Exploration of Smart Infrastructure for Drivers of Autonomous Vehicles

Design Space, Out-of-View Visualization and Explanations

Dissertation

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ABSTRACT

The connection between vehicles and infrastructure is an integral part of providing autonomous vehicles information about the environment. Autonomous vehicles need to be safe and users need to trust their driving decision. When smart infrastructure information is integrated into the vehicle, the driver needs to be informed in an understandable manner what the smart infrastructure detected. Nevertheless, interactions that benefit from smart infrastructure have not been the focus of research, leading to knowledge gaps in the integration of smart infrastructure information in the vehicle. For example, it is unclear, how the information from two complex systems can be presented, and if decisions are made, how these can be explained. Enriching the data of vehicles with information from the infrastructure opens unexplored opportunities. Smart infrastructure provides vehicles with information to predict traffic flow and traffic events. Additionally, it has information about traffic events in several kilometers distance and thus enables a look ahead on a traffic situation, which is not in the immediate view of drivers. We argue that this smart infrastructure information can be used to enhance the driving experience. To achieve this, we explore designing novel interactions, providing warnings and visualizations about information that is out of the view of the driver, and offering explanations for the cause of changed driving behavior of the vehicle.

This thesis focuses on exploring the possibilities of smart infrastructure information with a focus on the highway. The first part establishes a design space for 3D in-car augmented reality applications that profit from smart infrastructure information. Through the input of two focus groups and a literature review, use cases are investigated that can be introduced in the vehicle's interaction interface which, among others, rely on environment information. From those, a design space that can be used to design novel in-car applications is derived.

The second part explores out-of-view visualizations before and during take over requests to increase situation awareness. With three studies, different visualizations for out-of-view information are implemented in 2D, stereoscopic 3D, and augmented reality. Our results show that visualizations improve the situation awareness about critical events in larger distances during take over request situations.

In the third part, explanations are designed for situations in which the vehicle drives unexpectedly due to unknown reasons. Since smart infrastructure could provide connected vehicles with out-of-view or cloud information, the driving maneuver of the vehicle might remain unclear to the driver. Therefore, we explore the needs of drivers in those situations and derive design recommendations for an interface which displays the cause for the unexpected driving behavior.

This thesis answers questions about the integration of environment information in vehicles'. Three important aspects are explored, which are essential to consider when implementing use cases with smart infrastructure in mind. It enables to design novel interactions, provides insights on how out-of-view visualizations can improve the drivers' situation awareness and explores unexpected driving situations and the design of explanations for them.

Overall, we have shown how infrastructure and connected vehicle information can be introduced in vehicles' user interface and how new technology such as augmented reality glasses can be used to improve the driver's perception of the environment.

ZUSAMMENFASSUNG

Autonome Fahrzeuge werden immer mehr in den alltäglichen Verkehr integriert. Die Verbindung von Fahrzeugen mit der Infrastruktur ist ein wesentlicher Bestandteil der Bereitstellung von Umgebungsinformationen in autonome Fahrzeugen. Die Erweiterung der Fahrzeugdaten mit Informationen der Infrastruktur eröffnet ungeahnte Möglichkeiten. Intelligente Infrastruktur übermittelt verbundenen Fahrzeugen Informationen über den prädizierten Verkehrsfluss und Verkehrsereignisse. Zusätzlich können Verkehrsgeschehen in mehreren Kilometern Entfernung übermittelt werden, wodurch ein Vorausblick auf einen Bereich ermöglicht wird, der für den Fahrer nicht unmittelbar sichtbar ist. Mit dieser Dissertation wird gezeigt, dass Informationen der intelligenten Infrastruktur benutzt werden können, um das Fahrerlebnis zu verbessern. Dies kann erreicht werden, indem innovative Interaktionen gestaltet werden, Warnungen und Visualisierungen über Geschehnisse außerhalb des Sichtfelds des Fahrers vermittelt werden und indem Erklärungen über den Grund eines veränderten Fahrzeugverhaltens untersucht werden. Interaktionen, welche von intelligenter Infrastruktur profitieren, waren jedoch bisher nicht im Fokus der Forschung. Dies führt zu Wissenslücken bezüglich der Integration von intelligenter Infrastruktur in das Fahrzeug. Diese Dissertation exploriert die Möglichkeiten intelligenter Infrastruktur, mit einem Fokus auf die Autobahn.

Der erste Teil erstellt einen Design Space für Anwendungen von augmentierter Realität (AR) in 3D innerhalb des Autos, die unter anderem von Informationen intelligenter Infrastruktur profitieren. Durch das Ergebnis mehrerer Studien werden Anwendungsfälle in einem Katalog gesammelt, welche in die Interaktionsschnittstelle des Autos einfließen können. Diese Anwendungsfälle bauen unter anderem auf Umgebungsinformationen. Aufgrund dieser Anwendungen wird der Design Space entwickelt, mit Hilfe dessen neuartige Anwendungen für den Fahrzeuginnenraum entwickelt werden können.

Der zweite Teil exploriert Visualisierungen für Verkehrssituationen, die außerhalb des Sichtfelds des Fahrers sind. Es wird untersucht, ob durch diese Visualisierungen der Fahrer besser auf ein potentielles Übernahmeszenario vorbereitet wird. Durch mehrere Studien wurden verschiedene Visualisierungen in 2D, stereoskopisches 3D und augmentierter Realität implementiert, die Szenen außerhalb des Sichtfelds des Fahrers darstellen. Diese Visualisierungen verbessern das Situationsbewusstsein über kritische Szenarien in einiger Entfernung während eines Übernahmeszenarios.

Im dritten Teil werden Erklärungen für Situationen gestaltet, in welchen das Fahrzeug ein unerwartetes Fahrmanöver ausführt. Der Grund des Fahrmanövers ist dem Fahrer dabei unbekannt. Mit intelligenter Infrastruktur verbundene Fahrzeuge erhalten Informationen, die außerhalb des Sichtfelds des Fahrers liegen oder von der Cloud bereit gestellt werden. Dadurch könnte der Grund für das unerwartete Fahrverhalten unklar für den Fahrer sein. Daher werden die Bedürfnisse des Fahrers in diesen Situationen erforscht und Empfehlungen für die Gestaltung einer Schnittstelle, die Erklärungen für das unerwartete Fahrverhalten zur Verfügung stellt, abgeleitet.

Zusammenfassend wird gezeigt wie Daten der Infrastruktur und Informationen von verbundenen Fahrzeugen in die Nutzerschnittstelle des Fahrzeugs implementiert werden können. Zudem wird aufgezeigt, wie innovative Technologien wie AR Brillen, die Wahrnehmung der Umgebung des Fahrers verbessern können. Durch diese Dissertation werden Fragen über Anwendungsfälle für die Integration von Umgebungsinformationen in Fahrzeugen beantwortet. Drei wichtige Themengebiete wurden untersucht, welche bei der Betrachtung von Anwendungsfällen der intelligenten Infrastruktur essentiell sind. Durch diese Arbeit wird die Gestaltung innovativer Interaktionen ermöglicht, Einblicke

in Visualisierungen von Informationen außerhalb des Sichtfelds des Fahrers gegeben und es wird untersucht, wie Erklärungen für unerwartete Fahrsituationen gestaltet werden können.

COLLABORATION STATEMENT

This thesis presents the results of the research I carried out between August 2017 to June 2020. While Chapter 2 and Chapter 7 present original content which was exclusively written for this thesis, parts of Chapter 1, Chapter 3, Chapter 4, Chapter 5 and Chapter 6 are based on collaborations with co-authors, students and supervisors. In the course of this thesis, colleagues, students and supervisors contributed to this work. Throughout the thesis I use the scientific "We" to acknowledge this great support. I worked in close collaboration with my supervisor Heinrich Hußmann, who provided feedback on study designs, research ideas and manuscripts. The students I supervised contributed with their Bachelor, Master Thesis and semester projects to this thesis. In my role as main supervisor, I determined the research topics, ideas and goals. Regarding the steps of the student work (e.g prototypes, concepts, study designs, evaluations, implementations or conducting the study) I made the final decision. Table 1 presents the respective contributions of others, to paper and projects.

My contribution	**Collaboration**
Chapter 1: Introduction	
Section 1.1: Leading author of paper [297]	Feedback for the paper [297] (Yuanting Liu)
Chapter 3: Stakeholder	
Conducting and evaluating interviews for Section 3.2 and 3.1.1 Conducting and evaluating focus group Section 3.1.2 Conducting and evaluating focus group Section 3.1.2 Evaluating focus group Section 3.3	Conducting focus group Section 3.3 (Markus Bonk)
Chapter 4: Design Space	
Research idea, Literature review, Conducting and evaluating both focus groups, Leading author of resulting paper [298]	Research idea (Christian Mai) Literature review (Christian Mai, Kai Holländer), Evaluating focus group results (Christian Mai), Writing the paper (Christian Mai, Kai Holländer) [298], Feedback for the paper (Heinrich Hußmann) [298]
Chapter 5: Out-of-View Visualization of Highly Automated Vehicles in Augmented Reality	
Section 5.1: Original research idea, study design, statistical analysis	Implementation of the study, conducting the study, statistical analysis (Antoine Poppe, Dominik Hiemer, Ahmed Zitoun)
Section 5.2: Original research idea, Supervision of the study design and implementation, Leading author of the resulting paper [299]	Implementation and conducting the study (Hua Wentao), Writing the paper (Christian Mai) Feedback for the paper [299] (Yuanting Liu, Heinrich Hußmann)
Section 5.3: Original research idea, Supervision of the study design and implementation, Statistical analysis	Implementation and conducting the study (Beatrice Sax), Feedback for the research (Heinrich Hußmann)
Chapter 6: Identifying the Needs of Drivers in Unexpected Driving Situations	
Section 6.1: Original research idea, Study design and feedback for implementation, Conducting the study, Statistical analysis, Leading author of the resulting paper [300]	Study design, Implementation and conducting the user study, statistical analysis, writing the paper [300] (Matthias Schmidmaier, Thomas Weber) Feedback for the paper [300] (Yuanting Liu, Heinrich Hußmann)
Section 6.2: Original research idea, Supervision of study design, Implementation and conducting the study, Web search, Data Analysis, Leading author of the resulting paper [296]	Implementation and conducting the study (Maximilian Haubelt), Coding of qualitative data (Maximilian Haubelt), Writing the paper [296] (Malin Eiband) Feedback for the paper [296] (Heinrich Hußmann)

Table 1: Collaboration in this thesis.

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I want to thank fortiss in general, for giving me the opportunity to pursue my degree and especially **Mr. Vallon** for supporting me. During the project Providentia, I worked with different colleagues on developing use cases and putting up highway infrastructure. Therefore, I would like to thank **Markus Bonk** for always keeping the spirit and cheering us on, **Juri Kuhn** for introducing me to the Bavarian culture, **Annkathrin Krämer** for being the most knowledgeable data fusion expert, **Christoph Schöller** for all the insights in his research, **Gereon Hinz** for his visions, **Philipp Quentin** and **Maximilian Schnettler** for knowing each and every screw of the infrastructure, **Martin Büchel** for the sport talks and **Venkat Lakshmi** for being a person one can always turn to with problems. Thank you for managing all the up and downs together during the project. Furthermore, I would like to thank **Zhiwei Han** for having a great working spirit, **Andreas Bayha** and **Johannes Eder** for the great talks on the corridor, **Frederik Diehl** for bringing in a calm and relaxed spirit to the office and **Thomas Brunner** for sharing the office twice with me. Additionally, I would like to thank **Matthias Schmidmaier**, for introducing me to slow coffee brewing and **Thomas Weber** for my great PhD hat.

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TABLE OF CONTENTS

1

Introduction

Smart infrastructure can be the enabler for limitless autonomous driving. Road technology is getting smarter every day, by integrating infrastructure that can transmit information to vehicles. These infrastructure-to-vehicle (I2V) connections provide the connected parties with data and information that adds to the vehicle's own data and information. Autonomous vehicles can use this information to predict their driving paths, extend their data range or use the infrastructure data as redundant sensor set. In the context of cities, it is called smart cities that set up a digitally connected sensor network. Smart infrastructure is called for, to improve traffic safety, time spend in traffic and to reduce the environmental effects of traffic. In 2019, 3059 road users were killed in Germany[1] and 67.967 road users were gravely injured in accidents in Germany[2]. Traffic accidents result from several causes, such as drunk driving (2,4% of accidents with injured persons in 2018), turning off mistakes, mistake in starting off or entering the road from premises et cetera (10,6% of accidents with injured persons in 2018) or overtaking mistakes (2,5% of accidents with injured persons in 2018) [3]. If the traffic participants had an awareness of the environment, for example with smart infrastructure, accidents could have been prevented.

Smart infrastructure offers the potential to improve the information of drivers, improve safety, increase the comfort of drivers, efficient and anticipatory driving and reduced pollution[4] [120, 121, 152, 216]. McKinsey published a report on smart cities [306], investigating the effect of smart cities on not just mobility advantages, but on every aspect of living, for example, cost of living, safety of jobs. Mobility benefits, among others, from digital infrastructure by predictive maintenance of transportation infrastructure, real-time road navigation or congestion pricing. Smart city applications can improve the so-called quality-of-life indicators, such as health, environmental quality, safety or time and convenience, by 10 to 30%. Considering safety it would mean a decrease of 8 to 10% fatalities and of 20 to 35% shorter emergency response time. Greenhouse gas emission would be lower and air quality higher. Due to these advantages there are numerous smart city and smart infrastructure projects that focus on the adaptation of this new technology [54, 216].

This thesis investigates how smart infrastructure can be used to make the driver aware of the vehicle's environment and intention. This awareness enables user interfaces for intervention that effectively prevents user damage. Concretely, with additional data, drivers can be provided with information preparing them for take over requests (TORs) or warn them about traffic situations several kilometers away. If the vehicle reacts on information from smart infrastructure, drivers also need to be informed in an efficient and understandable manner.

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[1] `https://www.destatis.de/EN/Press/2020/02/PE20_061_46241.html`, last accessed May 2020

[2] `https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Verkehrsunfaelle/Publikationen/Downloads-Verkehrsunfaelle/verkehrsunfaelle-jahr-2080700187004.pdf?__blob=publicationFile`, last accessed May 2020

[3] `https://www.destatis.de/EN/Themes/Society-Environment/Traffic-Accidents/Tables/driver-mistakes.html`, last accessed May 2020

[4] `https://www.kassel.de/buerger/verkehr_und_mobilitaet/verkehrsprojekte/veronika.php`, last access April 2020

1.1 Problem Statement and Research Questions

With the potential of smart infrastructure many novel research problems are created that need to be addressed for a successful integration of smart infrastructure in current traffic systems. While some use cases and user groups are mentioned in smart infrastructure projects, a structured approach of identifying them is scarcely researched. Those need to be identified to derive solutions to integrate smart infrastructure information in existing interfaces, resulting in a true benefit for the user groups.

While some design spaces for the automotive domain exist [108, 144] in autonomous vehicles, new design requirements emerge through a changed use of the vehicle. Instead of driving manually and being turned towards the steering wheel, it is likely that drivers are immersed in secondary tasks and interact with the vehicle in new ways. Nevertheless, there is no structured way of designing new applications for future connected vehicles.

Considering the driver interface, there are knowledge gaps of how drivers should be informed about smart infrastructure information. While visualization concepts exist that provide drivers with information out of the view of the driver [101], the concrete problem of how to convey information that is farther away and comes from other sources than the own vehicle is not explored in depth. To improve the safety of drivers, it is crucial to gain in-depth information how smart infrastructure information can be transmitted to the driver to improve situation awareness and driving performance.

Autonomous vehicles connected to smart infrastructure, combine two highly complex algorithms, with each one providing possibly conflicting information to the driver of the vehicle. They derive their driving decision or traffic information from algorithms that remain non-transparent to drivers, if no information is provided to them. This applies all the more to smart infrastructure information which is part of the vehicle's driving decision.

With this thesis in-depth knowledge about the solution to this problem space is provided by answering following research questions (see Table 1.1):

Research Question	**No.**	**Chapter**
I Identifying Use Cases and Stakeholders		
What are potential user groups and use cases of smart highway infrastructure?	(RQ1)	Chapter 3
II Design Guidelines for Novel Interfaces		
What are design dimensions for 3D in-car AR applications when 5G and smart infrastructure enable communication, entertainment or more information about the environment?	(RQ2)	Chapter 4
III Visualization of Information Outside the Driver's View		
How can we display information about events outside driver's field of view?	(RQ3)	Chapter 5

IV Explaining Unexpected Vehicle Behavior		
What do drivers of autonomous vehicles in unexpected driving situations need and how do they want to interact with the vehicle in that moment?	(RQ4)	Chapter 6
How can vehicle behavior be explained if an autonomous vehicle reacts unexpectedly on smart infrastructure information?	(RQ5)	Chapter 6

Table 1.1: Summary of the research questions addressed in this thesis.

1.2 Research Approach

We approach the topic of designing for highly automated vehicles in smart infrastructure by starting with the definition of a problem space. In this thesis, each research question assumes that the vehicle uses vehicle-to-vehicle, infrastructure-to-vehicle or cloud information. Therefore, highly automated vehicles are considered that receive information from the outside which may be out of the driver's view or lead to an earlier information or warning of critical traffic situations. We investigated drivers of highly automated vehicles (SAE Level 3-5 [130]), even though manual driven vehicles could also benefit from smart infrastructure. With those level, drivers are either required to supervise the driving task and take over control of the vehicle in case of the vehicle reaching its system limitations or, in the other case, drivers drive fully autonomously and can immerse themselves in a secondary task. In initial brain storming sessions and focus groups (see Chapter 3), we identify use cases and users of smart infrastructure (RQ1). Next we focus on passengers of highly automated vehicles that are connected with smart infrastructure. From a use case set of applications of in-car 3D AR, we derive a design space for in-car 3D AR applications (RQ2). Afterward, we focus on drivers that still need to interact with the vehicle, but get infrastructure information to be prepared for an intervention in the driving task. We conducted four driving simulator studies to evaluate how smart infrastructure can increase situation awareness and driving performance (RQ3). Next we put a focus on the human needs in unexpected driving situations. If the vehicle acts on information from the infrastructure, do drivers accept it? Do they need an explanation? What are other needs that might arise from this? We did three studies to identify the drivers' needs in unexpected driving situations and to identify the explanation that one should aim for when giving context information and explanations in those situations. In this thesis, we used different research methods [163] to explore the problem space:

Informal Case Study An informal case study can be used when there is a lack of understanding of the application domain or if initial responses are aimed for. With observational techniques and interviews, we conducted an informal case study in Chapter 3 to first collect initial statements of potential stakeholder of smart infrastructure. In Chapter 5 we collected insights in visualization of critical traffic scenarios.

Ethnography Lazar et al. [163] describe ethnography in HCI as a combination of observation, interviews and participation to explore understanding for work cultures, in which the researcher does not have any expertise. In the work with firefighters and highway operators, we used this technique to get an understanding of their work. In Chapter 3, we visited a firefighter station and a highway operation center to observe the workplace and understand how these user groups conduct their everyday work. While we did not participate, we observed the workplace.

Interview In Chapter 3 we explored the problem space and potentials of smart infrastructure through interviews. From this we derived deep insights of experts in their field. Those are limited to single opinions or views, but we gained insights to an unknown field.

Focus Groups Focus groups can provide information from several persons at once and through brainstorming and discussion, aspects that were unknown could be discovered. Therefore, throughout the thesis (Chapters 3, 4, 5, 6), we did several focus groups.

Quantitative Study Within this thesis we conducted several quantitative studies (Chapters 5 and 6) to compare different condition.

Qualitative Study Qualitative Studies are good to gain in depth knowledge about the thoughts of the participants. We collected several statements during studies. In Section 6.1, we did a qualitative study through think-aloud statements of the participants. We develop a well-grounded theory from the qualitative data [163].

1.3 Main Contributions

We contribute with this thesis valuable results for the use of smart infrastructure for drivers of autonomous and manually driven vehicles. First, in an informal case study we identify potential use cases and user groups. Next, we develop a design space for in-car 3D augmented reality applications. With this design space researchers and practitioners can design visualizations that increase situation awareness in take over situations. Finally, we identify categories for a codebook that are important for drivers in unexpected driving situations. The research contributions can be classified by Wobbrock et al. [305], who introduced seven types of contributions, among others artifact contributions, methodological contributions or theoretical contributions. We follow with their description of the corresponding contribution.

Theoretical Contribution: Design Space for In-Car 3D Augmented Reality Applications The potential of connecting a vehicle to infrastructure and driving autonomously calls for novel vehicle interfaces. To facilitate the process of designing future applications, we derive a design space for in-car 3D augmented reality applications. In a structured approach, we set up a set of use cases of novel applications in 3D AR. From this we conclude a design space for which we present an example design process of an in-car 3D AR application.

Empirical and Artifact Contribution: Out-of-View Visualizations Since smart infrastructure will provide information that is not necessarily in sight of the driver, we explore, how those visualizations can be presented in the vehicle cockpit. We analyze how out-of-view visualizations can be used to convey context and hints on other vehicles and critical situations to prepare the driver for a take over request. For this purpose we implement different, some novel, visualizations, ranging from high detail level with a whole overview of the traffic situation to low detail level, with hints on other traffic participants. With those implemented visualizations, we improve the situations awareness of an upcoming take over request and the driving performance of drivers.

Methodological and Empirical Contribution: Explanation Design Guidelines for Drivers in Unexpected Driving Situations Smart infrastructure information causes the problem of providing information without the user exactly knowing the source and resulting outcomes of the system. In a qualitative study, we derive explanation design guidelines for drivers in unexpected driving situations. We approach this by first deriving unexpected driving situations that are based on naturalistic situations to get a high ecological validity [8]. While this approach is novel, it results in many scenarios that can be used as a basis to collect statements of drivers in these situations. From these statements, the needs of drivers in unexpected driving situations were analyzed in a codebook. This codebook then is used to identify design guidelines. In a next step an explanation is provided to the driver. From this, we derive an adaptable explanation that increases situations awareness of the driving situation and a target mental model which should be considered when designing explanations for drivers in unexpected driving situations.

1.4 Thesis Setting

This section is partly based on the following publication:

- Gesa Wiegand and Yuanting Liu. 2018. Highway Sensor System as Enabler for Autonomous Driving. In:vol. CHI 2018 Workshop - Interacting with Autonomous Vehicles: Learning from other Domains (2018).

Please refer to the beginning of this thesis for a detailed statement of collaboration.

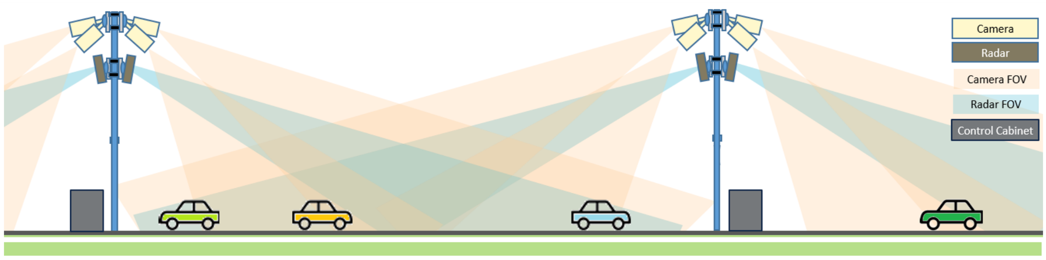

Figure 1.1: Sensor setup on the highway.

This thesis is written as part of the smart infrastructure project Proactive Video-Based Use of Telecommunication Technologies in Innovative Highway Scenarios (Providentia) [120]. The project duration was three years, lasted from December 2016 until December 2019 and it was funded by the Federal Ministry of Transportation and Digital Infrastructure (BMVI, Budget: 7.67 Million Euro). In the course of the project, a sensor system was built on poles and sign gantries along the A9 highway in Munich, Germany. With this sensor system, traffic on a stretch of the highway is tracked. The main vision of this project, was to provide a far-reaching view of the highway to the users, track and predict traffic flow and connect vehicles with the infrastructure.

1.4.1 Technical Description

Providentia's sensor system consists of several measurement points. One measurement point on a pole consists of four radars and four cameras to cover far and near range tracking in both directions (see Figure 1.1 and Figure 1.2). Data from the individual sensors is transmitted to data fusion units at the gantry. There, the signals are fused and the result from this data fusion is send to the system's backend. The results from all gantries that are included in the system, are then fused, resulting in an estimation of the vehicles' velocities, positions, vehicle type, height and length. With camera and radar data, it is possible to detect turn signals, obstacles, construction sites, as well as occurring traffic scenarios. With the information from the data fusion, a prediction can be determined of future driving trajectories, traffic flow and upcoming traffic scenarios. All this information can be included in a digital twin of the highway, representing digitally the physical infrastructure. Within the project, two digital twins are created. One is a digital twin that contains the calculated results from the data fusion and prediction that can then be transmitted to vehicles to extend their perception of highway objects. The other digital twin visualizes the simulated traffic on the highway which can be observed by human users.

1.4.2 Use Cases and Scenarios

The traffic behavior predicted by Providentia can be transmitted to different user groups, for example, drivers of highly automated vehicles, the operators of the highway and teleoperators. Autonomous vehicles can use the infrastructure information to improve the driving performance. Drivers can inform themselves of the route by retrieving information from the infrastructure sensors. Thus, the infrastructure data can extend the user's knowledge of the highway situation. This combination of vehicles and smart infrastructure ensures a far-reaching view which informs traffic participants early on about critical situations or situations that are very likely to happen. The scenarios that can be detected by smart infrastructure are manifold, among others emergency braking or accidents. Also, vehicles with high speed or vehicles that are obscured can be detected.

In the following, two examples for warnings that are enabled by smart infrastructure, are given. First, if there is an abruptly braking vehicle further ahead, it can result in an accident or braking cascade. In case of a braking vehicle three vehicles ahead of the driver, the scenario would just be detectable by connected vehicles or infrastructure sensors. Then the sensors need to transmit this information to shorten the reaction time, and thus shorten the braking time of the driver or, in case of an autonomous driving vehicle, braking time of the vehicle. In this scenario, the smart infrastructure can prevent accidents and braking cascades by informing all vehicles and drivers about the events. The resulting effect is that traffic jams can be predicted and the driver can react to this information by changing the route.

In the second example, the driver can be warned by the smart infrastructure of an accident that is not yet well visible in case of bad weather on the highway, These are just some examples and use cases for drivers that are imaginable with smart infrastructure, others are explored in Chapter 3.

Vehicles that are connected to smart infrastructure, can react on traffic events earlier, adapt an eco-friendly driving style, improve the navigation or connect with other vehicles which all leads to safer

Figure 1.2: Picture of radars on the highway tracking the traffic. (Credit to Maximilian Schnettler and Philipp Quentin)

and more efficient driving[5]. By transmitting information from the infrastructure to the connected vehicle, the sensor data of this vehicle can be enriched with environment information from the infrastructure. The connected vehicle itself can then also send information of its own surroundings to the connected infrastructure which further adds to the data that the infrastructure collects on its own. The data that is provided by Providentia can not be captured by vehicle sensors alone. For example, autonomous trucks that are connected to other trucks via sensors can drive in a platoon on the highway. Infrastructure sensors provide a way to add sensor information to, and control the platoons, such as the distances between the trucks. With optimized traffic flow information, these platoons can get information about the route ahead to improve their route planning. Current projects that research vehicle platooning have the goal to maintain a constant distance between vehicles or perform evasive maneuvers such as emergency braking [19]. Through connected driving, traffic flow can be predicted and controlled to ensure smooth driving. Furthermore, to make driving more comfortable, data can also be collected to model realistic human driving behavior in traffic. This model can then be used to test automated vehicles and verify the autonomous driving algorithms and also make driving more comfortable. To sum up, smart infrastructure has much potential which has not yet been explored thoroughly.

1.5 Thesis Structure

After we introduced this thesis in Chapter 1, we present the overall structure of this thesis. This thesis is organized in seven chapters.

Chapter 2: Related Work: Designing for Autonomous Vehicles in Smart Infrastructures We give an overview of the related work and the resulting implications on this thesis. This chapter is

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[5] `https://www.kassel.de/buerger/verkehr_und_mobilitaet/verkehrsprojekte/veronika.php`, last accessed May 2020

divided in six sections. Section 2.1 presents the most important insights in aspects of autonomous driving. Section 2.2 provides insights into smart infrastructure. Visualizations that are presented in related work with a focus on out-of-view visualizations is presented in Section 2.3. Since augmented reality is important for further studies in this thesis, we present related work in Section 2.4. The related work for design spaces is presented in Section 2.5. In Section 2.6, we summarize related work for explanations of artificial intelligence. Finally in Section 2.7 we discuss the gained insights. The thesis is divided in four main chapters:

Chapter 3: Stakeholder and Use Case Evaluation of Smart Infrastructure We conducted interviews and focus groups with infrastructure and autonomous driving experts. From the derived insights user groups and use cases are identified, which refine the users and use cases for this thesis. In Section 3.1 the conducted focus group and interviews are described that lead to use cases for drivers of connected vehicles. Section 3.2 focuses on emergency services and the conducted interview to derive use cases. In Section 3.3, we present a focus group with operators. At last, in Section 3.4 we summarize the lessons learned from the previous sections.

Chapter 4: Design Space for In-Car 3D Augmented Reality Applications In the next chapter, use cases were gathered for using, among others, infrastructure information for in-car augmented reality applications in 3D. With two focus groups we derive use cases that result in a use case set. This use case set resulted in a design space to enable designing for novel in-car applications.

Chapter 5: Out-of-View Visualization of Highly Automated Vehicles in Augmented Reality Third, we consider visualizing information that is outside of the view of the driver and the different methods to present them. Visualizations in 2D, 3D, stereoscopic 3D and AR were implemented and tested in user studies. Those visualizations showed warnings for upcoming critical situations and prepared drivers for a take over request (TOR). With those visualizations the situation awareness was improved and the efficiency of the visualizations was evaluated. In Section 5.1 we explore how visualizations can be presented to drivers. Section 5.2 introduces a novel visualization of the highway and how this can improve the situation awareness of drivers. Visualizations that give hints on objects outside the view of the driver are presented in Section 5.3 . The results are summarized in Section 5.4.

Chapter 6: Identifying the Needs of Drivers in Unexpected Driving Situations At last, we studied unexpected driving behavior and how explanations help the driver to understand the cause of it. Through three studies, we develop an understanding of how unexpected driving behavior of vehicles that might receive smart infrastructure information affects drivers and what kind of explanation should be provided to them to enhance their situation awareness. The chapter is divided into two sections, the first, Section 6.1, explores the needs of drivers in unexpected driving situations, and Section 6.2, presents a way to explain unexpected situations to drivers. These sections lead to guidelines which are further elaborated in Section 6.3.

Chapter 7: Conclusion Finally we summarize the results of this thesis and give an outlook on the future research direction in the conclusion.

2

Related Work
Designing for Autonomous Vehicles in Smart Infrastructures

Research about autonomous vehicles is broad and touches many topics: hardware, software, sensors, infrastructure, communication or also the interaction between vehicle and driver. In this thesis we focus on the latter aspect of the interaction, between vehicles and drivers and the additional connection to the infrastructure. In previous work, these aspects were covered in different extents. In the following insight about the research context of this thesis is given, discussing autonomous vehicles, the interaction and relevant measurement factors. Then smart infrastructure and connected vehicles and the interaction with traffic participants is covered. Finally, insights about explaining decisions and reasons of intelligent systems to the user are given.

2.1 Autonomous Driving

To gain knowledge what autonomous vehicles are and how they process information, we first give an introduction to test fields, the level of automation and the main hardware and software components that are required to come to a driving decision. Over the last years, the vision of having a fully autonomous vehicle for the daily commute, started to become reality. There are several pilot cities and states in which autonomous driving is tested, such as Pittsburgh[1] or Munich [2]. Nevertheless, some claim that fully autonomous vehicles will not be reached for end users [191].

The strategy of the OEMs (Original Equipment Manufacturer) differ in the steps to reach fully autonomous vehicle. Some, such as Waymo[3] or Lyft[4] started with a fleet of autonomous vehicles that are just observed by an operator. Others, such as BMW[5] or Tesla[6] implement autonomous functions stepwise. First, they implement driver assistance functions. Over time they enhance and extend these functions until fully autonomous driving function is reached. Nevertheless, a study by Banks et al. [16] showed some problems with the semi-autonomous level of a Tesla, among others overtrust or mode error. The vehicles' driving abilities are standardized by the Society of Automotive Engineers (SAE) Level [130]:

- Level 0: No Automation, the driver drives completely manually

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[1] `https://pittsburghpa.gov/domi/autonomous-vehicles`, last access May 2020

[2] `https://www.bmvi.de/SharedDocs/EN/Documents/DG/projects-on-digital-test-bed-selection.pdf?__blob=publicationFile`, last access May 2020

[3] `https://waymo.com/`, last access May 2020

[4] `https://self-driving.lyft.com/`, last access May 2020

[5] `https://www.bmw.com/en/stories/automotive-life/autonomous-driving.amp.html`, last access May 2020

[6] `https://www.tesla.com/support/autopilot`, last access May 2020

- Level 1: Driver Assistance, a driver assistance system supports the driver either when steering or accelerating/decelerating
- Level 2: Partial Automation, the system performs the steering and acceleration/deceleration, but the driver monitors everything
- Level 3: Conditional Automation, the vehicle performs in some driving modes all driving tasks, but the driver is still the fallback in a request to intervene
- Level 4: High Automation, in some driving modes, the vehicle is completely in control of the driving task
- Level 5: Full Automation, the vehicle is in full control of the vehicle's dynamic driving behavior in any condition

These levels classify the abilities of the autonomous vehicle. In this thesis, primarily levels 3-5 are considered, in which the driver either still needs to take over control of the vehicle or is driving fully autonomously. Since smart infrastructure aims to connect highly automated vehicles, the use cases of smart infrastructure are primarily covered with level 3-5 autonomous driving.

Today's highly automated vehicles rely on several sensors to observe the environment [82]. Autonomous vehicles use radar, lidar, GPS, camera and ultrasonic sensors to sense the outside world [82]. The overall characteristics of those sensors are accuracy, resolution, sensitivity, dynamic range, perspective, active sensor/passive sensor, timescale and output interface. With the accuracy of a sensor, the error between the true value and the sensor's reported measurement is described. The resolution is the minimum variance between two measurements. The timescale is the refresh rate of the sensor and the frequency of the measurement bandwidth time [277]. While cameras passively capture the reflected light of the environment, depending on the environmental conditions, lidar illuminates a target with pulsed laser light [82]. In this manner, a wide range of materials or structures can be detected with a high resolution, among others non-metallic objects, ice or road structures such as intersections [52, 315]. With radar, the range and velocity information of objects can be derived during daytime or nighttime and it can even collect data in humid conditions such as clouds [52]. The position of a vehicle can also be gathered with a GPS signal. Wing et al. [302] state that GPS performance varies according to the environment. Amani et al mention that the received position of neighboring vehicles or Road Side Units (RSU) improve the accuracy of the position of a target vehicle [5].

Even though road traffic is governed by rules, it is a chaotic system that includes many situations in which unambiguous rules can not be determined. In those situations the communication between drivers and other road users follows informal rules to guide the traffic [194]. Autonomous vehicles need to learn not just formal traffic rules, but also behavior conventions on the road. The vehicle gains situation awareness (SA) through the processing of gathered information. Reasoning on machine level can be done, for example by ontologies, which evaluate the context of a situation [11]. Golestan et al. [94] provide a taxonomy for situation awareness in connected vehicles. According to them, the main methods to get situation awareness and predict upcoming traffic scenarios are time, machine learning (ML), game theory (GT) and Probabilistic Graphical Models (PGMs). In connected vehicles, the individual situation awareness can be combined to a shared awareness of all entities involved. The last component included in their taxonomy is the interaction with human operators, to refine and evaluate the whole system [94]. From the presented related work, we narrowed down the automation level of this thesis. Furthermore, we gained the knowledge that autonomous vehicles process sensor information that can have different reliance, depending on the weather condition or daytime. The reasoning that determines the driving decision is based on complex algorithms. With the presented research in autonomous vehicles, we can build assumptions of the knowledge of autonomous vehicles of their surrounding, which will be relevant in the coming chapters that deal with the information interface of autonomous vehicles.

2.1.1 Situation Awareness of Drivers

The following section focuses on situation awareness while driving, to give an overview of the measurement methods and related work in the field. Situation awareness is in the following chapters an evaluation method of implemented visualizations. First, we define situation awareness and introduce the three levels of situation awareness by Endsley et al. [75] and the three levels of cognitive processing by Gugerty et al. [102]. Then we discuss how situation awareness can be measured and related work that assess the correlation between situation awareness and workload, trust and behavior measures.

Driving requires fast comprehension of the driving situation, traffic and environment. Situation awareness generally describes a person's ability to correctly asses a situation as a whole [226]. Maintaining situation awareness while driving requires perceptual and cognitive processes, such as event comprehension or task management [102]. Poor situation awareness often leads to poor driving performance [103, 272]. With a call for designing for situation awareness, Walker et al. [284] rise awareness of the importance of good vehicle design to reduce performance decrements due to lack of situation awareness. Previous work defined three levels that describe a person's situation awareness in a certain situation [75, 102]. The three levels of situation awareness are described by Endsley [75] as the perception of elements in a dynamic environment (Level 1), the comprehension of these perceived elements (Level 2) and the ability to anticipate the status of these elements in the near future (Level 3) [75]. While Endsley considers situation awareness rather as a conscious act, Gugerty et al. [102] argues that situation awareness is developed consciously and unconsciously. The author defines three levels of cognitive processing as "1) automatic, pre-attentive processes that occur unconsciously and place almost no demands on cognitive resources; 2) recognition-primed decision processes that may be conscious for brief periods (<1 s) and place few demands on cognitive resources; and 3) conscious, controlled processes that place heavy demands on cognitive resources" [102]. While driving is in some aspects performed unconsciously, in certain situations a conscious decision must be made. During a lane change, for example, for a short moment, conscious awareness is required. If the workload of the task increases, the driving decision is rather on a conscious process level [102].

With the levels described by Endsley [75], it is possible to assess the situation awareness of participants in a structured, comparable manner. By assessing if just the immediate environment is noticed or if a participant can also draw conclusions from the current traffic maneuver, the participant's improvement of perception can be measured. Many researchers use situation awareness to rate a take over request (e.g. [47, 86, 243]). In a hazardous situation it appears that drivers consciously assess the situation [127]. Horswill et al. [127] discuss that drivers that perceive hazards well, use a dynamic mental model to search for hazards actively. On an active level, a mental model, which is formed of the driving environment, is used to predict the upcoming traffic situation.

Situation awareness is difficult to measure [102], but there are many measurement methods [284]. The Situation Awareness Global Assessment Technique (SAGAT) [72], which is used in studies to evaluate situation awareness, blacks out the scenario at arbitrary times. Then the participants are asked questions, aiming for the three level of situation awareness, in which the accuracy of the answer is used to determine the driver's situation awareness level. Another method is using eye tracking, to have an indication of the region and object, a participant looked at during a study. Sirkin et al. [257] present the method "Daze" that measures situation awareness while driving, without halting a situation, in-situ and in real-time conditions. Without halting a situation and during the study, situation awareness in a driving context can be evaluated without being affected of the evaluation thereof. With respect to smart infrastructure, connected vehicles or highly automated vehicles, situation awareness requires a look-ahead on situations that are not necessarily in close proximity of the driver's vehicle.

While driving as a passenger, situation awareness is lower compared to being the driver, when one has more active control over the driving task. Also, when the workload of the driver increases, the percentage of recalled vehicles in a traffic situation decreases [103], which indicates a lower situation awareness. Gugerty [103] argues that it could be a result from the driver focusing the cognitive load on a subset of vehicles. From this subset of vehicles, most were nearby, in sight of the driver, not in the blind spot and apparently hazardous, which motivates a higher attention on the vehicles [103].

The driver can be enabled to acquire high situation awareness, by presenting information about the situation and an instruction to react on the predicted traffic situation. This increases trust in automation [222]. Petersen et al. [222] argue that the different level of SA need to be included in driver assistance systems. For low SA levels, drivers are provided with status updates, whereas higher SA level provide projections about future events. Interestingly, the difference of providing low SA information ("Stopped vehicle ahead") compared to high SA information, in which the low SA information is combined with instructional information (e.g."Take control now"), is insignificant on the trust assessment, but resulted in clear differences regarding behavioral measures. It can be argued that drivers think that their own judgment was sufficient [222]. From related work we gathered knowledge in how situation awareness is defined and that it can be measured by three SA levels. While some researchers measure situation awareness with eye tracking, in this thesis we assess SA with the three level of SA.

