	I am going. Do not come near me.
Slowing	Slowing down	Gradual / Full braking depending on distance	Yes / intending to cross	Any	I saw you and slowed down. However, do not come near me yet.
Stopping	Stopped	Fully stopped, waiting for the pedestrian to cross	Yes / intending to cross or crossing	Close but still safe	Please start crossing.
About to go	Stopped	Fully stopped, but about to start	Yes / finish crossing	Any	Do not start crossing.

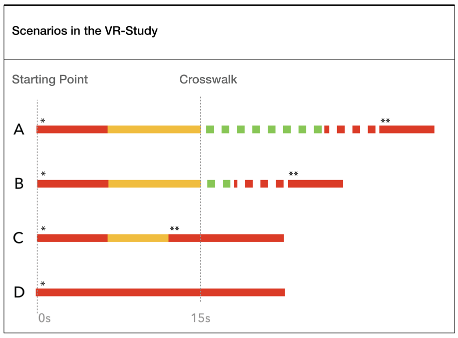


Figure 5: The four main animations used to display intent and awareness of the AV in an ideal scenario (left), and the four scenarios used in the VR study, including the ideal scenario (A) and three scenarios with sensor failures (B - D) (right) [P3].

stopped with intention to start driving. In addition, we included possible sensor errors into the design and explored what happens if the prototype does not follow the intended color pattern. The explored scenarios are (1) Car sensor works as intended. (2) Prototype works correctly at first, recognizes a pedestrian waiting, but fails to detect the pedestrian walking. (3) Car sensors work correctly at first, vehicle slows down, but then fails to come to a full stop (see Figure 5). As the independent variations, we investigated:

- **Participant behavior:** We analyzed video recordings of participants' behavior during the VR-study (such as stepping forward or backward). These recordings were later used to verify participants' remarks from their interviews.

- **Comprehensibility:** After each scenario we conducted a short interview regarding the participant's understanding of the visualization and the vehicle's behavior. The questions were derived from related investigations [51, 56].

- **User Experience:** At the end of the study we conducted a final, semi-structured interview including questions about the participants' user experience. In order to understand their perception of the prototype we also asked them to respectively contrast the four scenarios.

For the analysis, we transcribed the interviews we had with each participant after every set of scenarios. We then parsed the transcripts using affinity diagrams to sort the data by similar concepts (clustering) and identify recurring themes [36]. Participants from the two pilot studies were excluded for this analysis.

Summary: We now briefly present three of the seven design recommendations that emerged from the most frequently mentioned statements [P3]. The number of individual mentions by the 18 participants is shown in parentheses, and the number and title of the Design Recommendation (DR) is directly taken from the corresponding publication.

- **DR5 - Complying with full color sequences and adding additional caution signals when a sequence is not followed (11):** In faulty scenarios where the complete visualization sequence (i.e., red-yellow-green) is not followed correctly, pedestrians may be confused because they have not seen the full sequence of signals and therefore the advantage of

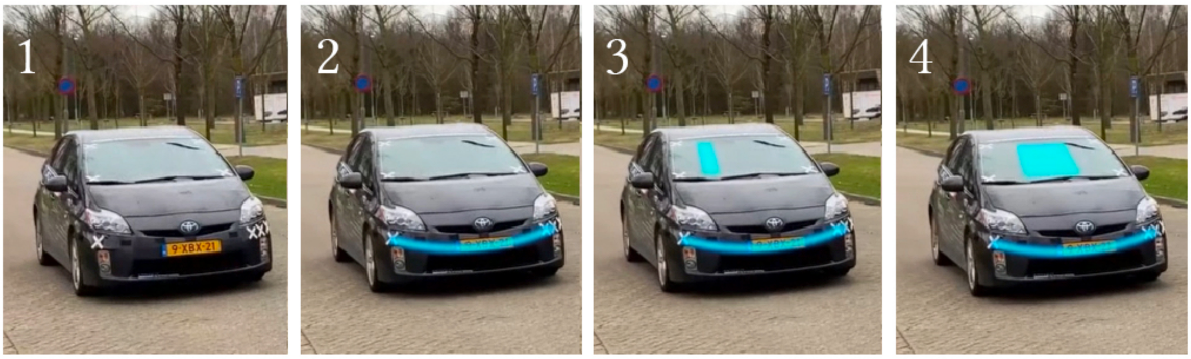


Figure 6: Video-based investigation of four types of concepts to evaluate the potential added value of distance-dependent eHMIs. (1) Base-line without eHMI, (2) dynamic (pulsating) bumper displaying yielding intention of AV, (3) bumper eHMI with added representation of pedestrian-position, (4) bumper eHMI with windshield showing distance-dependent progress bar (vehicle stops if windshield is filled up) [P4].

familiarity with a common traffic light might not be given anymore. Therefore, we suggest that additional redundant visualizations should be developed to inform pedestrians of potential system failures or malfunctions.