2.1.2 Take Over Request (TOR)

Since we narrowed down the automation level of this thesis to SAE level 3-5, take over requests are relevant for the transition of control. The control is shifted from manual driving, in which the driver is in control of the driving task to autonomous driving, in which the vehicle is fully in control. To gain knowledge how the control transition can be realized, we first give an introduction to TOR to understand what it is, then we give an overview of the times in TORs and then the effect of a TOR on the workload of drivers. Further, we discuss modalities that are used for TORs, and how context can be communicated during TORs. SAE level 3 and 4 of autonomous driving [130] require the driver to take over the driving task in case of system failures or system limitations. Take over requests have therefore been heavily researched in recent years. Flemisch et al. [84] described the cooperation of an automated system with a human as a system that can "lead to dynamic changes, e.g., of qualities like authority, ability, responsibility and control between the actors". TORs also exist in other domains, for example in aviation when the pilot needs to take over control of the plane from the autonomous system. Funk et al. [90] identified problems relating automation issues for pilots. They reported that in case of monitoring automation for a long period of time, the pilots' perception and cognition is insufficient and errors resulting from this are likely. Wan et al. [285] studied the effects of the lead time prior to a TOR. They found the highest take over performance with a lead time of 10-60s that among others lowers the crash rate and time-to-collision (TTC). Nevertheless, with 15-60s lead time the driver's acceptance was higher. Other researchers provide a time of 7 - 10s that a driver needs to take over the vehicle and that the safety increases with more time [93, 197, 203]. Nevertheless, Kim et al. [147] state that in their experiments the reaction times of participants experiencing different take over events were significantly different. Therefore, there is no single TOR time that is adequate for all TOR events and human factors should be considered [147].

In case of high cognitive and visual loads, results indicate that TOR behavior is affected by it. A visual distraction in automated driving could affect the response time for a TOR. Choi et al. [47] experienced a decreased response time, but an increased steering angle variance after a lane crossing. They argue that a low situation awareness concerning the surroundings of the vehicle may have lead to the poor task performance in keeping the vehicle steady. A high cognitive load, tested by a N-back task affected the driving performance similarly, but in a different time course [47].

The effectiveness of non-visual warnings combined with visual warnings for TOR was stressed by Blanco et al. [22]. A combination of a visual alert and a haptic seat alert resulted in the fastest take over reaction. In case that drivers did not immediately need to take over control of the vehicle, their experiments showed that the drivers would delay the TOR until they needed to take over full control of the vehicle [22].

Since this thesis concentrates on TOR when infrastructure information is available, the TOR can benefit from the extra time and information that is provided by the look ahead on a possible dangerous situation. The extra time is gained by informing drivers earlier of a critical situation. When more time is given to the participant, situation awareness could be increased in reference to the upcoming traffic situation. Epple et al. [78] investigated a two step approach in which the driver was primed of a TOR before being alerted. Mostly drivers took over control of the vehicle before the alert step was initiated [78]. Eriksson et al. [80] also found that in case of non-urgent TORs, drivers took on average 2.5s longer to resume control of the vehicle when being engaged in a secondary task. Other research found that with a visual warning of a TOR, drivers failed to regain control of the vehicle while engaged in smartphone interaction or phone calls [313].

Those results provide similar insights as research by Bazilinskyy et al. [17] that queries the modality preferences for different level of urgency when taking over control of the vehicle. TOR that are realized visually are preferred in low-urgency scenarios compared to vibrations. Verbal messages were preferred and led to faster reaction times compared to abstract sounds [17, 86] and female voices were favored compared to male voices. In highly urgent scenarios, multimodal TORs were preferred [17].

In a study in which TORs are performed repeatedly, Roche et al. found indications that sounds alerting drivers to take over control might be preferred to TOR with visual-auditory modality [243]. This is in line with the research by Naujoks et al. [209] who showed that it takes drivers longer to put the hands back on the steering wheel with visual alerts compared to visual-auditory alerts. Other research mentions lead times of 5-8s for faster reaction and optimal effectiveness, when a verbal warning with the cause of the TOR was uttered [286]. The advantage of a verbal TOR over text combined with a tone was also identified by Epple et al. [78].

Communicating context information to the driver in case of a TOR, such as the location of a road block that needs to be avoided, was perceived as helpful and led to shorter reaction times and safer driving. Dynamic cues, indicating the direction of driving appears to create frustration, but are less demanding than static context cues [27]. When being primed with the appropriate action that needs to be taken, drivers were faster to take over control of the vehicle and had thus a higher TTC. By tracking the eye gaze it was found that drivers still observed the environment to check if the vehicle's driving decision is correct [28]. When communicating the context of a take over request, simplicity is key. Politis et al. [228] gave drivers either a simple countdown until the control needed to be resumed from the vehicle, a dialog in which the drivers repeated the information uttered by the system, a dialog in which the participant answered questions posed by the system or a multimodal interface. From all interfaces the countdown was the best with respect to TTC, Usability and Acceptance. Providing drivers with predictive warnings could also lead to negative effects of behavioral adaptation such as an increased intensity in secondary tasks, increased maximum speed or a decrease of minimum time-to-collision [210].

Lu et al. [183] subdivide transitions in which control shifts in four cases: driver-initiated driver control, driver-initiated automation control, automation-initiated driver control and automation-initiated automation control [183].

Parasuraman et al. [219] simplified the components by information processing and cognitive psychologists to four stages in a model of human information processing: information acquisition, information analysis, decision/ action selection and action implementation. Those stages mirror the input functions on which automation can be applied. Systems can include all four classes of automation application on different levels, from high to low automation [219]. Highly complex system such as autonomous driving systems include all four classes on a high level. Eriksson et al. [79] took those stages into account when designing a HMI that primes drivers of TOR. They increased the information acquisition by highlighting obstacles and hoped to improve the decision making process of participants by it. But the highlighting resulted in unnecessary braking. In this thesis, the control transitions were straightforward, initiated from the vehicle with the driver being in control of the vehicle afterwards. From the discussion of the related work, we assume that smart infrastructure information should be presented more than 10 s before the driver needs to drive manually again to call it early take over preparation. Using visualizations are preferred in low-urgency scenarios, which is the case when informing drivers early of an upcoming critical situation. Context cues are helpful for drivers in TOR situations. Overall, we derive many insights in the design considerations that are relevant for this thesis.

2.1.3 Trust in Automation

The consideration of trust is relevant for the acceptance in a system. Therefore, we introduce the relevance of trust in automation, especially in autonomous vehicles by first giving an overview why trust is important to consider, and then why we should not aim for undifferentiated trust in autonomous vehicles. At last we give examples of related work that research how trust can be influenced. When interacting with technology some level of trust in the decision, result or consequence of the use of the technology is build. Choi et al. [48] state that the adoption of autonomous vehicles can be predicted by the level of trust in them. Especially with the increasing level of personalization and including technology in every aspect of life, trust is an important aspect to consider. The understanding of the involved person for how the context affects the automation's ability also determines the appropriate trust [166]. Khastgir et al. [145] defined two forms of trust in the automotive context: Trust in the system and trust with the system. The latter is defined under the aspect that the user is aware of the system's limitations and thus is able to adapt the own "usage to overcome the limitations of the system". The goal of building trust is not just increasing it, but also calibrating trust, meaning having an adequate level of trust in automation. Thus, problems such as over- or under-trusting a system can be avoided [218].

One example of over-trusting automated systems, without having an adequate understanding of the systems' functions is the deadly accident of a Tesla driver, who drove assisted, but did not pay attention to a truck on the road [7]. Under-trusting an autonomous vehicle may lead to the driver taking back control from the vehicle unnecessarily and thus not using the vehicle to its full potential. Parasuraman et al. [218] phrased it as disuse of a system, so the system is not used even though it is capable to handle the situation. While trust has been defined as a belief, attitude or behavioral state of vulnerability [57, 123], Hoff et al. state it should be viewed as a mental state. Feelings of trust can vary with new experiences or information about the system or the ability of the operator to compare manual to automated performance [123]. Hoff et al. [123] describe three layers of human-automation trust and include dispositional, situational and learned trust in a model. Dispositional trust reflects the constant tendency of an individual to trust in automation. The external environment and the context-dependent characteristics of the operator are two sources for situational trust, which depends on the specific context of an interaction. Learned trust derives itself from the experience with the system [123]. Next to people's values and attitudes, emotions and moods are feelings that Jones et al. [138] relate to the experience of trust. When meeting new persons, people tend to build an impression of trustworthiness based on their feelings to the new person. When behavior is witnessed that is not in accordance to one's values, negative feelings may arise [138]. Hoff et al. propose design recommendations to create trustworthy automation. The five categories include appearance/anthropomorphism, ease-of-use, communication style, transparency/feedback and level of control [123].

Khastgir et al. [145] researched the influencing factors of trust. They provided the participants with different levels of knowledge about the system by reporting the true capabilities and limitations of the automated system, compared to no knowledge. The information was given to the participant in a lay-man language to ensure higher level understanding and to build on the existing mental model of the participant. With the knowledge about the system the trust of the participant increased, but in some cases the participants showed some signs of under-trusting the system. This was the case in very low capability and too much knowledge about the system's limitations and capabilities. Providing the autonomous vehicle with anthropomorphism features such as name, gender and voice seems to increase trust in the vehicle [290]. Lee et al. [166] gave five guidelines to increase trust by providing context, among others to reveal the context of the situations and how past performance depends on situations [166]. We can conclude that an interface should aim for a proper calibration of trust, and to communicate the abilities and limitations of a system honestly. Trust can be increased by several factors, such as anthropomorphism or context information.

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[7] `https://www.tesla.com/blog/tragic-loss`, last access May 2020

2.2 Smart Infrastructure and Connected Vehicles

To get an understanding of the current state of smart infrastructure we introduce several research projects and the related research focus. Since vehicle-to-vehicle can provide similar information as smart infrastructure if sufficient vehicles are connected among each other, we introduce relevant related work. Some applications that drivers could use would not work without 5G, fusion and prediction, therefore we provide an overview about these topics in the end of this section. There is an increasing research interest in connecting traffic participants digitally with the surrounding infrastructure [292]. The expected benefits include, among others, improved safety, driver comfort, efficient and anticipatory driving and reduced pollution[8][120, 121, 152, 216]. Using sensors in infrastructure is considered for cities, urban environments, connected vehicles and other traffic participants. While in recent years the term smart infrastructure was used more prominently than intelligent infrastructure, both terms are used interchangeably [216]. Aktan et al. [4] defined it as a system that is able to "(a) sense its loading environment, as well as its own responses and any ongoing deterioration and damage; (b) reason by assessing its condition, health, capacity and performance needs and the actual performance that is being delivered; (c) communicate through proper interfaces with other components and systems, including human managers; (d) learn from experience as well as by interfacing with humans for heuristic and mechanistic knowledge; (e) decide and take action for alerting officials, diverting users, structural control, self-repair, closure etc." [4]. There is an increase of research in smart cities that use sensors to observe and control different sectors within the city. For example, a sewer system monitor is implemented in Indiana in the United States or an advanced analytics system predicts the location of future incidents, used by the Nashville Fire Department and social worker prioritize cases according to antisocial[9]. The so called "City Brain of Hangzhou"[10], created by Alibaba, gathers information through cameras or GPS data on the location of vehicles and buses. Alibaba claims that the daily accident reporting increased and the response time decreased. The average travel time was reduced by three minutes with automated traffic signal control[11].

Nevertheless, not just installed sensors are used to observe the infrastructure. Other projects explore the potential of using drones to detect the traffic movement [151, 254]. Those examples show that smart cities explore undiscovered opportunities that could enhance the quality of living through shorter travel times or less congestion. Research projects such as *AutoNet2030* or *Autopilot*[12] also explore the potential of use cases, e.g. the aspects of co-operative driving of automated vehicles [54]. The idea of the projects *Diginet-PS*[13], *KI4LSA*[14] or *VERONIKA*[15] is to use the existing infrastructure, such as traffic lights, and extend it with sensors. Those track the traffic in real time and thus improve the traffic flow, reduce noise and minimize pollution. Additionally, free parking spaces are identified

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[8] `https://www.kassel.de/buerger/verkehr_und_mobilitaet/verkehrsprojekte/veronika.php`, last access April 2020

[9] https://www.ft.com/content/140ae3f0-1b6f-11ea-81f0-0c253907d3e0, last access May 2020

[10] https://www.alibabacloud.com/de/solutions/intelligence-brain/city, last access May 2020

[11] https://edition.cnn.com/2019/01/15/tech/alibaba-city-brain-hangzhou/index.html, last access May 2020

[12] `https://autopilot-project.eu/`, last access May 2020

[13] `https://diginet-ps.de/`, last access May 2020

[14] `https://www.iosb.fraunhofer.de/servlet/is/105505/`, last access May 2020

[15] `https://www.kassel.de/buerger/verkehr_und_mobilitaet/verkehrsprojekte/veronika.php`, last access May 2020

and the upcoming traffic flow can be predicted. In case of *VERONIKA*, emergency vehicles receive infrastructure data. Those smart infrastructure projects share the idea of improving traffic behavior by tracking the vehicle's behavior. Another large german infrastructure project is the *UR:BAN* project[16]. This project aimed to develop traffic management systems and driving assistance systems in the city.

The just mentioned research projects show that there is an increasing interest in connecting vehicles with each other and the infrastructure. The idea of gathering data from remote traffic data acquisition and providing real-time traffic forecasts and route guidance is not new and similar ideas were presented by Xu et al. [310]. Smart infrastructure connects the infrastructure with vehicles, nevertheless, the vehicle can get its information through other means as well. Vehicle-to-everything (V2X) means the connection between vehicles to any other entity that could affect the vehicles. This term aggregates vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V), vehicle-to-network (V2N) and vehicle-to-pedestrian (V2P) connections [181, 182]. This communication and traffic infrastructure system, could extend the perception range of individual vehicles [164, 217] through cooperative sensing [121]. V2X is also investigated by Hobert et al. to identify potentials and core functionalities for cooperative autonomous driving. Within their work, vehicles cooperated with a V2X connection and infrastructure on intersections was taken into account [121].

The project *ConVex*[17] defined some use cases for connected vehicles. Those included forward collision warning, a warning to overtake, a blindspot warning or the information to follow other vehicles with the same destination. This can optimize the taken route. They also consider transmitting personal information to other vehicles. For example, in case of a connected pedestrian, the transmitted information could contain, if the person is a child, adult or has a handicap, which could result in a more careful driving behavior. Gerla et al. [92] and Lu et al. [182] describe the Internet of Vehicle (IoV), a vehicular network of autonomous vehicles. The members of this Internet of Vehicles upload their sensor data, such as GPS location or road condition to the cloud. Human control is removed, which enables a smoother traffic flow. Flexibility in critical and unforeseen events must be ensured as well as safety against malicious attacks. The data processing and forwarding can be designed in different ways, there can be local information, containing warnings about a certain corner, but also information with a longer explicit lifetime. This flexibility needs to be integrated in the vehicular cloud. Some long time information should be kept in the vehicle data itself, instead of the cloud, to ensure scalability. Collaboration will be one strong asset, since data is provided to every connected vehicle without considering the party that provides the data. With this open access, the cloud is just as good as the willingness of every participant to provide their data to all other participants. On the driver side, this IoV could provide photos or videos of traffic scenes, for example, in case of an accident. Since the vehicles travel with high speed and optimized distances, the driver needs to be prepared to intervene and decide quickly [92].

Concerning the integration of smart infrastructure in the vehicle, Human Horizon presented the HiPhi 1 vehicle that is supposed to be connected to the smart city via 5G[18][19]. Future 5th generation (5G) cellular networks promise disruptive changes for, among others, smarter devices. Device-to-device (D2D) connectivity, which includes the interaction between users via augmented reality or HD video streaming, requires local and non-local content and constraints of low-latency and high data rate [24].

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[16] `http://urban-online.org`, last access May 2020

[17] `https://convex-project.de/`, last access April 2020

[18] `https://www.human-horizons.com/home/smart_car`, last access May 2020

[19] `https://www.topgear.com/car-news/future-tech/human-horizons-hiphi-1`, last access May 2020

5G is said to be an enabler for autonomous driving, therefore, the automotive vertical market is a key driver for these systems. The challenge that developers of autonomous vehicles face is the small distance and high speeds (up to 200 km/h) on the road [40]. Campolo et al. mention also a data rate of 10 Mb/s(downlink/downlink) with a latency of 1 ms [40].

The single sensor data is fused with sensor data from the network. This results in data about the velocity, location and potentially personal data of the connected user. With the data about the environment, map and user, a prediction about the next movement and the resulting consequences can be made. With the fused and collected data, a prediction about the further driving trajectory of the vehicles can be calculated [230]. Polychronopoulos et al. [230] optimized in 2007 the path prediction for vehicles and had results of being able to estimate the path for 3-4 seconds. The accuracy was less than 50 cm. Mirus et al. [201] used an approach that takes the surroundings into account. Their results are promising, but the prediction of future driving behavior remains challenging. Since datasets of highway driving consist mainly of straight driving vehicles, the training for lane changes is difficult [201].

The emerging technologies of 5G, autonomous vehicles, augmented reality or vehicle-to-X are intertwined and a combination of these technology could enhance the experience of drivers of autonomous vehicles. Within this thesis the focus is on exploring the use cases, user groups and resulting benefits of smart infrastructure on the user. The main focus is on the highway, since this thesis is set in the problem space of Providentia, a highway infrastructure project. Nevertheless, some use cases can be applied for an urban setting, and some studies are primarily set in the city. Throughout the thesis, we take the ideas of having a look ahead and detecting traffic participants outside the drivers sight, and explore the potential resulting use cases.

2.3 Out-of-View Visualization

Smart infrastructure offers the possibility of providing drivers with information that is outside the view of the driver. To gain an overview of relevant techniques to visualize this information, we first introduce the topic, give then an overview of general visualization schemes and in the end put it in the context of automotive interfaces. Since the development of cheaper sensors, it became more relevant and possible to observe the context of a system [58, 251]. Autonomous vehicles have sensor systems that detect the immediate environment of the driving situation in close proximity of the vehicle. Infrastructure can extend this context awareness even further. Traffic situations that are not necessarily in close proximity of the vehicle, which might need the driver's attention, need to be communicated to the driver. Visualizations and hints on other objects are relevant in various scenarios, spanning from gaming, augmented reality, aviation and automotive applications [10, 141, 314]. In those applications, clues are given to the user of the system to direct the attention in a certain direction [100, 245]. The next level display technologies, such as head-up displays (HUD) allow the presentation of information or warnings within the driver's windshield [109, 240]. In potentially dangerous situations, the attention of the driver shifts from the immediate environment to the dangerous scenario that is not necessarily yet in the view of the driver. Research shows that priming drivers before the actual take over request, results in safer hand-over scenarios [116, 299].

Visualizations aim at making users comfortable and aim for an easy use of interactions [95] There are interface schemes that provide the user with a wider context than just a primary visualization screen. Some of the more known techniques are overview+detail, focus+context and cue-based techniques [50]. Overview+detail combines a view which gives an overview of a situation with a detailed focus on an aspect of the overview. In the scheme of focus+context, the idea is similar, a contextual view is displayed and a zoom is set on a focus region. One example for this scheme is a fisheye view, in which a certain region is zoomed, but the surroundings and context is shown as well [50]. Cue-based techniques selectively highlight or suppress items within the information space [50]. Known primarily from computer games and aviation, minimaps are similar to environment maps. They combine the initial aspect of focus+context views, by visualizing out-of-view objects with focus regions in a single screen, while at the same time relying on overview+detail elements. Other popular visualization solutions are Wedge, a technique that conveys direction and distance to the user [106] or arrows that point at a point of interest [252]. Gruenefeld et al. [99], used a visualization of out-of-view objects by a radar-like interface in augmented and virtual reality (VR) devices.

Visual warnings are suitable for non-urgent information, complex messages, discrete and continuous information and spatial information [39]. Some visualization schemes are more effective than others to prime users for the intended information, but the intended use needs to be considered when implementing an out-of-view visualization. For the automotive domain, visualizations might help with increasing situation awareness and with getting a faster reaction and better driving performance. Animated stimuli get a faster reaction from the driver and the visualizations help to locate other road users [101, 270]. Peripheral awareness displays can increase safe driving performance by combining a light strip with vibro-tactile seat feedback [156]. While reducing the time the driver spends glancing away from the road with this situation awareness display, simultaneously the situation awareness can be increased. Lenné et al. [168] implemented an advanced warning device to warn drivers about approaching emergency vehicles. The interface consisted of LEDs and an auditory warning, which improved the drivers preparation for the emergency vehicle. This is in line with the work of Popic et al. [231]. They compared a 3D HMI with a 2D HMI to assist driver in anticipatory driving. The differences of the results of the 2D compared to the 3D interface were small, whereas the 3D visualization was also continuous while the 2D visualization prompted new information upon approaching a critical situation. When using stereoscopic 3D (S3D) in the vehicle's dashboard, the combination of color and S3D increases the perceived urgency. Furthermore, it increases user experience [37]. Situations in which the driver needs to be alerted of situations or other traffic participants that are outside the view, are for example intersections, where traffic participants are obscured around corners or generally vehicles or traffic that are obscured by other vehicles or objects. The blind spot can also provoke situations in which drivers do not see other vehicles. With smart infrastructure information, the radius in which other vehicles or objects are detected is extended and therefore there are even more situations out of the line of sight of the driver. Werneke et al. [293] investigated the presentation of collision warnings at intersections. They compared an early warning, in which the possibly critical vehicle is not yet in view to a late warning with the vehicle in plain view of the driver. The early warning is efficient in preventing a collision accident with the critical vehicle. Early on, the drivers drove more carefully by waiting longer and accelerating slower. In a multi step approach, drivers are warned of critical situations in multiple steps. In a first phase, the information phase, drivers are primed of a critical situation. The next step is a pre-warning in which a multimodal approach could be chosen by additionally warning the driver acoustically [237, 303]. A multi step approach showed to be preferable in critical situations, drivers preferred to be informed at 450 m before the critical situation. In a less critical situation drivers preferred 340 m [303].

From the presented related work, we learn that visualizations are beneficial when the goal is to convey complex and non-urgent information [39]. Animated visualizations are more effective to gain the drivers attention and early warnings are efficient in preventing accidents. In the course of this thesis, the aspect of how smart infrastructure information influences the presentation of a TOR visually is considered, therefore, with this overview we discuss how take over requests can be presented to drivers.

2.4 Use of Augmented Reality in Vehicles

In this thesis we use augmented reality to support out-of-view visualization to increase situation awareness. Therefore, it is important to get an understanding of the technology and the advantages, disadvantages and best practices. Even though augmented reality cues for objects that are in view are an important field, the focus for this thesis is rather on augmented reality cues for vehicles and dangers that are outside the view of the driver. Therefore, following section is a short summary of work that gives cues about vehicles and traffic situations in the view of the driver. Possible AR visualization schemes for context information and for informing drivers of possible scenarios outside their periphery can build on existing research of AR cues in the driver's field of view. With regard to this research focus, the last paragraph summarizes the findings of using augmented reality to communicate context or out of view information.

In today's vehicles, augmented reality is used to add virtual objects or information, such as trajectories, speed information, hazards to the view [205] (see Figure 2.1 for exemplary visualizations from related work) Augmented reality is defined by Azuma as any system that combines real and virtual content, is interactive in real time and registered in three dimensions [13]. The displays that can be considered when using augmented reality applications are manifold, ranging from handheld displays, Head-Mounted Display (HMD) or desktop. There are many domains in which research is conducted using some sort of AR display, for example education, medical, interaction or entertainment and gaming [59].

Augmented reality use cases within the vehicle's cockpit are widely under research, with a special focus on acceptance of AR navigation cues [59, 266]. HUDs use AR elements to display velocity and navigation cues. It can also be used to display vehicles' driving behavior and information about the vehicle's sensor perception. While HUDs are constrained to a small area on the windshield, windshield displays (WSD) use the whole windshield to present information.

Application cases range from overlaying a certain area with color information, highlighting the edge of the street, enhancing night vision or highlighting dangerous objects on the road [165, 241]. Combining this with other modalities leads to novel interaction experiences. For example at CES 2016, BMW presented HoloActive Touch [56, 247], a haptic touch interface floating in midair. The interface is projected in the vehicle cockpit by a mirror plate to create the effect of floating objects. So far this interface is a prototype, displaying buttons and no real-time information.

Morrison et al. [204] compared augmented reality cues combined with a physical map to a 2D digital map. They found that combining the physical map with AR features fosters collaboration and discussion. When AR is being used to work in autonomous cars, this insight could help the development of new interactions to give an opportunity to foster collaboration via AR. Pervasive AR that "augments the physical wold digital with information registered in 3D, while being aware of and responsive to the users context” [98] could be valuable when applied in vehicles. Information overlays for example aim for a context-aware experience [98].

Devices that create mid-air 3D AR objects include HMDs, 3D Tabletops and Holographic projectors. A particular advantage is the high mobility of modern AR HMDs, with integrated natural input possibilities such as speech or gesture (e.g., Hololens[20]). Previous work on floating 3D objects inside vehicles focuses on communication [155], new input possibilities [247] or dashboard visualization [37, 174].

In Dikmen’s [62] study, augmented reality cues highlighting other vehicles, does not increase situation awareness [62]. This is in contrast to Lindemann et al.’s work [173] in which AR overlays significantly improved SA while driving. They dynamically included information about destination distance and time, traffic priority, confidence information, traffic regulations a primary driving panel, navigation, traffic light and high priority information in the WSD interface.

In TOR situations, AR does not influence the reaction times of TOR [159]. Langlois et al. [159] also did not find indications that AR cues increase the behavior of checking the surroundings before taking over even though the awareness for a lane change seems to be improved by AR. This could also be the effect of adding the AR visualizations in the driving scene itself. Another study, also investigating AR visualizations in take over requests, provides the study participants with two augmented reality conditions. The first condition displays in red the area which should be avoided by the driver whereas the second condition shows in green the right lane. Lorenz et al. [179] investigated the influence of the conditions on the take over process. Similar to Langlois et al.’s results, they did not find a significant effect of AR on take over times. The take over behavior of the participants differed between the conditions though. Especially in the red area condition, the participants brake harder, which could be explained by the alarming effect of that color. Nevertheless, this take over behavior did increase the lane change errors [179]. The HUD with augmented reality elements is appreciated and preferred compared to augmented reality elements in the instrument cluster [255].

Tönnis et al. [270] explored the difference of visualizing environment information either with a bird’s eye view with an indication on an alert position or an arrow pointing at a point of interest. Their results showed that the reaction time was faster for the bird’s eye view. The error rate was also higher withe AR HUD. This shows that using AR to indicate objects on the road needs precision and is not always the best solution. Presenting information fast and accurately is efficient when using AR in the HUD [89]. Others used augmented reality cues to improve the left turning behavior [205, 271] or direct attention on roadside hazards [248]

Even though many AR applications already exist in today’s vehicles, there are not many concepts that do not use the windshield or dashboard as interaction possibility. We explored new concepts of visualizing a preview of the highway in stereoscopic 3D [299]. Weidner et al. [291] used a similar approach and used different location to provide the participants with representations of the traffic scene and dangerous scenarios. They found that in two conditions those visualizations led to safer TORs compared to TORs in which no visualizations were provided. Furthermore, when compared with perspective displays, stereoscopic 3D performed better with regard to safety in TOR [291]. To summarize the findings, augmented reality is mainly used for navigation in HUDs, WSD or the infotainment display. It is used by overlaying areas with color information [165, 241]. Using HMDs is beneficial due to the high mobility that can be reached. In some cases AR overlays improve situation

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[20] `https://www.microsoft.com/en-us/hololens`, last access: May 2020

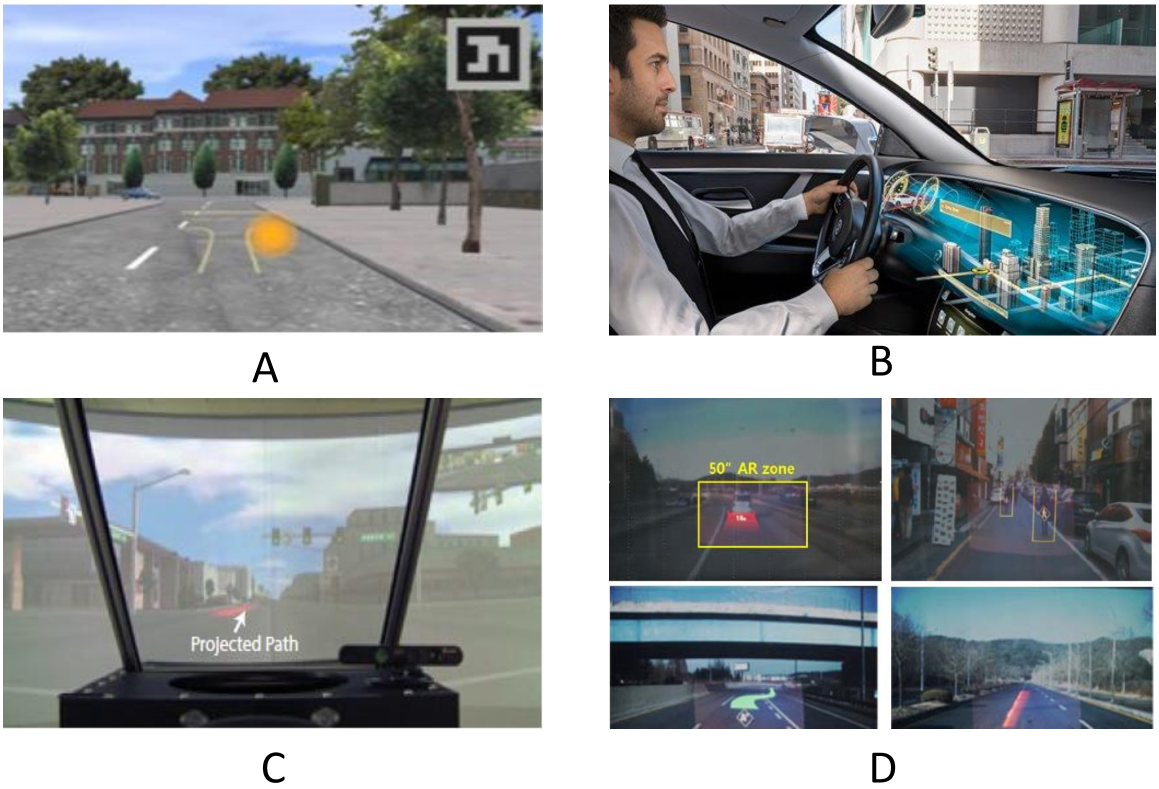

Figure 2.1: Examples of augmented reality in the literature:A: A hint on a critical situation after a turn by Werneke et al. [293], B: A concept of a stereoscopic 3D solution by Continental-Automotive[a], C: A projection of a path by Tran et al. [271] , D: Several highlighted objects, paths and persons by Park et al. [220]

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[a] `https://www.continental-automotive.com/en-gl/Passenger-Cars/Information-Management/Display-Solutions`, last access April 2020

awareness of drivers [173]. The take over times do not seam to be effected by AR [159], which means that AR cues does not seam to have a negative effect on the performance of drivers during a TOR.

2.5 Design Spaces for Automotive Interfaces

With a structured approach to derive new designs of applications, we can effectively construct novel applications that especially aim for drivers in vehicles that are connected to smart infrastructure. In the following section an introduction to design spaces is given, by first starting with the overall definition. Then the advantages of exploring existing design spaces is shown, followed by giving concrete examples of them in the automotive domain. The importance of design is stressed by Norman [214], who provides principles that focus on the need of users interacting with things. The design process can be described as "iterative problem solving" [14] with designers working on a product, which should be mutable, effective, manageable, learnable, needed and aesthetic. Ultimately, the final design should understand what the users need and want [6]. But of course, design works also towards meeting the business goals and it should fulfill the usability principles [14]. Gould et al. [96] for example formulated three usability principles: *Early Focus on Users and Tasks*, *Empirical Measurement* and *Iterative Design*. With those principles, users should be included as early as possible in the design process, use prototypes to test a low fidelity prototype and iterate over the designs regularly. To achieve a good design, designers are provided with tools, such as design spaces. According to Westerlund [294] all design solutions, provided that they work, are included in a design space. Design spaces originally provided a cartesian space in which individual designs were mapped with design variables [66]. Design variables are defined by the constraints that are defined by rules, principles, conventions and laws. Therefore the design variables define the possible adjustments that can be made within the design space [97]. Therefore, it can have predictive and analytical properties. Design spaces can be described as ”instances of conceptual spaces“ and can be set up by possible chosen values that build up quality dimensions [66]. In research, the term “design space” is interpreted varyingly, spanning from conceptual tools to network graphs [66]. The main benefits of design spaces is to provide members of a team, working on the same design, with a communication tool to get a common understanding and idea of the final design. Furthermore, through the representation of the framework it helps them to reason and explore the constraints of the design space [187], considering alternative designs and recognizing trade-offs resulting from decisions [256].

The exploration of existing design spaces holds several advantages. As an example, exploring the space of different designs and deriving a structure that represents the network of those designs is the idea behind design space exploration. Providing designers with such a tool can help to find suitable designs and to find the optimal solution to their problem space [308]. Woodbury et al. [308] propose properties and structures of design spaces to formalize design space exploration. Designs are in general partial, meaning that they can and should be changed by adding and removing components [308]. Design space dimensions are not uncorrelated from each other, and therefore, setting constraints can influence several dimensions at once. For example, setting constraints for interactions may influence display-technology constraints, but also modality settings [66]. Once the design space has been created, it is not final, but thrives on change. Dove et al. [66] discuss the benefits of reflecting on the design space of projects by introducing the concept of design space reflection. They propose to revisit the initial design space by questioning it and considering alternatives. With this procedure, the alternatives can reveal constraints on other dimensions and opens up new areas for investigation. That aids and simplifies the identification of influences of constraints in one design dimension on another dimension. They compare this procedure to the Design Space Analysis (DSA) with the Questions, Option, Criteria (QOC) notation of MacLean et al. [187]. Since there is no strict method or procedure to create a design space, MacLean et al. consider the processes involved in generating DSA. Using the QOC process, an existing design is analyzed by posing questions to understand how and why design decisions have been made. Thus, options represent the alternative answer to those questions and evaluation criteria are used to make a choice among the options [187]. Lim et al. [172] used a design space to filter design dimension by creating a prototype and exploring the yet incomplete design. Throughout this process, the advantage of gathering cumulative knowledge is stressed. Additionally, they identified the method as a “critical thinking guide” that helps in making differentiated choices.

Next we give concrete examples of automotive design spaces. The tool to support the design process was provided in previous work in different forms of design spaces. For example, Müller et al. investigate the required design elements for public displays by exploring the mental models of the user and interaction modalities [206], the design space for shape-changing interfaces was presented by Rasmussen et al. [234] or Card et al. set up an information visualization design space [41]. In the automotive domain, another example is the design space provided by Kern et al. [144]. They present a design space that is focused on manual driving and the classical dashboard input and output modalities. Their main interaction areas included windshield, dashboard, center stack, steering wheel, floor and periphery. In their design space, they map those interaction areas with different input and output modalities, such as hand/foot or audio output. In case of autonomous vehicles, in which the driver could be faced away from the front cockpit, the interaction area that defines today's cockpits is obsolete. Since vehicle cockpit faces a change from a focus on manual driving to a focus on autonomous driving, there are many opportunities to include new technology in the cockpit. This opens the already existing design space and new designs need to be explored. For example, mobile devices could be integrated in the vehicle, adding to the existing interface within the vehicle. This could then have different advantages, from adapting the music to the preferences of the driver to acting as multi-touch input [60]. Since it acts as additional monitor, touch input and output can be combined with existing interfaces, but it can also stand on its own.

Since the introduction of head-up displays in the cockpit, they are used to display information such as navigational cues in augmented reality. Endsley et al. introduce design heuristics regarding human factors, ergonomics and user experience of AR devices [76]. They establish eight design heuristics, among others "Adaptation to user position and motion" or "Fit with user environment and task". Especially the increased dynamic positioning and attention direction is explored. This clearly differs to fixed interfaces that are implemented in today's vehicles. In vehicles, the users are confined to a limited space, nevertheless, in autonomous vehicles the interaction area is likely to be more flexible compared to today's vehicles. In autonomous vehicles, drivers are not obliged to be faced towards the windscreen or have their hands on the steering wheel, forcing them to a confined area of interacting with the HMI. Instead drivers are more flexible in their movements, do not need to have their eyes on the road at all times, but can also be immersed in leisure activities. This trend of introducing augmented reality to everyday activities is also reflected in current research and the resulting design spaces. Those focus on the challenges emerging from autonomous driving and possibilities of integrating AR technology in the vehicle [108, 223]. The work by Tönnis [269] and Häuslschmid et al. [108] investigate head-up and windshield displays and their design dimensions. Different to the design space of the classical vehicle cockpit interior, those design spaces also include for example different dimensionality (2D and 3D Information Presentation), content registration or frames of reference. With regard to design dimensions for 3D spaces and Head-Mounted Displays (HMDs), Ens et al. [77] explored the so called "Ethereal Planes", the design space of planar 2D information spaces in 3D mixed reality environments. They identified three groups *Reference Frame*, *Spatial Manipulation*, *Spatial Composition* with the seven dimensions *Perspective*, *Movability*, *Proximity*, *Input Mode*, *Tangibility*, *Visibility* and *Discretization*.

In this section, we did an excursus on the definition of design spaces, on the advantages of exploring existing design spaces and on concrete examples of automotive design spaces. From this we learned that design spaces help to explore possible designs for a product or prototype. They are constantly changing and help identifying and refining constraints of concrete designs. Automotive design spaces introduce input and output interaction possibilities [144] or the visualization and features of windshield elements [108]. Those design spaces focus on existing manually driven vehicles in which the driver is still in control of the vehicle.

Since design spaces are set up by exploring existing designs and identifying common design dimensions and constraints, design spaces for emerging technologies do not exist. Augmented reality is used in the vehicle primarily on the windshield for navigation cues [59, 266]. Nevertheless, autonomous vehicles promise to change the vehicle interior. A design space for applications that do not use windshields, windows or the exterior of the vehicle, so for applications that could be very likely be included in future autonomous vehicles, is missing. In this thesis we explore this knowledge gap to be able to introduce new applications and designs, for autonomous vehicles connected to the infrastructure that use augmented reality and are not limited on the windshield or window.

In Chapter 4 we describe the process of deriving a design space for mid-air 3D AR applications inside the vehicle. To derive it we applied a similar approach as Häuslschmid et al. [108]. In contrast to Häuslschmid et al., we aim at a design space for a field that is just emerging, with a limited number of existing concepts, prototypes and consumer products. Therefore, the aim is to identify design dimensions for 3D in-car AR applications in a technology field in which 5G, smart infrastructure and AR applications are on the edge of being in end user products.

2.6 Explainable Smart Systems

Autonomous vehicles are intelligent systems that use artificial intelligence (AI) techniques such as Machine Learning (ML) to percept the environment and make decisions based on those elements.

However, most of these systems are black boxes, it remains unclear to the user of the system, why a particular decision has been made [104]. In this section, we give an overview of explainable AI methods and related research, by first introducing the topic, then provide insights of the benefits of XAI. Next we introduce method on how XAI can be reached and then what kind of explanation other researchers introduced. The dependability of the output on the input or the weight of features often remains unclear to the individual user [190]. This can negatively impact user trust [67, 186] and acceptance of system suggestions [53]. This has raised concerns about fairness, discrimination and opacity [68]. While this individual intelligibility remains important, the focus shifts to the need for understanding algorithms on a macroscopic societal accountability [1]. Fair, accountable and transparent (FAT) algorithms [169] become a legal obligation in europe through the general data protection right (GDPR [235]) and the USACM released a statement on Algorithmic Transparency and Accountability [22]. This call for transparency addresses all industries and domains.

With the introduction of explanations for the decision of the intelligent system, this call can be answered by making the system understandable. Explainable Artificial Intelligence (XAI), Transparent AI or Interpretable AI are techniques which focus on increasing the understanding of humans for the intelligent system [1, 65]. Interpretability is the ability of a system to explain or present in understandable terms to individuals [65]. With global interpretability, the whole logic of a model is understood, while with local interpretability, only specific decisions is understandable [104].

According to Adadi et al. [2], using XAI systems provides the required information to 1. justify results, particularly when unexpected decisions are made; 2. immediately identify and correct errors in low criticality situations; 3. continuously improve the model; 4. explain its learned strategy (knowledge) to the user [2].

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[22] `https://www.acm.org/binaries/content/assets/public-policy/2017_usacm_statement_algorithms.pdf`, last access April 2020

DARPA (Defense Advanced Research Projects Agency) launched a XAI program [105] that enables users to cooperate with the intelligent system and correct it. However, the field is still working towards finding suitable metrics for assessing the quality of explanations (see [65, 104, 124] for exemplary approaches). For example, Doshi-Velez and Kim [65] describe a taxonomy with for one, *application grounded evaluations*, in which real users use real applications. Then, other metrics are *human-grounded metrics*, in which a simplified task is performed by humans and *functionally-grounded evaluations*, which do not involve humans and use formal definitions of interpretable explanations, such as decision trees. The authors argue that users' expertise in a task plays an important role when designing explanations.

To clarify algorithm decisions, various visualization approaches have been researched. Bojarski et al. analyze a convolutional neural network (CNN) which is trained for autonomous driving by unveiling the learned image features [25]. Other explainability techniques include decision trees, LIME [238], rule lists or saliency map [2]. Nevertheless, even when producing visualizations, some fail in making the AI algorithm understandable [2].

In a concrete example, to provide users a system that is intelligible, Lim et al. [170] provided users with different explanations, among other "What if the factors are different, what would this inference be?". Participants spend significant time with it, when used, since it was interactive and they liked it. Nevertheless, the authors claim that their system is not excessive enough since it was used to the depth that was provided to them with their system. This can result in a call for explanations of deeper contexts instead of shallow application context [170]. Other attempts to explain AI systems include persuasive engagement, which emphasizes to take context and purpose into account to increase trust and satisfaction of the user [260].

Aiming for algorithms that explain AI systems is important to justify the algorithms decision and to provide a fair process. Visualizations are explored to make algorithms understandable.

2.6.1 AI Design and Mental Models

Human-AI interaction is very difficult to design. The challenges designers face, range from the understanding of the AI's capabilities, to AI prototyping until the inclusion of AI experts in the design process. For example, the AI system behavior or potential effects of AI are difficult to anticipate and therefore, to prototype. Other problems are with the interaction and shared control between users and AI. Explaining the behavior of the AI system or the constant evolvement is also challenging. The following section first introduces design processes and approaches. Next we discuss related work that explores mental models and finally we present design guidelines from related work. Yang et al. [311] used a user-centered design process and aligned design challenges related to AI, such as "how to bring a human-centered view to AI". They identified that the challenge of prototyping for AI systems lies in the complexity of the output and the capability uncertainty. According to design complexity, four levels of AI system exist: Probabilistic Systems (Level 1), Adaptive Systems (Level 2), Evolving Probabilistic Systems (Level 3) and Evolving Adaptive Systems (Level 4).

The interaction between users and systems is an extensive field and there are multiple design approaches to form the interaction. Rosson et al. describe a user interaction scenario as a sketch of use, to capture the essence of an interaction design [244]. For scenario-based designs, the focus for a suitable design representation is how people succeed in their work, by using narratives [42].

Scenario-based design methods of XAI focus on the use and anticipation of possible deployment scenarios at an early stage of system development [307]. Wolf [307] aims to change the design process from a less technology- or solution-first perspective, that rather focus on what an AI system is capable of explaining, to one that provides an intimacy with the problem space by asking what type of explanations users need. In explainability scenarios the perspective is on what types of explanations users need while using AI systems, to react on the system's output [307].

To measure the effectiveness of an explanation, Gunning [105] suggests to explore mental models and user satisfaction. The theory of mental models is one of the fundamental theories behind explanations and user perception. Tullio et al. [273] define mental models as a "hypothetical construct defined as a mental representation of a real or imagined situation". We argue that it is important to understand how users perceive intelligent systems to be able to gain their trust [273]. Mental models are always individual, but can be altered by explanations and change of the perception of the user of a system [46]. They are an important part of the theoretical basis for Human-computer interaction (HCI) and they help to understand how people use systems and can provide ways to improve them. Negative behavioral adaptation can occur when drivers have an inaccurate or incomplete mental model of vehicle functions. The behavioral adaptations include neglecting required supervising, when assistance functions are activated [261]. Sullivan et al. [261] provide approaches to improve the behavior through rewarding, driver monitoring, and not letting the driver out of the loop of the driving control task. Design guidelines for AI [7] include 18 criteria during different stages of interaction, e.g. "When wrong" or "During interaction". When wrong, the guidelines state to "Support efficient dismissal", "Support efficient correction" or "Make clear why the system did what it did" [7]. Those design guidelines are important aspects to consider when designing an AI application, especially supporting efficient correction or making clear why the autonomous vehicle did what it did. For autonomous vehicles, in which the scope is to not have the driver involved in the driving task, some design guidelines, such as "support efficient dismissal", described as "Make it easy to dismiss or ignore undesired AI system services" [7] might need some refining.

Concerning autonomous vehicles, Carsten et al. [43] states six crucial HMI design elements: "Provide required understanding of the AV capabilities and status (minimize mode errors). Engender correct calibration of trust. Stimulate appropriate level of attention and intervention. Minimize automation surprises. Provide comfort to the human user, i.e. reduce uncertainty and stress. Be usable." [43]. Since their work focuses on designs that are in current vehicles, the potential of an autonomous vehicle that is connected to smart infrastructure is not taken into account. Similar to that, Lee et al. explored the user needs in autonomous vehicles [167]. They identified in expert interviews an focus group interviews twelve user needs in autonomous vehicles, among others accessibility needs and personalization and customization.

From this section we can derive that the process of designing an interaction interface with an AI application is challenging. Effective explanations take the mental model of users of the application into account, and how the perceive the system to gain their trust. Finally we explored design guidelines, in which the challenges of designing for AI is taken into account.

2.6.2 Perception of Explanations of Reality

Explainable systems touch the field of human interaction researchers and psychology. Formulating explanations understandably while at the same time conveying technical information is a known problem. Technical advances require the adaptation of explanations in intelligent systems. Therefore, we explore the field, how explanations can be conveyed on a societal level. First, we introduce constructivism. From this we can derive, how situations can be interpreted and finally we discuss the influence and failing of common sense on explanations. One theory on how humans perceive the world is provided by *constructivism.* Constructivism is an approach to solve the problem of knowledge and knowing. The concept states that the thinking person constructs all knowledge on the basis of their own experience. What we construct from experience makes up the only world in which we live in.

Von Glasersfeld [279] says that reality is like a black box, since there is just a hypothetical connection between the own experience and the reality. Since a model tries to depict the black box, a good model is one that has, with the same input, the same output as the black box. It depicts the constraints given by the situation, nevertheless, it is not said that this model is unique and that no other model could produce the same results. To interpret situations and statements of others, we base the own interpretation of that situation on the own experience [279].

From the previous section on situation awareness in vehicles, we derive that especially in safety critical systems such as vehicles, situation awareness is important to quickly comprehend the driving situation. On this comprehension we build an informed driving decision. Logical behavior is therefore essential for autonomous vehicles. People believe the first explanation that is approximately conclusive when confused [287]. Watzlawick [287] discusses that paradoxically, common sense and “logical” behavior tend to fail, while “illogical and unreasonable [actions] succeed in producing a desired change.” [288]. Furthermore, trust in intelligent systems can be influenced by placebic explanations [70]. Therefore, programmers need to keep the user needs in mind since they tend to design explainable algorithms without focusing of users [199]. Communication and behavior anticipation guides also the behavior of road user [194].

From the exploration of explanations from the perspective of psychology we gained insights, how explanations can be perceived. The experience of drivers affects how situations are assessed and perceived. In case of confusion, we believe the first explanation that is rudimentary conclusive [287].

2.6.3 Explanations and Technology in Autonomous Vehicles

In the automotive context, different research aims for explaining the highly automated vehicle’s behavior. In the following we give examples of related work that investigates, what an explanation should include to increase understanding and situation awareness, and what aspects should be considered when aiming for high usability. Finally, we discuss the impact of uncertainties and predictions on explainability. Koo et al. [148] investigated the content of an explanation message in the automotive domain. Explaining to the driver how a vehicle behaved led to poor driving performance. In contrast, providing a reason for the driving behavior was preferred and led to better driving performance. Providing both information led to safest driving behavior, but increased negative feelings. The explanation was provided verbally [148]. Studying the user experience while driving autonomously, Frison et al. [88] found four factors that are mainly important to keep in mind when designing for UX: the subjective feeling of safety, pleasure of driving, perceived travel time and personalized user interfaces. Ribera et al. [239] puts an emphasis on the importance of the user, the explanation is targeted to and to follow human conversation which is thoroughly studied. Eiband et al. provides a methodology to derive a target mental model, that identifies the common features of the mental model of experts and user [71].

When driving autonomously, sources can provide information of a driving decision of the autonomous vehicle. The sources may be unknown to drivers such as smart infrastructure or V2V communication. This information is transmitted by other means and not just perceived by the autonomous vehicle [119, 212], and therefore is beyond the common observation horizon of a driver. This not just opens up new possibilities to inform the driver about future driving decisions of the vehicle, but also the need to explain driving behavior of the autonomous vehicle based on traffic scenarios out of the perception range of the driver arises. Since most highly automated vehicles nowadays base their driving decision on their own sensor systems [185], the information that also other systems could form the driving decision needs to be communicated to the driver. Then the mental model of the autonomous vehicle can be adjusted to consider the implication of having a new information channel.

Especially when having infrastructure information, the prediction horizon can change and uncertainties play an important role in the driving decision. Providing uncertainty information or information about the vehicle's state can lead to faster reactions and safer driving [18, 107]. When communicating reliability, the driving level and the corresponding secondary task should be taken into account [81]. Especially in take over requests, in which the driver takes over control of the vehicle, it is important that the driver is quickly fully immersed in the driving task. When presented with an explanation of the reason for a TOR, drivers have a stronger feeling of understanding the system [150]. But in the study of Körber et al. [150], the explanation for a TOR had no effect on acceptance and trust. The reasons for a TOR were explained by missing GPS signal, missing lines or roadworks [150]. Providing explanations before an event however, could build more trust [114]. Another approach is presented by Fridman et al. [87], who argues that the human operator can be involved, when two AI systems disagree over a decision to be made. While it is a proof of concept, it could help drivers of oncoming difficult situations [87].

From related work, we derive that the driving performance can be influenced by providing drivers with explanations. When designing for high user experience different aspects need to be considered, such as safety aspects or the driving pleasure. The prediction horizon with smart infrastructure can change.

2.7 Lessons Learned

From related work we acquired examples of how applications can be integrated into the vehicle, how other researchers have realized out-of-view visualizations, how autonomous system behavior is explained and how to approach a design process. Nevertheless, the research focusing on the benefit and the application of smart infrastructure information in the vehicle leaves open research questions. Therefore, the problem space can be explored further from different angles.

The connection of autonomous vehicles to other vehicles and smart infrastructure improves safety. When integrating smart infrastructure in autonomous vehicles, many elements are intertwined and need to work together. The infrastructure information can be added to the information from the own vehicle, but in a sensible manner, depending on the level of automation of the vehicle. Showing context of a driving decision can increase trust and situation awareness [166, 222]. While

TORs without an extended view are time critical, taking back control from the vehicle with smart infrastructure information can change this interaction. TOR performance can be improved when executed with priming drivers and adequate modalities [22, 28, 78]. A TOR can be designed according to the purpose, for example warning or priming drivers, in these situations. In this thesis, most TOR were issued in the studies as early preparation, therefore, the urgency to take over the driving task was low.

In the exploration of related work, we gained an overview of related infrastructure and autonomous driving projects, and gave an introduction to the sensing and decision making elements of autonomous vehicles. A measure of situation awareness can be used to rate a system and by an increase of situation awareness can improve safety, especially in TOR situations [93, 197, 203]. Next, we gained insights how TOR are designed in related work and that control transition are critical events while driving in a highly automated vehicle. An early preparation of a TOR holds the potential of informing drivers earlier of upcoming TOR.

Preparing a TOR visually is adequate when the urgency is still low and the information to convey is complex. Related work provided drivers with context information, which could help in TOR situations. An appropriate calibration of trust is important, since drivers should be able to assess correctly, if the automation can handle the situation or if an intervention in the driving situation is necessary. Trust can be influenced by several factors, for example psychological aspects, such as an increase of trust in a system that has anthropomorphic features [290].

Some applications, for example AR or VR in the vehicle could be enabled by 5G[23]. Predictions of the future traffic flow could predict critical events and therefore, the driver could be warned early of those.

Design Spaces are a powerful tool for designing novel applications. Exploration of existing designs is important to develop new design guidelines for the interior of fully autonomous vehicles. Not all use cases and their design dimensions are fully explored, which results in a lack of knowledge how to design for novel applications that take smart infrastructure information into account. Through lacking tools and a structured approach to address the challenge of designing for autonomous vehicle interiors that takes the environment into account, the design process is challenging. Not all dimensions and therefore limitations are known, which might result in loosing time through implementation errors that are caused by the lacking knowledge of the requirements for an application. Therefore, we further explore design dimensions and use cases for highly automated vehicles that are connected to smart infrastructure.

Augmented Reality extends the vision. Even though AR is still an emerging technology, it enables many application areas in the vehicle. These possibilities however currently are not explored to its fullest. Situation Awareness can be enhanced when choosing the right AR visualization. For complex and non-urgent information visualization is the most suitable presentation method [39]. With AR, new dimensions can be explored, especially when visualizations are not confined to windows, such as HUD or WSD. Current research focuses on visualizations in HUDs, WSDs or infotainment displays, yet HMDs offer the potential to visualize in new spaces, such as the interior of vehicles.

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[23] `https://www.zdnet.com/article/how-5g-will-affect-augmented-reality-and-virtual-reality/`, last access May 2020

Related work explores a limited number of use cases. AR in vehicles offers the possibility of diverse and novel use cases. Therefore, we aim to explore and extend existing use cases of AR in vehicles.

One should aim for transparent AI algorithms that can provide explanations for their driving decision. Explaining a situation in autonomous vehicles consists of numerous components, ranging from just visualizing surrounding objects, giving context information and explaining the whole traffic situation. When explaining autonomous driving decisions, different aspects need to be considered, for example, how certain information is.

Following the definition of Doshi-Velez et al. [65], our research follows a *human-grounded metric* (real humans, simplified tasks), as explanations need to be adapted to human needs in autonomous driving. Therefore we follow their recommendations to evaluate our application in our context and primarily focus on the needs of the human and the context while using the system. Designing transparent AI algorithms is difficult and providing explanations remains challenging. While some users might have an understanding of what the algorithm takes as a feature to come up with a driving decision, others mental model might need more and different explanation. Explanations are perceived differently by users and most base their decisions on their own experience. Therefore, for users to trust and adopt an autonomous vehicles, their mental model needs to be taken into account, by providing adequate explanations. This will result in an improved driving performance and ultimately enhance safety.

3

Stakeholder and Use Case Evaluation of Smart Infrastructure

This section is partly based on the following publication:

- Gesa Wiegand (2019, March). Benefits and Challenges of Smart Highways for the User. In IUI Workshops.

Please refer to the beginning of this thesis for a detailed statement of collaboration.

Smart infrastructure can connect, inform, warn and help traffic participants on the road and while planning a route. Governments and industry undertake an effort to increasingly integrate smart infrastructure in the existing traffic and infrastructure landscape. The previous chapter presents research projects that integrate sensors and network communication into the infrastructure to create a connection between different traffic participants. The initiated projects aim to improve communication and information throughout the whole highway and across borders[1][2][3]. The process of integrating sensors on the highway, building up smart infrastructure and connecting it with traffic participants, is complex. The advantages and the potential of setting up smart infrastructure for different stakeholders is still under research. For example, warnings about construction sites are communicated to drivers of connected vehicles through installed road side units (RSU) on highways crossing international borders [4]. Other use cases that can be realized by smart infrastructure are, for example, warnings about wrong way driving or co-operative merging assistance, in which involved vehicles and RSUs negotiate and cooperate with each other [143]. There are different research directions for smart infrastructure projects. Communication protocols, hardware setups, 5G network slicing, data fusion and prediction are important topics that are explored in different research projects and in the end aim for improving the journey of a driver connected to smart infrastructure. Concerning the users of the systems, the projects focus on vulnerable road users, vehicles and the general traffic management system.

Depending on the quality of the data collected by the smart infrastructure, the resulting use cases for smart infrastructure differ. For example, in case of data fusion results, for which the accuracy for position estimation is good enough on a centimeter scale, precise warnings in critical situations can be given. The prediction, which gives an estimate about the possibility of an event or the course of a path, can be used to inform the driver of a possible accident or an upcoming traffic jam. Depending on the precision of this forecast, take over requests or warnings can be designed. The cause of a take over request might be interesting for drivers of vehicles, but also for the maintainer of the road or in case of an accident, the police, ambulance or firefighters. For one occurring event, it can be therefore necessary to inform different stakeholders.

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[1] `https://c-its-korridor.de/`, last access April 2020

[2] `http://testfeld-a9.de/en/home-2/`, last access April 2020

[3] `https://www.mobility.siemens.com/global/de/portfolio/strasse/connected-mobility-solutions.html`, last access April 2020

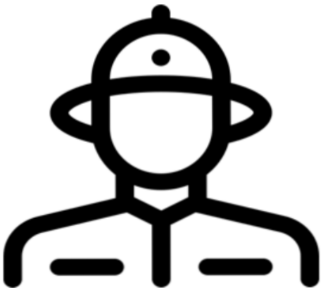
[4] `https://c-its-korridor.com/?menuId=42&sp=en`, last access May 2020

In the course of this chapter we examine the question who the stakeholders for smart infrastructure are and what the use cases for smart infrastructure are. In an informal case study [163], we collected initial responses of potential users about use cases. We follow the approach of an informal case study to collect insights in interviews and focus groups. Through ethnographic research, we gain insights in a field in which we do not have much expertise. The participants were selected through cooperation with the research project Providentia and Interview enquiries.

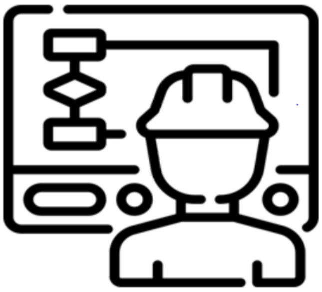
Since numerous traffic participants can be involved, the use cases are manifold and will be extended with the development of sensor, communication and interaction technology. For highway infrastructure, the main use cases and stakeholders are still under exploration. Smart infrastructure information can be included in future vehicles and the potential advantages for drivers need to be explored. Apart from drivers of vehicles, other traffic participants also benefit from connected infrastructure, such as operators of highways or emergency services. Emergency services such as firefighters need to plan their operation as efficient as possible to save time. With smart infrastructure information the path planning could be optimized and detailed information about the scene could be provided. Operators of the highway need to observe the highway and make changes to the route or velocity of the vehicles, therefore, they could benefit from smart infrastructure by adding smart infrastructure information to their system. Identifying use cases and user groups is beneficial to argue for setting up smart infrastructure which is still costly and faces many challenges. Thinking beyond highways, in cities, with multiple building regulations and a limited amount of space for smart infrastructure, the motivation for changing or extending the infrastructure with sensors needs to be sound. Identifying the right direction of research is important to increase safety, reduce emission and improve the overall traffic flow.

To explore the problem space of use cases for smart infrastructure and define the further course of research, we collected statements from different stakeholders of a smart infrastructure system. The focus in this chapter is on exploring the users of smart highway infrastructure, even though some use cases can be applied in urban environments. In this way, we identify benefits of smart highway infrastructure systems. In the following we refer to scenarios in the meaning of critical or alerting traffic situations. To understand the problem space of this thesis and identify stakeholders, benefits and use cases we conducted interviews, focus groups and studies with different possible stakeholders of smart infrastructure. From the focus group, described in the section Driver of Vehicles, we derived the other user groups, such as highway operators and emergency services. We focused on following three main groups:

Drivers of Vehicles[5]
In Section 3.1 we describe an interview and two focus groups that we conducted to identify use cases for drivers of vehicles that are connected to the infrastructure. In an interview with a leading expert for future vehicle design, we discuss the effects of smart infrastructure on the drivers. To identify the main benefits of smart infrastructure for drivers, we conducted a focus group (N = 9). Scenarios that are detected and transmitted by smart infrastructure are collected in another focus group (N = 4, m = 3, f = 1).



Emergency Services[6]
Firefighters are a potential user group of smart infrastructure data. Being the first responder in case of emergencies, it is utmost important to ensure a fast and smooth operation. In Section 3.2 we describe the results of an interview with a representative of this group in which we discuss the current main pain points during operation planning and execution. The results reveal that route optimization or exact location information can be beneficial for operations.



Highway Operator[7]
Operators maintain the highway and provide driving safety and efficiency. Accurate data from the highway and the resulting prediction of upcoming traffic events such as traffic jams would help operators to improve their traffic flow management. In Section 3.3 we describe the process of acquiring use cases of smart infrastructure for highway operators. In a focus group (N=8) consisting of operators of the highway (N=5) and smart infrastructure experts (N=3) potential benefits were collected.

3.1 Drivers of Connected Vehicles

Vehicles that are connected to smart infrastructure can provide users with numerous information and warnings. Depending on the level of automation, traffic environment or the overall purpose,

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[5] Icon made by monkik from www.flaticon.com

[6] Icon made by Freepik from www.flaticon.com

[7] Icon made by Freepik from www.flaticon.com

the notification can be adapted. In case of autonomous driving, the driver could be provided with rather leisure information. In case of manual driving, warnings would be more beneficial to the driver. Considering the traffic environment, when also considering traffic environments apart from highways, it depends if the traffic area is rather urban or if the vehicle is on the highway. Combined with the overall purpose, drivers could be then notified about an offer in a shop they are passing by or of an upcoming traffic jam on the highway. While drivers mainly refer to active drivers, in the case of autonomous vehicles, drivers are rather passengers of the vehicle. In the following we do not distinguish between vehicle occupants that are actively driving or being driven by autonomous vehicles. To collect possible use cases, focusing on a vehicle, connected to smart infrastructure on the highway, we conducted an interview and two focus groups.

3.1.1 Interview: OEM of Autonomous Vehicles

We conducted a semi-structured interview with an expert of an OEM in UI/UX Research. To include the look ahead of infrastructure in future vehicles, it was interesting for us to talk to a decision maker of the vehicle of tomorrow. By discussing the potential inclusion of infrastructure information in future vehicles a further research direction is identified of how drivers benefit from smart infrastructure in the vehicle. Therefore, in the interview, a focus was put on the cockpit information that one could enrich with infrastructure information: what is the effect of information about scenarios in a distance, which modalities could make sense, which technologies should be used for the output, how can uncertainties be communicated to the driver and what level of abstraction should be used when displaying the information. The interview was conducted in a briefing room at the expert's office. The interview started with the following question:

What is the consequence of the distance to critical scenarios, on smart infrastructure visualizations in the vehicle?

After posing this question and following up in a semi-structured way, the next question that considers different technologies and interaction options was asked:

Which other modalities and technologies would be useful to alert drivers of critical situations?

The categories that should be considered when including infrastructure information in the cockpit are distance, visualization, modality, technology, automation level and uncertainties.

Distance The interview resulted in insights about the impact of distance on potential warnings in the vehicle. In a larger distance (approximately more than 100 meters or if the scenario is out of the view of the driver) to a potential dangerous scenario, drivers could be observed. For example by identifying the mental load it can be assessed if they are capable of processing further information. Then, the information level should be adapted according to the mental load level, to not overload the driver with too much information. In case of the driver already being informed about the situation or being able to assess the situation correctly, it might irritate the driver to get even more information or suggestions about it. In case of a shorter distance (less than 100 meters) to the critical situation, an acute warning should be the only presented information. This should be visualized in the HUD, since other devices, such as the mobile phone, are distracting and thus it could influence the safety.

Visualization In situations, which can be handled by the automation itself without the need of a control instance, drivers should not become involved. For example, if the vehicle in front brakes, the autonomous vehicle should be able to keep a safe distance to the vehicle. In case of take over scenarios, the driver should not be shown even more information to not increase the workload in this situation. According to the interview, there is no need for the driver to understand the context of a situation, as it is also distracting and potentially dangerous. The visualization of the environment information needs to be abstracted as much as possible. For example warning symbols could be put in the driver's direction of sight. The visualization could be displayed in 2D or 3D when driving autonomously. An open question is, what detail level should be used for the visualization. Another challenge that needs to be solved, is if the visualization needs to comply with ethical guidelines.

Modality Concerning the modalities, drivers could be informed by different modalities, such as light, about critical situations. In very critical situations, it is imaginable to support the driver with brake assistance. While the already implemented steering wheel vibration is used to warn drivers about leaving the lane, it distracts the driver from the actual task, for example braking. Since every user has their own preferences, there should not be an exclusion of a modality. Every user should choose their modality according to their own preferences.

Technology The expert was convinced that HUDs should be used. If the mobile phone is used as a navigation system, it could also be used within the driver's sight. Information about more distant scenarios could be displayed in the instrument cluster or the central information display (CID). In the CID it is imaginable to display the situations according to their distance in a list. Another option would be to visualize it first as an information overview with the option to go more into detail for certain events.

Autonomous Driving The level of autonomy has an influence on the activities drivers can do and the mental load of the driver. This has an influence on the interface and information that can be provided to the driver.

Uncertainties When displaying information about a situation that is several kilometers away, uncertainties exist. On the one hand, the system could collect unreliable information, because the sensors are not good enough. On the other hand, the situation could resolve itself before the vehicle arrives at the scene. To accept the forecasting information of the system, the uncertainties need to be reliable and accurate. It is imaginable to visualize it, assuming that it is possible to communicate them accurately. Overall following conclusions could be gained from the interview:

Impact of Distance	The information transmission should depend on the workload of the driver in that situation
Visualization	Visualizations should be as simple as possible to not distract the driver
Modality	All modalities should be an option for the driver, when driving manually it should not distract the driver from the actual driving task
Technology	The driver should be able to see everything in the HUD when driving manually
Automation Level	It is possible to visualize more complex scenarios when driving autonomously
Uncertainties	The communication of system uncertainties needs to be accurate and dependable, to give drivers a good approximation of the estimated travel time or urgency

3.1.2 Focus Group: Smart Infrastructure Experts

After getting a first input how the vehicle interface could change with integrating smart infrastructure information, we next identify concrete use cases for drivers. For that, we conducted a focus group (N = 9). The focus group consisted of sensor, infrastructure, and data fusion experts, mainly working in smart infrastructure or autonomous driving projects. In a first brainstorming session all participants were asked to identify use cases and user groups that potentially benefit from a smart highway. In a second session, the participants were divided into three groups. Each group was told to brainstorm use cases for different user groups. The first group thought about the driver and co-driver of a manually driven, highly automated or autonomous vehicle (SAE Level 2-5 [130]), the second of use cases for teleoperated drivers and the third about operators of the highway. The results for the operator of the highway are reported in Section 3.3. The collected results were clustered in the groups according to common themes and then presented by the group to all participants. After the presentation the results were discussed.

Driver of Manual, Semi-autonomous and Autonomous Vehicles The smart infrastructure information can be provided to different user groups of the system within a vehicle. Those are: Drivers of manual, semi-autonomous and autonomous vehicles (SAE Level 2-5 [130]). Manually driven vehicles nowadays have some sensors, but with a limited range. Therefore, those vehicles can detect objects up to 250 m away[8]. They could benefit from infrastructure information by brought-in devices. In case of drivers using their phone for navigation, infrastructure information can be provided to their phone. Additionally, warnings of dangerous traffic situations or route information can be transmitted via the phone, even in case of a vehicle without higher technology. In semi-autonomous vehicles, it is still necessary to take over the control from the vehicle. This take over situation can be supported through infrastructure information by giving drivers early on information about the upcoming traffic situation. Autonomous vehicles that drive without input from the driver, can include infrastructure information in their system and treat it as additional information. The smart highway is a redundant sensor system that can be used by the algorithms of autonomous vehicles to validate its own sensor information or extend the sensor information of the vehicle. Planning and reacting on upcoming traffic situations can then be improved. Drivers of autonomous vehicles benefit from smart infrastructure

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[8] `https://www.bosch-mobility-solutions.com/en/products-and-services/passenger-cars-and-light-commercial-vehicles/driver-assistance-systems/left-turn-assist/long-range-radar-sensor/`, last access April 2020

rather indirectly as they do not distinguish between the sources of information that the vehicle needs to drive.

Teleoperator of Autonomous Vehicles Autonomous vehicles will likely face limits in operability in certain situations in which their sensors break down or there is not enough environment information to securely operate the vehicle. In those situations, a teleoperator, who is steering the vehicle remotely, might be able to steer the vehicle to its destination [265]. By providing teleoperators with information about the surroundings of the vehicle, they are able to steer the vehicle from the distance, for example by joystick [177]. In case the vehicle is connected to smart infrastructure the surroundings of the vehicle are also monitored by infrastructure sensors. Even if the sensors of the vehicle itself do not work, infrastructure sensors do not face the same limitations as the vehicle sensors and can serve as a redundant sensor set. Therefore, the lost information of the vehicle can be replaced. By connecting the teleoperator with the smart infrastructure, situations could be prevented in which vehicle's passengers are not able to continue their journey.

3.1.3 Focus Group: Traffic Scenarios

While we now have identified users within the vehicle that could benefit from smart infrastructure, we now identify use cases and traffic scenarios that could be detected by smart infrastructure. In the course of a focus group (N = 4, m = 3, f = 1), a scenario catalog was set up of traffic scenarios that drivers of a vehicles could be warned of or in which they could benefit from smart infrastructure information. This scenario catalog was initially set up in a brain storming session (N = 4, m = 3, f = 1) and extended over the course of the Providentia project. The following incomplete list contains some examples of these traffic scenarios that were determined as most important and easiest to realize and which reoccur in studies in the next chapters. The rest of the scenarios are described in Section 5.3, Figure 5.1.

- **Standing Vehicle**
  If a vehicle that breaks down on the highway, other vehicles can be warned of that vehicle.
- **Ghost driver**
  A driver that mistakenly enters the highway in the wrong way, can be identified by the smart highway and it can warn other vehicles on the highway of the ghost driver.
- **Bad weather**
  During bad weather, the orientation on the highway might be difficult for the driver. In this case, the surrounding traffic and the distance between vehicles can be provided to the user. By combining sensor data from the vehicles on the road and sensor data from the smart infrastructure, the accuracy of detected objects could be increased. The data from, for example cameras that use deep learning-based object detection and radars that provide object detection can be fused in a data fusion unit. By combining the strengths of the sensors, for example cameras are good classification sensors because they can extract individual objects while radars provide distance measuring data to determine velocities [194], a system that covers all weather conditions is used that is more robust than the sensors of individual vehicles [120].
- **Early Warning**
  In case of a smart highway with sensors that are distributed along several kilometers of the

highway the driver can be warned of possible accidents or dangerous situations along the route early on [299]. The infrastructure system has the advantage of having an overall overview of accurate information about the traffic on the highway. Today's advanced driver assistance systems (ADAS) detect objects and traffic situations in close proximity and warn the driver of braking situations in the surroundings of the own vehicle. Smart infrastructure though is able to detect braking scenarios that lead to brake cascades. A brake cascade originates from a fast braking vehicle and can lead to traffic jams and accidents of following vehicles. An early warning of fast braking vehicles can, therefore, result in smoother traffic flow and a faster and safer journey.

3.2 Emergency Services

Emergency services such as firefighter, police or ambulance are the first who have to be notified of emergencies and critical situations. They are connected to a control center to get information about their deployment and the location of their vehicle is tracked. In the control center all information is collected and processed further, which is a highly demanding process [309]. With cameras and detection algorithms, it is possible to accurately detect emergency vehicles in traffic and control the traffic to provide emergency vehicles with a more efficient path through traffic [246] Smart infrastructure can improve the efficiency of navigation by changing traffic lights or controlling the traffic [213]. It is imaginable to provide parties from the outside, such as the control center or a firefighter unit on the way to an operation, with a video stream from the critical event to improve planning and coordinate resources. To explore the problem space of emergency services we conducted an interview with a firefighter that coordinates deployments.

Interview: Firefighter To get information from a rescue person communicating with infrastructure operators, we carried out a semi-structured interview with a Fire Chief Superintendent. The interview lasted about two hours. In the course of the interview we visited the firefighter station (see Figure 3.1) and observed the control center. Within the control center the responders answer calls, plan operations, distribute resources and supervise active vehicles. In the middle of the room is a large monitor with several interfaces that control and operation. The initial questions were:

Figure 3.1: Firefighter Station [10]

What are the current pain points during a deployment?

How can smart infrastructure improve the deployment?

In the course of the interview with the firefighter, representing emergency vehicle operators, it became clear that the information from the infrastructure needs to be integrated seamlessly to get quickly to the place of operation. In Germany, the fire fighters have an assistance period of ten minutes to get to the place of operation, from the beginning of the emergency call. Within one minute, it has to be decided, what emergency personnel and vehicles are needed for

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[10] https://www.muenchen.de/rathaus/Stadtverwaltung/Kreisverwaltungsreferat/Branddirektion-Muenchen/Brandbekaempfung-und-Technische-Hilfe/Feuerwachen/Feuerwache-4.html, last access May 2020.

the deployment. This calls for accurate and swift information. To get to the place of operation the trip needs to be optimized to get there as quickly as possible. Emergency vehicles are allowed to use roads that other vehicles can not use (e.g. one-way streets or pedestrian roads). It could be also helpful to notify other vehicles or road users of the upcoming emergency vehicles. Currently, due to data protection, the exact position information of the emergency is not transmitted during an emergency call from the phone. Additionally, temporal changes in the route are not updated dynamically in the navigation information. To conclude, following use cases are imaginable for smart infrastructure for emergency staff:

- Optimization of the route to the place of operation
- Exact traffic jam information
- Notifications to other vehicles
- Exact localization of the emergency
- Warning of temporal change of routes
- Connection of emergency vehicles

While the exploration of the pain points of firefighters revealed many points that should be addressed in future work, it does not lay in the scope of this thesis and could not be further investigated.

3.3 Highway Operator

In the previous Section 3.1.2 we collected use cases of smart infrastructure that could benefit operators. Those results already provided some insights in the advantages of smart infrastructure for highway operators. The operator of the highway needs to maintain the highway, know about damages and accidents to redirect the traffic flow. Currently, the traffic on the highway is directed manually by changing speed limitations or by indicating that the emergency lane can be used by vehicles. The additional information collected by smart infrastructure can be transmitted to the operator to improve traffic planning. Emergency vehicles can be supervised from far to find the best and fastest way to an accident. Traffic flow management could be enabled by smart infrastructure by predicting the vehicles trajectories and behavior. By providing the operator with an accurate traffic density on the road, the average speed of the vehicles and predicted maneuvers part of the traffic flow control could be automated. The attention of the driver can be directed to critical situations on the highway and as a consequence reduce the reaction time. An automatic detection of hazardous situations would be desirable and realizable with smart infrastructure. It was mentioned that especially hazardous situations in tunnels through standing vehicles or persons should be detected fast so that the operator of the tunnel can quickly react on it.

Figure 3.2: Highway Operator Room ©Siemens [12]

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[12] www.siemens.com/presse, last access May 2020.

Focus Group: Highway Operator In a focus group with highway operators (N=8) the potentials and challenges of smart infrastructure information were highlighted. The highway operator monitors the highway, changes speed limits with speed indicators, controls a release of the hard shoulder when no vehicle is on the hard shoulder. In addition, tunnels are monitored when vehicles are stationary. The monitoring is carried out by cameras on masts and gantries.

Within the focus group two questions were answered:

What challenges do you currently face in changing and influencing traffic flow control?

What challenges do you face at road works?

Some ideas were already mentioned in the first focus group with smart infrastructure experts. Smart infrastructure can support highway operators with data to improve traffic flow management. The potential of an smart infrastructure is to provide traffic data, road works data and supervise tunnels. With accurate environmental data and the possible inclusion of environmental data from vehicles, potentially critical areas (e.g. slippery or uneven roads) can be identified and the operator can be notified. By giving highway drivers precise reasons for the cause of a speed limit, the acceptance of the speed limit could be increased and overall safety improved. Accurate sensor data can influence following traffic after road works or traffic jams. Forecasting the flow of traffic can improve traffic management. In addition, the control of road users as a collective can prevent traffic jams. At present, the legal framework hinders the personalized information prompts in the vehicle, e.g. through the radio, but it is conceivable to provide improved lane recommendations through displays. By determining times of low traffic and the current traffic flow, road works could be better planned. An automated detection of dangerous situations would be desirable. Especially in current dangerous situations, such as vehicle breakdowns or people in tunnels, the operator could react immediately to this situation with automatic detection.

Concluding, the following use cases of an smart infrastructure for the operator of the highway can be identified. The use cases belong to the categories *Informing in Critical Situations*, *Traffic Flow Management* and *Informing Drivers*:

Critical Situations

- Automatic detection of critical situation, e.g. in tunnels
- Supervision of emergency vehicles to make navigation more efficient
- Identification of dangerous rough roads

Traffic Flow Management

- Accurate and smart traffic flow management through driving behavior prediction of traffic participants
- Identification of low traffic times to improve construction site planning
- Identification of the optimal driving lane
- Identification of traffic participants

Informing Drivers

- Redirect attention of drivers on critical situations through accurate and informative displays

3.4 Lessons Learned

We approached the exploration of use cases and user groups from diverse angles and with diverse methods. Many ideas and visions can be derived from the focus groups and interviews and a good overview of the topic can ge gained. Three main stakeholder for smart infrastructure were primarily mentioned by the participants of the focus group: Drivers, Highway Operators and Emergency Services. In an interface that provides the user with information about the infrastructure, additional information about traffic situations in a distance, can be communicated. Therefore, some reflection is needed on how to integrate intelligent infrastructure information into the interface of the stakeholders. In the following we present more insights on how this could be realized for each user group.

Driver of a Semi-autonomous and Autonomous Vehicle While design spaces for windshield applications and driver-based automotive user interfaces exist [108, 144], there is no design space for interfaces of autonomous vehicles in general. The cockpit of autonomous vehicles will gradually change with the automation level. As mentioned by the focus group of smart infrastructure experts, brought-in devices might get integrated in the vehicle interface. As mentioned by the autonomous vehicle expert, in manual vehicles, the focus is on keeping the distraction of the driver to a minimum. In autonomous vehicles, the driver can focus on other tasks than driving, and therefore the focus is more on leisure activities [223]. To put an emphasis on infrastructure interaction, the design dimensions need to be adjusted accordingly, including different indications of information from far or close to the vehicle or explaining the cause for a changed driving behavior. In theory, information from the whole length of a highway can be collected with smart infrastructure on the highway. Therefore, from the interview of the autonomous vehicle expert (see Section 3.1.1) it can be concluded that the information *what* has happened, *where* it has happened and *how reliable* that information is, are important aspects that can help drivers to form an informed decision for the route planning.

The information *what* has happened is crucial to understand the context of the information. Nevertheless, in a situation that requires a fast reaction of the driver, too much context information could be distracting and lead to dangerous situations. Given traffic situations that are further along the route from the own vehicle, and the driver does not need to react immediately on, more context information could be given. The same can be applied for the automation level of the vehicle. In case of higher automation, the driver does not need to pay attention to the road at all times, therefore other activities can be considered. Information about a scenario, so a traffic situation a driver needs to be informed about, also needs to be accompanied by distance information. As mentioned in the interview of the autonomous vehicle expert (see Section 3.1.1), the notification modality could differ, if the scenario is close by, compared to the modality of notifications of scenarios in a far distance. Otherwise, the drivers can not estimate if immediate action needs to be taken or if the scenario might change over time. The criteria, *how reliable* the information is, depends on the certainty of the information. Maurer et al. [194] discusses three types of uncertainty that can be accounted for: the *state uncertainty*, which describes the uncertainty of the physical measured variables such as speed or position. Then there is the *existence uncertainty*, if a detected object actually exists. And then there is the *class uncertainty*, which describes if the assigned class is correctly semantically assigned [194]. This information is then sent to the vehicle. Since the scenario could be in some distance, the scenario could already change, until the vehicle traveling on that highway arrives. The traffic jam could have been resolved, or the standing vehicle could already have continued with its journey. Therefore, the information how certain the system is of information should be communicated as well and need to be accurate and reliable (compare with Section 3.1.1).

Predicting whether a scenario will change until the vehicle arrives at the scene, could help the driver make an informed decision about changing the driving maneuver or route. In case of an accident, the algorithm could calculate that it might take some time to clear the highway. Therefore, the prediction could be very certain that the driver will lose time on the route. In case of fog in the morning, in far distance, the prediction could communicate to the driver that the fog will probably lift itself before the vehicle arrives at the scene.

Considering all this, the interaction possibilities and the displayed content will change with smart infrastructure information involved.

Teleoperator of Autonomous Vehicles Teleoperation, as mentioned by the focus group of smart infrastructure experts, is needed in several contexts, e.g. drone control, robot control in space operations or medicine. In automotive vehicles, the design of teleoperation interfaces is under research [29]. Teleoperated driving requires a network that has a high uplink data rate and a much lower downlink data rate according to Boban et al. [23]. Teleoperated driving is preferably latency free, therefore a minimal delay between the steering decision of the teleoperator and the movement of the vehicle is desirable [91]. To get an experience similar to that of a regular driver of a vehicle, several sensors (two or more cameras and other sensor information) need to transmit their information to the teleoperator interface. Berggren et al. test a teleoperated bus on a test bed [20]. To transmit the environment information and steering relevant information of the bus to the teleoperator, a driving simulator interface is used. Operators see a camera image of the cockpit of the bus on a screen in front of them. The input control can be manipulated by a steering wheel that is handled by the remote operator. The bus speeds up to 20 km/h. In another study by Georg et al. [91] teleoperated driving with head-mounted displays is compared with teleoperated driving with conventional computer screens. Even though they did not find significant differences between the two output modalities, the participants thought, the top down view of the vehicle surroundings was helpful. As mentioned by the participants of the focus group, with smart infrastructure and map information, this top-down view and all other visualization angles could be realized in teleoperated driving. Situation awareness would then increase if the whole environment would be visualized. Passengers of a vehicle that is steered by a teleoperator might not have transparency of the system that is in control of their vehicle. To regain control of the vehicle this information might be necessary though. Therefore, a clear and transparent communication of who is in control is necessary to gain trust of the user. Therefore, the accuracy of the sensors and the classified and identified vehicles on the road must be high enough to make accurate steering decisions. The participants of the focus group (see Section 3.1.2) do see the potential of smart infrastructure for autonomous vehicles. It is challenging to test and integrate teleoperated, connected autonomous vehicles in the infrastructure and for it to drive safely, technology needs to be enhanced.