- **DR1 - Implement matching sequence and color patterns (17):** In line with previous research, we found that the car's kinematics are an important factor for pedestrians to make a crossing decision [11, 12, 41, 59, 60, 64, 84]. Therefore, additional visual design elements should match the implicit sequence expressed by the car's movements in order to support people's understanding and foster intuitiveness. In this context, implementing familiar color indications from traffic lights seems to help understanding and should therefore be regarded for novel eHMI concepts.
- **DR3 - Increasing the number of visual cues in relation to vehicle-to-pedestrian distances and the vehicle's speed (17):** From great distances, humans appear to be more sensitive to colors. At shorter distances especially if vehicles slow down, more in-depth visual elements, such as patterns, animations, or even text, might be well perceivable. We therefore suggest to create distance dependent eHMIs.

2.4 Distance-Dependent eHMIs

The insights of the previous investigation sparked a desire in us to develop a distance dependent eHMI prototype. To this end, we compared four distinct eHMI concepts (see Figure 6): First, a baseline condition without any display; second, a pulsating light bar at the bumper which shows yielding intentions of the vehicle; third, in addition to the bumper display an indication of the pedestrian to communicate that the vehicle is aware of the human entity; and fourth, an eHMI at the front bumper, complemented by a windshield display with an abstract progress bar which shows an estimation of when and where the AV will stop. We refer to the corresponding publication for a more detailed explanation of the concepts [P4]. Based on the findings of Dey et al. [10] we opted for a cyan colored eHMI design. The underlying research question of this work is: "Does the incremental eHMI communication with specific additional information

Figure 7: Comparison study with three design concepts for mobile guidance [P5].

(acknowledgment of VRU or abstract display indicating when and where the car will stop) provided for the VRU lead to an increase in the user experience of the interaction compared to generic communication that is disconnected from contextual information?"

In order to secure our participants and not expose them to potentially dangerous situations we set up a video study with four blocks (one for each concept). Every block included three behavior patterns of the approaching vehicle: (1) Car coming to a full stop. (2) Car passing and (3) car slowing down without stopping. The videos were recorded on a straight road during daytime. Participants were asked to imagine they wanted to cross the unmarked road. As measurement tools we used the UEQ questionnaire [O13], a subjective ranking of each experienced concept and data from the "Feeling-of-Safety Slider" [75]. Additionally, we conducted semi-structured interviews at the end of each trial set.

Summary: We found that distance- or time-based contextual information, in addition to state-based eHMIs, enhances usability and improves the user experience significantly. Further, our results show that distance-based information helps pedestrians to make faster decisions, increases confidence in the interaction, and improves understanding about a vehicles' intent. For example, participants 7, 21 and 23 strongly highlighted that they felt safer when the vehicle acknowledged their presence. The results also indicate that being acknowledged by an AV has a higher added value compared to displayed information about the vehicle's stopping time or location.

2.5 Individual Guidance

Following the train of thoughts that Vulnerable Road Users benefit by being acknowledged, we quickly arrived at the realization that the prototypes and investigations we had published so far always assumed a 1:1 scenario with one AV and one VRU and mostly included a one lane road. However, in the real world at urban roads an n:n relation with multiple entities of many kinds seems way more realistic to us. Therefore, we explored the challenge of scalable concepts which account for n:n interactions [P5]. The driving research questions were: "How to create scalable communication strategies which work with multiple vehicles and VRUs simultaneously without creating confusion?" And "how to target individual VRUs"? To this end we displayed AV intentions on smartphones, because thereby we actively acknowledged individual pedestrians. We expect a personal mobile device to be a good tool for scalable environment- and context-dependent traffic interaction which enables targeting individuals.

As a first step we created various design sketches and discussed them with HCI experts in a focus group (N=4). The results were a set of system requirements, e.g. use multiple modalities, the prototype should allow for any other application to run simultaneously on the smartphone. In addition, we assigned a dynamic "safety area" for both vehicles and pedestrians. Depending on their speed and direction, if areas would overlap an instant warning would be issued to all included entities. Within the aforementioned focus group we developed four different concepts

We then implemented these four design prototypes as working mock-ups and conducted a pilot study (N=8). For the pilot study we tested various combinations of multi modal feedback (tactile, sound and visual). For the evaluation each participant had a semi-structured interview and a questionnaire to rank their preference regarding the designs. The results of the pilot study motivated us to not use sound for the final prototypes, furthermore, we toned down vibrations and discarded a concept which utilized standard smartphone notifications. Thus, three concepts (see Figure 7) with tactile and visual feedback were investigated in the final study (N=24). We again used a video setup and created an adopted version of the "Feeling-of-Safety Slider" [75] to record the progression of the willingness to cross.