Emergency Services From the interview with the firefighter, we identified six use cases for smart infrastructure information. Emergency services such as police or ambulances have many applications for connected traffic, such as surveillance, optimized traffic flow or identification of vehicles. Currently, the use cases are limited through the General Data Protection Regulation (GDPR) in Europe [235]. For example, number plates can not be tracked, which could be used by the police to track speed offenders. From what we learned from the discussion of the potential of smart infrastructure for firefighter departments (see Section 3.2), there are some benefits. There is the restriction that all information needs to be efficiently integrated and easily available. The information available through sensors in smart infrastructure, can primarily be used, to make the navigation more efficient. This information is processed in the control center, where the information about available routes is available. Since the decision for a certain route needs to be made quickly, it is necessary to have an automated route optimization algorithm that takes all eventualities into account. In case of a daytime construction site or an accident, the information for a better route needs to be calculated instantly. Exact information is key for an efficient navigation. Therefore, the localization of other vehicle, traffic situations, temporal changes of the route and the exact localization of the emergency needs to be accurate and efficiently communicated to control centers and emergency personnel.

Highway Operators From our ethnographic research we learned that highway operators observe and control the highway. We identified eight needs of highway operators. First, we discuss the current workplace of highway operators before we elaborate the findings and the resulting conclusions of their needs. The velocity of the traffic can sometimes be regulated and the emergency lane can be blocked or authorized for traffic[13]. The design of control rooms consists of several working desks that have screens to show control applications or videos of the highway [131, 175]. One challenge of those large screen applications is the loss of orientation on the screens. Looking for the mouse cursor on large displays creates high physical demand. One possibility of improving control operators input techniques is eye tracking as suggested by Lischke et al. [175]. Some control rooms, such as nuclear power industries, have a strong focus on safety and performance of operators [180]. Therefore the control rooms need to be designed in a way that operators have no spatial constraint and have fast interaction possibilities. The importance of traffic flow management was stressed by the focus group participants (see Section 3.3). With smart infrastructure, operators of the highway could improve their planning, control and information management. Therefore they need an effective way to communicate and process the given information. In the automotive domain especially tunnels need to be observed. In case of an emergency, they need to be closed for incoming traffic right away. Therefore, the operator needs information of dangerous scenarios on the highway right away. Then, emergency vehicles can be informed and traffic can be controlled.

Challenges The benefits of the system promises unlimited autonomous driving, early warnings of take over requests, early traffic information or ecological driving. Nevertheless, there are some challenges that need to be addressed. Most presented ideas and concepts require the information to be fast and seamlessly integrated in existing technology. Drivers, as well as highway operators need to react to that information. In case of using the system as redundant sensor system for teleoperators or drivers, the system needs to be spread to the whole length of the considered highway. It is imaginable though, to focus the system on a limited stretch of roads with higher accident potential. To prevent others to harmfully interact with the system, safety is also an important topic that needs to be addressed. If wrongful information gets distributed, the algorithm of the vehicle might make a decision that can result in an accident or undesired behavior. The statements of the stakeholders led to numerous open questions. In the course of the thesis, the driver of a vehicle with smart infrastructure connection is put into focus. Especially the design of applications with smart infrastructure

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[13] `http://www.stmb.bayern.de/vum/strasse/verkehrsmanagement/verkehrssteuerung/index.php`, last accessed April 2020

connection, visualizations of scenarios outside the periphery of the driver and the interaction with a vehicle with unexpected driving behavior due to infrastructure information is researched.

Through the case study on stakeholder of smart infrastructure we gained in depth knowledge about pain points and possible use cases. Since the scope of this work is set on drivers, this work provides an overview of open research points for future work.

4

Design Space for In-Car 3D Augmented Reality Applications

This section is based on the following publication:

- Gesa Wiegand, Christian Mai, Kai Holländer, and Heinrich Hussmann. 2019. InCarAR: A Design Space Towards 3D Augmented Reality Applications in Vehicles. *In Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (AutomotiveUI '19)

Please refer to the beginning of this thesis for a detailed statement of collaboration.

Innovative and emerging technologies such as connected vehicles, 5G [24] and smart infrastructure will change the way our traffic system works. In autonomous vehicles, these technologies could enhance, for example take over requests, by extending the vehicle's knowledge of the surrounding environment and infrastructure information [27, 28, 299]. The change within the transportation domain leads to visions of radically different vehicles in the future[1][2]. Concepts of vehicles in which passengers are turned towards each other, or passengers watching movies on big screens while driving autonomously have already been envisioned by industry. The focus from the HCI perspective is on drivers that do not need to pay attention to the road in fully autonomous vehicles anymore.

With autonomous vehicles, a change in public mobility towards vehicle sharing is likely [176]. In this case, multiple people share the same vehicle, interface and sometimes the ride. A new driver might need to adapt to new vehicle functions and interfaces that were adapted by the previous vehicle sharer. It is therefore challenging to provide an intuitive user interface that quickly provides all necessary and personalized functions.

Augmented reality glasses or applications could offer a solution for fast changing and customizable interactions. AR glasses become more usable, smaller, have a bigger field-of-view and can be integrated in everyday activities. Head-mounted displays (HMDs) that display AR objects and support user input, are very likely to shrink in their size and might become as small as contact lenses [258]. There is no security risk of wearing HMDs inside an autonomous vehicle in which the driver does not need to pay attention to the road anymore, therefore, even today's technology can become relevant for a wide range of use cases. Due to the high transportability of compact HMDs a fixed physical interface might become obsolete. Vehicle manufacturers [56, 304] and researchers [37, 38] have already presented concepts to use AR for the design of novel in-car interfaces, e.g., augmented buttons floating in the air. To sum up, autonomous vehicles, infrastructure information and augmented reality interfaces offer the opportunity to create innovative automotive cockpit systems.

Nevertheless, this call for a change in the future vehicle's cockpit design is lacking a design space that clarifies the design criteria and constraints for new augmented reality applications. There is no

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[1] `https://www.volvocars.com/intl/cars/concepts/360c`, last access May 2020

[2] `https://www.youtube.com/watch?v=-8wWwYhBGhE&feature=youtu.be`, last access May 2020

systematic approach to explore design alternatives for in-car 3D AR applications. Lacking tools and experience in designing new systems is time consuming, poses the risk of not using design dimensions to their full extend and thus missing out on important aspects. The problem remains how to integrate AR applications into highly autonomous and connected vehicles.

Design spaces for cockpit elements and windshields [108, 144] are tools to design and optimize applications on the windscreen or the cockpit of vehicles. Therefore, we propose a design space for 3D AR applications in highly automated vehicles that also considers use cases of vehicles that are connected with the environment. Those use cases go beyond safety and navigation to include entertainment and interaction functions [154, 223]. The strong advantage of design spaces is an overarching view of elements to consider, when designing new applications or demonstrations [142]. We build on existing automotive design spaces [108, 144] and develop them further, by investigating the use of AR in the highly automated vehicle's interior. In contrast to related work, presenting design spaces based on implemented examples, we present a design space to a recently emerging field of research. It is important to provide designers and researchers a design space in this early stage of development to give guidelines and support the research and development.

Our design space supports the concept development of in-car AR systems, serves as a communication tool, enables objective comparison of systems and can be used to formulate standardized requirements descriptions for building prototypes. We focus on SAE Level 4 [130] since the use of augmented reality could pose a distraction on a driver in control of the vehicle. Nevertheless, in control transition cases, it could also be helpful to use augmented reality to introduce a take over request.

To derive this design space we conducted a literature review of scientific publications, patents and commercial products. Two focus groups ($N = 3$; $N = 5$) with experts from the AR and automotive domain provided 84 additional novel use cases. Combined with the literature review, 98 examples for in-car AR are identified and clustered (Table 4.1, 4.2 and 4.3). By analyzing the design dimensions of the use cases and combining them with existing design spaces and taxonomies, we derive a design space for in-car AR applications. Hence, we contribute to the emerging field of in-car AR by transferring previous insights into a new context and drawing attention to possible differences. To motivate the feasibility we explore the design space by sorting in existing concepts and present a fictional usage scenario. By deriving a design space for in-car AR, designing applications in AR for in-car usage can follow a structured approach.

Within this chapter, we answer the questions what possible use cases and design dimensions for in-car 3D AR applications in highly automated vehicles exist when 5G and smart infrastructure enable communication, entertainment or information about the environment. Furthermore, we answer how designers of new applications can be supported with the design space, by giving an example of a design process and by analyzing the designs of this thesis. In this way, we experience the benefits of using the design space to find new designs in a structured approach.

4.1 Methodology

To define the categories describing the design space for in-car AR, we followed four steps:

1 – Literature Review: *Related Work*
We reviewed related work on related design spaces and design categories for the development of user interfaces, namely public displays [206], head-up displays [108, 144] and windshield displays [108].

2 – Literature Review: *In-Car AR Use Cases*
To verify existing, remove unnecessary and add important categories found in Step 1, the literature review focused on existing in-car AR applications (Section *Literature Review*). Those existing applications were the first examples in the use case set.

3 – Focus Groups: *In-Car AR Use Cases*
We identified examples for in-car AR usage by conducting focus groups with experts from the field of AR and autonomous driving (Section *Focus Groups*). This way, we avoid missing application cases that are not yet published or developed, e.g., due to technical limitations. In the focus groups the novel use cases were sorted into the use case set of Step 2 while critically reflecting upon them.

4 – Building the Design Space
Based on the resulting use case set (Table 4.1, 4.2 and 4.3) we went step by step through the dimensions of related design spaces collected in Step 1. When going through these dimensions and discussing the applications, missing dimensions or unsuitable categories and characteristics became obvious. Some design categories were removed, enhanced, split or extended. To get a better impression of this process, we show in Figure 4.2 use cases, which are exemplarily fitted into the final design space (Figure 4.1).

4.2 Creation of the Design Space

This section describes the systematic procedure for developing the design space. We describe the previously introduced individual work steps such as literature review, focus groups and building of the design space of the methodology in detail.

4.2.1 Literature Review

We conducted a literature review using the following search terms: *hologram*, *holographic display*, *3D representation* and *S3D* and combined them with the terms: *augmented reality*, *AR* and *auto-*

Entertainment, Communication and Work		
Commercials	Commercials for products or services, e.g. promotions of stores	Display products to support buying decision and to draw attention to offers of products (P)
Economy & Costs	Economical driving and costs display	Show optimal trajectory in 3D world (D)
Work & Tasks	Information about general tasks, activities or (office) work tasks	Display route/map to visualize topography (P) Calendar with interactive elements (P) Visualize weather like clouds/ current weather in vehicle (P) Virtual keyboard (P)
Driver Mood & Status	Track the driver's status to promote a mood or physical state	Display basic requirements of single persons as a bubble over head (stress, fatigue, . . .) (P)
Education	The driver can gain knowledge or learn a specific behavior	After Take over: Show Status of traffic situation/vehicle before take over (D,C) Highlights within vehicle interaction elements that are needed (D, C, P) 360° view of the last 30 seconds to recapitulate past traffic situation (D, C, P) Sightseeing objects and information about them are displayed that one is driving past (D, C, P) Certain body movements are augmented to train the body (C, P)
Gaming	Game play alone or together with others	Board games in AR (P) Cooperative AR games with other passengers (P) Extended world, the horizon of the visualization extends over the boundaries of the vehicle (P) Virtual play partner for kids (P)
Multimedia & Web	General information; music or video player; access to the Internet or news; specific for passenger entertainment and waiting times	Entertainment interface (D, C, P) Locked interface wherever the passenger is turned to, to manipulate entertainment depending on the view direction (P) 3D world to look at (P) Extended interface cooperating with laptop, so that contents can be dragged and dropped. (P) 3D movie (P) Floating text (P) 3D AR Video Calling [155]
Arts & Photography	Picture or arts presentation, applications that enable drawing and taking photos	In Air Drawing (P) Taking pictures of situations outside and sharing them with others in the vehicle (P) Taking picture of environment as 3D picture (P)
Atmosphere	Creation of a different atmosphere in the vehicle by displaying different surroundings or ambient lights	Blend out dangers outside (P) Relaxation/reduction of information like counting sheep (P) Personal spaces during ride sharing (P) 3D curtain to block out distraction from other passengers (D, C) Visual Overlay of other vehicle passengers (P) Relaxing abstract forms that adapt to the vehicle movement (P) AR sound curtain [55]
Observation	Observation of a person, normally relatives, or an object and its state	virtual huts/routes in the mountain (P); other chosen vehicles relative to destination (D, C); Prediction and visualization of vehicle trajectory (D,C)
Social Interaction	Social interaction with other parties than drivers	Teleport friends in vehicle (P) Easier conversation with back seat, like showing kids virtually where snacks are (P) Virtual personal assistant (P) Telephone partner in AR (P)
Driver2Driver Communication	Communication with other drivers	3D avatars (vehicle, person) to communicate with other vehicles/people on the road (P) Shared interface during convoy driving to plan trip/ choose music (P)
Internet of Things	Access to or control of things	Smart Home: model of house and easy interaction, see status of connected devices/house (P)
Health	Encourage and support healthy behavior in the vehicle	AR trainer shows movements to follow (P) Virtual Sport: Sailing or Golf that adapt the movement of the vehicle (P)

Table 4.1: The use case set for entertainment applications. Each category features entries accompanied by a short title, description and examples from either related work or focus groups. The entries from related work are cited and the results from the focus group are labeled with the primary user group (D = Driver, P = Passenger, C = Co-Driver).

motive. We specifically investigated literature regarding in-car usage, hence, applications within the vehicle. To that end, we searched on the following platforms: Google Scholar [3], Springer Link [4], ACM DL [5] and IEEE Xplore DL [6]. We excluded all papers that use windows and windscreens to place applications.

4.2.2 Focus Groups

We organized a first ($N = 3$) and second ($N = 5$) focus group to find possible applications for the use case set that resulted from the literature review. In our focus groups, we had one female and seven male participants between the ages 25-35. Four were AR experts, two autonomous driving experts and two professionals working in both domains. In the first focus group, use cases were generated by a Brainwriting session [276]. To prepare for the writing, participants were introduced to the topic and several examples from related work were presented and discussed. They were told to focus on highly automated vehicles from Level 3 to Level 5. Additionally, we specifically told them to just think of use cases that do not need windows or dashboards. After finishing the writing, resulting ideas were sorted by the participants into the existing subcategories – e.g., Subcategory *View Point* in category *Safety* (see Table 4.2) – of the use case set of Haeuslschmid et al. [108]. The first focus group came up mainly with ideas in the category *Entertainment and Communication*. To create a richer set of possible use cases, the initial question in the second focus group was: *"What is important for you during a journey in the vehicle during the start (navigation), the driving on the highway/city (safety and entertainment) until the end (looking for a parking lot)?"*. Additionally the following scenario was outlined: *"Imagine you live in the year 2040. You are a designer for vehicle interiors. Your new task is to design the next vehicle's interior with focus on floating 3D AR interfaces. You have the following information: vehicle status, vehicle2vehicle information, information of the surroundings, infrastructure information and passenger information."* We then asked the participants brainwriting ideas for AR systems that address a particular user group in the vehicle. They should imagine a *"driver"* that is conducting a take over request. Then to think of the *"attentive co-pilot"* that also pays attention to the road and helps the driver. Finally they wrote concepts for a *"passive passenger"* in the vehicle. The other categories were not explained to not bias the participants towards the existing use case set. The examples from the brainwriting were discussed and similar ideas were put in relation to each other by the group. After the focus group two study supervisor compared the created clusters with the existing use case set. Further we sorted the resulting ideas in the subcategories of the use case set independently, again to find possible gaps. The focus groups lasted about 120 minutes each.

4.2.3 Building the Design Space

We identified 14 use cases for our problem space through the literature review. The focus groups resulted in 84 novel use cases for floating 3D in-car AR applications (see Tables 4.1, 4.2 and 4.3). AR applications are dominantly imaginable in the category *Entertainment and Communication* with

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[3] `https://scholar.google.com`, last access: May 2020

[4] `https://link.springer.com`, last access: May 2020

[5] `https://dl.acm.org`, last access: May 2020

[6] `https://ieeexplore.ieee.org`, last access: May 2020

Safety		
Vision Extension	Extension of the driver's view by displaying occluded objects	Using 3D AR to visualize occluded objects on the road (D,C) Visualization of approximate traffic situation (D,C) Visualization of Countdown until dangerous situation (D)
Vision Enhancement	Enhancement of the driver's vision in bad viewing or lighting conditions	Visualization of surrounding to aid with decision making in uncertain situations (D,C)
View Point	Display of the views of virtual or real cameras; often replacing mirrors	Camera image of accompanying drone in vehicle (D, C)
Spatial Awareness	Improvement of the driver's understanding of the space around the vehicle	Enlarge vehicle interior with virtual objects to see dangers further on (D) Comparison between vehicles 3D sensor model and reality by overlaying camera pictures to enhance situation awareness and give recommendation for action (D) 3D AR avatar that reacts on the environment [107] 3D representation of the highway to prepare take over request [299]
Monitoring Surroundings	Safety-relevant information about the environment	Birds-eye view of possible dangerous situation to inform about dangers and limitations and give information about route and alternatives (D) Adaptive virtual map with dynamic objects of surroundings and information about other drivers on the road (risk and aggressiveness) (D)
Driver Monitoring	Driver performance and physical state observation	Inform passengers about status (attentiveness, tiredness, aggressiveness) of driver with a 3D overlay over the driver (C)
Breakdown	They help the driver in breakdown situations	Help of virtual assistant of breakdown service (D,C,P) Block doors with virtual signs to prevent passengers from leaving through wrong door (D,C,P) 3D tutorial what to do (D,C,P)
Specific Support Systems	Systems directed at a specific party, support several tasks or provide various information	3D Highlight to focus gaze of driver on situation that requires his/her attention (D) Giving action recommendations (D) Show where hands and feet should be to steer vehicle (D) Visualization of trajectory planning and showing alternative routes in possible situation (D) Guiding of drivers attention on highly prioritized external factors (D) Co-driver guides attention of the driver on specific situation by manipulating virtual arrow (C) Visualization of intention of other drivers when they are crossing my way (D) Using an avatar of other drivers to communicate with them (D, C) AR Warning [174]

Table 4.2: The use case set for safety applications. Each category features entries accompanied by a short title, description and examples from either related work or focus groups. The entries from related work are cited and the results from the focus group are labeled with the primary user group (D = Driver, P = Passenger, C = Co-Driver).

43 examples. The use cases were clustered into five categories: Safety (see Table 4.2), Entertainment, Communication and Work (see Table 4.1), Navigation, Convenience and Vehicle Monitoring (see Table 4.3). The use cases identified by the literature review were in the category *Safety* (e.g. an AR warning [174], a 3D AR avatar [107] or a 3D representation of the highway to prepare a take over request [299]), *Vehicle Monitoring* [174, 227], *Entertainment, Communication and Work* such as a 3D AR video calling interface [155] or a sound curtain [56] and in convenience, as alternative interfaces to the dashboard [35, 36, 37, 56, 247, 304]. The category *Navigation*, includes path finding, planning and public transport. We identified the need for a category regarding *Convenience*. A similar category is also described in the work of Brandt [31] in which it is linked to the category Entertainment and Communication. The focus of the category “Convenience” in Brandt's paper is on telecommunication and radio. For a clearer separation of the use cases, we decided to separate

the categories into *Convenience* and *Entertainment and Communication*. The new subcategories in the category *Convenience* are: Well-being Aid, Load and Interface Enhancement. It also describes alternative interfaces to the dashboard [35, 36, 37, 56, 247, 304]. Exemplary use cases are related to level out bodily effects of the ride, storage of objects in the vehicle or providing alternative interfaces on surfaces. *Entertainment and Communication* relates to leisure activities in the vehicle. *Vehicle Monitoring* combines the status of the vehicle, its supervision, maintenance and fuel or battery status [174, 227]. The methodical approach of sorting exemplary use cases in the design space is clarified in Figure 4.2 and a design process is described in Section 4.4. The colored lines indicate the design categories that are used or should be considered in designing the example application. The visualization can be used to not forget about certain design alternatives during the creative process.

Defining the Targeted User Groups

The user group benefiting most of this design space are drivers of SAE Level 4 [130] vehicles or higher, attentive co-drivers and passive passengers. Drivers of SAE Level 0-3 vehicles need to observe the road and should not be distracted by floating 3D in-car AR applications [111, 126]. *Drivers of SAE Level 4* vehicles may benefit from in-car AR before the situation of a take over request occurs and while driving manually. *Attentive Co-drivers* support the driver in navigational, safety and dashboard control tasks within their range of control. *Passive Passengers* is the umbrella term for the driver who is driving autonomously, the co-driver who does not pay attention to the road and other passengers.

4.3 Design Space

This section presents the outcome of our methodological approach described in the previous section which resulted in a design space (see Figure 4.1). In the following, we describe the dimensions (e.g., *User*), categories (e.g., *User Mode*) and their characteristics (e.g., *Single User*).

4.3.1 User

We identified three user groups which are defined in the section above (*Defining The Targeted User Groups*): Drivers of SAE Level 4, Attentive Co-drivers and Passive Passengers. Resulting from those target user groups, there are three categories: User Mode, Observer and Actor.

User Mode The user mode contains *Single User* and *Multi User* as the systems can either be used alone or in cooperation with others.

Observer Users observing the system are part of our identified user groups: the *Driver*, *Attentive Co-driver* and *Passive Passenger* of a vehicle. Additionally, observers are only in this role if they are focused (either with their gaze or mind) on the application.

Actor An actor is defined as a user manipulating the interface [108]. All observers might be actors. Additionally, a remote actor can interact with the interface. For example, a service transmitting information to maintain the vehicle or a non-present colleague cooperating via a shared interface with actors inside the vehicle.

Navigation		
Path Finding	Support in finding the way to the target	Digital representation ("digital twin") of highway to visualize real-time route information (D,C)
Vehicle-Following	Support when following a vehicle	Compass that points towards vehicle to follow (D,P) Visualization of distance and status of other vehicle (D)
Traffic & Street Signs	Display of traffic signs currently applying; street signs and names	Representation of current speed limit sign (D)
Points of Interest	Additional on-route information to find people, shops or services	Visualizing map with parking spaces (D,C) Visualization of POI along the road in map (D,C,P) Preview of route highlights in AR (D,C,P)
Public Transport	Support for commuters who switch to public transportation	3D model of vehicle park/train station with visualization of walking routes (D,C,P) Visualization of time of arrival of train by displaying train model in different locations depending on time of arrival (D, C,P)
Path Planning	Support in planning the route and adjusting the route while driving when external influences force a route change	Activity planning on interactive map that notify all passengers of their tasks (C, P) Support to plan route when several passengers need to pick up by using avatars in interactive map that can be dragged & dropped (C, P)
Convenience		
Wellbeing Aid	Aids to prevent motion sickness	Abstract 3D forms and pictures to visualize vehicle kinematics (P) Inform passenger visually about routes ahead to prepare him/her for the next section of the ride (P)
Load	Everything that is related to loading the vehicle.	Luggage Tetris to visualize best packing strategy (P)
Interface Enhancement	Alternative interfaces	Interface elements in 3D (D,C,P) 3D highlight of individual interface elements and own touch zones (D,C,P) 3D AR Dashboard [35, 36, 37, 56, 247, 304] Multimodal Feedback with AR [247]
Vehicle Monitoring		
Vehicle Status	Information about vehicle parts and the momentary status of the engine	3D model of vehicle with status information and eventually statistics of vehicle functions (D,C, P) Miniature 3D model of vehicle with luminated defective parts (D,C,P) AR owner manual [227] AR vehicle status [174]
Supervision	Support in supervising the vision of the vehicle's sensors; most of them aim to increase trust	Visualize breakdown of sensors in virtual digital twin of vehicle sensors (D,C,P)
Fuel & Battery	Information about the current fuel or battery status	Status information of fuel/battery in sight (D,C,P)
Maintenance	Information of the overall status of the vehicle	3D avatar of vehicle with a character that indicates that everything is ok (D,C,P)

Table 4.3: The use case set for navigation, convenience and vehicle monitoring applications. Each category features entries accompanied by a short title, description and examples from either related work or focus groups. The entries from related work are cited and the results from the focus group are labeled with the primary user group (D = Driver, P = Passenger, C = Co-Driver).

4.3.2 Context

The *context* of use is defined as the nature of the users, tasks and equipment. Furthermore, it includes the physical, social and cultural environment in which a product is used [98, 259]. Within this dimension, there are the categories Application Purpose, Information Context, Driving Mode, Level of Automation, Privacy and Travel Time.

Application Purpose The *Application Purpose* contains the characteristics *Safety*, *Navigation*, *Vehicle Monitoring*, *Entertainment, Communication and Work* and *Convenience*. These characteristics are defined by Brandt et al. [31]. *Work* was added to the category *Entertainment and Communication* because of the possible importance of this category in autonomous driving. We added one category since we believe productive (office) work will become a relevant aspect of highly automated driving [49, 162, 229, 249]. *Navigation* includes information about the trip or path and in contrast to previous definitions, we include route planning as well.

Information Context This dimension describes factors influencing the situation in the vehicle. *Environment* includes e.g., the size of the available space inside a vehicle, the amount of seats and their orientation or people who are present. *Vehicle* considers the vehicle and its purpose, e.g., information about the engine or the vehicle type. *Personal* includes all information about a person, such as position, age or physiological data. *Time* describes the time of the day, date and season.

Driving Mode The driving modes are based on Häuslschmid et al. [108] and include *Driving*, *Waiting* and *Parking*.

Level of Automation We focus on SAE Level 4 [130] of automation. Hence the level of automation can be *Manual*, *Semi-automated* and *Autonomous*.

Privacy The privacy settings of an application can be *Public* (e.g., sports results), *Personal* (available for family or business insiders) and *Private* (only accessible for a single person) as proposed by Häuslschmid et al. [108].

Travel Time We added this category to distinguish between *short*, *medium* or *long* duration of a drive. Depending on the travel time different side effects might occur. Especially long rides require planning breaks or considering energy loading stations.

4.3.3 Visualization

In this dimension we describe relevant categories (Level of Augmentation, Registration, Placement Strategy, Field of View Position, Presentation and Graphic Design Factors) related to the visual presentation and perception of in-car AR.

User	**User Mode**	Single User	Multi User				
	Observer	Driver (SAE Level 4)	Attentive Co-Driver	Passive Passenger			
	Actor	Driver (SAE Level 4)	Attentive Co-Driver	Passenger	Remote Actor		
Context	**Application Purpose**	Safety	Navigation	Vehicle Monitoring	Entertainment, Communication and Work	Convenience	
	Information Context	Environment	Vehicle	Personal	Time		
	Driving Mode	Driving	Waiting	Parking			
	Level of Automation	Manual	Semi-automated	Autonomous			
	Privacy	Public	Personal	Private			
	Travel Time	Short duration	Medium duration	Long duration			
Visualization	**Level of Augmentation**	Reality ←	Augmented Reality	→ Virtual Reality			
	Registration	Unregistered	2D registered	3D registered			
	Placement Strategy	None	Binary	Linear	Exponential/Higher Order		
	Field of View Position	Foveal	Central	Peripheral/Ambient			
	Presentation	Symbolic ↔	Naturalistic				
	Graphic Design Factors	Color	Transparency	Size	Motion	Depth	
Interaction	**Input Modality**	Touch & Control	Gestures	Gaze	Speech	Behavior	Physiological
	Multimodal Feedback	Haptic/Tactile	Auditory	Olfactory	Sense of Balance	Temperature	
Technology	**Image Generation**	Glasses-Based Displays	Head-Worn Displays	Autostereoscopic 3D Displays	Hand-Held Displays		
	Size	Full Space	Full Dimension	Static Area	Situated	Dynamic	
	Depth	2D	Pseudo-3D	3D			
	Display Factors	Color Depth	Resolution	Contrast	Brightness	Transparency	

Figure 4.1: Design Space for In-Car AR.

Level of Augmentation In contrast to previous design spaces we do not include discrete categories such as AR and VR. We base the definition of the *Level of Augmentation* on Milgram's Mixed-Reality Continuum [198]. The Mixed-Reality Continuum is an axis with real world content on the one end and exclusively virtual content on the other end. The idea of the continuum is that an AR system can be anywhere along the axis. A designer can use this continuum to decide for the degree of virtual content presented to the user. Furthermore, Mann's Mediated Reality continuum [189] adds the idea of filtering to Milgrams concept [198].

Registration *Unregistered* visuals are placed unrelated to an physical object within the vehicle. *2D registration* is defined as being registered to an object, but not meeting its depth. *3D registration* means a positioning of elements with regards to a physical objects position and its depth. Different to previous definition [108], we do not include gaze-dependency in this category. We argue that the definition of AR registration describes a positioning of virtual objects relative to the physical world. In case of a visualization that follows the gaze, the *2D or 3D registration* changes based on the focus of the gaze. Therefore the gaze-dependency is a result of a change in the *3D registration* based on the users *input* via *gaze*.

Placement Strategy Previous work lacks in a description of the change between two points of registration, therefore we add the new category *Placement Strategy*. The placement strategy describes animations, needed to change positions of an AR object or the registration state, e.g. from 2D to 3D registration. We came up with categories based on work by Lauber et al. [161]: *None* (the former visualization stays untouched, a new one appears), *Binary* (e.g. disappearing on one spot and emerging at a new one), *Linear* (e.g. following the head movement) and *Exponential/ Higher Order* (e.g., inertia on an element when turning the head, it follows slowly, then catches up).

Field of View Position Häuslschmid et al. [108] propose the characteristics *Foveal*, *Central* and *Peripheral/Ambient* which we are using.

Presentation The Presentation of augmented reality objects can be *symbolic* (abstract) or have a *naturalistic* (real-world) appearance. There are no discrete distinctions between the characteristics, but a smooth transition with infinite states in between.

Graphic Design Factors In addition to the definition of Häuslschmid et al. [108], we add *depth* as characteristic to the category *Graphic Design Factors*. Many of the examples found in the focus groups rely on having objects in different depths available. Zooming, panning, moving and interacting with objects benefit from providing a depth dimension.

4.3.4 Interaction

Interaction with 3D AR applications can be designed by altering the following categories.

Input Modality Inputs can be triggered in an implicit or explicit manner. Implicit actions describe a reaction of the system without a conscious decision of the user, whereas explicit inputs include only informed actions of the user. *Touch & Control*, *Gestures* and *Speech* are normally used for explicit input. *Gaze* can be used for explicit input, but might also be executed without any intentions. *Behavior* and *Physiological* are mostly used to define implicit input. *Behavior* describes facial expressions, eye movements, body position and posture of the driver [206]. To avoid implicit *Gestures*, they should differ from natural movements and thus be learned. However, gestures can reflect movements used in natural interactions, such as unscrewing a bottle by turning the hand [224].

Multimodal Feedback In this category we include *Haptic/ Tactile*, *Auditory*, *Olfactory*, *Sense of Balance* and *Temperature*. The use of *tactile* feedback is well established in the domain of smartphones and could be transferred to in-car AR objects. The *sense of balance* can be activated via movements of the vehicle chassis. For example, to support virtual sports experiences such as sailing (use-case ”sailing” in Table 4.1). *Temperature* has been used as a feedback modality [301]. It could indicate points of interests on a map (e.g., feeling warm spots indicating restaurants on a map).

4.3.5 Technology

The technology used to create 3D images in a vehicle is based on an effect achieved by showing two slightly different images for each eye [184]. We refer to Billinghurst et al. [21] for more detailed information of AR technology.

Image Generation Based on previous work [35, 274, 275], we identified four suitable classification categories for in-car AR display technologies: *Glasses-Based*, *Head-Worn*, *Autostereoscopic 3D* and *Hand-Held Displays*.

Current *glasses-based* commercial products e.g., the "3D Vision 2 Wireless Glasses" by NVIDIA [7], combine a display with glasses worn by the user. The glasses separate the two stereoscopic pictures for the left and right eye respectively and often implement active shutter systems [30, 184]. Other

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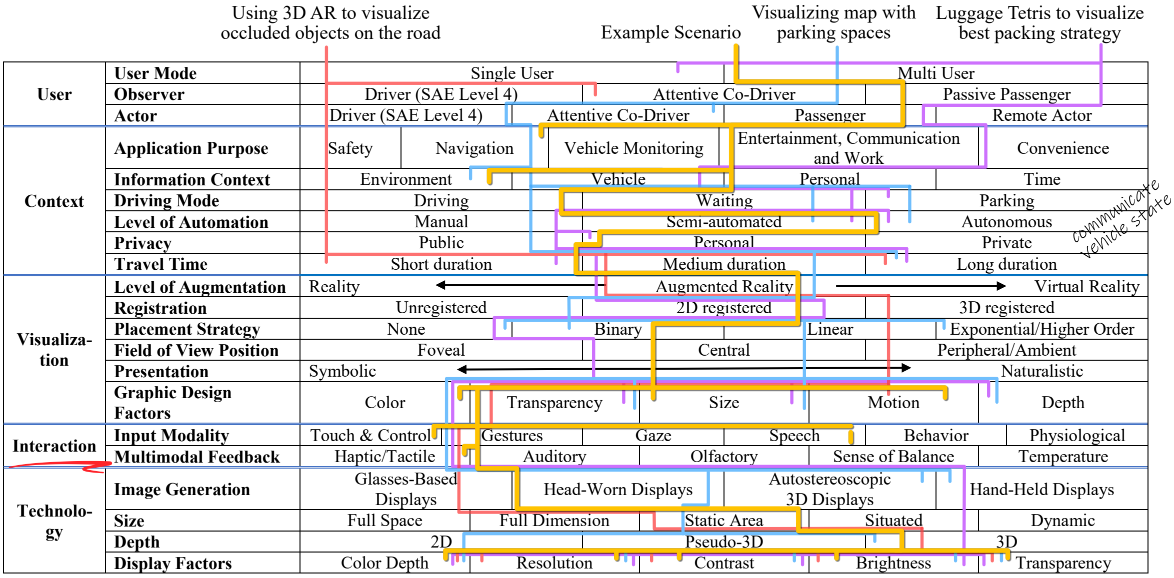
[7] `https://www.nvidia.com/object/product-geforce-3d-vision2-wireless-glasses-kit-us.html`, last access: May 2020



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	Information Context	Environment	Vehicle	Personal	Time		
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	Level of Automation	Manual	Semi-automated	Autonomous			
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	Travel Time	Short duration	Medium duration	Long duration			
Visualization	**Level of Augmentation**	Reality ←	Augmented Reality	→ Virtual Reality			
	Registration	Unregistered	2D registered	3D registered			
	Placement Strategy	None	Binary	Linear	Exponential/Higher Order		
	Field of View Position	Foveal	Central	Peripheral/Ambient			
	Presentation	Symbolic ↔ Naturalistic					
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	Multimodal Feedback	Haptic/Tactile	Auditory	Olfactory	Sense of Balance	Temperature	
Technology	**Image Generation**	Glasses-Based Displays	Head-Worn Displays	Autostereoscopic 3D Displays	Hand-Held Displays		
	Size	Full Space	Full Dimension	Static Area	Situated	Dynamic	
	Depth	2D	Pseudo-3D	3D			
	Display Factors	Color Depth	Resolution	Contrast	Brightness	Transparency	

Figure 4.2: The lines visualize the possibility to sort in and compare exemplary use cases from the use case set (Table 4.1, 4.2, 4.3). Lines crossing a field vertically indicate that it belongs to the use case. In yellow, underlain with a shadow, the line for the implication example (Section 'Example Scenario') is shown.

glasses use interference filters [140, 184] or polarization [184], to produce the 3D effect. Especially for *glasses-based* AR applications, the field of view becomes an additional factor for consideration. Current technology, such as the HoloLens or Vuzix Blade [8] enable a field of view of about 30°x17.5°(HoloLens). Designers need to understand if their chosen technology is able to comply with their field of view requirements. *Head-worn Displays* include two optical micro displays to produce a 3D experience [125, 221, 233]. Benefits are independency of the user's position and head-tracking possibilities. They can support the full spectrum of the *level of augmentation* [135, 262, 263]. *Autostereoscopic 3D Displays* show 3D images without additional devices [64, 125, 184, 274]. Well-perceivable 3D-visual effects created by such systems are restricted to a specific point of view. Additionally, they can suffer from distortion, lead to fatigue or display flipping images [9, 139, 158, 196]. Broy et al. [37] implemented a stereoscopic 3D interface in the dashboard of a vehicle and showed that it enhances the presentation of spatial information (e.g., navigational cues) compared to 2D presentations. *Hand-Held Displays* are a useful tool for implementing optical see-through applications to augment reality [202, 281].

Size The AR content can make use of the *Full Space* of the vehicle interior. Alternatively, it could cover a *Full Dimension* in one of the three spatial axes limited by the vehicles interior dimensions. AR objects could also fill any geometric *Static Area*, e.g., floating circularly inside the interior. Additional AR features could be placed contextually *Situated*. Hence, information regarding the status of the vehicle could overlay parts of a physical instrument cluster. Furthermore, the image size could actively adapt to the displayed content by using a *Dynamic* range.

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[8] `https://www.vuzix.com/products/blade-smart-glasses`, last access: May 2020

Depth Images for in-car AR features could render *2D* views e.g., for a digital speedometer, a web browser floating inside the vehicle or the top-view of a map. *Pseudo-3D* imitates depth with perspective *2D* images in a way that objects do not appear flat, but rather cubical (e.g.,[146]). Real *3D* images show a spatial illustration which has visual information in three dimensions analog to real world objects [15, 51, 128, 208]. Thus, these representations contain an explicit value for depth perception. Kulshreshth et al. present active *3D* stereoscopic rendering techniques adapting to the displayed content [153].

Display Factors The attributes *Color depth*, *Resolution*, *Contrast*, *Brightness* and *Transparency* are crucial attributes for a well perceivable illustration. The source of the image has to meet specific requirements to present a satisfying in-car user experience. Changing light conditions (day / night) and rapidly passing-by shadows are potential aspects of everyday drives and need to be considered in the design process.

4.3.6 Differentiation From Other Design Spaces

We refer to our suggested classification system as design space, although we introduce more than two dimensions and no x- or y-axis to locate content. We consider our work as a tool to enhance future developments of in-car AR, therefore it is more than a taxonomy. Also, it is not structured hierarchically. Hence, our work extends the usual appearance of a design space and could be perceived as a meta-design space with influences of common taxonomies. Our proposed design space builds upon previous work from the automotive domain and therefore has some overlapping factors [108, 144, 206]. However, we did not find similar work focusing on in-car AR. In contrast to the previous work there are manifold additional opportunities for positioning, interaction, use cases and users. With our design space we add the novel categories *travel time* and *placement strategy*. We have also significantly redefined the categories *level of augmentation*, *registration*, *graphic design factors*, *multimodal feedback*, *observer*, *actor* and *image generation* to meet the needs of in-car AR. To distinguish our design space further from others, we discuss the particular differences below:

Positioning The position of the interaction element plays a significant role for its use case. Augmented objects on the windshield force the user to actively turn towards a window. 3D AR objects can be boundlessly adapted to the user's field of view and orientation in three spatial dimensions. Therefore, our suggested design space expands beyond multiple positioning options and includes placement strategies.

Interaction Floating 3D objects are manipulated with different gestures than 2D interfaces [224]. Direct touch interaction is not recommendable for windshields applications as it would obstruct with the vision [108]. Public displays need to count on attracting the passers-by attention and need a different interaction design [206]. In-car AR demands a consideration of interaction strategies, which is reflected in this design space.

Use Cases and Users The use case set of 3D in-car AR and windshield displays both include a majority of entertainment and communication applications. However, use cases for 3D in-car AR applications are not limited to a position (e.g., windshield) and can address all passengers of a vehicle without occlusion. Especially, if the vehicle design changes in the future, the windshield might not be a point of interest anymore. For example, all seats could face each other. Use cases for in-car AR include every possible user inside of a vehicle and furthermore, could be used to digitally augment passengers or even replace empty space with people who are not present.

4.4 Usage of the Design Space

In the following section we suggest a way how to use the Design Space and motivate its validity. We intend the design space to be a tool during the creative design process that **(1)** helps to keep all dimensions in mind, **(2)** provokes an objective and thorough discussion of each design category, **(3)** supports identification of critical design categories. In the following example we will refer to these numbers, wherever the story addresses one of the prerequisites. We present a fictional scenario that showcases the ability of the design space to achieve these goals. As input we introduce personas and a user story. The aim of the fictional example is to develop a new concept for a system that enables joint planning of the drop-off point at the destination.

4.4.1 Personas and Use Case

We introduce two personas that are different in their background and abilities, still they are very likely to work together in a UX design process.

Laura is a 29-year-old UX designer that just graduated from university. She has some background in the automotive domain from lectures at university and is a specialist in the application of UX methods and user-centered design. However, she does not yet have a proper overview on technological trends and user needs when designing in-vehicle applications.

Peter is a 45-year-old computer scientist with 15 years of experience in developing for the automotive domain. He is responsible for the implementation of technology for the human machine interface in the vehicle. Throughout his working experience he gained some knowledge about UX design, however his main interest is in making things work.

Use Case Due to the current success of AR technology and the ongoing progress in the development of automated vehicles Laura and Peter are asked to think about how these two domains can complement each other. On a higher management level it was decided to work on concepts that explore collaborative route planning. When several persons drive together in a vehicle, the route is defined early on. If spontaneous alterations in the route occur due to the needs of the passengers, for example due to a sudden changed meeting point, the drop off location changes as well.

4.4.2 Example Scenario

Peter feels overwhelmed by the problem. Although, he knows a lot about the traditional driver centered interface design, he does not know yet how to approach in-car AR solutions. Laura got to know the design space for in-car AR (Figure 4.1) in her studies and introduces it to Peter. Peter has a look at it and finds a number of familiar words and categories drawing his interest. They agree to focus on the *multi user* aspect of the problem due to the prerequisites of their management. The request is to built something for a *passive passenger* as an *observer* and *actor*. To stay aware of the characteristics, they mark it in the printed out design space, which makes it visible to everybody (final result: Figure 4.2, yellow). Next they discuss the application purpose to be partly *navigation* and *communication* between the collaborators. Peter knows that navigational tasks can benefit from switching view points, e.g., from a birds view to a perspective view, as not everybody is able to read a 2D map. Peter then starts with a lecture about interaction design for a 2D map. Laura, agreeing with the idea of changing the viewpoint, interrupts Peter. She reminds him to stick to the higher level of the previously decided *multi user* aspects **(1)**. They decide that the tool is used while *driving* in the *autonomous* vehicle. They make a note on the side of the design space to keep in mind the communication of the vehicle state to passengers, as there is no *driver* performing this action. In the category *privacy*, they get stuck in their discussion. Peter argues that *privacy* is never an issue as people in the vehicle know each other and are willing to share information. Laura highlights that they do not really know yet about the usage of the vehicle. What if the users are sitting in an autonomous taxi that they share with strangers, a *public* context. Peter and Laura agree that this is a critical, not yet decided design factor and needs clarification **(3)**. As they are short on time, they decide to design for a group of friends going to a festival willing to share *personal* data. Two friends want to go to the tent area first while the other two want to go directly to the concert. To take full advantage of 3D AR, Laura suggests that festival organizers could already provide a 3D map of the campsite. By exploring the amenities and the distance to the concerts, discussion between the friends can be improved. The *travel time* will be *short*, requiring a quick and easy system setup and strong decision support. To make it fast and easy to use, it should be part of the vehicles infrastructure to prevent connectivity problems and a setup of external devices. To speed up the decision making process, Peter is thinking about an application that has the *personal* preferences of the single user. The system also knows the time to arrive at the destination and the input of one user that requests a change towards a specific drop off location. Based on this information the system will provide three alternatives for planning the route and parking, which reduces the negotiation time. After having decided the structural boundaries for the system, they proceed with designing the implementation by starting with decisions on the *visualization*. *Augmented reality* would be ideal, as the passengers can still see each other and discuss on a common map. *Virtual reality*, Peter explains, could provide advanced spatial knowledge about the destination, but would hinder interaction as it covers the wearer's face **(2)**. A *2D registration* is ideal to position a map *centrally*. A shared display influences interior design decisions because it requires users to be able to rotate towards each other. To ensure that everybody is able to see the display the system might need information about the *environment* and add a tick to *information context* **(1)**.

A *placement strategy* might be used to blend between the 2D representation of a map and a 3D point of view image to support spatial knowledge for the desired destination. The *presentation* style should have two levels as it is common from other navigational tools. To make a clear distinction they plan to change from a symbolic visualization to more a naturalistic one in a *binary* way. All *graphic design factors* should be optimized for best viewing conditions in the diverse automotive everyday context. In particular, motion and color could be used to support the group awareness about who requested a change and the three alternative destinations the system suggests.

They decide for *touch* and *gestures* as *input modality* and use well known interaction metaphors. Laura had sorted in other concepts for in-car AR experiences beforehand (Figure 4.2). Hence she suggests to distinguish the input modality from competitors, by adding *behavioral* input **(2)**. For example, as the time frame for the decision is short, the system could detect the single users attention by tracking gaze or head orientation. Peter doubts the practical usefulness of this input modality and suggests to collect more information on this design category. They speculate that *haptic* feedback will be used to support single users interaction with the display. In contrast, *auditory* sound can be used to communicate system states through space that are important to everyone. However, they postpone the detailed work on the interaction and underline it red in the design space (Figure 4.2) **(3)**.

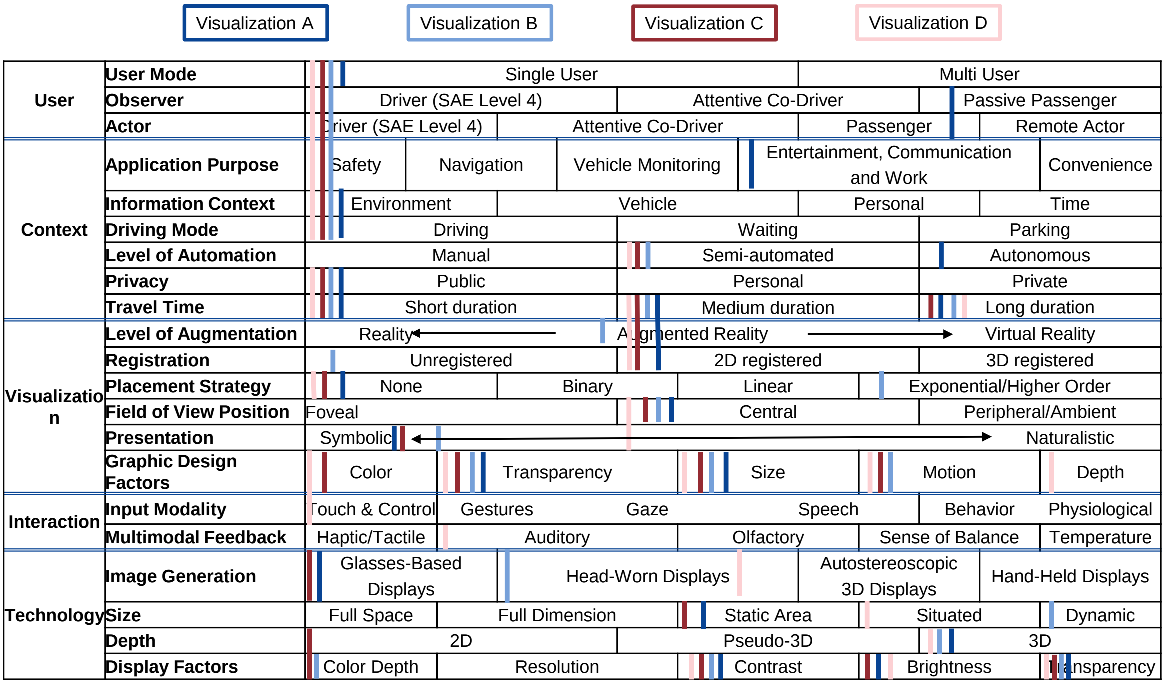
To support spatial awareness at the destination, they want to have the possibility to present *3D* images. Peter says that *autostereoscopic 3D displays* are feasible however, they are limited in the number of possible users **(2)**. Therefore they should focus on the integration of *head-worn displays* within a *static area* of the vehicle. The *display factors*, he says are not of major importance for a possible prototype.

Laura is happy with their progress, as it provides a focused description of the system specifications. In a further step she will process the results and create some storyboards showcasing possible design solutions, within the decided characteristics of the system (Figure 4.2, yellow).

4.5 Experience with the Design Process

In the course of the thesis different applications were designed for which the design space was relevant. In Section 5.1 we designed an application that is displayed in AR glasses that shows a warning to prepare the driver of an upcoming take over request. With a floating stereoscopic 3D representation of the highway in Section 5.2 drivers can inform themselves of an upcoming critical traffic situation. The next visualization in Section 5.3 shows hints in a HUD on out-of-view objects. Finally, the design in Section 6.2 presented an explanation to the driver on the windshield. Further information and pictures on the designs can be found in the corresponding chapters. While not all fit in the problem space of the design space for in-car 3D augmented reality applications, the design dimensions are also suitable for applications that use windscreens to display information. All design dimensions of the corresponding design are sketched in Figure 4.3.

While most categories are the same for all designs, there are some outliers. One design (Explanations in Unexpected Driving Situations(Section 6.2)) is aimed for autonomous vehicles, therefore the application purpose differs. Another design (Trust (Section 5.1)) is implemented in AR glasses, therefore the registration or image generation differs. While using the design space, we experienced that through the design process, the purpose was clarified and the limitations have been explored. Nevertheless, designing applications on paper can face complications. For example, when designing for the AR glasses, it was crucial to know the possibilities regarding the field of view. We expected the application to have the potential to visualize in a dimension, similar to windscreens. Since the dimension of the visualization was much smaller than expected, we had to change the design accordingly. Especially when designing for new technology, it is beneficial to first explore the possibilities through practical testing.



User	User Mode	Single User	Multi User				
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	Depth	2D	Pseudo-3D	3D			
	Display Factors	Color Depth	Resolution	Contrast	Brightness	Transparency	

Figure 4.3: Classification of the design spaces of the visualization implemented in this thesis: Visualization A: Explanations in Unexpected Driving Situations (Section 6.2), Visualization B: AR Warnings in a Take Over Request (Section 5.1), Visualization C: Out-of-View Visualization (Section 5.3), Visualization D: Visualization in Stereoscopic 3D (Section 5.2). The colored lines indicate the category that is suitable and most important to consider for the corresponding implementation.

4.6 Discussion

Although research of in-car AR is very limited, previous work on automotive interface design gives us a strong foundation to base this work on. Thereby, we were enabled to transfer and expand insights from other design spaces into an AR-centered design space. We took great care in creating a use case set covering a large field of applications. To this end, we conducted focus groups with experts from AR and automotive domains. The design space can be used as a source of inspiration and to discover gaps of ideas in the current development. Although some use cases can be implemented on other devices, we aim to encourage new interactions with new technologies. However, some design dimensions might not be complete yet. In the course of time, new ideas develop during the practical use of these systems, which lead to applications that may not yet be known to us. For example, bodily effects such as motion sickness in context of AR are still under research. We do not restrain the creation of ideas by reporting current technological limitations, but foster the curiosity to search for the latest trends. The design space is an initial step towards supporting the ideation for novel prototypes. However, we are aware that it might need to be expanded in the future, since design spaces are partial and are subject to change with future technological developments. Due to the limited related work, the design space is mainly based on examples derived from focus groups. The approach of setting up a design space , based on theoretical application possibilities, is exceptional, therefore, this methodology extends the concept of a design space.

4.7 Lessons Learned

The main motivation for this chapter was the exploration of designs for applications for driver and passengers of autonomous vehicles with the possibility to connect the vehicle to the infrastructure or other vehicles. The considerations of existing design spaces and the identification of a design space gap for in-car 3D AR applications, led to further exploration of this knowledge gap. Autonomous vehicles hold the potential for new interactions and unexplored interaction areas. The target group interacting in certain areas could change and thereby the interface changes accordingly. By providing a design space for in-car 3D AR applications, the design creation for applications in autonomous vehicles can be supported and developed in a structured way.

We derive the design space from a comprehensive literature review and 84 novel AR application cases from focus groups. Our results are based on previous knowledge reported in taxonomies and design spaces from the design of vehicle interiors and AR systems. The work on use cases for applications in 3D AR showed that many of those applications need information from the infrastructure, connected vehicles or a stable and fast network connection, but also travel companions, traveling with each other. In our opinion, providing this to autonomous vehicle users is essential to enhance the experience when using in-car 3D AR. This work helps people from all professional backgrounds to develop, analyze and report in-car 3D AR applications.

In this work, we discuss similarities and differences between our use case set and previous work on user interfaces, HUDs and windshield displays and we identify the design parameters that we expect to be of primary importance for in-car AR applications. Using a fictional application example, we validated the design space and show the advantages and the applicability of it when used in a real world design process. Nevertheless, we are certain that the design space will evolve in time when more AR applications are implemented and different categories emerge.

A lesson learned was that the consideration of different design dimensions was necessary and helpful to identify correlations and constraints between dimensions. The concrete development of the details of a design dimensions is best assessed by collaboration. By discussing about it, but also questioning the necessity, different aspects occur and become relevant. For example the necessity for the category *Convenience* became apparent by discussing the difference of it, to the category *Entertainment, Communication and Work*. Designing for an application is not straightforward and problems rather surface by discussing the different aspects of application designs. A design space helps to have a structured approach and to get back on track when deviation in the design processes occur. Especially the constraints of some design dimensions became apparent. If one wants to design a rather active application, that requires a high mobility, the limited degree of freedom must be taken into account, resulting in compromises that need to be made.

By being open about the potential applications, we did not limit the technological applicability, resulting in a very diverse use case set for different user groups. This provides enough space to potentially change and further develop the design space.
To conclude, the main lessons from this work were:

- **Explore every possible design dimension with discussions**
  By design space reflection and exploration, the dimensions increase their validity and meaning.

- **Work with the constraints of the design**
  The constraints of some designs can result in creative solutions. At the same time, by identifying the constraints, impossible or impractical designs can be avoided.

- **Stay open for designs with technical limitations**
  Even though some use cases seem to be not yet relevant with the current technology, new ideas and design encourage solutions that overcome technological limitations. Therefore, in the first step it should not be prioritized to develop with existing technological solutions only.

- **Use user stories to explore and reflect upon the design space**
  User stories help to think of every aspect of a certain design and to put yourself in the place of the designer. With user stories, an imagined design process identifies missing dimensions and constraints and verifies the existing design space.

5

Out-of-View Visualization of Highly Automated Vehicles in Augmented Reality

Due to better sensors and smart infrastructure information, which gathers traffic data, it will be possible to inform drivers about critical situations that are outside their field of view. Out-of-view visualization is common in several fields such as virtual reality, gaming or aviation, for example with minimaps, object overlay or traffic collision avoidance system (TCAS) [10, 141, 232, 314]. Current highly automated vehicles have a limited sensor detection range. Drivers are informed in a display about the environment, vehicles in the surroundings, the current lane or navigational cues. Situations that are farther away, are not detected by the vehicle.

Smart infrastructure can have a significant impact on the information available to drivers in critical situations. It enhances the identification of the surroundings of vehicles and traffic situations that are not in the own vehicle's sensor range [92, 112, 207, 212]. Connected vehicles get traffic information that is not in close proximity of the vehicle, but might be even several kilometers away. Smart infrastructure can also detect occluded vehicles that are for example around the corner of a house, and thus drivers can be informed about their position, distance and velocity.

On the one hand information about situations that need an immediate reaction, for example in case of events in close proximity of the vehicle, can be provided. And on the other hand, smart infrastructure can provide information on which the driver does not need to react immediately on (non-urgent situations). Depending on the desired reaction of the driver and the automation level of the vehicle, the provided information can have different level of urgency. In both cases, imminent critical situations that require the drivers attention, and non-urgent situations, such as an upcoming flexible construction site, drivers can be informed of the location, context and focus of attention.

For non-urgent situations some considerations need to be taken into account. Drivers can be prepared by giving more information without the need for an instant reaction. In those situations, they have more time and mental resources to prepare the take over request, which leads to a more informed driving decision. When communicating context information, a particular focus should be put on increasing the situation awareness of a driver with it. With good situation awareness, the driver knows the status of the vehicle, where it is located in reference to other vehicles, the velocity of the own and surrounding vehicles, and can also predict the next steps of the surrounding traffic [72]. With good situation awareness it is therefore possible to drive adapted to the situation or to perform better in a take over situation [93, 278, 312]. For a safe take over request drivers have to shift their attention from being immersed in a secondary task to taking over control of the vehicle. Required information for taking over control, like the necessity for an emergency braking, has to be presented effectively.

However, in case of drivers not seeing the cause of a warning, they might not trust the information from the system, take the warning seriously or react adequately on that information. On the one hand, the driving quality depends on the time before a reaction is needed [93, 197, 203]. On the other hand, warning the driver too early, can result in the situation resolving itself or warning the driver of too many scenarios at once. This can cause frustration and loss of trust in the system. Therefore, it is important to find a balance between informing drivers early on, providing enough information about problems, but also to not overload the driver, since this could reduce the driving performance [188].

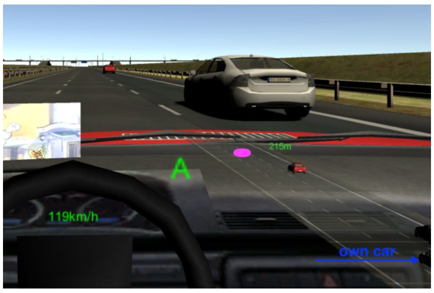
In this chapter, it is assumed that drivers still need to take over control of the vehicle, therefore SAE Level 3 [130] of autonomous driving is considered. The implications of fully autonomous vehicles are considered in Chapter 6. Within all sections in this chapter, the potential of visualizations that indicate critical traffic situations and the driver's benefit thereof are explored. Many researchers rather focus on the optimal take over time and getting the driver as quickly as possible back in control of the vehicle [93, 197, 203]. Different to that, we include augmented reality information of an early warning in a take over scenario. We implemented several visualizations that prepared drivers with information about a upcoming situation. First, we focused on how to visualize that information. We evaluated, if the performance improves, and if the situation awareness increases by providing the driver with a representation of the highway. Next, we conveyed information about the critical situation in a non-intrusive manner. Since secondary task become more likely when driving autonomously, drivers may want to stay immersed in this task. With this visualization it is possible to get hints about upcoming take over situations in a HUD.

We contribute with this chapter a concept of a 3D AR representation of the highway for smart infrastructure information to improve the take over performance and an evaluation of design concepts for early warnings on head-up displays to improve situation awareness.

This chapter is divided in the following sections:

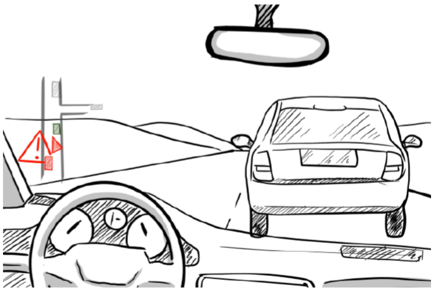
Sketching Context to Improve the Trust in the Driving Decision

The first aspect to consider is how smart infrastructure warnings and information can be conveyed to drivers. In Section 5.1 we investigate how to sketch context information and to prepare drivers for upcoming critical situations. In an informal case study, consisting of one survey and two studies, we examined how to visualize and interact with situation information from the highway.



Preparing Take Over Requests in a Stereoscopic 3D Representation

In Section 5.2 the concept of providing driver with highway information before the actual TOR is investigated. We provided participants with a miniature digital twin in stereoscopic 3D which showed upcoming critical situations and tested the TOR for performance, workload and user experience. The representation enabled participants to react earlier and the performance of the TOR was improved.



Visualizations that Look Beyond
In Section 5.3 a visualization in the windshield that prepares drivers for upcoming take over maneuvers is explored. The visualization gives hints on upcoming possibly critical situations and other traffic participants in some distance. Three visualization concepts were tested for situation awareness, user experience and performance. Wedge visualization had the best situation awareness score, but overall a symbol visualization resulted in the best performance.

5.1 Sketching Context to Improve the Trust in the Driving Decision

In the following, we explore visualizations that inform drivers of situations that are outside their current view. In Chapter 3 we identified drivers as a user group for infrastructure information. We do not know yet how smart infrastructure information can be presented to them and how to convey context information. For example, when an accident is detected, this information could be communicated, including the number of vehicles involved, the lane on which the accident occurred and if a traffic jam is forming. Furthermore, it is not clear if participants use context information to make an informed driving decision. This information needs to be conveyed to drivers in an understandable and trustworthy manner. Building trust is important to establish acceptance for systems, and presenting information about upcoming traffic situations in AR can increase this trust. To explore the potential problem space, we first prototyped visualizations and explored the potential of presenting smart infrastructure information early on.

In an informal case study, we explore visualization schemes and presented participants implementations in AR glasses. This section is organized as follows: First, we implemented critical situations in a simulation environment. Then, we sketched possible warnings and distinguished between sketch, picture and video of the situation that could be displayed to drivers. In the next step, in Section 5.1.1, we implemented a warning using AR glasses to prepare drivers for a potential take over request.

Simulating Critical Situations In the initial step to provide users with context visualization of traffic situations, we first implemented possible critical situations in visualizations in a simulation environment (see Figure 5.1). This digital twin, a digital representation of the whole highway, is simulated with Carmaker[1], in which traffic objects, for example, trucks, vehicles, pedestrians or traffic signs such as velocity limitation or gantries can be simulated. The traffic objects are assigned with attributes, such as autonomous driving, length, velocity or braking behavior. In this simulation environment, traffic situations can be prototyped. With these visualizations, a better understanding of possible visualizations is build.

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[1] `https://ipg-automotive.com/products-services/simulation-software/carmaker/`, last access April 2020

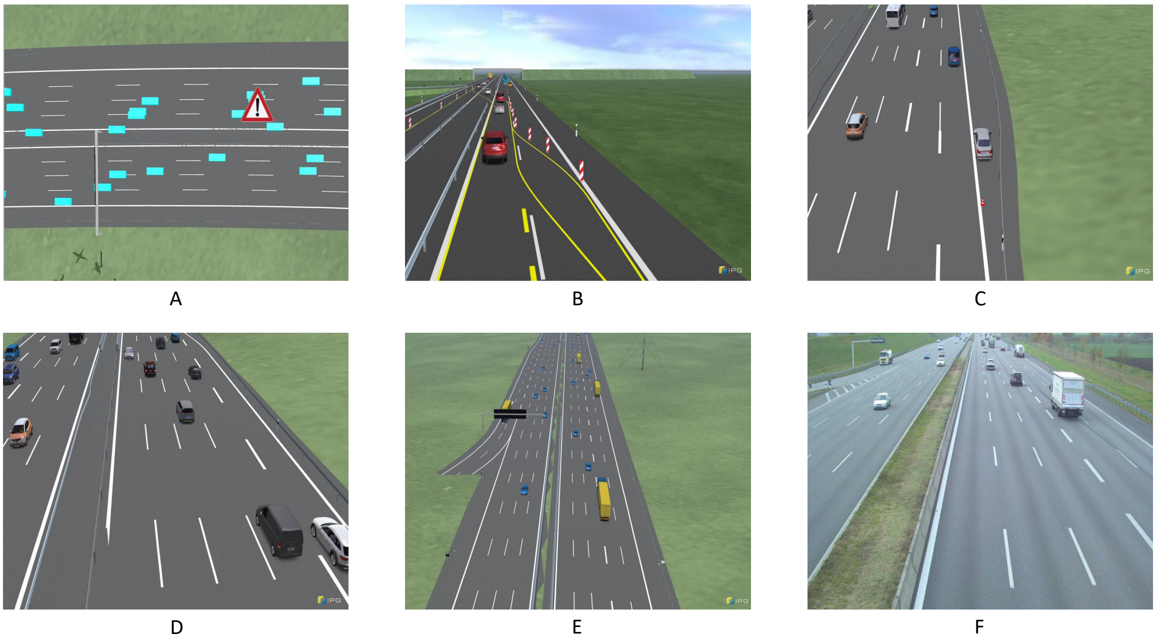

Figure 5.1: Example use cases and prototypes of the digital twin of the highway. A: Birds eye view with warning symbol, B: Construction site, C: Standing vehicle on the side shoulder, D: Beginning of a traffic jam, E: Simulated traffic scene, F: Real image of traffic scene in E.

Context Visualizations in a Sketch

> *This section is supported by the semester project of Antoine Poppe and Ahmed Zitoun. Please refer to the beginning of this thesis for a detailed statement of collaboration.*

The use cases of the stakeholder (see Chapter 3) led to the conclusion that with smart infrastructure information, drivers could inform themselves about upcoming critical traffic situations long before it was necessary to react. Therefore, complex visualizations and information could be taken into account to inform driver. We chose the six scenarios identified in Section 3.1.2 to evaluate the type of context presentation: bad weather, merging on highway, ghost driver, fast vehicle from behind, standing vehicle and abrupt braking. Some established visualizations from those situations exist, for some we sketched the situation (see Figure 5.2). In an evaluation we asked participants (N = 8), if they understood those visualizations. We asked them, what happened in those situations and in what kind of distance the scenario took place.

Next, with the resulting feedback, we sketched possible context information on paper and asked participants (N = 20) which condition they preferred. We had three conditions: symbolic presentation, pictures combined with a symbolic presentation and a short video of the scenario with a symbolic presentation. The pictures and videos were taken from the previous implementation of traffic situations in the simulation environment.

Overall, the symbolic presentation was preferred by 46.72% of the participants. The video presentation was favored least (18.06%). The visualization of the ghost driver was not well understood, in this scenario the symbol had the same preference rating as the video (28.60%), but the most preferred visualization for this scenario was the picture combined with a symbol. We can derive from this that overall the sketched context information have a good acceptance among the participants. We used those findings in the next step to implement a scenario of an accident in a simulation environment and implement a warning thereof in AR glasses.

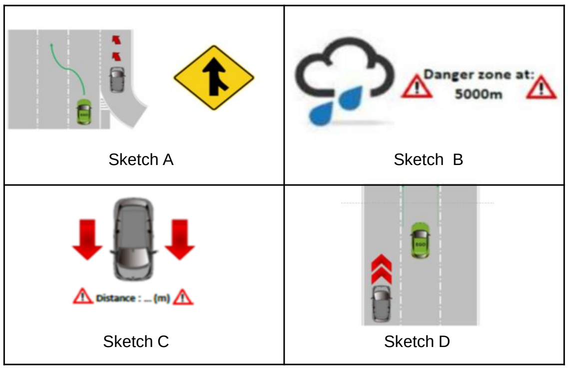

Figure 5.2: Sketches for visualizations of critical situations: Sketch A: Merging, Sketch B: Bad Weather, Sketch C: Ghost Driver, Sketch D: Fast vehicle from behind.

5.1.1 AR Warnings in a Take Over Request

This section is supported by the Bachelor's thesis of Dominik Hiemer. Please refer to the beginning of this thesis for a detailed statement of collaboration.

[2] In a pre-study to derive a visualization that can later be used to warn drivers of an upcoming critical scenario, we just visualized different warnings in AR glasses. Eleven participants tested six warning visualizations of an accident in AR glasses. Two visualizations were in 2D, two visualizations in 3D and two visualizations were animated, one in 2D, the other in 3D. The not animated visualizations can be seen in Figure 5.3. The warning consisted of the information that an accident occured due to bad weather. In the animated visualization, the vehicle drove to the accident and then changed lane. The bad weather was animated rain. These sketches of scenario visualizations were then presented to participants in a HoloLens. We asked the participants how they would react when seeing this visualization. In the vertical visualization, 72.7% of the participants would change the lane, whereas in the horizontal visualization, overall 63.6% of the participants would change the lane. 54.5% of the participants stated that the animated vehicle did not help their understanding of the accident situation. 33% of the participants did not understand the animated rain. 90.9% of the participants found it harder to understand the visualization in 2D Overall, this evaluation confirmed our assumption that the best visualization to convey context information would be the 3D vertical visualization. We conducted a study to explore, if the visualization of an accident scene increases trust in the vehicle.

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[2] *This section is supported by the Bachelor's thesis of Dominik Hiemer. Please refer to the beginning of this thesis for a detailed statement of collaboration.*

Method:

The independent variable were the visualizations in the AR glasses. The first condition was the baseline. The participant watched a video as a secondary task for 40 seconds. Then the video disappears and after 10 seconds, a TOR is initiated and the participant takes over control of the vehicle. In the second condition, the participant also drives autonomously for 40 seconds, then the 3D vertical visualization of the accident is displayed in the HoloLens for 10 seconds. Then a TOR is initiated. The dependent variable is the trust in the vehicle. 20 participants (f = 8, m = 12, 19-76 years) took part in the study. The study was conducted in a driving simulator with one monitor. The simulation environment was Unity 3D (Version 2017.3.0f3). Before the study, the participants were asked on a 6 point Likert scale if they generally trusted autonomous systems, if they would enter an autonomous vehicle and if they would hand over control to the autonomous vehicle. Then they got accustomed to driving in a driving simulator by testing it without the HoloLens. After the conditions, we asked six questions on a 6 point Likert scale (1-not at all, 6-extremely) based on the trust evaluation of Jian et al. [136]. The two questions that evaluated distrust were: *I am suspicious of the system's intent, action or outputs* and *The system's actions will have a harmful or injurious outcome*. The four questions that answer the trust in the system were: *I am familiar with the system*, *The system provides security*, *The system is reliable* and *I can trust the system.*

Additionally the participants answered for which system they trusted themselves most, to take over control of the vehicle successfully and safely. Furthermore, if their trust increased through the system, for which drive they had the feeling to take over control of the vehicle safest and if their driving behavior is improved through the visualization on the HoloLens.

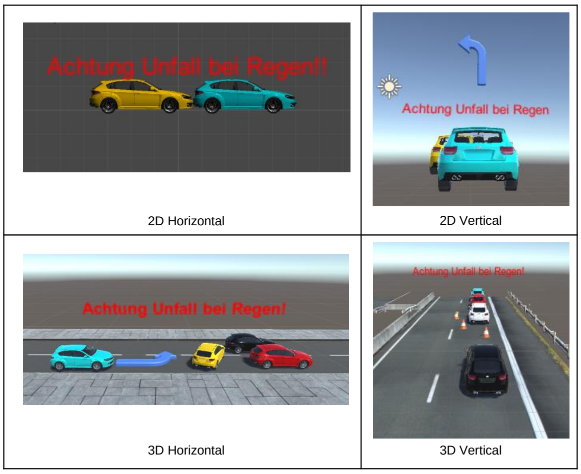

Figure 5.3: Visualizations of warning drivers of accidents with context information in AR.

Results: Before the study, 50% of the participants generally did not trust autonomous systems (SD = 0.51). They preferred to keep the control of the vehicle. One participant was unsure if the system would react as well as a human driver. The participants that trusted the autonomous vehicle mentioned the advantage of saving time with autonomous vehicles. One participant mentioned that s/he would just trust autonomous systems if it was 100% reliable and that in case of an accident the liability for damages would be clear. The data for the trust score is not normally distributed, tested with the Kolmogorov-Smirnov test (p=0.98). The average scale for trust was with the visualization at 4.53

points (IQR = 2) and at 4.26 points (IQR = 2) without a visualization. A paired T-test revealed statistical difference in the trust scales between the two conditions (p<0.001). In the end of the study, 85% ($\sigma = 0.51$) of the participants indicated that they trust the system.

This study indicated that a visualization of a traffic scenario could improve trust in autonomous vehicles. We gained insights in visualizations of scenarios and the effects of AR glasses during a take over situation.

5.2 Preparing Take Over Requests in a Stereoscopic 3D Representation

This section is based on the following publication:

- Gesa Wiegand, Christian Mai, Yuanting Liu, and Heinrich Hußmann. 2018. Early Take-Over Preparation in Stereoscopic 3D. *In Adjunct Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (AutomotiveUI '18).

This section is supported by the Master's thesis of Hua Wentao. Please refer to the beginning of this thesis for a detailed statement of collaboration.

From the previous section, we learned that context information, such as a ghost driver on the highway, is difficult to visualize without overwhelming the driver. Take over requests (TORs) are issued in case of critical situations ahead or in case of system limitations of the autonomous vehicle. Due to sensor limitations and the detection of a critical situation, the driver needs to react quickly on an issued take over request. This section focuses on the driving situation before the TOR, so the preparation phase. A novel output interface is presented, to prepare the driver of a TOR. It is investigated, if a floating 3D AR representation (or S3D) of the real traffic situation within the cockpit, improves the driver's take over performance.

In industry, the goal to include a 3D representation in the vehicle is a comfortable and intuitive interaction with the vehicle[3]. By visualizing the traffic situation in a bird's-eye view, the driver is able to assess the appropriate driving trajectory or route. By displaying an as accurately as possible representation of the highway the driver gets more information about possible limitations on the road. We put a focus on conveying context information without limiting the amount of provided information. This means, drivers get an accurate and complete representation of the highway with the possibility to interact with it. This representation is called digital twin in the following. With this representation of the digital twin it is possible to change the viewpoint of the highway, jump to critical situations, get distance information of the critical event to the own vehicle and an overview of other vehicles on the highway. For construction sites, it would then be possible to get an overview of the construction site, its length and active construction site vehicles. Furthermore, it is possible to inquire if a traffic jam is starting, the extend of it and if it makes sense to change the route.

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[3] `https://www.continental.com/en/press/press-releases/2019-06-11-3d-instrument-cluster-174836`, last access May 2020

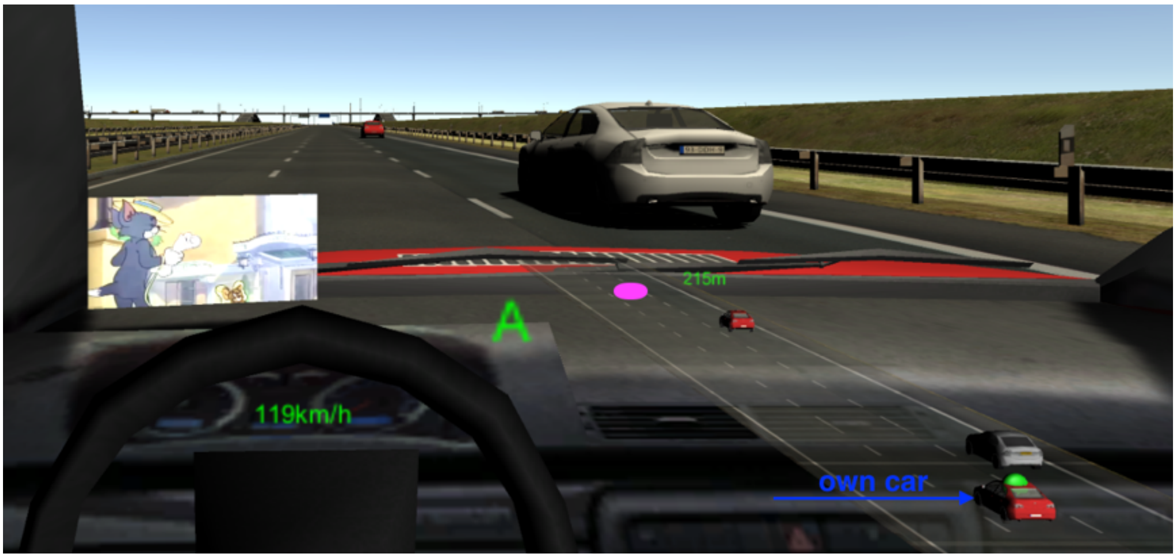

Figure 5.4: VR Cockpit with digital twin and representation of the own vehicle. The secondary task, which is used in the study is placed near the A-Pillar, above the steering wheel. The digital twin is floating above the gearshift in between driver and passenger. Within it, one can see the surrounding traffic situation. The green A indicates the autonomous mode.

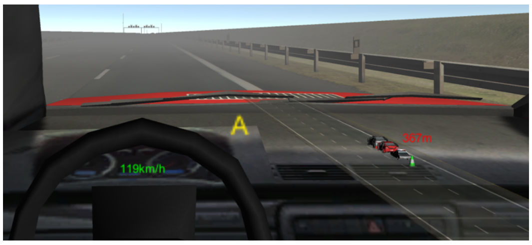

Figure 5.5: Pre-Warning of accident on own lane. The mode indication turns yellow since a take over request is imminent.

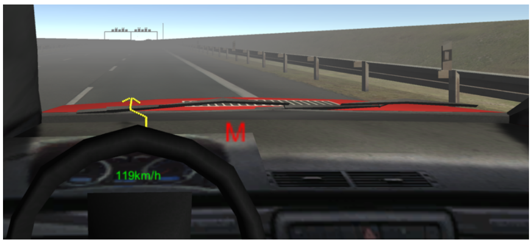

Figure 5.6: Take over request with video task turned off, the proposed driving trajectory is display next to the manual mode indication.

By showing the driver an accurate traffic representation, the driver is able to get more information to plan the driving trajectory of the vehicle. The following study considers a vehicle with SAE Level 3 automation [130]. Most of the time, the vehicle drives autonomously, but the driver needs to take over the vehicle if the autonomous system fails.

We present a study to increase situational awareness and thus improving the driving trajectory planning. With this study, we assess the workload, usability and performance when using the representation of the highway.

5.2.1 Method

A study (N = 20), comparing the proposed system to a system without a possibility to foresee the situation, was conducted to gain insights into driving performance and workload of drivers. The digital twin appeared before the take over request. A possible reason for a take over request, such as bad weather or an object on the road, is displayed in the digital twin. Drivers can interact with the digital twin before a take over request to inform themselves about the traffic situation on the highway.

To test the system there were two conditions that the participants experienced. One condition served as a baseline and no digital twin was displayed. The second condition (S3D Visualization Condition) included the AR representation of the highway. To eliminate possible learning effects due to this setup the participants were divided up into two groups. Both groups get the same introduction to the setup. Group 1 experienced the baseline condition first and then the S3D Visualization condition and for Group 2 the order is reversed. Both groups did a preliminary driving test to get used to the system. The study is designed as a within-subject study, so every participant performed both driving tasks. The system was evaluated by the NASA TLX [113] questionnaire and an acceptance scale questionnaire [157]. To evaluate the effect of the system on the driving behavior, the steering wheel angle, velocity and the position of the vehicle were tracked.

Participants

20 participants (f = 8, m = 12) with a mean age of 25.3 (STD = 2.2) took part in the study. Most (80%) have a driving license and one to three years of driving experience. 60% of the participants never used VR glasses.

Apparatus

To be able to simulate the S3D interface and for an easier implementation, the study was conducted using a VR head-mounted display based driving simulator. Within the VR environment, the driver sits in the cockpit of a highly automated vehicle. Inside the cockpit of the vehicle an AR representation of the highway is displayed above the gearshift (see Figure 5.4). The digital twin displays a sector of the highway the own vehicle is driving on. The driver can move the section in the digital twin forwards and backwards by pressing a button. They can center the digital twin again on their vehicle if they want to focus on the situation around the own vehicle. The distance of the current sector of the highway to the own vehicle is shown as a floating digit next to the highway. The virtual environment was set up using Unity 3D (Version 2017.3.0f3)[4].

Procedure

Before the study, the participants signed consent to collect their data. Then they filled in a demographic questionnaire. During the introduction the AR representation of the highway and the functions of the setup were explained. In the next step, the take over process was explained. The S3D representation of the highway was displayed to drivers before they needed to take over the driving task (Figure 5.4). They could scroll through the whole traffic situation and change the view to get an overview of the current situation on the highway. With the distance information, the driver knew where the possibly dangerous situation was in respect to the own vehicle. After informing the driver of the highway situation with the S3D (Figure 5.5) the TOR itself is executed (Figure 5.6). The take over time was set to 10 seconds. Within the study there were four phases:

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[4] `https://unity.com/`, last accessed May 2020

1. Autonomous Driving During this phase the vehicle controls the steering. The driver concentrates on the secondary task. The secondary task consists of watching a movie and counting objects within the movie.

2. Information Phase This phase begins by a sound to inform the driver that the digital twin is displayed. Drivers can interact with it and thus inform themselves about the current traffic situation. The secondary task is not available to the driver anymore. This phase lasts 10 seconds.

3. Take Over Phase A take over request is issued when the own vehicle has a time to collision (TTC) of 10 seconds. A warning sound initiates this phase, and the driver is prompted to take over the steering wheel. At the end of the take over phase, the digital twin disappears.

4. Manual Driving After the driver regains control of the vehicle, the driver needs to decide on the driving maneuver. To avoid a collision with the objects on the road, the participant needs to change lanes.

After getting used to driving in the simulations, participants experienced the following conditions:

Condition Baseline	**Condition S3D Visualization**
The first driving test is the baseline of the study. The driving phases consist of Phase 1 - Phase 3 - Phase 4.	During the S3D Visualization condition the introduced system is used. Different to the baseline condition, an additional phase is added. The driver experiences Phase 1 - Phase 2 - Phase 3 - Phase 4.

After every condition, the dependent variables were measured through a questionnaire.

5.2.2 Results

In the course of this study, the performance during the take over maneuver, the workload of the participants and their user experience was assessed. In the following we present the results of the study. To assess the significance of the results a paired t-test, Friedman test [200] and Wilcoxon Signed-Rank Test [236] is used.

Take Over Performance

We compared the driven trajectory of the baseline and the S3D visualization. To assess the driven trajectory, the lateral lane position is recorded. As the driving task requires the driver to change the lane the objection was to drive on the lane without the obstruction on the road. In the S3D condition the lateral lane positions were generally closer to the lane without an object (Mean = -108.31, SD = 1.15) and results obtained by a t-Test revealed a significant difference between the baseline condition (Mean = -109.51, Sd = 1.08) and the S3D condition (p = 0.04). Additionally the steering wheel angle of the driving maneuver was recorded. This gives us information about the steering behavior of the driver, like uncontrolled or smoother lane changes. Though the S3D condition has overall smaller values with a mean of 10.24° and a SD of 4.82° and the baseline condition has higher values with a mean of 15.86° and a SD of 8.45°, the p-value indicates no significant difference between the two conditions. As a third evaluation measure the speed was taken into account. The speed in the S3D condition was lower (Mean = 3.82 m/s, SD = 5.93 m/s) than the baseline condition (Mean = 8.63 m/s, SD = 10.72 m/s), which indicates that the user adapted the speed earlier and more appropriately with the S3D visualization. The p-value of a t-Test is 0.04, indicating significant differences in the speed values in both conditions.