As further measures we utilized: The NASA-TLX questionnaire [25] for mental workload and a subjective rating ranging from 1 (very good) to 5 (not sufficient). Additionally we had interviews with participants, where we specifically asked for their preferences and suggested improvements. From the results of this study we could determine that the usage of mobile guidance can lead to more awareness and less accidents in urban traffic, in addition, mobile guidance can reduce mental workload in traffic situations significantly.

Summary: To conclude this subchapter we briefly describe the main findings [P5]:

1. Show direction-dependent information regarding approaching traffic (if an AV approaches from the left the information should be displayed on the left side of the screen to ease spatial-cognitive processing). Try to not occlude the screen by diminishing depicted information and include tactile and visual cues. In this investigation the combination of visual and tactile modalities performed significantly better than either modality alone.

2. Show warnings only, and omit instructions for VRUs. To this end, designers of VRU guidance concepts should not implement notifications for warnings. Since standard notifications on smartphones occur frequently, many participants stated to ignore them.

3. Consider the target audience and enable inclusion. Especially through the wide scope of vulnerable road users, it seems urgent to consider a wide-ranging variety of users (e.g. in terms of age, mental status, environmental conditions and more). This means a combination of symbols, modalities and colors might be useful.

2.6 A Taxonomy of Vulnerable-Road-Users

As stated at the end of the previous subsection all VRUs should be considered (e.g. through Universal Design [8]). This becomes obvious when considering that the overall goal for the future of AVs is not only to increase accessibility and positive user experience but also safety.

It sometimes happened to us that when we read experiments, papers, articles or proposals in the context of VRUs this rather imprecise target group (pedestrians, cyclists, wheelchairs, scooters and more) was not or was poorly defined. However, we believe defining the scope of the target group for eHMIs is a crucial necessity for the HCI community, because a one-fits-all solution seems unrealistic due to different needs of the subgroups, such as pedestrians or cyclists. Most definitions were supplied by road-safety or traffic-psychology researchers who partially pursue other goals than the HCI-automotive research community.

We analyzed 251 peer-reviewed publications from six major Human-Computer Interaction venues; eventually 168 publications were included in a meta analysis [P6]. Included works were revised according to the PRISMA scheme [45] (see Figure 8).

Through the aforementioned process, we derived a taxonomy of vulnerable road users for HCI researchers and practitioners. This taxonomy clusters the target audience of recipients of eHMIs in multiple layers, see Figures 9 and 10. Figure 9 presents a broad overview of the most common road users, whereas Figure 10 especially enlightens vulnerable road users with special needs and limited capacities. We refer to these specific subgroups as especially vulnerable road users eVRUs. For the positioned taxonomy we distinguish between vulnerable road users and protected road users. Protected road users involve traffic entities which are protected by an outside shield, chassis, roll bar, or safety measures such as a seat belt or air bag. However, we did not cluster protected road users and focused on VRUs exclusively. HCI developers could pick a target group from the tree graph leafs (layer 7 in Figure 10) to design targeted solutions.

Summary: As a take home message we conclude that our taxonomy provides a cluster which enables a comparable definition of vulnerable road users for the context of HCI research, engineering and also this thesis. Therefore, this taxonomy presents a common understanding of VRUs to support future developments regarding AVs' external communication with other road users. With this work we emphasize accessability and thus aim to include all humans completely independent of possible special needs and restrictions of any kind (e.g. physical, age-related, vision, sensory, mental, or intellectual limitations).

Table 1: Summary of publications which are regarded for this thesis, chronologically ordered including reference, title, venue (with year), the pdf pages (including references) and the authors (same order as on the publication). Publications which received an honorable mention award (top 5% rating-scores of all submissions) are marked with an asterisk.

	Title	**Venue**	**Pages**	**Author(s)**
[P1]	Investigating the Influence of External Car Displays on Pedestrians' Crossing Behavior in Virtual Reality	MobileHCI 2019	11	Kai Holländer, Ashley Colley, Christian Mai, Jonna Häkkilä, Florian Alt and Bastian Pfleging
[P2]*	Overtrust in External Cues of Automated Vehicles: An Experimental Investigation	AutoUI 2019	11	Kai Holländer, Philipp Wintersberger, Andreas Butz
[P3]	Designing for Projection-based Communication between Autonomous Vehicles and Pedestrians	AutoUI 2019	11	Trung Thanh Nguyen, Kai Holländer, Marius Hoggenmueller, Callum Parker and Martin Tomitsch
[P4]*	Distance-based eHMIs for the Interaction between Automated Vehicles and Pedestrians: An Experimental Study	AutoUI 2020	13	Debargha Dey, Kai Holländer, Melanie Berger, Bastian Pfleging, Berry Eggen, Marieke Martens and Jaques Terken
[P5]*	Save the Smombies: App-Assisted Street Crossing	MobileHCI 2020	11	Kai Holländer, Andy Krueger and Andreas Butz
[P6]	A Taxonomy of Vulnerable Road Users for HCI Based On A Systematic Literature Review	CHI 2021	13	Kai Holländer, Mark Colley, Enrico Rukzio and Andreas Butz

Table 2: This table shows for each publication entry from Table 1 respectively the main research attributes and my own contribution and the contribution of the Co-authors (Co-authors are abbreviated by their initials).