Workload and User Experience

The workload of the system was assessed using the NASA TLX (see Figure 5.7) on a 20-point Likert scale. The temporal demand of the S3D condition is highest (Mean = 7.65, SD = 5.27), which indicates that the participants needed to spend time on the digital twin to understand the digital representation. The biggest difference between both tests is the effort value (Baseline condition: Mean = 11, SD = 1.02; S3D condition: Mean = 5.6, SD = 4.86). That could be an indication that the digital twin mentally prepares the driver better on the TOR and thus lessens the effort of the TOR. We tested the data on significance with a Friedman test [200], since the data is not normally distributed (tested with the Kolmogorov-Smirnov test [63]). The measurement scales of mental demand ($\tilde{\chi}^2(1) = 7.2$, p = 0.007), performance ($\tilde{\chi}^2(1) = 4$, p = 0.046), effort ($\tilde{\chi}^2(1) = 14.22$, p = 0.0002) and the overall measure ($\tilde{\chi}^2(1) = 11.84$, p = 0.0006) show a significant difference between the two tests. The Wilcoxon Signed-Rank test confirms the statistical significance (mental demand (p-value = 0.007), performance (p = 0.037), effort (p = 0.0004), overall measure (p = 0.02314)). The S3D condition has a lower score in most measures and performs better than the baseline condition.

The acceptance scale is used to analyze the acceptance of the digital twin. The acceptance is measured by evaluating the usefulness and satisfaction scale. Participants have a positive attitude towards the digital twin with a mean of 1.06 (SD = 0.76) in the usefulness and a mean of 1.16 (SD = 0.80) in the satisfaction scale. One remark of a participant indicated that the understanding was better, when a TOR was issued and in assessing the proper point of time to take over the vehicle with the S3D visualization.

5.2.3 Discussion

The results show that a visualization of the digital representation of the highway can improve the driving performance. The driven trajectory was significantly improved by the S3D visualization compared to the baseline. Furthermore, the speed was significantly lower with the S3D visualization. Drivers adapt their speed earlier and more appropriately with a S3D visualization. Additionally, the workload is significantly lower regarding the mental demand, performance, effort and the overall measure. The participants generally have a high acceptance of the S3D visualization. Overall it can be concluded that a digital twin in S3D does prepare drivers of upcoming take over requests. This results in a more foresighted, safer driving.

Limitations In this study it is assumed that the driver has enough time to interact with the digital representation of the highway and that therefore, an overview of the traffic situation can be gained. While the overview completely represents all traffic objects, the placement of it forces the driver to look away from the road. If drivers need to take over control of the vehicle, first they need to turn towards the steering wheel again. Therefore, this visualization would just be beneficial if drivers have enough time to react on the critical situation. It is questionable that a digital twin would be very helpful in case of a high frequency of take over requests.

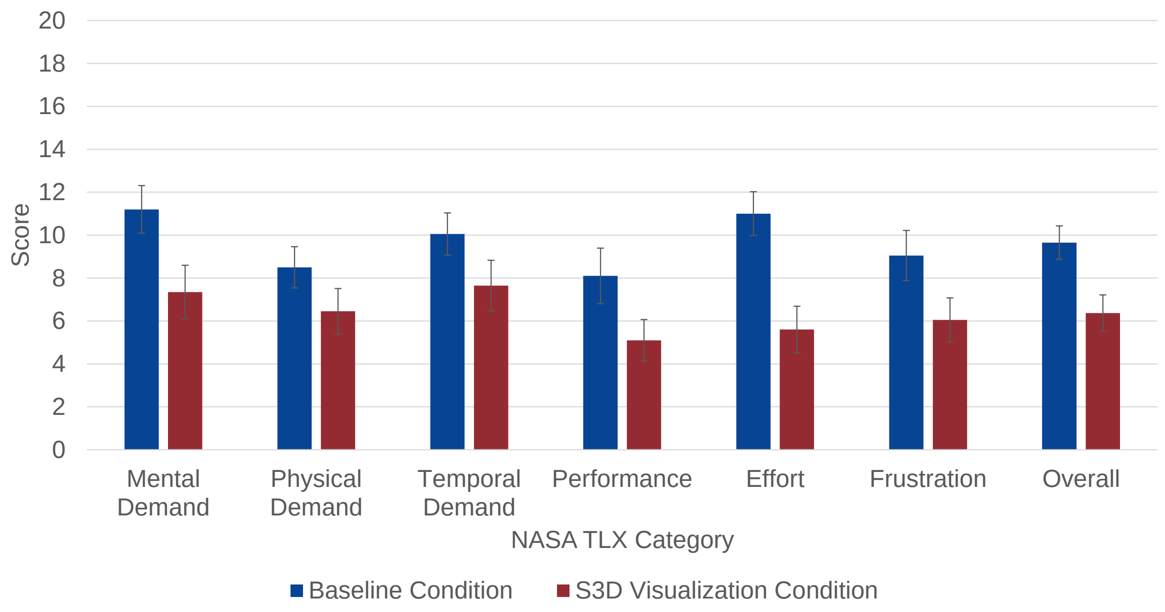

Figure 5.7: Workload scores of the NASA TLX. The error bars show the standard error of each category.

With an automated detection of critical events, drivers could still inform themselves about the critical situation, how the situation looks like and how the traffic is reacting upon it. Emergency vehicles could get information, if a rescue lane is formed, if other emergency vehicles are on their way and the location of the accident.

Nevertheless, for smart infrastructure representations for drivers, many questions remain. For example, if it is possible to increase the situation awareness of drivers in a more non-intrusive manner, without having a complicated real world representation. The digital twin is not abstracted and the context information needs to be derived from the representation itself. In the next section, we therefore look at abstract visualizations of upcoming situations that indicate that a critical situation is ahead.

5.3 Visualizations that Look Beyond

This section is based on the following publication (submitted to AutoUI'20):

- Gesa Wiegand, Beatrice Sax and Heinrich Hußmann. 2020. Looking Beyond the Visible: Exploring Out-of-View Visualizations in Cars. *Submitted to WiP Adjunct Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (AutomotiveUI '20).

This section is supported by the Bachelor's thesis of Beatrice Sax. Please refer to the beginning of this thesis for a detailed statement of collaboration.

In the previous section we explored to prepare the driver of a take over request with a digital representation of the highway. While this approach is valid in some cases, in other cases, in which the driver quickly needs to take over control, other visualizations are more appropriate. While environment information is implemented in most current vehicles, in which the own vehicle and surrounding vehicles are displayed, smart infrastructure offers the possibility to visualize vehicles that are further away.

The challenge that remains, is visualizing the vehicles in a non-intrusive way without loosing distance information or how the vehicles could influence the own driving behavior. When not using a digital twin to display all vehicles in the surrounding, out-of-view visualizations could offer the possibility to give hints on vehicles and possible critical events. The goal of this section is a visualization that delivers environment information in an understandable manner to improve situation awareness.

To identify, which visualizations are best to increase situation awareness in situations in which the cause of the warning is outside the view of the driver, we design a warning interface. That conveys the information of a dangerous situation outside the view of the driver. The hypothesis is that by informing the driver of the surroundings, situation awareness can be improved. In the last section we showed that driving performance is already improved by a digital representation of the highway, therefore, we hypothesis that situation awareness can be improved as well.

To test this hypothesis, we first set up a scenario catalog (see Table 5.1) to identify the possible use cases and constraints, such as the time the driver needs to be able to brake in time. To get an understanding of possible visualization concepts in situations in which the driver is warned early of dangerous situations, we analyzed existing prototypes in automotive and other domains. Furthermore, we conducted two focus groups (N = 9) in which we asked participants to sketch a visualization. Next, we implemented four different visualizations and conducted a study (N = 24). The visualizations were examined according to their improvement in situation awareness, workload via the NASA TLX [113], System Usability Scale (SUS) [34] and the braking performance of the participants.

5.3.1 Identification of Visualizations

Our objective is to find a visualization that informs about a dangerous traffic scenario out of the driver's view that increases situation awareness. In four steps we approached the identification of possible warning visualizations:

ID	Scenario Description	Short distance	Long distance
1	Letting vehicles merge	x	
2	Traffic jam on exit		x
3	Detailed traffic jam information		x
4	Warning of obstacles on the road	x	x
5	Warning of accidents	x	x
6	Early formation of a rescue lane	x	x
7	Warning of fast cars	x	
8	Instructions for zip merging	x	
9	Road condition	x	x
10	Improving awareness in bad visual conditions	x	
11	Exit planning	x	
12	Braking cascade	x	
13	Warning of a vehicle that suddenly shears out	x	
14	Early warning of slow driving cars in the middle lane	x	x
15	Foresighted driving to reduce fuel consumption and emissions	x	x
16	General anticipatory driving in relation to other road users	x	x
17	Warning of defective vehicle/non-reactive user/Safe Stop	x	x
18	A look ahead over the hilltop ahead	x	
19	Lane - Departure - Warning for legacy cars	x	
20	Wildlife crossing detection	x	x
21	Warning of vehicles on released hard shoulder	x	x
22	Capturing information of mobile traffic signs	x	
23	Persons (on bridge) throwing objects onto the carriageway	x	x
24	Early lane change in case of an obstacle on the road		x

Table 5.1: Scenario catalog in which the scenarios are sorted in ones that are relevant for warnings in short and long distances.

1. Set up a scenario catalog
2. Collect visualization ideas through literature review and two focus groups (N = 9)
3. Test prototypes in a pre-study
4. Implement the visualizations and conduct a study in a driving simulator

Scenario Catalog A scenario catalog of 24 scenarios was set up, of highway scenarios that infrastructure sensors could detect and the driver could be warned about early on. We got these scenarios from two brainstorming sessions with experts, working in infrastructure projects (N = 4, m = 3, f = 1). The participants were between 25 to 35 years of age. The scenarios were sorted in those that the user can be warned of early on (in a distance of more than approximately 5 minutes) and those to which the driver should respond more directly (approximately 2-5 minutes). The scenario catalog gives an outlook, on the potential of the early warning visualizations, but is just a first draft and can be extended over time.

Focus Groups and Literature Review To develop a new visualization concept of objects and traffic participants that are outside the visual periphery of the driver, we conducted a literature review and two focus groups. The literature review revealed concepts to visualize objects that are outside the periphery of the user in augmented reality (AR) or virtual reality [26, 100, 252]. Most computer games use minimaps to give the player an overview of the surroundings and visualize objects in some

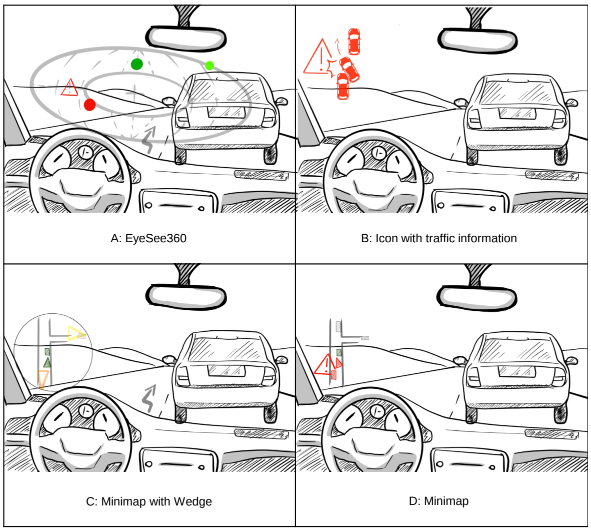

Figure 5.8: Sketches for the pre-study.

distance [178]. In the further course of the work we concentrated on the results and visualization ideas of wedges [106], EyeSee360 [99] and arrows [252]. In two focus groups we collected visualization methods for driving scenarios that are outside the view of the driver. One focus group (N = 6) consisted of non experts, the other (N = 4) of design students. We wanted to explore different ideas from experts and non experts and chose the focus groups accordingly. The participants were between 20 and 35 years of age. We started the focus group by showing a video of a vehicle that needs to do an emergency braking because vehicles in the front do an unexpected lane change. Next the participants made a sketch, how they would warn the driver in this situation, with manually driven vehicles in mind. Then we varied the distance of the scenario to see if the sketch would differ if the driver had more time to react on this situation with highly automated vehicles in mind. In the end there was an open discussion about possible different modalities, uncertainty visualizations and if drivers should even get the information about situations that are further away. The participants identified six cockpit elements(e.g. Steering Wheel, Sound or Light), nine different visual methods (e.g. arrow on vehicle ahead, ghost overlay on windshield display (WSD), bird's-eye view of scenario), 19 overall methods to warn the driver (e.g. colored WSD framing, red flashing or pump seat upright) and three different warning modalities (e.g. Vision). A warning symbol was mentioned most often. Most participants sketched some sort of environmental model or minimap in which the scenario can be visualized. Others sketched information on the whole windscreen or used the frame of the windscreen for displaying the location of the object.

Pre-Study In a pre-study (N = 9) we sketched possible visualizations (see Figure 5.8) to collect opinions on those. Five paper prototypes visualized a minimap, icons, wedge, EyeSee360 and a combination of the minimap and the wedge. Each paper prototype consisted of three frames, which should reflect a period of about 30 seconds to show dynamic functions of the interface components. The participants were asked to rate the visualizations on a 5-point Likert scale, where 5 was the best score. The minimap got the highest and the EyeSee360 visualization got the lowest score. The icons and the combination of minimap and wedge got good results (3.44 and 3.33 points). The wedge got

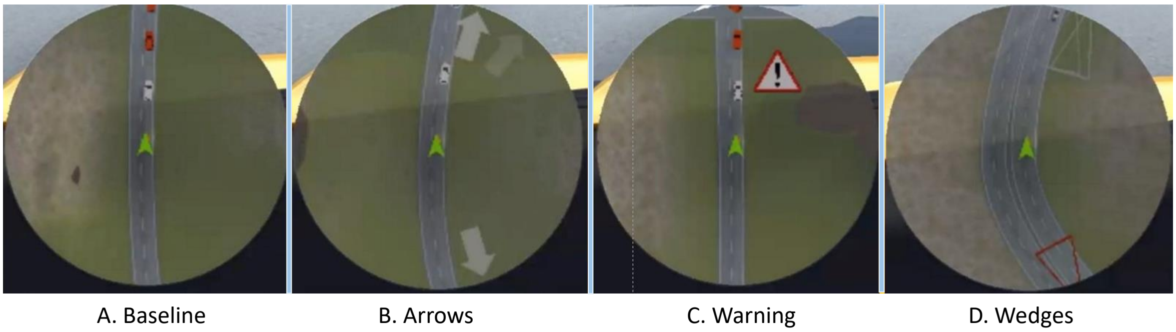

Figure 5.9: Implemented visualizations, from left to right: Baseline, Arrows, Symbol, Wedge.

a rating of 2.67. Due to the 2D inanimate visualization the participants had difficulties to understand the concept of the EyeSee360 visualization. Based on the feedback we got from the participants we decided not to use the EyeSee360 visualization in the following study, but to implement the minimap, wedges, a warning symbol and arrows. With those visualizations the distance of the scenario could be visualized, the urgency and in case of the wedge and the arrows the location of the other traffic participants.

5.3.2 Method

After defining and implementing the scenarios, we conducted a study to evaluate the visualizations. The dependent variables were workload, situation awareness, system usability scale and performance. We used a within-subject design with visualization as the only independent variable resulting in four conditions. The conditions are counterbalanced by a latin square design, so all participants had differently ordered visualizations. The study lasted about 30 minutes per participant. We concentrated in this study on scenarios that are in closer proximity of the driver, but are occluded or out of the view of the driver. We determined two key scenarios from the scenario catalog (see Table 5.1) that were used in the study: 1) Fast vehicle from behind 2) Braking cascade. We chose those scenarios since the participants can relate to those scenarios easily and since both scenarios result in many accidents or traffic jams on the highway. These two scenarios were implemented two times, but slightly differently to avoid learning effects. In the first two scenarios is a fast vehicle, invisible to the driver, either from behind or the front. The own vehicle would try to overtake the front vehicle resulting in an accident. Therefore, the participant needs to brake to prevent it. Those braking incidents were recorded. In the other two scenarios, there is a braking cascade which is caused on two different intersections. The participant would need to brake to prevent an accident. In the baseline visualization just the minimap is displayed. The minimap shows the environment of the own vehicle from a top down view with a radius of about 25 m. The own vehicle is marked with an arrow. In case of a dangerous scenario that requires braking action from the participant, the involved vehicles are colored red. Using this as the baseline of the visualizations, we add the different visualizations on top. First, we add arrows on the side of the minimap. They point towards the vehicles in the distance and change the color in case of a dangerous action of that vehicle. The next interface shows a warning sign in case of a dangerous situation. The last interface is similar to the visualization with the arrows and displays wedges that indicate the position of other traffic participants. All participants drove through eight scenarios and tested four visualizations: baseline, wedge, arrow and symbol (see Figure 5.9).

Figure 5.10: Driving simulator in the study setup.

Participants In the study we had 24 participants (f = 11, m = 13). All participants had a driver license. 13 participants had much experience with video games and 14 participants had experience with VR glasses.

Apparatus The study was conducted in a driving simulator (see Figure 5.10). The simulation environment was Unity 2019.2.8f[5]. The scenarios were shown on three screens in front of the vehicle. The visualizations were placed on the windscreen in front of the driver. Thereby it is directly connected to the primary driving task such as maneuvering and reacting to critical situations [268]. The participant was able to brake in case of a dangerous situation.

Procedure Before the study, the participants filled in a data protection sheet and the questionnaire. Then the participants drove first through two scenarios with one of the four visualizations. The two scenarios consisted of one of the two variants of the scenario of a fast vehicle approaching and of one of the two variants of the braking cascade. All scenarios lasted until shortly before the time to collision was zero. Then just a black screen was shown. To assess the situation awareness we did not show the resulting possible accident. After driving through two scenarios with one of the four visualizations the participants assessed the system usability scale, workload and situation awareness. This was repeated for all visualizations.

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[5] `https://unity.com/`, last accessed May 2020

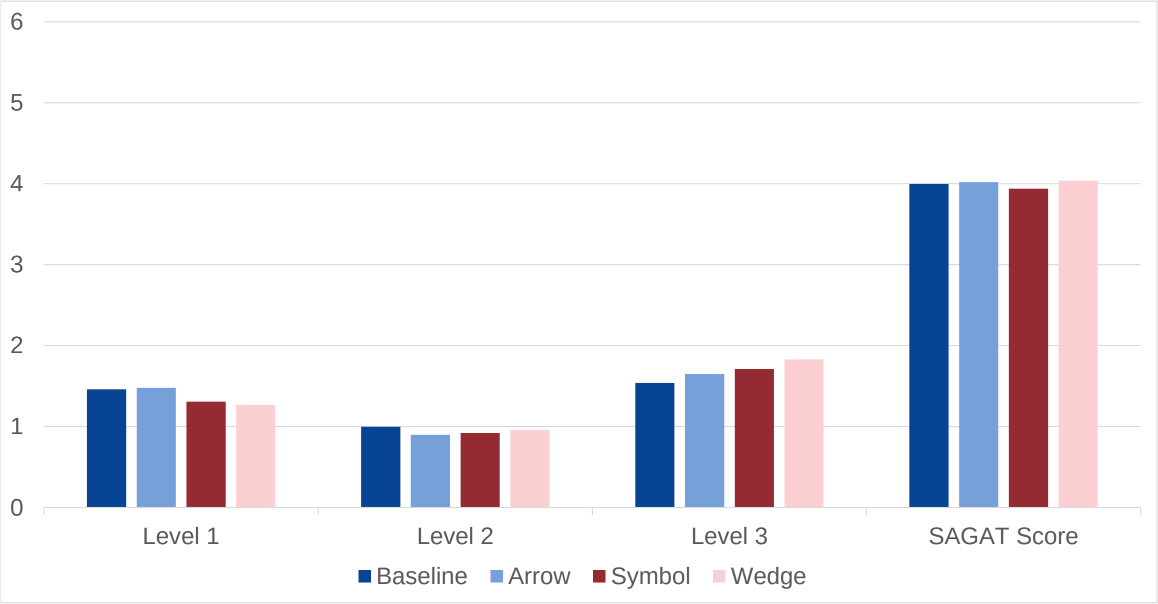


Figure 5.11: Situation Awareness Levels and overall SAGAT score.

5.3.3 Results

The study was assessed according to the participant's situation awareness, workload, system usability and performance. We first tested the data on normal distribution with the Kolmogorov-Smirnov Test [63]. The data for the situation awareness, workload, system usability and the braking times is not normally distributed. Therefore, we used the Wilcoxon Signed-Rank Test [236] to test for significance in the results.

Situation Awareness Situation Awareness (SA) is assessed by using SAGAT, measuring each level of SA by two questions. We asked about the positions of the other traffic participants and the color of their vehicle (Level 1), about the distance to the other traffic participants (Level 2) and about the future driving behavior of the own vehicle and of the traffic scenario (Level 3). Altogether six questions were asked. From the participant we took the mean of the answer concerning the level of situation awareness. Then we had one value for each participant for each of the three levels of SA. We tested the significance of the differences of the conditions for each level (see Figure 5.11). For the third level, there are some significant differences: symbol (Mean = 1.71, IQR = 0.5) between baseline (Mean = 1.52, IQR = 0)((p = 0.04), wedge (Mean = 1.83, IQR = 0.5) and arrow (Mean = 1.65, IQR = 0.5) (p = 0.04) and wedge and baseline (p = 0.001) Participants were more aware of the surroundings and the future development of the scenario with the wedge visualization.

Workload We tested the workload (see Figure 5.12) for statistical difference between the conditions. The subjective workload was highest with the wedge visualization (Mean = 31.35, IQR= 27.5) and lowest with the symbol (Mean = 23.61, IQR = 24.17). This difference is statistically significant (p = 0.012). The baseline (Mean = 25.76, IQR = 17.08) was second highest, followed by the arrow

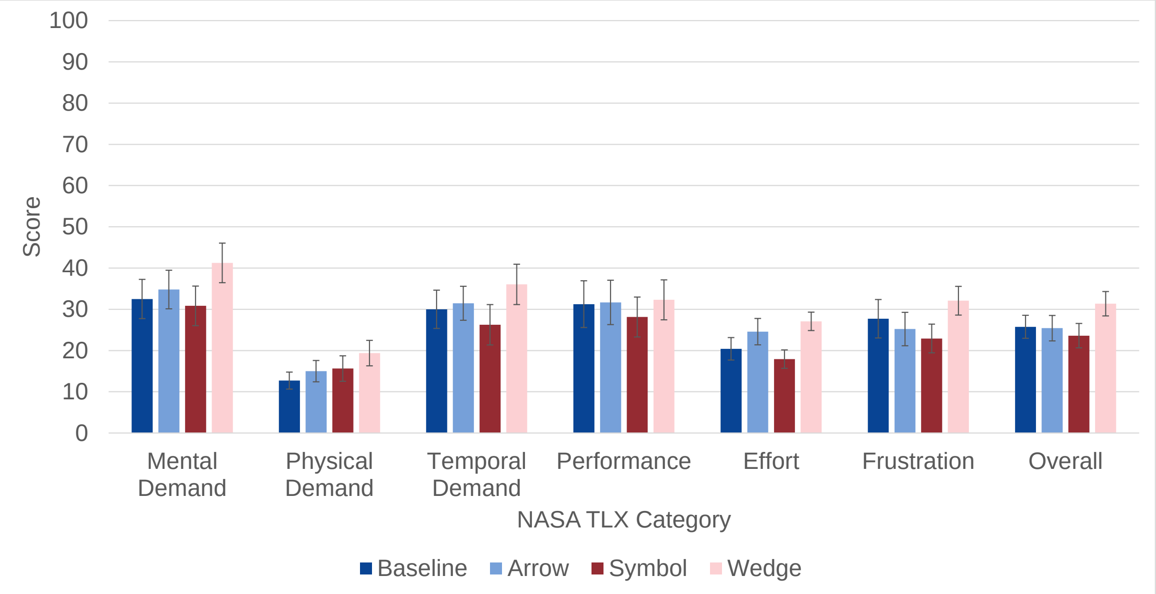


Figure 5.12: NASA TLX Scores. The error bars show the standard error.

visualization (Mean = 25.42, IQR = 23.75). Looking at the data, the cause for the statistical difference between symbol and wedge is revealed. The mental demand of symbol (Mean = 30.83, IQR = 45) and wedge (Mean = 41.25, IQR = 46.25) is statistical different (p = 0.03). Furthermore, the temporal demand between symbol (Mean = 26.25, IQR = 32.5) and wedge (Mean = 36.04, IQR = 47.5) is statistically different (p = 0.04) . The effort of symbol (Mean = 17.92, IQR = 15) and wedge (Mean = 27.08, IQR = 31.25) is statistically different (p = 0.009). The physical demand between wedge (Mean = 19.38, IQR = 21.25) and baseline (Mean = 12.71, IQR = 10) is also statistically different (p = 0.04). Between symbol (Mean = 17.92, IQR = 15) and arrow (Mean = 24.58, IQR = 25) and wedge (Mean = 27.08, IQR = 31.25) and baseline (Mean = 20.42, IQR = 20), the effort is statistically different (p = 0.01 and p = 0.03).

The results indicate that the wedge visualization requires more workload from the driver to understand than with the symbol condition. The low NASA TLX value for the symbol can be explained by the previous experience of the participants of what to expect when seeing the warning sign. There is a trend towards a higher workload of the baseline compared to the symbol. That can be explained as upon seeing the baseline visualization, the participants still have to put some effort into interpreting the visualization. Since the baseline visualization did not show much more information compared to the observation of the environment it could be rather distracting to the driver to observe the Minimap visualization. This could lead to the conclusion that the Minimap should be more minimalistic to be less distracting.

Usability The usability, measured by the SUS, of the symbol was highest (see Figure 5.13). Since scores above 80% indicate good to excellent usability, the baseline visualization also has an excellent usability score. We tested the SUS Scores on differences between the conditions. The Friedman test [200] revealed significant differences between the conditions ($\tilde{\chi}^2(3) = 11.88$, p = 0.007).

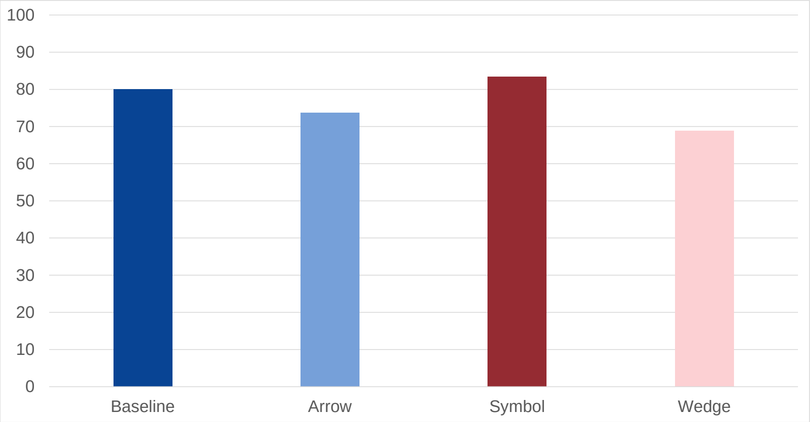


Figure 5.13: System Usability Score.

There is a significant difference between symbol (Mean = 83.4, IQR = 8.75) and wedge (Mean = 68.8, IQR = 15.63) with p = 0.002 and wedge and baseline (Mean = 80.1, IQR = 17.5) with p = 0.05. This was also mirrored in the feedback of the participants who thought that wedges are not easy to use.

Performance The performance was measured by tracking the braking behavior of the participants. We calculated the braking time with the mean time of the two conditions with one visualization. If no brake was applied in one condition, just the condition with braking time was considered. We had to exclude the data from participants in which the braking time was more than 5 seconds before the optimal braking time or the standard deviation of the data was more than three times the mean. Then we assume the braking incident was not relevant to the scenario. The braking times indicate the time to the optimal braking point, at which an accident can still be prevented. A negative number indicates that the participants braked earlier than the optimal braking point. The moment at which braking is required to prevent a collision is zero. The braking times were the following: baseline (Mean = 0.725 s, IQR = 1), arrow (Mean = 0.6 s, IQR = 1.13), symbol (0.35 s, IQR = 1) and wedge (Mean = 0.6 s, IQR = 1.13). We used the Friedman test to test for significance. The braking times are not statistically significant ($\tilde{\chi}^2(3) = 2.2931$, p = 0.51). Nevertheless, on average the point of time for braking is later than the optimal braking time. In the baseline condition the participants brake latest.

5.3.4 Discussion

The key findings of the study can be summarized by following: A wedge visualization had the best situation awareness score, indicating that better situation awareness can be achieved. Furthermore, established visualizations such as a warning sign overall perform best. By informing drivers of their surroundings we assumed that the situation awareness could be improved. There was a statistically significant effect of the wedge compared to the symbol visualization. So even if the score for wedge for the system usability was low, the situation awareness could be improved by indicating early on the location and distance to a dangerous situation. Therefore, further research is needed, but our results are promising that especially situation awareness can be improved by combining the environment map with other visualizations. Although the SUS was quite low for visualizations in which the participants had to interpret the required action themselves, such as arrow and wedge, it would benefit the situation awareness to indicate a problematic situation on the road.

A warning symbol indicates that immediate action is required, but if the transmitted information is not urgent it would cause stress to get the attention of the driver with a warning symbol. Smart infrastructure enables information about scenarios that are further along the route and therefore do not need immediate attention. It would be even safety critical if a mere information would be misunderstood as a safety critical warning, resulting for example in sudden braking that could lead to an accident. Therefore an increased focus should be put on improving the system usability and workload of the visualizations that indicate location and distance of other out of view objects. Since there is much potential of displaying information in future vehicles, for example through windshield displays, new visualization concepts can help providing information about traffic situations outside the periphery of the driver.

5.4 Lessons Learned

The goal of the research presented in this chapter is to understand how information from a smart infrastructure can aid drivers to improve their driving performance during take over maneuvers. Thus, the fundamental underlying questions that we answer are:

Does warning with smart infrastructure information differ from warnings from the sensor system of the own vehicle? How does it differ? Is it better than warning the driver with just vehicle sensor information?

To answer these questions, in section 5.1 we explored visualizations that convey information from smart infrastructure or connected vehicles to the driver. There is no one-fits-it all solution for visualizing context information of traffic scenarios. It is possible that symbols for certain traffic situations need to be learned, as it is the case with many traffic signs. In section 5.2 the driver was informed of the current traffic situation and the possible reason to take over the vehicle in a stereoscopic 3D interface within the vehicle. The performance, workload and user experience was measured. The participants drove slower with a visualization of the upcoming traffic scene, and the lateral lane position was closer to the lane without an object. The overall workload of the system with visualization was lower and the participants had a positive attitude towards the visualization. In section 5.3 we collected possible scenarios in a scenario catalog. With this scenario catalog we categorized the scenarios according to the urgency of a warning. Then, we focused on the design of warnings of objects that are outside the periphery of the driver. We compared the warnings by measuring situation awareness, workload, system usability and braking performance. With that we can show that a symbol visualization resulted in the highest usability and the lowest workload, whereas using wedge resulted in the best situation awareness. Through the study we show that well known symbols outperform not established symbols. For a visualization to result in a high situation awareness as well as a high usability, both aspects need to be combined. The discussed attributes gave insight on the user's preferences of visualizations of situations that are outside the view of the driver and with the collected knowledge in the sections we can answer the fundamental questions from the beginning.

Warnings with smart infrastructure information are different to those that are based on the own vehicle's sensor information. Warning drivers with smart infrastructure information differs in some cases from warning them with information derived from the immediate surrounding of the vehicle. With the scenario catalog we explored the potential of the situations in which smart infrastructure warnings can be presented to drivers depending on the distance to the critical situation. From this, we can conclude that not in all critical situations the warning would differ from warnings with just vehicle sensors. In case a short reaction time is needed, the warning should warn the driver efficiently. In case the critical situation is further away, the warning can be presented differently. Drivers can get more context information, for example, information how certain the smart infrastructure is that this situation will not resolve itself by the time the vehicle arrives. Especially warnings with the color red should be avoided since participants are trained to react immediately on that color. With the smart infrastructure, the traffic situation on the highway can be rated. The number of vehicles and their velocities can be tracked. With much traffic, the situation can be estimated as more stressful for the driver therefore the warning and information can be adapted accordingly. Depending on the stress level of the driver the warning can be personalized with influencing factors such as the maneuver of the own vehicle or neighboring vehicles, weather and other environment factors.

Warning with smart infrastructure information differs regarding reaction time, urgency and content. Drivers that are warned with smart infrastructure information do not need to react immediately, but can first increase their situation awareness with the information provided to them. The warnings differ regarding warnings that need immediate action and can alert the driver in a more non-intrusive manner. With the preparation of the upcoming critical traffic situation, more context of the situation can be provided to the driver.

Warning drivers with smart infrastructure information is better than warning the driver just with vehicle information. The conducted studies that we performed showed that the take over performance can be improved by early visualizations of upcoming critical situations. With the adjustable degree of context information, drivers can choose for themselves, how much context information they need and want. For semi-autonomous vehicles in which it is still necessary to take over the control of the vehicle, the context information can also be provided to the driver, but the distraction from it can not lessen the driving performance. In this situation, the context information needs to be presented intuitively and easy to grasp.

6

Identifying the Needs of Drivers in Unexpected Driving Situations

In the previous chapters we explored the use cases and user groups for smart infrastructure and introduced a design space for 3D augmented reality. Furthermore, we presented concepts to increase the awareness of drivers of situations outside the periphery of the driver. From these sections, we identified how we can convey information about objects, or other traffic participants in the surroundings, to drivers of manual driven and autonomous driven vehicles. While those concepts concentrated on the design of applications and prepared the driver for upcoming take over situations, one question that remains is how drivers are affected if the driving behavior of the vehicle remains unclear. Unexpected driving behavior results in perceived risk [61]. This results from a study of Dikmen et al. [61], in which participants experience automation failure in a Tesla which resulted in unexpected driving behavior. Through the infrastructure or connected sensors, an autonomous vehicle might get information about the environment and react on that information. This vehicle might still be within the autonomous driving limits of the system and therefore does not issue a take over request. In that situation, without more information, the driver is not be able to comprehend which information the vehicle received and the resulting driving decision of the vehicle. For example, if the own vehicle receives information that an emergency vehicle will pass, it reacts on that information by braking. Without the information about the emergency vehicle, the driving behavior is unexpected to the driver. In that case, the vehicle drives unexpectedly without the driver knowing the situation context for this behavior. This can cause various problems, for example, drivers would not know if their intervention is necessary. This can result in drivers taking over control of the vehicle without the need for it and drivers that are not prepared to drive, resulting in critical situations. Additionally, the driver's trust could decrease resulting in lower acceptance of the vehicle and thus in a reduced usage of autonomous driving functions.

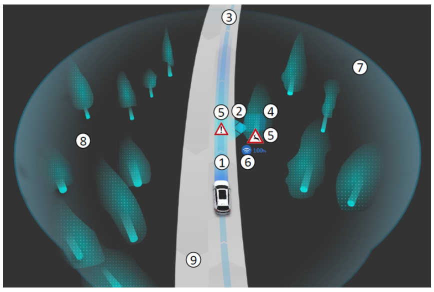
Explanations for autonomous system behavior can make the reasons for an algorithm to choose a certain solution clearer. Since autonomous vehicles will probably not immediately work perfectly and without unexpected driving decisions, it is important to keep traffic participants in the loop and informed about the behavior of autonomous vehicles and the context of a driving situation. However, in case of unexpected driving situations that occur often or in which the causes are obvious to the driver, explanations might annoy the driver. Therefore, it is necessary to find those driving situations that are actually unexpected to the driver and to then provide drivers with an explanation that is understandable and upon which the necessary action from the driver is clear.

Drivers in autonomous vehicles that do not have the possibility to intervene in the driving behavior have been taken of their autonomy to decide for themselves. When experiencing this situation, we explored what explanations could be presented in an by a user interface.

In this chapter, two driving simulator studies are presented. Both studies focus on situations in which the vehicle is driving unexpectedly and in which drivers do not know the cause for the unusual and different driving behavior. While one study explores the needs of drivers in unexpected driving situations, the other derives the content of an explanation. Based on the studies, we derive design guidelines that are beneficial for explanation designs in autonomous vehicles. Afterward, we define features of what vehicles detect that are necessary to be mentioned in explanation interfaces for unexpected driving behavior.

This chapter introduces two driving simulator studies to answer research questions RQ4 and RQ5:

Influence of Unexpected Driving Behavior on the Driver of an Autonomous Vehicle
In Section 6.1, we explore the needs of drivers in unexpected driving situations. We identify situations in which those unexpected driving behaviors could occur and examine what drivers need in those situations. Therefore we searched for unexpected driving recounts and did a study (N=26) in which we collected qualitative results. We derive a codebook and design implications for autonomous vehicles.



Developing Adequate Explanations in Unexpected Driving Situations
In Section 6.2 we explore a possible explanation interface for drivers in unexpected driving situations. We first identified interface elements in a focus group. In a study (N=16), we let participants design their preferred interface, providing the reason for the unexpected driving behavior. From this we can then derive a target mental model that should be addressed when designing for explainable interfaces.

6.1 Influence of Unexpected Driving Behavior on the Driver of an Autonomous Vehicle

This section is based on the following publication (conditionally accepted for MobileHCI'20):

- Gesa Wiegand, Malin Eiband, Maximilian Haubelt, Heinrich Hussmann (2020, October). "I'd like an Explanation for That!" Exploring Reactions to Unexpected Autonomous Driving. *MobileHCI '20: 22st International Conference on Human-Computer Interaction with Mobile Devices and Services.*

This section is supported by the Master's thesis of Maximilian Haubelt. Please refer to the beginning of this thesis for a detailed statement of collaboration.

Fueled by considerable research and commercial interest, autonomous driving has seen major technological advances in the last years. Under certain conditions, it has become reality: Early rider programs have been launched by companies such as Google[1], Uber[2] or Aptiv[3]. Beyond the technical challenges, autonomous driving raises major questions for HCI [122]. Drivers, or when driving truly autonomously rather passengers, of highly automated vehicles can experience unanticipated and unpredictable vehicle behavior. Furthermore, decisions can be difficult to comprehend and can be different from those, a human driver would make. This can lead to anxiety as well as lack of trust in, and acceptance of, highly automated vehicles [118, 250]. It has been shown that providing *explanations* to drivers can mitigate these negative effects [148, 149]. Providing explanations can adequately support drivers in such situations. By addressing the question *when* and *what kind* of explanation drivers need for vehicle behavior can give them back the feeling of power over the driving decisions.

In this chapter we refer to the research question what drivers of autonomous vehicles need and how they want to interact the vehicle in that moment (RQ4). Furthermore, we determine what the situations are in which drivers need explanations of autonomous driving behavior. Therefore, we first conducted a systematic web search of blogs, video material and experience reports to analyze and classify situations in which the need for an explanation arises. Those unexpected driving situations describe real-life experiences with autonomous driving. To derive the situations, we clustered the experience reports into 11 themes to get a common understanding of the context of the collected situations in which drivers need explanations. Through filtering the situations to our problem space, we derived 17 scenarios. We implemented these experiences in a simulation and conducted a study, simulating a fully autonomous ride through the situations. Participants shared their thoughts through think-aloud [134] and were asked to indicate their need for an explanation by pressing a button. Thereby, we collected 2499 statements from participants and their indication if an explanation is needed. Through qualitative analysis, we derived 37 codes and six categories. The codes build up the codebook from which we derive nine design guidelines. The steps are shown in Figure 6.1. We found that some interaction options should be given to the driver of an autonomous vehicle. This is in line of the work of Walch et al. [282] who presented participants with an interface that enables cooperation with the vehicle. Furthermore, we found that autonomous vehicles should give users the chance to ask for explanations when unexpected driving behavior occurs. Participants request an explanation especially in situations with a long waiting time. When no obvious reason is visible there is a higher demand for an explanation.

The contribution of this chapter is a thorough and methodical approach to derive experience reports of using autonomous vehicles, a classification of stereotypical reactions of users when confronted with unexpected vehicle behavior and design implications for a user centered explanation interface.

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[1] `https://waymo.com/journey/`, last accessed May 2020

[2] `https://www.uber.com/`, last accessed May 2020

[3] `https://www.aptiv.com/`, last accessed May 2020

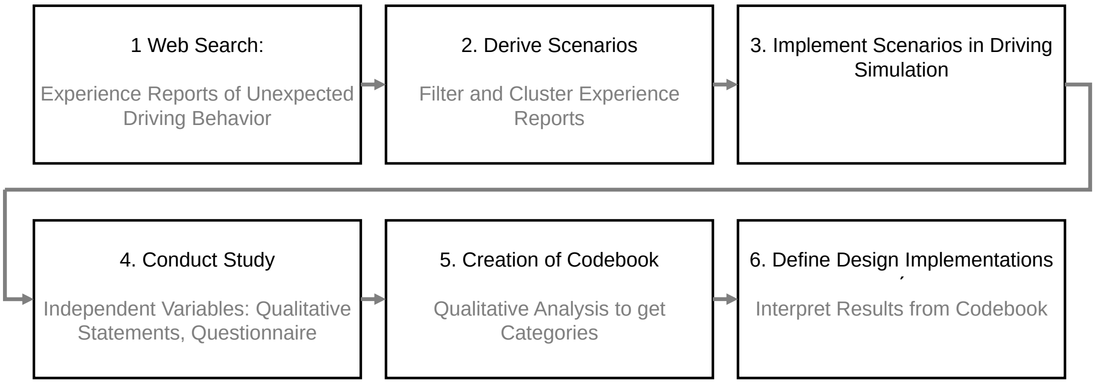

Figure 6.1: Work flow to derive unexpected driving scenarios and conclude design implications.