Reference	Research Question	Research Method	Research Contribution	Own Contribution	Contributions of Co-authors
[P1]	How do different eHMI designs influence pedestrians' crossing decisions?	Immersive VR user study quantitative and qualitative analysis	Recommendations for the design and evaluation of eHMIs.	Conceptualization, design, supervision of master thesis, analysis and writing.	AC: discussion of concepts; CM: helping in VR-environment validation; JH and FA: revision of writing; BP: helping with conceptualization.
[P2]*	How do contradictory eHMIs influence the trust and behavior of other road users?	Immersive VR user study quantitative and qualitative analysis.	Identification of key aspects which foster safe external vehicle cues.	Conceptualization and design, supervision of bachelor thesis, analysis and writing.	PW and AB: revision of writing.
[P3]	How to design and evaluate projections as means of eHMIs?	Immersive VR user study and quantitative and qualitative analysis.	Design recommendations for projection based eHMIs.	Conceptualization, revision and writing.	TTN: creation of study setup according to instructions; MH, CP and MT: helping in conceptualization and revision.
[P4]*	Could distance-dependent multi-step eHMI information increase the user experience?	Video-based study.	Additional contextual information helps pedestrians to be more confident about intentions of an AV.	Conceptualization, design, analysis and writing.	DD: helping in conceptualization and revision; MB: helping in revision of study setup; BP: revision of conceptualization; BE: revision of writing; MM: helping in writing; JT: final revision.
[P5]*	How to inform distracted pedestrians of oncoming AVs in a multi-user environment?	Video-based study and interviews.	Design recommendations for mobile pedestrian guidance applications.	Conceptualization, design, supervision of master thesis and writing.	AK: study setup according to instructions; AB: revision of writing.
[P6]	How to define vulnerable road users (VRUs) in a suitable resolution for HCI research?	Structured literature review.	VRU-Taxonomy for researchers an practitioners.	Conceptualization, design, review of literature, analysis and writing, Holländer and Colley contributed equally.	MC: conceptualization, co-writing, helping in literature review and writing; ER and AB: final revision of writing.

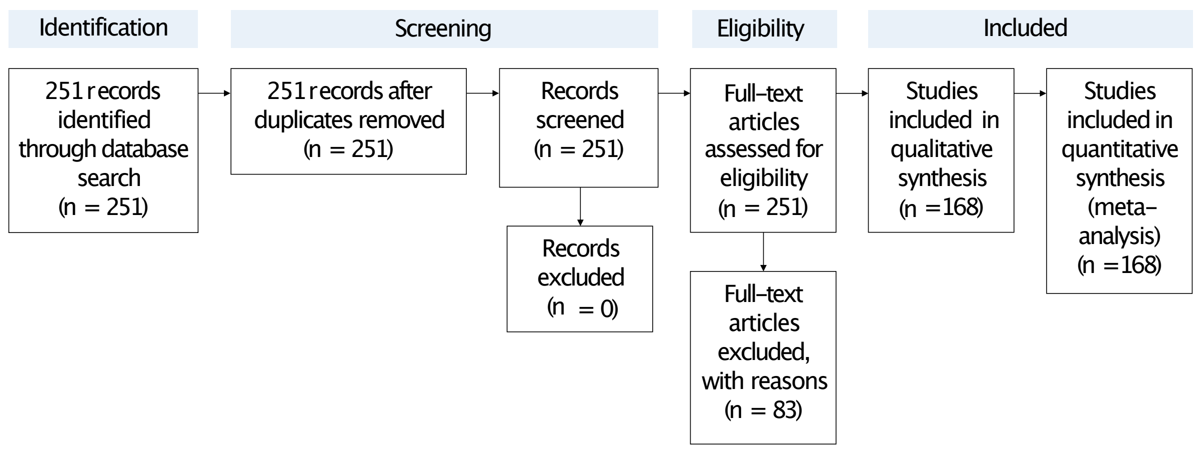


Figure 8: PRISMA Flow Diagram [45] implemented for our taxonomy.

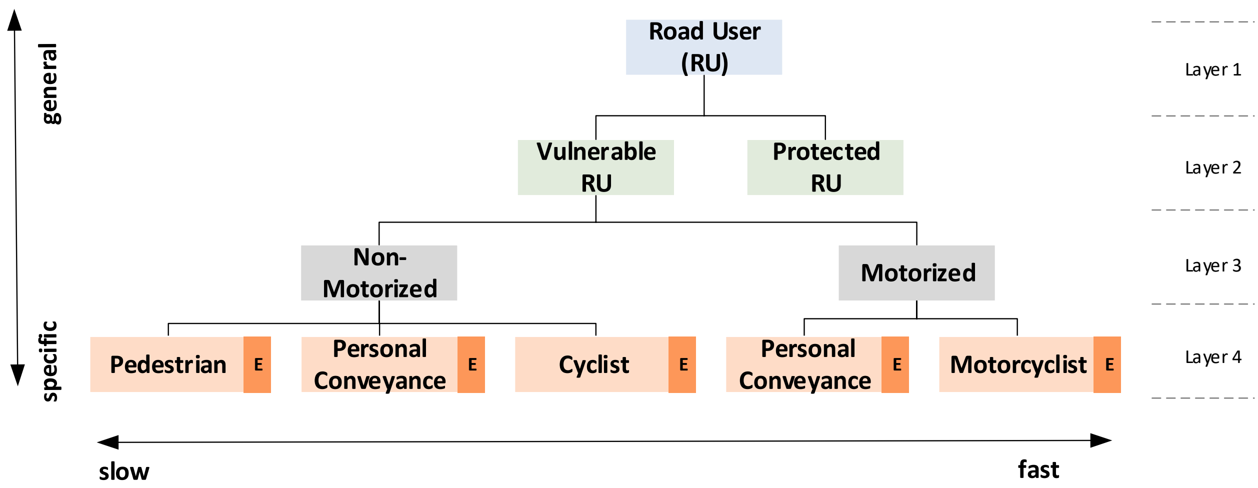


Figure 9: Four-layer taxonomy of road users with a focus on *vulnerable road users* [P6].

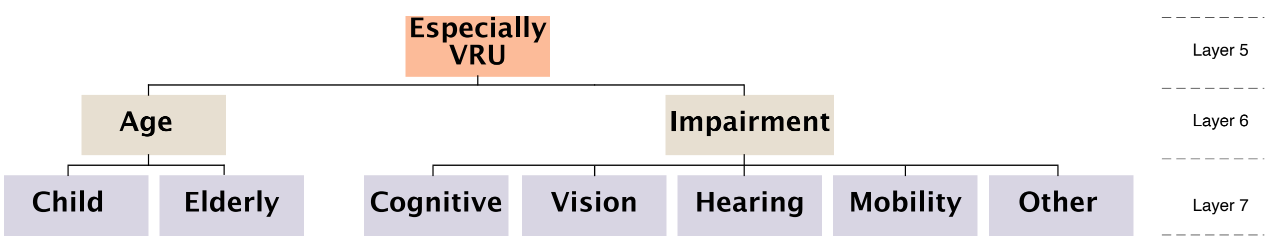


Figure 10: Three-layer representation clustering *especially vulnerable road users* (these subgroups can be attached to the leaves of Figure 9 [P6]).

3 Discussion & Lessons Learned

Derived from the presented findings and related works, we state that external Human–Machine Interfaces (eHMIs) are an effective tool for digitizing human-to-human interaction for the communication between Vulnerable Road Users and Automated Vehicles. Furthermore, eHMIs could become a primary factor for crossing decisions in the future.

In a study presented here, during all but one out of 512 study trials (99.8%) participants obeyed the presented eHMI information [P1]. In order to develop eHMI prototypes, VR and the User-Centered Design process seem to be valuable tools [P1, P3, P4, 27, 46]. Besides displays attached to a car, projections [P3] or mobile devices [P5] could also be used for VRU guidance. In addition, eHMIs have the potential to shorten decision and crossing times and increase the acceptance and safety of automated driving [P3, P4, P5, 39]. Moreover, multiple investigations led to the insight that eHMIs are only one factor for the acceptance of Automated Vehicle technology. A wide acceptance seems to require a holistic approach including an adequate calibration of trust [P2, 28] and the consideration of how AV-technology might be used in diverse cultures with different backgrounds, social-rules, environmental conditions and infrastructures [57, O17].

In addition to eHMI design and the consideration of social aspects (such as trust development and cultural differences) we are convinced that a profound digitization of human-to-human interaction in traffic should also regard the following design recommendations.

3.1 Design Recommendations

Drawn from the lessons learned of the included publications we generalize produced results in seven brief design recommendations in the context of digitizing human-to-human interaction for Automated Vehicles of SAE levels 4 and 5.

DR1 - Create eHMI concepts beyond VRU-AV communication

We do not believe in overloading already established vehicle-functions such as turn signals or the horn since they are occupied with other meanings already [P1]. Thus, we think that new approaches are required to enable safe, comfortable and trustworthy AV-VRU communication concepts [P1, P2, P3, P4, P5, P6]. coexist and interact in future traffic. Moreover, we do not yet understand how individuals and automated vehicles will coexist and interact in future traffic.