6.1.1 Extracting Scenarios

Similar to take over requests, in which the vehicle abruptly hands over control to the driver [132, 253], unexpected driving behavior can disrupt the ride. To explore the reactions of drivers of autonomous vehicles with unusual driving behavior, scenarios are required that identify as unexpected and strange. Unexpected driving scenarios can be implemented in a driving simulator to observe the behavior of potential drivers and collect feedback from participants. In papers from AutoUI (Automotive Use Interfaces) and CHI (Conference on Human Factors in Computing Systems), two premier conferences for HCI and automotive interfaces, studies were conducted that research take over requests and autonomous driving. We reviewed the chosen scenarios in papers from the years 2018 and 2019. Since autonomous driving is a fast changing technology we concentrated on the most recent years. We looked at studies that included take over requests or unexpected driving situations, to get an understanding of the used scenarios in autonomous driving studies. From seven selected papers just one indicated a real life event for their chosen simulated driving scenario [156]. In other cases [160, 195, 283], the chosen scenario was based on assumptions of the autonomous vehicle's limitations.

To collect scenarios, based on real experiences, we conducted a systematic web search. We searched for experience reports from videos, blogs or news articles. The derived scenarios were clustered using thematic analysis [33] and then relevant scenarios were chosen. The procedure to derive scenarios can be summarized as follows: First we conducted a web search, then extracted scenarios, clustered them through thematic analysis and finally filtered the relevant scenarios.

Deriving Scenarios

To find realistic scenarios that are based on real life experiences, we collected experience reports of users of autonomous vehicles. We conducted a web search to identify real life experiences of unexpected autonomous driving, preferably from users that use autonomous vehicles regularly and in everyday situations. We searched for experience reports using the following keywords on Google and YouTube: “Driving in an autonomous vehicle”, “Waymo annoying” [4], “autonomous vehicle an-

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[4] https://waymo.com/, last accessed May 2020

noying", "Tesla error"[5], "autonomous driving strange" and "self driving vehicle anecdote". Only results that reflect a real life experience with autonomous vehicles were considered. Since currently the vehicles are not always capable of driving fully autonomously, the collected experiences were only considered for this work if the vehicle was driving autonomously at the moment of the scenario. From the web search, we identified 25 potential situations, with unclear driving behavior, and performed a thematic analysis [33] with those scenarios to identify relevant scenarios. We clustered the situations first according to the vehicle's motion state: *driving (N=23)*, *approaching vehicle (N=3)* and *parking(N=2)*. We excluded the cluster *driving* as it is beyond the scope of this work. We continued by clustering the remaining situations into the following cluster: *road type* [*highway (N=1)*, *city (N=11)*, *undefined (N=11)*] and *influence factors* [*speed (N=5)*, *robotic behavior (N=12)*, *amount of other vehicles (N=13)*, *personal preferences (N=4)*, *error (N=6)*]. We investigated if we can find a balanced amount of scenarios from different road types and influence factors, but there was a majority of city and undefined scenarios. From each of the influence factors the scenario groups we included scenarios in the final scenario group for the study. We excluded all situations in which the vehicle clearly drove against the traffic rules. Situations that occurred while not driving (e.g. "...we approached it [to get into the vehicle], [the vehicle] moved away from us repeatedly, it would not completely stop."[6], describing a situation in which the driver wanted to board a vehicle, but it moved away) were also excluded. Scenarios that were vague without a concrete description of the situation were also excluded ("Volvo admits its self-driving vehicles are confused by kangaroos."[7]). Our scope just included the driver's perspective on these scenarios, but we implemented also scenarios that were observed by other road users than the driver. The process resulted in 17 scenarios (see Table 6.1).

Resulting Scenarios

We implemented the scenarios in carmaker [8], a software for driving simulators. From the web sources and videos we only have short descriptions of the situation or video clips without the complete situation and from different filming angles, which results in room for interpretation, how the scenarios actually happened. Therefore, we repeatedly discussed and interpreted the situations and decided how the situations should be implemented. Some situations could be interpreted in a different manner, hence we decided to implement one described situation in two scenarios. Scenarios 1 and 4 and scenarios 2 and 8 are based on the same source, but are implemented differently. The stopping times and distant of the vehicle to the pedestrian or intersection and the driving behavior varies between the scenarios. We tested all scenarios with two participants (male, 28 and 32 years old) in a pilot study. Based on their feedback, small changes such as vehicle speed or timing with other traffic participants were adjusted.

Limitations

The situations are based on the report of individuals, describing the situation on the internet. Since experience reports are subjective and not meant for interpretation for a driving simulator, the scenario

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[5] https://www.tesla.com/, last accessed May 2020

[6] https://pbs.twimg.com/media/D2RVjLUUwAIvOFi.png, last accessed May 2020

[7] https://www.theguardian.com/technology/2017/jul/01/volvo-admits-its-self-driving-cars-are-confused-by-kangaroos, last accessed May 2020

[8] https://ipg-automotive.com/products-services/simulation-software/carmaker/, last accessed May 2020

Scenario	Description	Experience Report	Scenario	Description	Experience Report
1: Abrupt stop at right turn	City: Vehicle approaches an intersection with give way sign. Without stopping at the sign it starts turning right. Then it stops, already on the road. An oncoming vehicle passes. Vehicle continues driving after 5 seconds.	*"... she nearly hit a Waymo Chrysler Pacifica minivan because it stopped abruptly while making a right turn at the intersection." [83]*	**10: Unnecessary lane change**	(Two-lane) Highway: Vehicle is driving on right lane of two-lane highway. Two vehicles are in front. Vehicle changes to left lane.	*"[...] made an "unnecessary" lane change and, lastly, experienced the apparent near-collision." "When turning left into a 2 lane turning lane, the car whipped fast across to the inner lane which was unnecessary and scary." [225]*
2: Reluctant turn right due to pedestrian	City: Vehicle stops before a right turn, a pedestrian stands on other side of street, moves a little. There is no crosswalk. Vehicle slowly turns with some stopping.	*"... When the road cleared and it was safe to turn right, the car didn't budge. I thought this was a bug at first, but [...] there was a pedestrian standing very close to the curb, giving the awkward body language that he was planning on jaywalking." [129]*	**11: Unexpected stop**	City: Vehicle brakes after a while. In some distance is a green traffic light. After a while, oncoming vehicle passes. Vehicle still waits. Scenario is similar to Scenarios 6 and 7.	*"She nearly hit a Waymo Chrysler minivan because it stopped abruptly.." [83]*
3: Long wait at intersection to turn left	(Two-way) Highway: Intersection is approached, traffic light is green. Vehicle stops behind traffic light, then turns left, then waits for 10 seconds to turn a bit, then it stops again. After 60 seconds an oncoming vehicle passes. The vehicle finally turns left.	*"… Seconds tick by, and the vehicle (...) is letting too many opportunities pass by without turning …" [115]*	**12: Strong brakes and quick decisions**	City: Vehicle enters the city and strongly brakes to reach speed limit. A curve is taken relatively fast, and a right turn at intersection is taken without stopping. The behavior of the vehicle should reproduce robotic driving.	*"Google can adjust the level of aggression in the software, and the self-driving prototypes currently tooling around Mountain View are throttled to act like nervous student drivers. In the early versions [...], the vehicles were programmed to be highly aggressive." [129]*
4: Abrupt stop at right turn	City: Identical scenario as Scenario 1 except for waiting time: 20 seconds instead of 5 seconds.	*See Scenario 1.*	**13: Fast acceleration and slow downs**	(Two-lane) Highway: Two vehicles in front of the own vehicle. After a while it accelerates until distance between vehicle and the front vehicle is needlessly short. When distance is dangerously short, vehicle brakes and vehicle falls off. This is repeated three times.	*"... It kept accelerating unnecessarily fast to reach speed limit from stops and slow downs" [225]*
5: Stopping vehicle at intersection	(Two-way) Highway: Similar scenario to Scenario 3, but own vehicle immediately starts left turning process and remains in intersection. After more than a minute the vehicle finally turns.	*Stopping vehicle on intersection. [12]*	**14: Vehicle is very slow**	(Two-way) Highway: Vehicle drives and after a while drives relatively slow. While driving slowly, it passes parking vehicles. After a while it accelerates again.	*"Car does not really drive fast." [133]*
6: Vehicle stops at an invisible red traffic light	City: Vehicle stops after some driving at intersection. Intersection has traffic lights, but they are invisible to driver. After a while oncoming vehicle passes. Vehicle still waits and then continues driving. Scenario is similar to Scenarios 7 and 11.	*"Sometimes, the vans don't understand basic road features, such as metered red and green lights that regulate the pace of cars merging onto freeways." [83]*	**15: Vehicle got way too close to another vehicle**	(Two-lane) Highway: Vehicle slowly gets closer and closer to vehicle driving in front. When distance is too small to be able to brake, vehicle slows down a bit to increase distance to other vehicle.	*"Car tried to turn left into oncoming traffic, driver had to avoid collision," The [..] robotaxi got "way too close" to another car […] [69]*
7: Vehicle stops at green traffic light	City: Scenario is similar to Scenarios 6 and 11. Different to Scenario 6 green traffic light is visible.	*"..the car was too hesitant to make a left turn at an intersection where it had a green light, but not a separate light for left turns." [242]*	**16: Vehicle moves very slow**	(Two-way) Highway: Vehicle drives and slows down. After a while it accelerates again.	*[...] moved "super slow" at one point [...] [69]*
8: Unclear vehicle pedestrian interaction	City: Vehicle turns right, there is a crosswalk with a pedestrian in front of it. Pedestrian moves a bit, but does not cross the street. Vehicle stops in front of the crosswalk and waits. After a while it slowly moves forward. Then it stops again. It repeats this behavior. After a while it crosses the crosswalk and continues driving.	*See Scenario 2.*	**17: Slow truck is not overtaken**	(Two-way) Highway: In front of the own vehicle is a vehicle and a truck. The other vehicle overtakes truck, own vehicle stays behind the truck. Different road types are passed: curvy and straight, view on the road ahead is clear.	*"..a Waymo vehicle that got stuck behind a city bus that pulled over to load and unload passengers while still partially blocking the lane." [242]*
9: Vehicle stops, child crosses	City: While driving, vehicle stops abruptly. It waits and after a while a child crosses street. Vehicle continues driving.	*"Car stopped all of the sudden. Why? [...]Child run out between some cars." [289]*			

Table 6.1: Description of the resulting scenarios, derived from the experience reports. On the left is the related scenario with a short description, in the middle column is the scenario description derived from the discussion while clustering the scenarios and in the right column is the relevant extract from the original scenario description.

descriptions lack details or information about the environment. Other traffic participants could also have been involved, the weather could have been different to how we imagine it, and we do not know on what road type the scenario was set. Through thorough discussion and testing, we got a common ground on how the scenarios could be interpreted. We had three main settings in the simulation. Therefore, the participants had a bias towards some scenarios since the landscape looked familiar, which sometimes resulted in expectations in a certain driving behavior.

6.1.2 Method

Figure 6.2: Screenshots from selected scenarios. Top row (from left to right): a) Scenario 1: vehicle just turned right and stopped while an oncoming vehicle passes b) Scenario 2: vehicle is about to turn right, a pedestrian is on the other side of the road c) Scenario 9: a child crosses the street in front of the vehicle. Bottom row: d) Scenario 11: vehicle stops in the city unexpectedly before green traffic lights e) Scenario 8: vehicle waits in front of a crosswalk, a pedestrian is on the sidewalk f) Scenario 3: vehicle is standing on the intersection in the middle of a left turn, an oncoming vehicle passes.

After defining and implementing the scenarios (see Figure 6.2 for example screenshots), we conducted a study to determine the key topics and thoughts of the participants in those unexpected driving situations. We used a within-subject design with 17 scenarios. The independent variable was the condition which were the simulated situations. The conditions are counterbalanced using the Mersenne Twister algorithm [192]. The dependent variables were think-aloud statements [134], explanation requests and the time until this requests. The study lasted one hour per participant. Each scenario had one unexpected event at prescribed times that was unique for each condition.

Participants We recruited 26 participants (m=15, f=11), 15 were between 20-29 years old, 3 were 30-39 years old and 3 were older than 60 years. All participants had a driving license and had experience in driving regularly. The majority agreed or totally agreed that they enjoy not to pay attention when being the co-driver (N = 17, Mean = 1.88, IQR = 2), stated that they were rather patient while driving (N = 17, Mean = 2.3, IQR = 1) and preferred to drive rather defensively (N = 20, Mean = 2.11, IQR = 0) on a scale from 1 to 4. They stated they would like to request further information in case of disturbances during a train ride (N = 22 agree or strongly agree, Mean = 1.69, IQR =1). One can see some parallels in riding a train compared to driving in a self-driving vehicle, therefore we expect that participants that require further information in a train, would also request information in unexpected driving situations in autonomous vehicles.

Apparatus The study was conducted in a driving simulator. The scenarios were shown on three screens in front of the vehicle. A keyboard tracked the input of the participant in case of an explanation request. The level of automation was a SAE Level 5 [130], the driving was conducted by the simulation and the participant was in the driving seat, but did not need to intervene.

Procedure The procedure and aim of the study was explained to the participants and they then signed a consent form. After filling in a demographic questionnaire, the participants took part in the study. All participants experienced each of the 17 scenarios. During the study the participants were asked to think-aloud and report anything they notice, what the consequence might be and why the vehicle drives the way it does. If they wished to have an explanation from the vehicle they could indicate so by pressing a button. After each scenario they completed a questionnaire. It surveys, if and how the participants wanted to influence the driving maneuver by asking them to write a short statement. Furthermore, it asked if they were glad to be able to request an explanation on binary scale. On a 4 point Likert scale they rated how safe they felt and how frustrated they were with the driving behavior of the vehicle. After the study the participants were asked if there were any questions.

The qualitative data was first transcribed and then analyzed, using qualitative analysis [3, 85]. The data was coded by an open coding scheme [45]. Following this approach, we first assigned codes to distinct participant's statements separately and then collected the codes of two participants. Those codes were then compared and the two participants were re-coded on a common first draft of the codebook.

The next two participants were coded separately again before counter-checking and adapting the results. Rules concerning certain repetitive statements (e.g. “That is annoying.”) were assigned to follow in the further coding process. Some codes were defined as redundant by us in the process and new codes were defined. Through this, a common understanding of the codes and their representation in the data was found. The rest of the participants' statements were then divided among us and coded separately. In the end we compared the codes of a part of the participants. The inter-rater reliability was evaluated by calculating the Cohen's Kappa coefficient [110]. This resulted in a value of 0.86, indicating a very good agreement between the raters. Using this iterative approach, we developed and refined the codes until everyone agreed with the assigned codes. By identifying relationships between the open codes, the axial codes or also code categories, were defined.

6.1.3 Results

The results of the study are presented in two parts: the qualitative part in which the statements of the think-aloud method are analyzed and the quantitative part in which the collected explanation request events are presented.

Code	Definition	Count	Example
Emotion and Evaluation - Negative			
E1	Dissatisfaction with driving behavior	**265**	"This is totally unnecessary."
E2	Desire for explanation	**138**	"I would like an explanation for that."
E3	Irritation / Confusion	**131**	"[...] for no real reason."
E4	Annoyance	**122**	"That's kind of frustrating already."
E5	Feeling of safety	**116**	"I think it is totally dangerous."
E6	Impatience	**61**	"We need to move on now."
E7	Uncertainty	**34**	"We're not going any faster. Or do we? "
E8	Helplessness	**19**	"I feel abandoned."
E9	Comfort	**13**	"[...] that's not very comfortable for me."
E10	Envy of others	**13**	"Well, now we are pretty slow and the others are faster. Isn't this nice *[ironic]* ?"
E11	Feeling of being left out	**4**	" [The car knew that but] that wasn't obvious to me, though."
Emotion and Evaluation - Positive			
E12	Satisfaction with driving behavior	**82**	"I would call that reasonable driving now."
E13	Feeling of safety	**37**	"[...] and that makes me feel safe."
E14	Praise	**29**	"So far the situation is perfectly solved by the car."
E15	Understanding	**22**	"I understand the behavior of the car."
E16	Relief	**15**	"Hats off! Phew, I wouldn't have noticed."
E17	Trust	**2**	"[...] but I trust the [system] already pretty much."
Interpretation and Reason			
R1	Looking for reason in the environment / other traffic participants	**252**	"It might have slowed down because of the kid. It could also be that we simply reached the destination."
R2	Cluelessness	**131**	"It's absolutely impossible to understand why we are standing here."
R3	Vehicle status	**100**	"There is no car visible far and wide. It feels to me like there's been a mistake."
R4	Interpretation of vehicle	**44**	"It may have noticed that other cars were trying to overtake us and therefore slowed down the speed."
Capability of the Car			
C1	Comparison to own driving behavior	**180**	"I would do that completely differently."
C2	Mental model autonomous system / driving	**163**	"[...] but I do not think [the car] saw that, at least I did not."
C3	Humanization / Assigning personality to car	**41**	"Please keep driving, dear car, and do not stay there. Hello?"
C4	Competence of the car	**40**	"[...] but I can't imagine it's predicted that before."
C5	Ignorance of car driving behavior	**25**	"And I think that you have such a tension whether the car still registers everything."
C6	Driving style	**19**	"I would definitely see the situation [...] as aggressive driving and it is not quite clear to me why we are driving so aggressively."
C7	Overestimating ability of car	**7**	"Okay, I guess the car knew the other car would turn right."
Interaction			
I1	Desire to interact / Change driving behavior	**154**	"I would really like to step in and get on the gas right now."
I2	Awareness of being an impediment for others	**29**	"Well, we're pretty much obstructing other traffic, too."
I3	Desire to communicate with car	**26**	"Okay, [...] car, Please explain to me why you're not overtaking [...]?
I4	Social interaction with pedestrians	**12**	"I would honk on [the pedestrian], go or don't go!"
I5	Temporal demand	**12**	"So it would be cool if the car had a short message: we're still waiting 2 minutes or half a minute."
I6	Safety of others	**4**	"And maybe the car thinks he's running into me. And so, he rather stops. [...] the car was unsure whether the pedestrian was crossing the road improperly."
Prediction			
P1	Confusion of future driving maneuvers	**60**	"We will overtake this time. I suppose. But don't drive faster. Or do we?"
P2	Expectation of future driving maneuver / behavior	**50**	"No oncoming traffic. Then I would say now, we drive left, before another car comes."
P3	Prediction of driving behavior out of own experience	**47**	"Looks like the track is gonna straighten up again now. I would probably try to overtake at some point."

Table 6.2: The codebook of the qualitative study. The codebook is set up of the six categories and the corresponding codes. Related to every code is an abbreviation is on the left, the definition of the code, the number of counts and an example of the code.

Analysis According to the Codebook Results

We assigned codes for 2.499 statements. 37 individual codes and 5 axial codes, or *code categories*, were found through open coding. Table 6.2 shows the codebook with example participant quotes. The code categories are *Emotion and Evaluation*, *Interpretation and Reason*, *Capability of the vehicle*, *Interaction* and *Future Driving Prediction*.

Emotion and Evaluation

The code category *Emotion and Evaluation* is divided according to positive and negative emotions. More than a third of codes belong to this category, showing that emotions had a strong influence on the thoughts of the drivers in the study. Negative emotions clearly prevail positive emotions (83% of all emotion codes).

Negative Emotions The negative emotions include *Impatience, Dissatisfaction with driving behavior, Helplessness, Irritation/Confusion, Envy of others, Feeling of being left out, Uncertainty, Comfort, Desire for explanation, Annoyance* and *Feeling of safety*. The code *Comfort* refers to the driving style of the autonomous vehicle in a scenario and not the driving simulator itself. Most often (in 35% of all negative emotion statements) participants mentioned that they were dissatisfied with the driving behavior during the scenarios. This validates the implemented scenarios and indicates that driving behavior in these scenarios were indeed unexpected. Additionally, participants desired an explanation, had a feeling of irritation or confusion about the situation or were annoyed by the driving behavior. Many participants mentioned that they thought that the driving maneuver was dangerous, represented by the high number of codes in “Feeling of safety” (15%).

Positive Emotions The positive emotion category consists of the codes *Praise, Relief, Satisfaction with driving behavior, Feeling of safety, Understanding* and *Trust*. If the uttered emotion was coded positive it was rather general satisfaction with the driving behavior. Sometimes the participants mentioned that even though they understood why the vehicle behaved in a certain way, they would have driven differently. Moreover, in scenarios in which they thought to have understood the behavior of the vehicle, participants also praised the driving decisions of the vehicle. That happened mainly in two scenarios, in Scenario 8, in which the vehicle waited for a pedestrian in front of a street crossing and in Scenario 9, in which the vehicle waited for a child that ran across the street. In Scenario 12, in which the vehicle is aggressively braking and accelerating, some were startled by a fast right turn, but the others (N=15) were satisfied with the driving behavior.

Feeling of safety was both related to negative and positive emotion and either meant that the participants thought the driving behavior was dangerous or that they felt safe.

Interpretation and Reason

The category *Interpretation and Reason* is the second largest category. Since participants were prompted to explain the vehicle’s driving behavior, they tried to interpret the driving behavior of the vehicle. With a representation of 48%, the most influential code was *Looking for reason in the environment or other traffic participants* (e.g. “Hello? Ah it’s probably about, I don’t know, pedestrians? Cyclists?”). They suspected that the other traffic participants influenced the driving behavior and guessed that the vehicle got some information about other vehicles and behaved accordingly.

Moreover, they expected that the status of the vehicle (Code: *Vehicle Status*) could have some influence on the driving behavior, either that the sensors did not work properly or that there was an error in the software of the vehicle.

They also thought that the vehicle might have interpreted the situation wrongly (Code: *Interpretation of vehicle*) and therefore changed the driving behavior.

Depending on their mental model of the abilities of the vehicle, participants overestimated the abilities of the vehicle and wondered, for example, if the vehicle could have detected a vehicle that was not yet visible. Some provided an explanation by assigning anthropomorphic characteristics to the vehicle (e.g. "Maybe he (the own vehicle) is afraid of the other vehicles.", "Because he could feel the vehicle from a distance."). These statements are very different to a statement of a different participant ("Software is not advanced enough to perform an overtaking maneuver"), which describes the vehicle behavior on a more technical and logical level. These two examples show the spectrum of the mental models of the participants. Others considered technical aspects that could have influenced the situation such as erroneous software or hardware ("The sensor isn't working that's my assessment").

Moreover, participants were uncertain of the abilities of the vehicle ("The situation is not very transparent, maybe that is also difficult for the vehicle."). Interestingly, participants' own explanations did not change during the study. Participants who explained the behavior with sensor errors in the beginning tended to stick to that explanation.

The code "mental model" (see Code *C2*) and the reasoning of the participants are similar, and sometimes overlap. We coded the mental model when a participant expressed statements about the capabilities of the vehicle and reasoning when there is a conclusion referring to the current vehicle behavior.

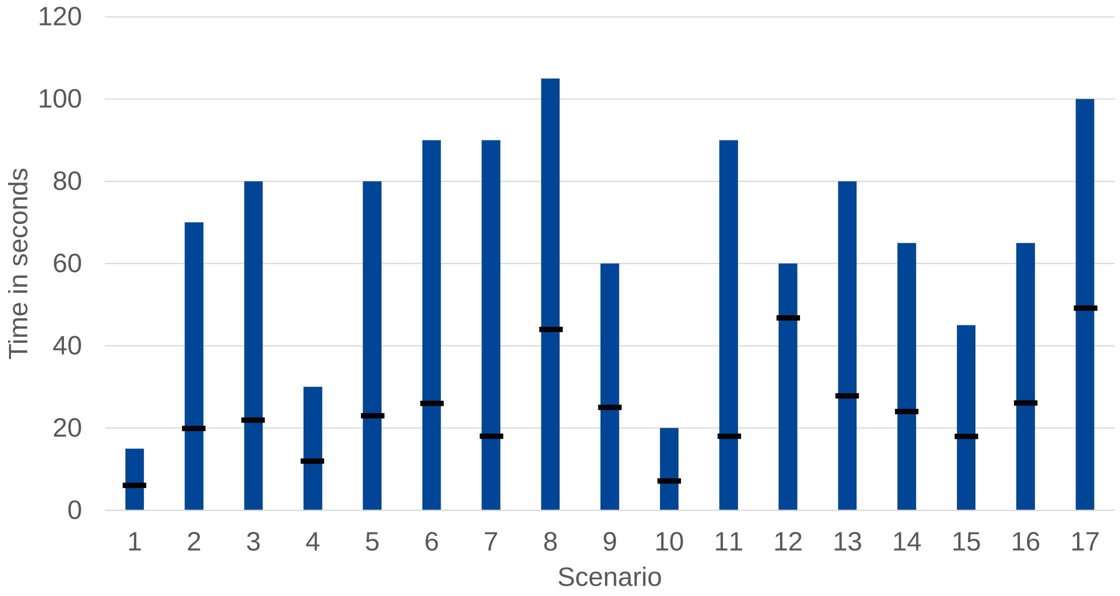

Figure 6.3: Time in the scenario and the corresponding average explanation request times in black indication for each scenario.

Capability of the Vehicle

The most prominent code in the category "Capability of the vehicle" is *Comparison to own driving behavior* followed by the *Mental model of autonomous system*. Participants notably often compared the driving behavior of the vehicle to their own driving decisions which often would have be different. One participant, for example, remarked in Scenario 13, in which the vehicle follows a vehicle and accelerates and brakes several times that "I wouldn't always change the spacing so abruptly, I'd do that differently if I was driving myself.".

Especially in Scenario 8 participants compared their driving behavior to the driving behavior of the autonomous vehicle. In this scenario the vehicle slowly approaches a crosswalk. Since there is a pedestrian in front of the crosswalk, participants mentioned that they would also slowly approach the crosswalk, but eventually drive on. This indicates that participants would have liked to adapt the driving style of the autonomous vehicle to their own driving style – however, only in scenarios in which participants rated their own competence higher than that of the vehicle. In Scenario 9, the vehicle stops until a child crosses the street. In this scenario some participants mentioned that they themselves would not have noticed the child. Even though some doubted that future vehicles would be able to handle this situation well, reactions were mostly positive.

It is insightful to collect statements about the mental model of the participants. Since the mental model is just a representation of the real world, all aspects, such as the capability of the vehicle or how it works, are covered in several categories. The code in this category collects all those aspects from different categories.

Interaction

Even though participants were informed that no interaction with the vehicle was possible, they often wanted to have options to interact. A significant amount of codes (65%) in this section indicates the *Desire to interact or change the driving behavior* of the vehicle. This can be distinguished between the wish to take over control of the vehicle and the mere wish to change the driving behavior of the vehicle.

While less frequently mentioned, other interesting aspects were the fear of being an impediment for others when other vehicles need to wait (Code: *Awareness of being an impediment for others*, 12%) and communication with the vehicle (Code: *Desire to communicate with vehicle*, 11%). This also includes a certain degree of feeling embarrassed for the driving behavior of the vehicle and a feeling of discomfort.

In contrast, the wish to interact with pedestrians was not very prevalent (Code: *Social interaction with pedestrians*, 5%). Within our study, participants wanted to get information about the driving decisions of other autonomous vehicles. Especially the codes "Safety of others" and "Awareness of being an impediment for others", are a sign that the participants were aware that their vehicle could be a traffic hazard.

Future Driving Prediction

Participants either were confused about future driving behavior or they expected a different driving maneuver from their own driving experience. The codes in this category are *Confusion of future driving maneuvers*, *Prediction of driving behavior out of own experience* and *Expectation of future driving maneuver / behavior* (e.g. "He might want to overtake him now.").

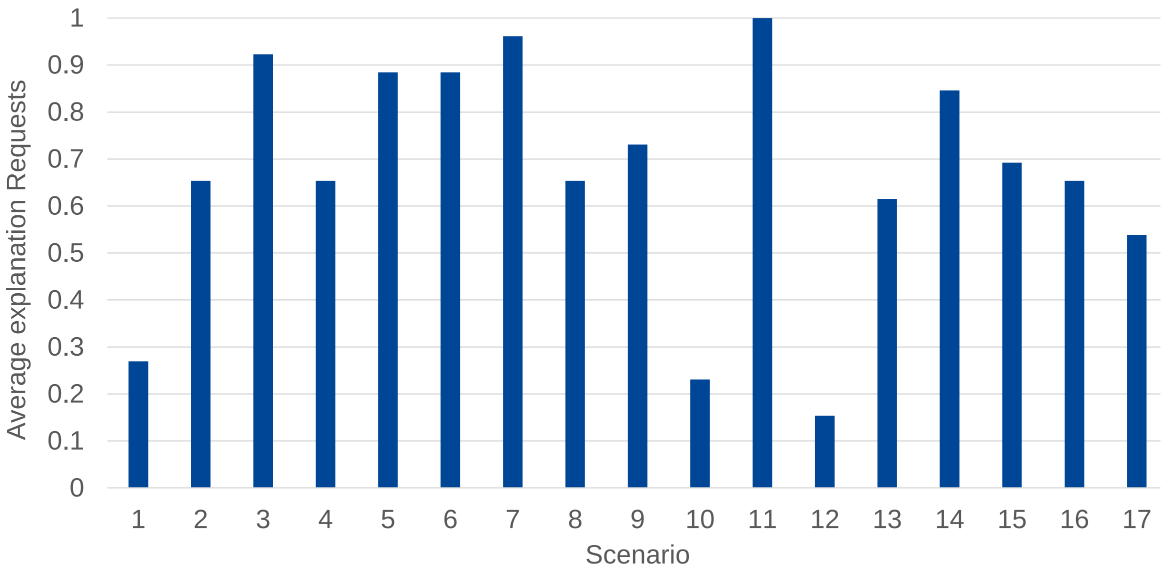

Figure 6.4: Average explanation requests for each scenario in percent.

Explanation Request Times

Participants were not shown an explanation of the scenario by default, to not influence the driver with the content of a particular explanation. Instead, the participants were informed that they could indicate that they would need an explanation in the course of a scenario by pressing a button. We thus assessed *whether* a participant requested an explanation and *when* the request was made. The moment to request an explanation can be either *before*, *during* or *after* the scenario. We defined the start of a scenario when the vehicle depending on the scenario, either has stopped (Scenarios 1-9 and 11), starts to de- or accelerate (Scenarios 13 - 16) , has the same velocity as the truck (Scenario 17) or starts the lane change maneuver (Scenario 10). Scenario 12 is an exception since it does not have a clear starting time. The end of the unexpected driving behavior is defined at the moment when the vehicle drives smoothly again or the scenario is finished.

In most cases participants asked for an explanation *during* the scenario (N = 288 times) (see Figure 6.3 for the time in a scenario and the corresponding average time for an explanation request). This is somewhat still surprising as we expected that for some scenarios the participants will ask for an explanation *afterwards*. But this was just sporadically the case (7 times). In four times, an explanation was requested afters scenario 10. This can be explained by the definition of the scenario, the vehicle was driving normally again therefore, for the evaluation the scenario was over. Nevertheless, the participants probably still waited for something to happen that would explain the lane change. When that did not happen, they requested an explanation. In some scenarios, some participants did not request an explanation, such as scenario 10, 1 and 12 (compare with Figure 6.4) On average participants requested an explanation after 24.3 seconds. Scenario 17 was the scenario in which participants requested an explanation the latest (t = 44s) and Scenario 1 was the scenario in which participants required an explanation the earliest (t = 6s). The high explanation request numbers indicate that the chosen scenarios are suitable to test unexpected driving behavior of autonomous vehicles. We assume that if the system itself detects unusual driving behavior it should suggest to provide an explanation to the driver.

6.1.4 Discussion

The results show that drivers are interested in getting explanations. There are just three situations (scenario 1, 10 and 12) in which less than 50% of the participants requested an explanation. Scenarios 1 and 10 last less than 20 seconds which could explain why participants did not ask for an explanation. In scenario 12, the vehicle drove not smoothly which also lasted for a short time. Therefore, it can be concluded that participants are higher likely to ask for an explanation in case of a long lasting unexpected behavior of the vehicle.

Nevertheless, the expectations for the level of explanations vary depending on the mental model of the driver, the state of technology available and the type of situation. The identification of the needed explanation level for a specific user is generally difficult. The explanations ideally should provide experiences which enable users to adapt their current mental models towards a better reflection of the reality. For instance, one participant stated that the vehicle always has problems at the same intersection, even though the situations were unrelated to each other. This is a typical misconception created by the urge to find an explanation of a phenomenon which cannot be explained with the current mental model. For this user it would already be helpful to get further information, for example that the system takes its decision based on information about the traffic situation. Many participants assume that the information used for decisions comes only from the vehicle's sensor system. In particular when future mobility infrastructure will provide much better networking between vehicles and environment, explanations can help to broaden the mental models of drivers adequately. For instance, indicating the source of the information (vehicle-to-vehicle communication, smart infrastructure, sensor system of the autonomous vehicle) on which the current behavior is based on, might be beneficial for the driver. In summary, the diversity of observed mental models is a challenge for explanation design. Good explanation design can trigger a learning process in drivers, which improves the mental model of the driver and minimizes the difference between the mental model and the reality. Simply providing a one-size-fits-all explanation, which most likely will be too complex or too simple for some users, is rather unlikely to achieve this goal. Therefore, information about the context of the driving situation and interaction with the environment or the own vehicle is relevant to drivers in unexpected driving situations. The study uses scenarios that occur nowadays on the road with still supervised autonomous vehicles. Therefore, our findings pertain to the limited automation today, but are not validated for autonomous driving experiences in future autonomous vehicles.

6.1.5 Design Implications

From our results, we derive design recommendations for cockpit elements of SAE Level 5 vehicles that can be grouped into two broader categories, *design for adequate control and communication*, and *design for different mental models*. We acknowledge, however that the suggested implications might not be comprehensive. They should therefore be extended and validated in further studies.

Design for Adequate Control and Communication

Our results motivate a closer look at drivers' interaction options. Across most driving situations, participants expressed a wish for interaction during autonomous driving. These wishes can be summarised into two categories: Either *direct control* of the driving task or *communication* with the vehicle and other road users.

Regarding direct control, participants wanted to adjust speed (i.e. to accelerate or brake), to stop or continue driving, to back up or to navigate differently. Participants did not necessarily want to take over full control of the vehicle in all situations, but to slightly adapt the driving behavior. Taking over full control was even perceived as not desirable in autonomous driving. For example, one participant stated that *"[...] here I would have to intervene and continue driving by myself [which] would be stupid"*. With regard to communication, participants wanted to get more information on the situation in general and to update the vehicle's system information about traffic rules, signs and context interpretation (*"[I would like to] tell the vehicle that the pedestrian won't cross the street."*). They also expressed their wish for communication with other road users, that is, other vehicles or pedestrians. Taking drivers out of the loop in this regard, evoked feelings of frustration.

To date however, the most prevalent form of interaction with highly automated vehicles are take over requests that primarily evolved from technical or legal considerations, not from an HCI perspective. Such take over requests may lead to a lower acceptance of and loss of trust in autonomous driving [282]. In contrast, the insights gained in this study highlight the need for interaction options beyond this "all or nothing" approach – designing interaction in a way that provides *adequate* means for control and communication in autonomous driving.

More concretely, we suggest the following design implications to design for adequate control and communication:

- Input option to change driving behavior [282]
- Change characters of vehicle information system [32]
- Option to collaborate or interact through an interface with pedestrians or drivers of other vehicles [211]
- Collaboration with the own vehicle/ Helping the vehicle decide in difficult situations [282]
- Option to request an explanation from the vehicle [300]

Design Explanations for Different Mental Models

Mental models represent individually constructed, subjective interpretations of the world based on prior experiences and assumptions [137] and are usually incomplete [215]. This presents a challenge for designing communication between user and system, for example, through explanation. The results of our study confirm this challenge: When prompted to explain autonomous driving behavior, participants do so in very diverse ways.

Adapting explanation interfaces in a way that takes into account the diversity of mental models could support drivers in "speaking their language". This is in line with the work by Miller [199] who, drawing on psychology, argues that the recipient of an explanation is more likely to trust the system if the explanation is simpler. Another example for the different needs of users regarding explanations is the work by Cawsey [44], who presents the user modelling component of the EDGE explanatory dialogue system. It shows that adapting an explanation according to a user's level of understanding and thus updating the user model according to the input and knowledge of the user, the explanation is more effective.

From our results, we suggest that explanations for different mental models should address the following aspects in particular:

- An indication of confidence of the vehicle in the driving decision [117]
- Retrievable information from the environment (for example through smart infrastructure or connected cars) and from the vehicle system (for example detected vehicles by the vehicle) [295, 299]
- Navigation interface that indicates future driving path [264]
- Internal vehicle status about possible errors or service information

Their concrete implementation could be assessed in user-centric research processes as presented in [71].

6.2 Developing Adequate Explanations in Unexpected Driving Situations

This section is based on the following publication:

- Gesa Wiegand, Matthias Schmidmaier, Thomas Weber, Yuanting Liu, and Heinrich Hussmann. 2019. I Drive - You Trust: Explaining Driving Behavior Of Autonomous Cars. In: *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (CHI EA '19).

Please refer to the beginning of this thesis for a detailed statement of collaboration.

In the previous section, we identified design guidelines for explanations provided by autonomous vehicles. We know now what to consider when designing for an interface that puts the drivers needs in unexpected scenarios into focus. In this section, we determine the explanations that should be provided to drivers of autonomous vehicles in unexpected driving situations. This section explores the practical implementation of an explanation interface to answer what needs to be visualized in the vehicle, for the user to understand autonomous driving behavior (SAE Level 4 or 5 [130]).

Situation awareness (SA) describes a driver's awareness of the surrounding environment while driving autonomously [74]. Situation awareness should not just increase trust, which might lead to over-trust in autonomous systems and accidents, but should calibrate trust to an adequate level. With calibrated trust, the user is aware of the limitations of the systems and therefore can adjust the trust either by trusting the system more or less. SA calibrates trust in the automation algorithm, by clarifying the abilities of the algorithm, and can enhance the take over behavior [171].

In case of a driving maneuver of the autonomous vehicle, the driver might require an explanation, to prevent distrust in the vehicle or take back the driving control from the vehicle. Explanations can increase trust [267], but transparency of systems does not automatically achieve that goal [53]. Therefore, explanations have to be designed in direct agreement to its expected purpose. For example, when aiming for system transparency, the user of the system must understand the abilities of a system to be able to intervene competently in the control of the system. To design explanation components for the driving decisions of autonomous vehicles, we first need an understanding of the expert and non-expert mental model of autonomous systems to identify the differences between the user mental models [71]. The targeted explanation is intended to improve the driver's situation awareness in driving decisions of the autonomous vehicle that have no obvious cause.

According to Eiband et al. [71] a target mental model can be identified by adding evaluated key components of the user mental model to key components of the expert mental model. We evaluated the improvement of situation awareness with a visual explanation of the scenario in a study. Additionally we evaluated the user's mental model of the autonomous vehicle to identify a target model. With this, the elements that should be included in an explanation for unexpected driving maneuvers, are listed.

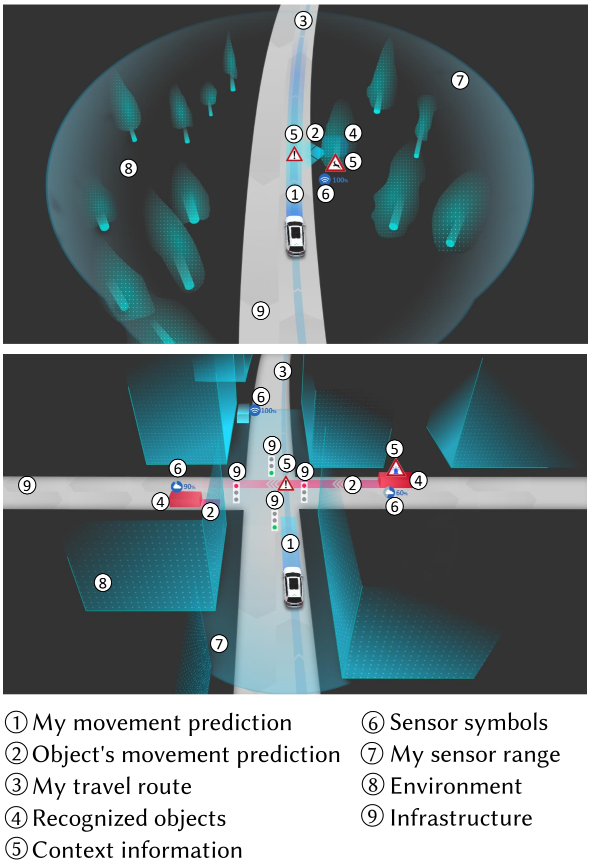

Figure 6.5: Configurable explanation screen consisting of nine visual components.

6.2.1 Method

To have a basic understanding of explanation visualization preferences of users, we did a questionnaire (N=20). We compared statistical explanations, represented by a decision tree, text and speech based explanations, an environment model, graphical sensor data and real world image explanations. The preferred visualization was an environmental model, which we chose as visualization output. According to Eiband et al. [71] a deep understanding of what to explain is an advantageous prerequisite to set up a transparent system. To achieve that, an expert mental model of the system is first elicited by conducting a focus group. In the next step a user mental model is evaluated by conducting a study in a driving simulator. Those results enable us to set up the target mental model of the system, which answers the question what information should be visualized to explain autonomous driving behavior.

Expert Mental Model We first gathered insights from autonomous driving experts, how they explain an autonomous driving system. Therefore, we conducted a focus group (N = 6, f = 1, m = 5). The experts defined three categories which describe an autonomous driving system: perception, deliberation and action. *Perception* includes all components concerning sensors, object detection, localization, tracking, maps, data fusion and fusion. *Deliberation* includes route planning, environment model, environment prediction and trajectory planning. Conducting the calculated driving *actions* requires control of the car's actuation and a Human-Computer-Interface (HCI). Concerning the comprehension of autonomous systems, the experts stated: "To understand the driving decision of the autonomous vehicle an environment model would be sufficient for most end users." and "Trajectory planning is too complex for normal users."