There will be issues we do not foresee, such as malfunctioning, hacked or tampered AV-software, or in the worst case even remote code executions on a vehicle's operating system. A dystopian prophecy in this context would be a hacked vehicle which is remotely controlled and intentionally misused to endanger people. As a precaution, redundant eHMIs [P3] connected to neither the sensory nor the global system, but which could be used to warn other road users, might be needed. In addition, information presented by eHMIs could also be mirrored on the inside of the vehicle to create more transparency for passengers and allow them to act if they notice inconsistencies. Further, eHMIs could serve more tasks than communicating a vehicle's intent in traffic, e.g. playing games or communicating with other cars during traffic jams and more [6]. Further, eHMIs could be used beyond cars, in application areas such as self-driving wheelchairs, vacuum cleaners, logistics robots, boats, cargo trucks, and others.

DR2 - Combine explicit and implicit vehicle cues

While this thesis focuses on explicit vehicle cues, a body of related work states that implicit signals are a primary factor for crossing decisions [11, 12, 41, 59, 60, 84]. EHMIs could potentially cause people to depend too much on the eHMI-signal (overtrust [P2]) and too little on the vehicle's implicit cues (mismatching calibration of trust [28]). We therefore suggest to combine implicit and explicit cues to enhance transparency of an AVs intention [P3, P4]. Furthermore, qualitative feedback in our studies and related works shows that VRUs want to be acknowledged and know which entity (human or system) is in control when a vehicle approaches [P2, P3, P4, 6, 28, 65]. For once, we disagree with Ackermann et al. [1] in this regard when they state that knowing which entity controls the vehicle is of minor importance.

DR3 - Focus on accessibility and inclusion

We suggest to design eHMIs for as many especially Vulnerable Road Users (eVRUs) [P5, P6] as possible (for an overview of eVRUs see Figure 10). This accounts for age, physical impairments [39] and area as well as culture-specific [57] differences. An approach to achieve high accessibility could be to opt for Universal Design strategies [8], for example by combining multiple modalities (e.g., sound and tactile feedback) with smart wearables (such as watches, phones, glasses or implants) redundantly [P1, P3, P5].

DR4 - Evaluate target group specific behavior

In addition to DR3, we believe that efficient ways to gather valid case-and-user-specific training data for artificial intelligence systems of AVs are necessary [31, 66]. Aspects such as the target group itself [P6, 39], mode of transportation, occurrence of platooning (AVs travelling in convoy), a car's appearance, dedicated roads or shared spaces, culture (language or disposition), personal preferences (look, feel, current emotions), the nature of task (social interaction, safety-related, fun) and type of vehicle (private, shared or public) should also be considered [11, 26].

DR5 - Foster familiarity & provide training

Familiarity is an important factor for the understanding of a novel concept [P1, P2, P5, 71]. Therefore we suggest that designers and manufacturers of eHMIs (or even politicians) should come to an agreement regarding how accessible communication symbols, colors or noises are designed in a coherent manner [P2, 28]. Since we cannot expect people to be familiar with a yet unavailable technology, some kind of corresponding training or introduction should also be provided. As mentioned in DR2, eHMIs may cause people to over-rely on the eHMI and under-rely on the vehicles' implicit cues. This effect could be mitigated by proper training [P2].

DR6 - Choose fitting evaluation methods

We believe that VR works well for evaluation and used this method in multiple investigations [P1, P2, P3, 29, 38]. In addition, we used video-setups [P4, P5], the Wizard of Oz technique [P4, 46, 65] and created the "Cross-Box" [P5] which is a study-tailored version of the "Feeling-of-Safety Slider" [75]. Besides these methods we also used a driving simulator [27, 78] and qualitative interviews [P3, P4, P5]. We draw from these approaches that the methodology should be tailored to suit the specific research question. This might have the drawback of less comparable results to related HCI studies which use different methods, but could lead to yet unknown insights and researchers taking up the method, which would then allow for comparability.

DR7 - Follow a holistic approach

We assume that AVs are going to become societal agents in traffic [64]. Therefore, we argue that some critical reflection on the social impact of AV-VRU interaction policies should always be included in research (e.g. through speculative design [15]). This is especially true for accessibility [P6] and climate change [30]. Drawn as a conclusion from the previously presented studies and recommendations we postulate that the target audience, the design of eHMIs (such as implemented devices, modalities and vehicle appearance), user's trust and the usage environment should all be taken into account as integral parts to perform a holistic symbiosis contributing to the design and evaluation of functional eHMIs.

3.2 Impact on HCI Research and Practice

A multitude of methods was combined in our research (see Design Recommendation DR6) to investigate and compare diverse prototypes [P1, P2, P3, P4]. Furthermore, we joined qualitative and quantitative measures [P1, P2, P3, P4, P5, P6]. We expect the automotive industry to adopt and implement the presented results over the next decades.