They additionally stated that the vehicle should apologize to the user in case it made a mistake and it should be triggered and adapted according to type and significance of a situation. Also, offering a real-time description of the system's behavior by pictograms or some kind of abstract visualization could be helpful for the developers of the system. However, the experts did not believe that normal users would want to get deep insight into the system's algorithm, as it would be hard to understand.

Target Mental Model To determine the target mental model, key components of the user mental model need to be enhanced by key components of the expert mental model. Within this work we identify the user mental model in the scope of a study (N = 16, f = 4, m = 12). By defining the differences between the expert mental model and non-expert mental model and by priority allocation, the key components for the target mental model are extracted.

6.2.2 Study

We used a within-subjects design so every participant with the only independent variable being the situation through which every participant drove through. Eight participants started with condition *Deer* and the other half started with condition *intersection*. The conditions were two different situations, which are described in Table 6.3.

	Situation A: Deer	**Situation B: Intersection**
Scenario Description	The autonomous vehicle drives through a forest, after some time there is a deer behind a tree on the right hand side.	The autonomous vehicle enters a town and stops at a green traffic light at an intersection.
Autonomous Vehicle Behavior	Slowing down.	Stopping at green traffic light.
Behavior Explanation	The deer might run on the street and get hit by the vehicle.	An emergency vehicle is detected by cloud information and might cross the intersection even though the traffic light is red.

Table 6.3: Situation description and the corresponding explanation for the situations.

The dependent variables were visualization elements of the explanation. The explanation consisted of abstract visualizations of different layers (1-9), representing the autonomous system's components (see Figure 6.5). The element "My movement prediction" (1) was an area in front of the vehicle which indicates, where the vehicle might move next. "Object's movement prediction" (2) was an area in front of the object visualizing the estimated next movement of the object. "My travel route" (3) was a line on the road visualizing the planned route. The detected objects were visualized by the element

"Recognized objects" (4). "Context information" (5) included the background information of the situation, abstracting information e.g. from the cloud. Abstract "Sensor symbols" (6) showed from which sensor (e.g. the sensors of the own vehicle or vehicle2vehicle information) the information was retrieved. The "Sensor range" (7) information of the vehicle was visualized by a transparent region around the vehicle. "Environment information" (8) included houses or trees in the scenario. "Infrastructure" (9) displayed the road and the traffic lights.

The other dependent variable was the level of situation awareness. The participants reached a certain level of situation awareness according to their perception (L1), comprehension (L2) and prediction (L3) of the situation. The statements of the participants were classified using the following levels:

> **Level 0**
> No situation awareness level: We are driving.
>
> **Level 1: Perception** (Elements)
> *Situation A:* Deer in the forest. Vehicle is slowing down
> *Situation B:* Green traffic light. Vehicle stopped.
>
> **Level 2: Comprehension**: (Dependencies and significance of objects recognized)
> *Situation A:* Vehicle is slowing down because there is a deer/object in the forest.
> *Situation B:* Vehicle stops even though traffic light is green.
>
> **Level 3: Prediction**: (Future actions are predicted)
> *Situation A:* Vehicle could collide with deer.
> *Situation B:* Vehicle stops because a rescue vehicle could turn around the corner and collide with the own vehicle.

Participants The study was conducted in a driving simulator with 16 participants (12 male, 4 female) with ten participants being between 20-30 years old, three between 31-40, two between 41-50 and one between 51-60 years old. All of them were employees of a research institute and therefore had a high technical affinity.

Apparatus The study was conducted in a driving simulator (see setup in Figure 6.6) with three monitors. The steering wheel had no function during the study since the vehicle was driving autonomously and the participant is not able to intervene in the driving. The driving simulation was controlled by the supervisor while participants were manipulating the explanation screen via a separate interface on a tablet and answered a questionnaire on an additional laptop. The simulation was implemented in Unity 3D (Version: 2018.2.8f1) [9]. The explanation screen (see Figure 6.5) was displayed in the main monitor.

Procedure The participants were first welcomed and the demographic questionnaire was filled in. The participants answered before the study the question: *In your own words: How would you explain an autonomous vehicle? (What does it do? How does it work? How does it come to its decision?* Before driving in the simulator, the participants were informed that they are driving in an autonomous vehicle, therefore no intervention of them is needed during the study. As secondary task

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[9] `https://unity.com/`, last access May 2020

Figure 6.6: Participant selects explanation interface elements during the study.

the participants watched a video and counted people therein to simulate a realistic autonomous driving experience. As main task, participants were confronted with the two different driving situations (see Table 6.3) After each condition they were asked what happened in the environment and what the vehicle did. Those statements were used to assess the situation awareness of the participants without an explanation. Then, subsequent to the vehicle's reaction, a visual explanation of what happened in the environment was presented to the participant. The participants chose their preferred explanation by removing those elements that were not necessary for their situation understanding. Afterwards the participants were asked again what happened in the situation. The statements of the participants were divided into the three level of situation awareness. According to these statements, the situation awareness of the participants after receiving an explanation was assessed. The participants answered after the study the question: *After seeing the autonomous vehicle in action, how has your view on how an autonomous vehicle works changed compared to your previous answer?*

6.2.3 Results

We first analyze the situation awareness level [73] of the participants to derive the difference of the SA of the participants before an explanation of the situation was given to them and after an explanation was given. Then we formed a user mental model from the statements of the participants during the study. From this user mental model we can derive a target mental model by comparing it with the expert mental model.

Situation Awareness The difference between the level of situation awareness before (Situation A: Mean = 0.81, SD = 0.83, Situation B: Mean = 0.88, SD = 0.96) and after (Situation A: Mean = 1.81,

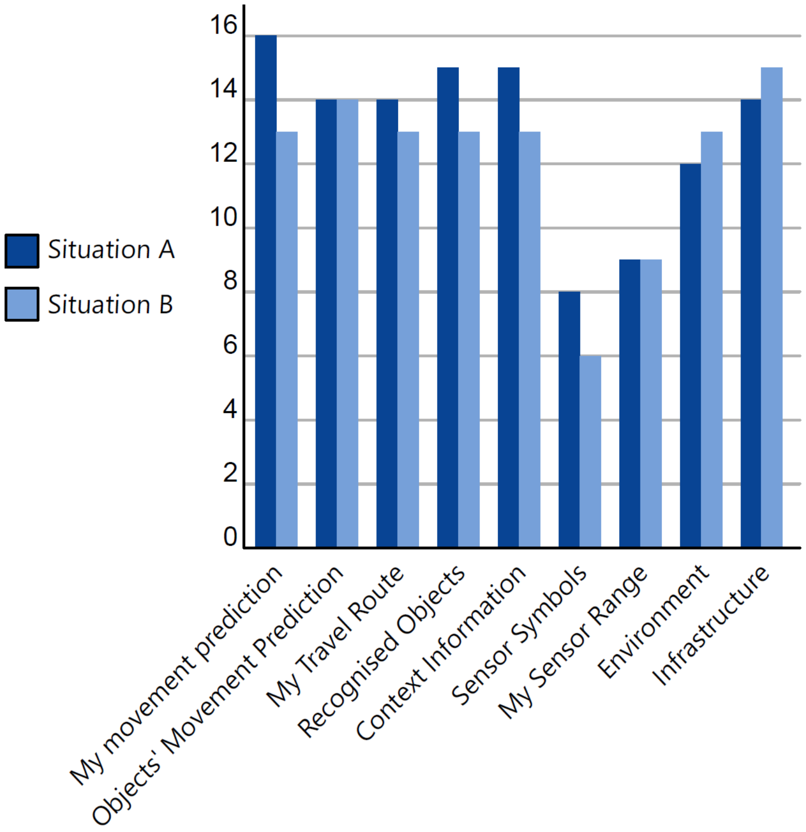

Figure 6.7: Frequency at which participants chose the explanation elements.

SD = 0.98, Situation B: Mean = 2.06, SD = 1.12) the explanation was evaluated with the Wilcoxon signed rank test. The results (p = 0.0001) showed significant increase in situation awareness (see Figure 6.9).

Preferred Explanation Elements The other independent variable that was evaluated are the preferred explanation elements. The chosen elements are shown in Figure 6.7. The least chosen element is sensor symbols which indicates that the interpretation of sensor symbols might not be intuitive.

User Mental Model From the participants statements after the study, we derived a mental model of the participants towards autonomous driving systems. The mental model of users composes of elements that are similar to the components of the mental model of experts (see Figure 6.8). The statement *"An autonomous vehicle is a vehicle, equipped with different types of technologies that work together in a way that allows the vehicle to move and navigate in its environment freely and independently and according to given rules - without human interference."* includes the description of sensors, algorithms, fusion, navigation, trajectory planning and actuation in the words of a non-expert. But the description of an autonomous system in the words of an non-expert also differs significantly from expert knowledge. The ability of an autonomous vehicle is overrated by non-experts ("It is able to foresee dangers") or the user has other expectations of the system ("Explains what it is doing"). It

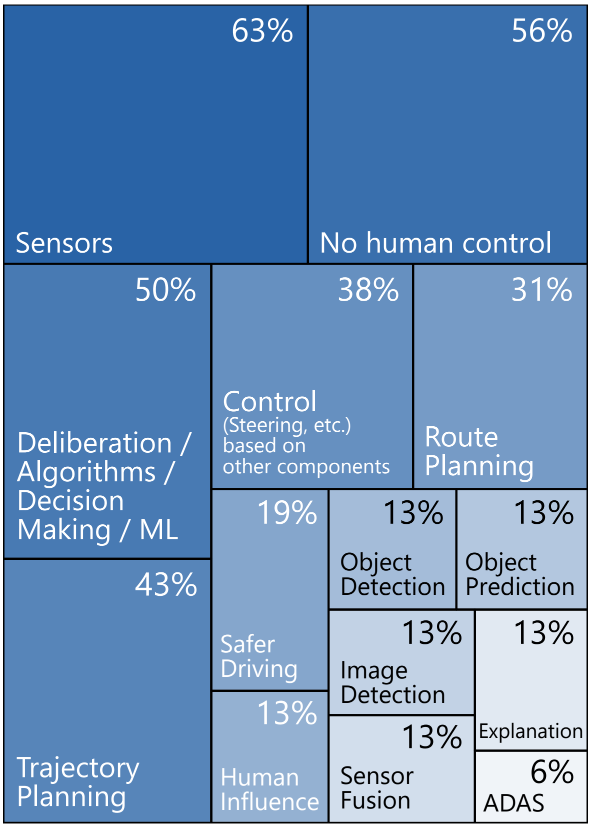

Figure 6.8: Elements mentioned during User Mental Model evaluation. The numbers indicate the percentage of participants that mentioned each element.

remains in the study supervisors assessment to assign the mental model components to the statements of the participants.

Target Mental Model After the evaluation of the non-expert and expert user mental model a target mental model is identified (see Figure 6.10). The common notion of the functionality of an autonomous system is displayed in the overlapping area. The key components that are rated by the users as not as important and the wrongly identified elements of the users are excluded from the target mental model. Therefore, even though "Data and Sensor Fusion", "Map" and "Environmental Model" was mentioned by non-experts and experts it is excluded from the target mental model. The element "Sensors" is rated low as chosen element (see Figure 6.7). Nevertheless, as it is a high priority component during the User Mental Model evaluation (see Figure 6.8) we added it in the target mental model.

6.2.4 Discussion

In this section we measured the effect of an explanation on the situation awareness level of the participants. Additionally, we identify the context information needed in an explanation. In the third evaluation part, we identify a target mental model by identifying the differences and similarities of

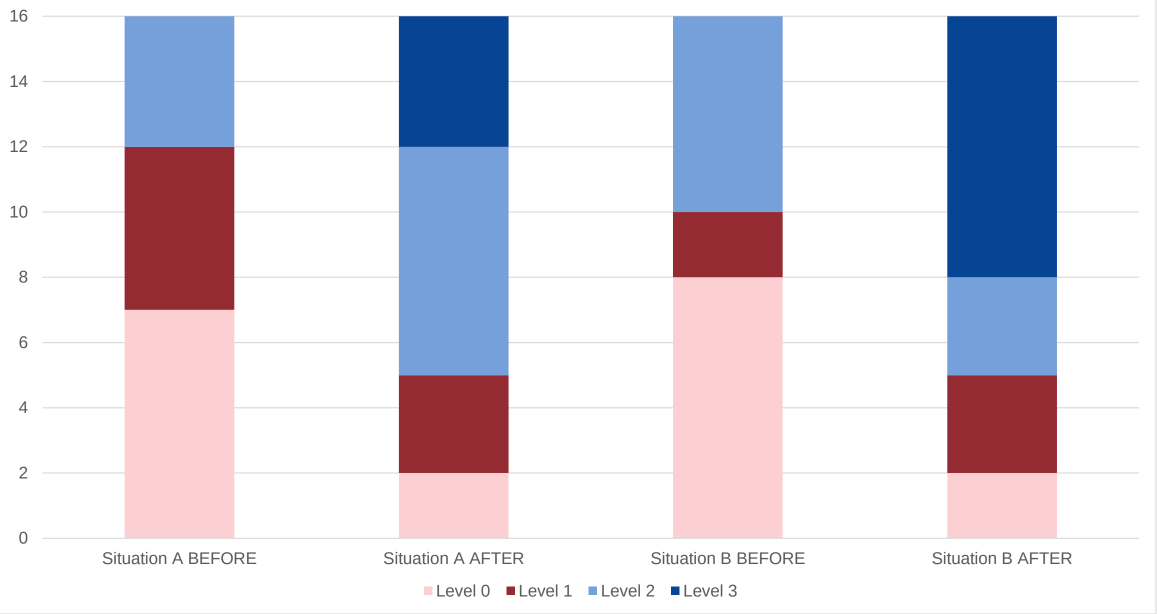

Figure 6.9: Situation Awareness of the participants before and after getting provided with an explanation of the driving scenario.

the mental model of experts and users. We measure the quality of explainability using the driver's levels of situation awareness. Situation awareness is important if the driver needs to take over control during a driving scenario. With this study, we showed that situation awareness can be increased significantly by showing an explanation of the cause of unexpected driving behavior. It remains to prove the benefit of increased situation awareness through explanation screens in autonomous driving. In our scope of work, the driver is not required to driver manually, therefore the driving performance does not need to be improved by increasing situation awareness. It is imaginable that the acceptance and joy of driving can be increased by offering an explanation of the driving context.

The participants were able to adapt the explanation to their personal preferences. The resulting explanations were very similar, resulting in some explanation elements that are chosen less often than others. Adaptable interfaces and personalization are important topics that are discussed frequently. In our study though, we can not see of a clear benefit from changing the explanation elements when an improved explanation is chosen. Nevertheless, it is imaginable though, to adapt explanations according to the workload of the driver when driving manually or on the immersion of the driver in a secondary task. Depending on this immersion, the driver is more willing to get more information about the driving context or decides to stay immersed in the secondary task.

The third contribution of this work is the target mental model that we identified by comparing expert and user mental model. While it is a legitimate approach to identify a suitable explanation, the target mental model needs to be verified in a next step. It needs to be proven that some explanation elements should be excluded while others are crucial to the understanding of the driving context.

Design Implications From our study we can derive following design implications:

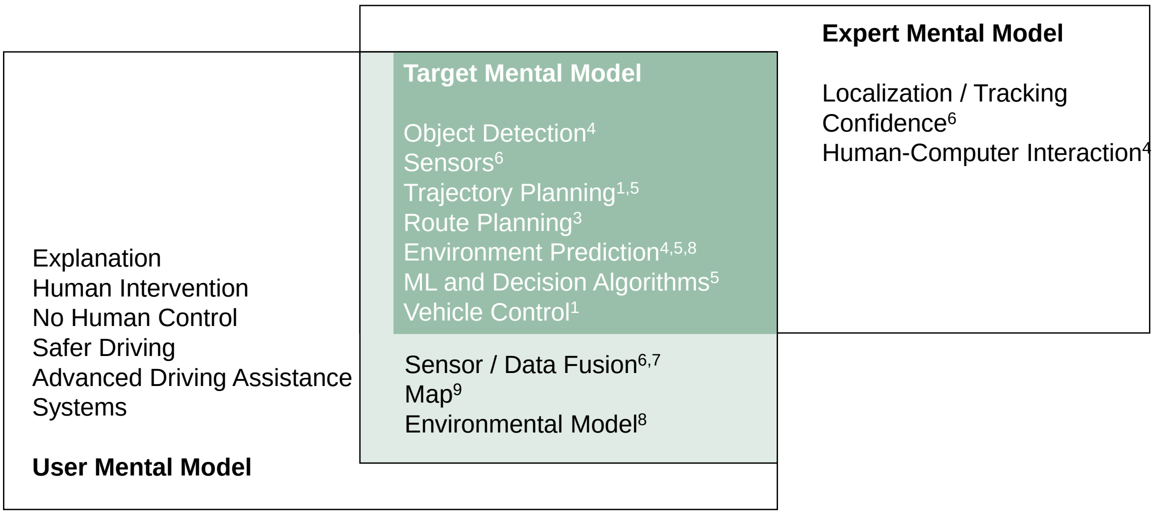

Figure 6.10: Target mental model consisting of components found in both mental models (shaded) with a selection of the key components (green). Superscript numbers (1-9) indicate which explanation components are used for visualization (Figure 6.5).

- **Situation Awareness** Aim for increased situation awareness when it is needed to increase safety and acceptance.
- **Adaptation** Know what to adapt: Aim for optimized system acceptance.
- **Target Mental Model** Aim for a broad target mental model on which most users can agree upon.

6.2.5 Limitations

Within the scope of our work, the driver is not required to take over the steering wheel and therefore has no time limit for explanation interpretation. In a real driving environment the time to interpret and understand the explanation is limited and also the driving context changes rapidly. Therefore, the explanation needs to be adapted situation dependent for the driver to quickly grasp the context of the driving behavior.

As we focused on *what* to visualize, a next step is to evaluate in a structured manner *how* to visualize the explanation and *how* to evaluate the quality of an explanation. In this context, adaptive explanations can be addressed to provide individual optimization for various user types. Considering the expert level of the user can result in different visualization methods. The technical interested user might need an explanation of the deep learning algorithm to fully understand the vehicle's behavior. The optimal time to show the explanation can lead to the question if the driver wants to influence the autonomous driving behavior. Possible advantages could be the constant control of the driving behavior and adaptions through the driver if the current autonomous driving behavior differs from desired or expected actions.

6.3 Lessons Learned

In this chapter, we focused on drivers in unexpected traffic situations, driving in an autonomous vehicle. We first explored the thoughts and statements of participants experiencing a simulated unexpected driving situation. From this qualitative study we gained design implications for autonomous vehicles. Then, in the next section, we developed an explanation for drivers in unexpected driving situations. From this study we identified a target mental model which includes the explanation components to understand the cause of the driving behavior. Furthermore, we increase situation awareness by displaying an explanation to drivers. This explanation is then adapted by the participants. In the following, wo focus on some lessons that we learned during the last two sections.

Realistic scenarios can be derived by analyzing experience reports In the first section we developed 17 scenarios resulting from a web search, which were implemented in a driving simulation. From this first step we examine how real world scenarios can be deployed in a driving simulation. It is an unusual approach, but holds several novel ideas: in other studies, the scenarios are not based on real world scenarios, but on scenarios that the designers of the study have specified. Those are valid and the study design can be easily fitted to those scenarios. For example, studies that use vehicles that are parked on the side [282] are good for conditions that require similar scenarios since it has a high repeatability. In the scenario of a person crossing the road, the person can cross from right, left or with different velocities to avoid a learning effect. Nevertheless, the scenarios stay comparable. With realistic scenarios that are derived from a web search, the scenarios are very diverse with different numbers of participants and in different traffic settings.

In our case we aimed for many scenarios and approached the question about how the participant feels and thinks in diverse scenarios. Therefore, we needed many scenarios. From our approach we can learn that collecting real world examples and use them in a study gives the necessary basis to gain diverse insights of the driver's behavior and thoughts. Our approach can be applied for other studies as well to gain broad insights in case that diverse scenarios are aimed for. Furthermore, it is suitable for studies based on real world experiences without having the means to collect them with current technology. Another lesson learned was that this approach of collecting real world scenarios leaves space for interpretation of the concrete scenario. Every scenario description is subjective and the perception of driving behavior can differ between people. While one describes a driving behavior as stressful or aggressive someone else might describe it as normal driving behavior. Therefore, we got diverse opinions, by discussing scenarios through clustering among several persons. Then one might find an agreement on how a situation might have happened. We argue that the approach of using real world scenarios increases the ecological validity of the study. "Ecological validity [...] examines whether the findings of a study can be generalized to naturalistic situations" [8]. We took good care of including naturalistic situations of autonomous driving behavior in the selected scenarios from the web search. While the autonomous driving behavior will further develop with advancements in the technology, the scenarios will be valid for current studies when aiming for naturalistic situations.

With the codebook we identify overarching themes and correlations between categories. After developing and implementing the scenarios in a driving simulator, we conducted a think-aloud study. In this way we collected qualitative statements of the participants concerning the current driving behavior of the vehicle. While this is an effortful process, the resulting codes build up a diverse codebook with codes concerning every driving impression of the scenario. Through the discussion to develop the categories, coding guidelines can be developed which help in coding consistently. Additionally, overarching themes can be identified and correlations between categories are identified. Sometimes, the content of one category is similar to another category, but the meaning is slightly different. In this case, insights can be gained, by exploring the definition of the category. For example, the code *Mental Mode Autonomous System/Driving* is included in other categories as well for example in the category *Humanization*. In one case, it stands for how participants think the vehicle works and in the other case how drivers behave towards the vehicle. This distinction is important, but is sometimes difficult to code in some statements. Qualitative analysis is a powerful tool to get opinions and information from participants. Nevertheless, the coding is dependent on the coder, therefore, the coders have great responsibility to stay as objective as possible, without a certain goal in mind.

The environment influences the desire for an explanation request. During the study, participants rather requested an explanation when no apparent cause for the unexpected driving behavior is visible. From the codebook (see Table 6.2), it can be derived that participants request interaction options and explanations. Those results give indications for future studies. For the design of a study with focus on explanation interfaces, it might be better to not show the reason for unexpected driving behavior. Then the cause of the behavior can be derived from the explanation interface. Since some sort of interaction is desired by the participants, the focus can be put on the interaction itself. Through future work, it can be identified, if an explanation is sufficient to lessen frustration and dissatisfaction with the driving behavior, or if a take over request is a better option to offer drivers.

The adaption of explanations should take drivers' mental models into account. In Section 6.2, we surveyed the mental models of how people explain how autonomous vehicles perceive their environment and manage to drive on their own, first in a focus group and then in a study. Even though we took great care to evaluate the mental models in depth, the mental models give just an impression of the current opinion of the participant. The mental model changes over time and experience and might differ after experiencing other driving scenarios. Mental models are very individual, depending on the person and their experience, but some attributes are mentioned more frequently than others. It depends on the target design whether the general mental model of users is important or whether individual outliers give more understanding of how adaptive and user centered explanations can be designed.

Explanation should aim for high situation awareness. From the study in Section 6.2, we derive preferred visualization components in explanations for unexpected driving behavior. While the explanation elements differ depending on the situation, the difference is negligible. There is a trend towards the usefulness of some elements such as the object's movement prediction compared to others, such as sensor symbols. Since visualizations should be as easy as possible to swiftly understand the meaning of the situation, the work on developing a target mental model showed that explanations need to be optimized for every use case. The target mental model gives an indication for the concrete case of autonomous vehicles that drive unexpectedly. To evaluate the explanation interface, we used situation awareness and assessed if the explanation improved situation awareness of the driver. In our case, the explanation significantly improved the situation awareness. The quality of an explanation does not solely rely on situation awareness therefore in a next step, other criteria need to be developed to rate a provided explanation. This can aim for good usability, understanding, stress reduction or unobtrusiveness, to name just a few.

Conclusion The just discussed attributes gave insights on the lessons that we learned with the present chapter. Developing methods to evaluate unexpected driving scenarios, collecting user statements during unexpected driving behavior and then constructing a target mental model for explanations was valuable to derive design guidelines for explanations of unexpected driving behavior. Users' previous knowledge and mental models is crucial to adapt explanations of smart systems. Through the reflection of the results from this chapter, we call for an explanation design that aims for a high level of acceptance instead of completeness and accurate terminology. We derived design implications to design for *adequate control and communication* and *different mental models* in autonomous vehicles (see Section 6.1.5). By developing methods to quantify eligibility of provided explanations, the explanations become comparable and optimizable. With the work of a quantitative analysis and by setting up a codebook, it is possible to develop a standardized approach to quantitatively asses explanations. We have shown the focus and the important categories of explanations in case no explanation is provided to the user. By providing users with explanations, it can be evaluated if these categories improve and if the importance of the categories remains. From the two sections we derived 12 design implications. To sum them up, we have four overarching themes:

Adaptability

With the individual adaptation of, for example, vehicle driving behavior or the interface of the vehicle infotainment system, the user's individual preferences can be taken into account. By optimizing for system acceptance, it can be prevented to adapt features that do not need to be adapted.

Providing information

The user should be provided upon request with various information. Complete and easy explanations, confidence of the vehicle, information about the environment, smart infrastructure information or the internal vehicle status are necessary information to be able to decide upon future driving actions and to form an own opinion about the driving behavior. While driving autonomously, increasing situation awareness through information should be in accordance with the acceptance of the system.

Prediction

Showing future driving decisions and behaviors gives the driver the autonomy to intervene and change the course of driving.

Collaboration

The possibility to collaborate with the environment and the own vehicle, leaves the driver with autonomy.

7

Conclusion

With the results of empirical research projects, we contribute a thorough analysis of the opportunities of smart infrastructure. This thesis investigates the potential of smart infrastructure for the user, with a focus on drivers of autonomous vehicles. We focus on three different aspects: A design space for 3D in-car AR, out-of-view visualizations to create awareness of traffic objects or situations that are outside the view of the driver, and the needs of drivers in unexpected driving situations. Through this research, we gain a thorough understanding of the potential of smart infrastructure for drivers of autonomous vehicles. This chapter first answers the corresponding research questions of this thesis, then summarizes the contributions and finally gives an outlook on future work.

RQ1 What are potential user groups and use cases of smart highway infrastructure? *The potential user groups and use cases are drivers of semi-autonomous vehicles, operators and emergency services. The use cases are identified and collected in a scenario catalog and evaluated in studies.*

The analysis to identify potential stakeholder and use cases for smart infrastructure is based on several interviews and focus groups (see Chapter 3). We identify highway operators, emergency services, drivers of autonomous vehicles and teleoperators as stakeholder of smart infrastructure. Identifying potential user groups is important to analyze individual needs and to find solutions for those. The needs of the highway operators and emergency services include for example accurate traffic flow management or the exact localization of emergencies. Over the course of the exploration, we narrow down the problem space for this thesis to drivers of vehicles. Through the analysis of what it means to be the driver of an autonomous vehicle, we realize that drivers can fulfill different roles, depending on the level of automation of the vehicle. Drivers can either be in an active role, when they are manually driving the vehicle, or with increasing level of automation, the role changes to the role of a supervisor of the vehicle. With fully autonomous vehicles, the role is equal to a passive passenger who is free to be immersed in secondary tasks. Depending on the role in the vehicle, the use cases range from aiding drivers in TORs or explaining unexpected driving behavior to a passenger.

The goal of implementing smart infrastructure is to improve the driving experience and traffic flow for all traffic participants. Through a case study, we collect scenarios in a scenario catalog. These scenarios can be differentiated between scenarios that drivers instantly need to react on and scenarios in which drivers have more time to inform themselves and prepare for upcoming traffic situations. Establishing a scenario catalog enables to design studies and consider the consequences of individual scenarios. If, for example, a traffic jam is hidden behind a curve, the degree of criticality can increase or decrease depending on the distance of the scenario. Smart infrastructure can furthermore realize explanations of unexpected driving behavior by communicating context information in a traffic situation. Summarizing, the case study helps to clarify the problem space and to identify first application purposes for smart infrastructure applications.

RQ2 What are design dimensions for 3D in-car AR applications when 5G and smart infrastructure enable communication, entertainment or more information about the environment? *The* *design dimensions for 3D in-car AR applications that include environment information are identified through a use case set and a design space.*

In Chapter 4 we define a design space for 3D in-car AR. From two focus groups, a literature analysis, and the resulting use case set, we derive the design space and its design dimensions. This defines the design dimensions for applications that are set in 3D augmented reality for the interior of vehicles. Use cases span from entertainment applications to navigation or security. In the course of this thesis we benefit from this design space which provides us a tool to design applications for semi-autonomous and autonomous vehicles. This design space extends existing design spaces [108, 144] for the use of applications of 3D augmented reality within the vehicle. By limiting the problem space to the interior and excluding windows, many existing use cases are not within our problem space. This reflects the expectation of a changed vehicle interior in future vehicles, in which passengers might be turned towards each other. With user stories and the designs of 3D in-car AR applications, this thesis reflects on design dimensions and the limitations of them. Over the course of this work, we come to the conclusion that novel application cases that exploit the full potential of autonomous vehicles and 5G are still rare. We argue that by providing a use case set of possible applications, the direction of future applications can be shaped. The use cases are defined without considering technical limitations. Therefore, even though the low latency of 5G, necessary for more interactive AR and VR applications in vehicles[1], is not yet available, we define use cases that can be accompanied with our design space in the design process. Therefore, the design dimensions might need to be extended when further applications are realized.

RQ3 How can we display information about events outside driver's field of view? *A complete digital twin of the highway prepares drivers for take over requests and hints on objects outside the view of the driver improve situation awareness.*

In three driving simulator studies in Chapter 5 we explore possibilities of displaying information of events outside the view of the driver. We display critical traffic events in a digital twin that shows a replication of the highway, and implement different out-of-view techniques to point to critical events. The implemented visualizations increase the situation awareness of drivers and enhance the performance in a TOR. Therefore, we conclude that information from smart infrastructure improves the safety during a take over request.

Most visualization techniques that we explore further in this thesis are new, such as a stereoscopic 3D representation of the highway, or are usually not used in automotive contexts, such as a wedge [106]. Therefore, using these visualization techniques in a new context, the validity is tested. Nevertheless, automotive visualizations have different features than visualizations in virtual reality or games, for example the height dimension is not as relevant when using the whole windscreen, since the street is often on one height level. Therefore, using visualizations from other domains can be useful, as we show it with the minimap visualization, but for some, the requirements of drivers in SAE Level 3 need to be taken into account. While increasing situation awareness with non-intrusive hints on other objects is relevant for drivers that are still required to take over control of the vehicle, visualizations of out-of-view events need more research to fit more adequately to the problem space. Even though we explore multiple out-of view visualizations, we could not find a one-fits-all solution. In situations in which drivers need to take over control from the vehicle, a hint on objects outside their field of

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[1] `https://www.digi.com/blog/post/5g-applications-and-use-cases`, last accessed May 2020

view with the wedge visualization can increase driver's situation awareness. If the situation does not require the driver to take over control immediately, a more detailed visualization, such as a representation of the highway, can be shown to the driver to improve situation awareness and take over performance. All studies were Wizard-of-Oz [193] studies, in which we assume that smart infrastructure can communicate with the vehicle and that out-of-view information is available to the driver. While this limits the ecological validity, the controlled environment in the lab provides the advantage of communicating a concept with minimal effort, and without the technical implementation of several kilometers of smart infrastructure. It enables to explore visualizations which could result in a high workload in take over situations.

RQ4 What do drivers of autonomous vehicles in unexpected driving situations need and how do they want to interact with the vehicle in that moment? *Drivers of autonomous vehicles want to have the option to have some sort of control, need the opportunity to interact and to intervene with the vehicle and get an explanation for the unexpected driving behavior.*

In a qualitative study (see Chapter 6.1), we evaluate the thoughts of participants while experiencing unexpected driving situations. We derive a codebook, which points out required cockpit elements for autonomous vehicles and derive design recommendations for autonomous vehicles. With the study, we explore the fundamental need of a driver, who is experiencing a driving situation without the option to interact with or change the vehicle's driving behavior in a qualitative driving simulator study.

From this study, we derive that unexpected driving behavior often provoked negative feelings in drivers. Furthermore, drivers were expecting to see the reason for the vehicle's behavior in the environment. This was not the case, therefore, we can conclude that in case of situations in which drivers can not conclude themselves, what caused the driving behavior, an explanation should be provided. Since many drivers compared their driving behavior to the autonomous vehicles' driving behavior, personalizing it should be considered in future vehicles. Furthermore, drivers want to interact or communicate with the vehicle and are confused about the future driving maneuver. This clearly indicates a lack of situation awareness level 3, therefore, interfaces need to take the future driving path into account as well.

The qualitative study combined with realistic driving scenarios provides insights from participants struggling with an automated driving decision. To increase the ecological validity, we base the study on scenarios that we derive from a web search of real world accounts of unexpected driving. The method to derive those can be used by researchers who also struggle with the problem of having to design a study of real life events without having a good understanding of the settings of those events. With that, researchers can choose from 17 unexpected driving scenarios when testing their interaction with autonomous vehicles in unexpected driving situations.

Since not every road type and surely not every unexpected driving scenario is covered by the study, the codebook can be extended to include other categories that are relevant when technological limitations change. Nevertheless, the design dimensions and guidelines based on the codebook, should be taken into account when designing future autonomous vehicle concepts.

RQ5 How can vehicle behavior be explained if an autonomous vehicle reacts unexpectedly on smart infrastructure information? *Unexpected driving can be explained by developing a target* *mental model and adapting the explanation to the user's preferences. In the course of this thesis, we develop design guidelines for autonomous vehicles that drive unexpectedly.*

In Chapter 6 we show how the vehicle behavior can be explained, when the vehicle is reacting on situations that get transmitted through I2V or V2V communication. Through the development of design guidelines, we show that HMI designers should take the drivers in autonomous vehicles into account to enable them to intervene, communicate and receive information. In Section 6.1 we derive design guidelines for designing an interface for drivers in unexpected driving situations. Not just explanations are important in this situation, but also interaction possibilities. The explanations should aim to increase the situation awareness of drivers and the design could also include anthropomorphic features. The driver should be informed about the informations the vehicle received and how reliable the received information is. In Section 6.2 we compare the user mental model to an expert mental model and derive a target mental model, which combines elements of both mental models, for example detection of objects in the surroundings. This can be used to explain the driving behavior of an autonomous vehicle in an unexpected driving situation. The explanation interface increases the situation awareness of the drivers.

7.1 Summary of the Contributions

We contribute with this thesis an exploration of user groups and use cases for smart infrastructure information. Furthermore, we provide a design space for 3D in-car AR to encourage and support designers with a tool to design novel interaction and interfaces for highly automated vehicles, in which the interaction space is centered in the interior of the vehicle.

Next, we contribute an exploration of visualizations that inform drivers of upcoming critical traffic situations and improve the driving performance and situation awareness. We present a novel visualization in S3D that represents the traffic and environment of a highway, to prepare drivers of upcoming critical events. By setting up a scenario catalog, we can distinguish between scenarios in which drivers should be warned immediately and scenarios in which the driver can be informed earlier of a required intervention. We compare HUD visualizations that inform about other traffic participants and warn drivers of upcoming critical situations to increase situation awareness.

We identify drivers' needs in unexpected driving situations. With a systematic web search of experience reports, we explore a method to increase the ecological validity of simulated situations in studies. With the results from a qualitative study, we set up a codebook that contains the categories that concern drivers in unexpected driving situations. Furthermore, we contribute the elements, providing context and situation information, which explanations could contain and sort them according to their importance for drivers. Furthermore, we contribute a target mental model, which contains categories that should be considered when designing explanations for drivers in unexpected driving situations. Finally, we present design guidelines for the interaction with drivers in unexpected driving scenarios.

7.2 Directions of Future Work

From this thesis, researchers and practitioner can derive in-depth insights about applications of information from smart infrastructure which can be further examined. We learned that smart infrastructure offers great potential for drivers on the road. We are faced with new technology such as autonomous vehicles, connected vehicles, brought-in devices or platooning, which can enhance the journey on the road, make traffic flow smoother and reduce the environmental impact. By providing all drivers with information independent of their vehicles' abilities, a shared knowledge base is created. This knowledge base can be retrieved by the system itself, but also by other drivers. Since this thesis has a focus on the highway, the use cases for urban scenarios remain largely unexplored. It is imaginable that through smart traffic lights and connected mobile devices, pedestrians, cyclists or other vulnerable road users greatly benefit from smart infrastructure as well. In the following, we focus on the future direction for design implications, visualizations and explanations in vehicle interfaces with smart infrastructure information.

Design Opportunities of Connecting Smart Infrastructure and Vehicles The work on the design space shows that it is valuable to provide designers with a tool that allows them to explore possible designs and gives them a structured approach to design new concepts and applications. While we validate the design space for applications in the context of this thesis, it has not yet been validated for other design requirements, for example for entertainment purposes. Furthermore, the design space is limited to the technological advances, therefore it needs to be adapted with progressive technical development. For example, the dimensions of a technological implementation to realize S3D need to shrink in their form factor to be implemented in vehicles. This results in new opportunities, not yet existing design dimensions or newly found solutions. With our design space, we hope to encourage designers to explore new use cases and engineers to develop new technologies that enable use cases from our use case set.

Aim for Improved Situation Awareness in Driver's Visualizations So far, not much research has been done to visualize information coming from the infrastructure or connected vehicles. This thesis reveals new aspects that have not yet been fully explored. It is safety critical to not distract the driver from the manual driving task. For autonomous vehicles, this does not apply. Since the automation level of vehicles today shift further to fully autonomous functionalities, the realization of visualizations which require a higher cognitive load becomes possible. The time of the TOR can be extended as the system analyzes data from traffic situations in several kilometers distance. Drivers can be provided with additional information concerning the reason why a take over is necessary.

This work combines visualizations in augmented reality while driving. A study in the wild, under real life conditions would open new challenges. For example, motion sickness while wearing an AR HMD could occur. Static objects in AR or darkening the windows to obscure the moving environment outside could therefore limit the application. The problem of motion sickness refrains many people from reading while driving, even though they would like to spend their time in an autonomous vehicle effectively. While Vovk et al. [280] could not find motion sickness during simulations, they did not test automotive use cases. Motion sickness is not covered in depth in this thesis, but should be considered in further research in dynamic AR visualizations.

Considering our work with a digital twin visualization, a digital twin that shows the whole scenario from a top down view is implementable with smart infrastructure or even just with connected vehicles. Nevertheless, this work implements only a limited number of possible visualizations, and future work should explore different aspects that have not been covered by this work, such as the level of abstraction of the digital twin or how to manage visualizations with a high traffic load.

We can derive from the conducted studies that the problem space of the visualizations should be matched to a clear automation level and situation. One visualization might allow for small distances in a take over request maneuver while another visualization is too distracting in that case and makes more sense while driving fully autonomously. A factor that plays a role in this context is also the mental state of the driver, which has not been considered in this work. This influences the readiness of the driver to take over control of the vehicle. If the driver is fully immersed in a secondary task, it might be more difficult to prepare for the driving task and could therefore reduce the performance during a TOR. To continue this research direction, it would be recommendable to assess the workload of various visualizations in the context of different automation levels. Considering different concept vehicles, it is possible that the location of visualizations changes in future automated vehicles, because the driver is turned away from the steering wheel. The visualizations should then adapt and consider the differences that would arise due to the changed orientation of the driver.

Explaining Autonomous Driving Behavior We propose a concept of what should be included in an explanation in case of unexpected driving behavior. In a next step this concept should be transferred to a quantitative study to assess the advantage of the proposed explanation elements over other explanations. Today, researchers tend to implement system limits in their studies without reflecting on the cause of the system limit. Even though this is valid, a more realistic study design could improve the study validity with a realistic take over maneuver. Many TOR situations that are implemented in studies today, such as a standing vehicle, could already be solved by autonomous vehicles itself. The advantage of implementing realistic TOR scenarios lies in the improvement of credibility for participants as to how they should react in such situations and a more accurate TOR design. The study is limited to the experiences of unexpected driving behavior, therefore it can be expected that the needs change as soon as the technology is further developed, leading to less or different unexpected driving situations. When comparing the results we derived in our study, we see similarities compared to Lee et al. [167]. Their method is different to ours and they did not implement a study, but collected their results with focus groups. Nevertheless, some categories are mentioned in our study as well (e.g. Information Needs, User Interface, Safety & Security). The different method results in categories that are rather generally valid, also for other automation level (e.g. personalization, accessibility and privacy). While our design guidelines apply to a specific problem area, related work recommends further design guidelines [7, 167]. When combined, a more exhaustive guide can be derived how users should be supported in their interaction in autonomous vehicles.

Autonomous driving is a technology that will change the mobility of people in a fundamental way. There is considerable effort from research and industry to enable autonomous driving and smart infrastructure. Nevertheless, industry is still facing technological limitations concerning the implementation of smart infrastructure. Through the results and reflections of this thesis, we derive that traffic participants benefit extensively from the connection with smart infrastructure and paves the way for better integration of autonomous vehicles and smart infrastructure.

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Eidesstattliche Versicherung

(Siehe 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 2.6.2020

Gesa Wiegand