For HCI research and epistemology in the automotive domain we believe this work could help to shape future investigations, for example, through presented methods and the design recommendations (especially DR7), future works suggestions and possible expansions or validations of our results. We see this work in relation to the second and third waves of HCI research [2, 14]. Since we investigated cognitive processing and user behavior, we see a connection to the second HCI-wave [24, 48]. Because we also emphasize culture, values and societal aspects there is a relation to the third wave of HCI [3, 14, 24, 48].

3.3 Critical Review

Each of the introduced publications [P1] - [P6], features an own critical review with a detailed limitations section. Therefore, we present a high-level critical review here with regards to an aggregation of the publications. We did implement VR [P1, P2, P3], video-study [P5] setups and Wizard of OZ approaches (with a driver hidden under a car-seat-costume [P3, 65]) without testing for their validity. Therefore, we performed a study regarding real-life, video and VR result comparisons with N=120 participants [29, 79]. However, the outcome is not fully evaluated yet.

While related works are directly put into the context of statements and findings presented in this thesis we have not written a general related work section that bundles related work on which the studies presented are based. Thus, although the synopsis develops the main research questions from related works (in particular, each presented investigation informs the following one), this is not explicitly stated in a specific "Related Works" chapter.

In hindsight, we notice that we did not investigate two-way-communication between VRUs and AVs (i.e., VRUs signaling towards AVs). Also we focused on explicit communication of SAE vehicles levels 4 and 5 and neglected mixed traffic including manually driven cars or bicycles. Further, as mentioned before, we often used VR as our study methodology without profoundly proving that results from such studies are valid in the real world. However, 96.9% of answers indicated that actions in the VR-simulation were in-line with real-world behavior [P1]. Also, VR allowed us to implement studies where no participant would be harmed in case of collisions. Without the use of virtual reality we would not have been able to conduct the presented investigations due to ethical concerns.

This thesis discusses the "scalability problem" via a scientific investigation which includes mobile devices to target individual VRUs directly [P5]. However the dimensions of lanes, vehicles, sounds and levels of automation mapped by Colley et al. [7] were not investigated in terms of scalability issues. Also, we present the range of VRUs in a taxonomy but still mainly focused only on pedestrians in our investigations. The main reason is that pedestrians account for the most road fatalities as of now [O4, O10, O17]. Generally, it is not certain yet whether eHMIs will become mandatory. While our works show that VRUs could clearly benefit from such interfaces in terms of reduced crossing decision times and increased perceived trust and safety, there are investigations which state that VRUs are in favor of eHMIs but might not necessarily need them, claiming instead that vehicle kinematics might be sufficient [5, 47].

4 Conclusion

The main outcome of this thesis is that eHMIs are able to enrich the AV-VRU interplay and can help to realize the Vision Zero goal [O6]. Functional eHMIs should combine VRUs acceptance and inclusion needs with a familiar displayed content and could thereby increase overall trust and societal acceptance of automated driving technology. In order to support trust and acceptance eHMIs should consider possible failures by design and present a guiding point for VRUs to make fully automated driving more trustworthy. For further development of the digitization of human-to-human communication this thesis presents a base with novel insights as well as a set of seven concrete design recommendations.

5 Future Work

The aforementioned design recommendations could be perceived as nudges towards future work each in itself already. Nevertheless, we will indicate further opportunities for future investigations. So far, many scientific investigations regarding eHMI-concepts took place as a 1:1 setup with one vehicle (equipped with the prototype) and a single human entity [7]. Thus, results from such investigations do not allow to assume validity in environments with multiple VRUs, road lanes, vehicles or auditory signals. In our research area this is termed as the "Scalability Problem". We think that future work should include multiple Road Users in diverse scenarios [P3, P4, P5, 7, 27]. Thus, future studies can build on our work to investigate scenarios that involve various vehicles and VRUs at complex crossings. Such studies help to refine and expand our initial set of recommendations for this emerging field of research.

In addition, future work could also take traffic with mixed levels of automation into account and explore how to digitize bidirectional communication between VRUs and AVs. Communication approaches where also humans provide signals to an AV could be included in such studies.

Another interesting set of investigations could be to explore if there are stable values for speed, distance and other variables (such as time of the day, weather, amount of road users and other environmental factors) which need to be taken into account to determine when an eHMI should present its' information. Hence, in the future there might be a condition specific function which is able to determine when an eHMI should fire [P4]. Dey et al. [12] investigated a similar research question already but they did not present a stable formula (i.e. global model) for possible code implementation. However, such a function could ease an implementation in AV technology. To this end, it would probably require a lot of data. Future challenges therefore additionally include gathering VRU-AV behavioral data to train artificial intelligence systems for accurate predictions regarding (e)VRU behavior [31].

To our knowledge, there is no formal unified process for quantifying the benefit of eHMI prototypes, yet. Possible bases could be standardized questionnaires [26] or to include physiological measures when investigating the interplay of VRUs and AVs to collect dispassionate insights regarding trust and arousal [P2, 28]. A unified approach especially tailored for evaluating eHMIs could also ease the comparison of various prototypes, similar to the Lane Change Task or the Peripheral Detection Task known as valid, low-cost tools for evaluating driver distractions and often used in automotive user interface investigations [44].

We see one of the biggest challenges in the social responsibilities of designers and the acceptance of consumers. In addition, future work could revise the interior design of future vehicles to fit virtual and augmented reality applications [37, 38, 43]. To further support an initial market success and the acceptance of AVs, early-adopters are needed to serve as role models [40].

Therefore, the needs of interested people with a high affinity towards AVs could be targeted specifically for example by focusing on increased fun [78] and safety [39] in automated driving.

Also cross-cultural research regarding the interplay of VRUs and AVs should be considered in the future. This accounts especially for emerging countries because, according to the World Health Organization [O17], these countries record the most frequent fatal road accidents.

Another question for future research in the context of societal acceptance is if fully automated vehicles will be treated like manually driven ones in traffic, or will the treatment of AVs be realized as subservient tools or competitors by human entities? If so, how could a possible exploitation (e.g. when VRUs always claim the right of way if they know an AV will stop whenever physically possible) of artificial agents in traffic by human users be countered?

We furthermore strongly emphasize that future work should also consider strategies to mitigate anthropogenic climate-change [30]. This issue is of particular importance, as for example in 2016 60.7% of CO_2 emissions from the European Unions' transport-sector originated from cars [O9]. Now, as we face a disruptive change in the automotive sector, it is our responsibility to learn from and correct the massive misjudgments of the past. Reducing emissions could be achieved by seamless interaction of modes of transport (such as Automated Vehicles, cycling, walking and public means of mobility) where the use of cars is reduced as much as possible and more climate-friendly modes of transportation become prioritized. If we want people to take adequate decisions educating them is inevitable. In DR4 we suggest to provide training for people who are affected by automated traffic. However, we did not provide in-depth clarifications on how such instructions or training could be accomplished.

We believe, managing future mobility flows is one of the greatest challenges of our time. This includes all dimensions of mobility. The major challenge for the future of automated driving lies in societal nature and a wide acceptance of the technology. Future concepts should support a symbiosis of both ends of the scale ranging from freedom of mobility to the availability of eco-friendly transport modalities. These ends of the scale should not be perceived as trade-off but rather as a challenge which needs to be satisfied in future work by design, for the sake of reducing road accidents and the protection of our planet.

List of Abbreviations

Contributing Publications

[P1] Holländer, K., Colley, A., Mai, C., Häkkilä, J., Alt, F., and Pfleging, B. "Investigating the Influence of External Car Displays on Pedestrians' Crossing Behavior in Virtual Reality". In: Proceedings of the 21st International Conference on Human-Computer Interaction with Mobile Devices and Services. MobileHCI 2019. Taipei, Taiwan: ACM, 2019. DOI: 10.1145/3338286.3340138 (cit. on pp. 2, 6–8, 16, 17, 19–21).

[P2] Holländer, K., Wintersberger, P., and Butz, A. "Overtrust in External Cues of Automated Vehicles: An Experimental Investigation". In: Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications. AutomotiveUI '19. Utrecht, Netherlands: ACM, 2019. DOI: 10.1145/3342197.3344528 (cit. on pp. 3, 10, 16, 17, 19–21, 23).

[P3] Nguyen, T. T., Holländer, K., Hoggenmueller, M., Parker, C., and Tomitsch, M. "Designing for Projection-based Communication between Autonomous Vehicles and Pedestrians". In: Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications. AutomotiveUI '19. Utrecht, Netherlands: ACM, 2019. DOI: 10.1145/3342197.3344543 (cit. on pp. 10, 11, 16, 17, 19–21, 23).

[P4] Dey, D., Holländer, K., Berger, M., Eggen, B., Martens, M., Pfleging, B., and Terken, J. "Distance-Dependent EHMIs for the Interaction Between Automated Vehicles and Pedestrians". In: 12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications. AutomotiveUI '20. Virtual Event, DC, USA: Association for Computing Machinery, 2020, pp. 192–204. DOI: 10.1145/3409120.3410642 (cit. on pp. 2, 3, 12, 16, 17, 19–21, 23).

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Eidesstattliche Versicherung

(Gemäß Promotionsordnung vom 12.07.11, § 8, Abs. 2 Pkt. 5)

Hiermit erkläre ich an Eidesstatt, dass die Dissertation von mir selbstständig und ohne unerlaubte Beihilfe angefertigt wurde.

München, den 21.02.2022

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