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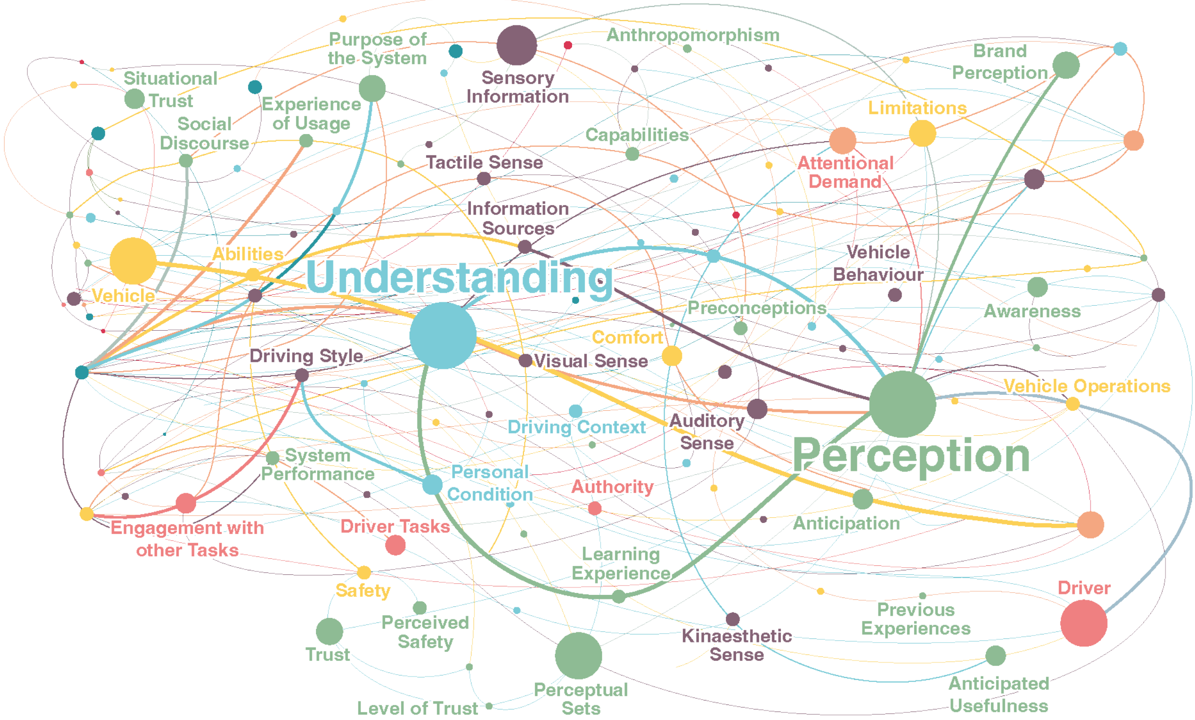

Design for Perception

A human-centric approach to the design of driving automation systems based on the driver's perception

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Gothenburg, Sweden 2023
www.chalmers.se

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ISBN: 978-91-7905-947-7

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Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 5413
ISSN 0346-718X

Published and distributed by
Department of Industrial and Materials Science
Division Design & Human Factors
Chalmers University of Technology
SE-412 96 Gothenburg, Sweden
Telephone + 46 (0)31-772 1000

Cover by Johannes Nilsson.

Printed by Chalmers Reproservice
Gothenburg, Sweden 2023

Abstract

The automotive industry is rapidly developing driving automation systems (DAS) with the aim of supporting drivers by means of the automation of longitudinal and lateral vehicle control. As vehicle complexity increases and update-over-the-air features are enabling continuous development of vehicle software and functionality, the driver's understanding of their responsibility and their vehicle's capabilities and limitations is becoming significantly more important. In order to motivate manufacturers to adopt a human-centric perspective for the development of driving automation systems, the factors influencing the driver's perception of these systems during their usage needs to be understood. Therefore, the aim of this thesis is to contribute towards the systematic development of DAS from a human-centric perspective.

The core research for this thesis is organised into four empirical studies, embedding a mixed methods research design. Study I aimed to investigate the usage of DAS in different driving contexts by facilitating an online survey to drivers in Germany, Spain, China, and the US. Study II aimed to explore the driver's contextual usage of DAS and which factors affect their understanding and employed an explanatory sequential mixed methods approach consisting of a Naturalistic Driving Study (NDS) in the greater Gothenburg area over a 7-month period. This was followed up by in-depth interviews to elicit knowledge about how drivers understand the DAS, and which factors influence their usage. Study III and Study IV aimed to gain further insights into which factors in the driver's perception of the DAS affect their understanding and consequent usage of DAS. Thus, Study III applied a Wizard-of-Oz on-road driving study, simulating a vehicle offering a Level 2 and a Level 4 DAS in the San Francisco Bay Area paired with pre- and post-driving in-depth interviews. Finally, Study IV applied a Wizard-of-Oz on-road driving study, simulating a vehicle offering a Level 2 and a Level 3 DAS, and contrasting two different human machine interfaces in Gothenburg, paired with post-driving in-depth interviews.

The results from these studies allowed a contribution to the body of research in a theoretical and practical form. The theoretical contribution is the unification of aspects that shape a driver's understanding of a DAS into a conceptual model. The unified model describes the process of how this understanding is shaped through the driver's perception of the DAS. The developed model further facilitated the development of a design toolkit by applying a participatory design approach (Study V) that facilitated co-creation sessions with domain experts (designers of DAS) in an industrial setting, which is considered a practical contribution to the field. The toolkit serves as a common foundation for aligning the motivations and goals of developers, designers, and strategists with regulators. Consequently, it can support practitioners to: 1. explore possible solutions driven by a systematic approach; 2. identify areas of improvement by applying the lens of the user; and 3. ideate and evaluate design decisions through a structured process. Thus, it facilitates the identification of design, evaluation, and training approaches that promote appropriate usage strategies for drivers and the building of a sufficient understanding of a DAS.

Keywords: Driving automation, levels of automation, perception, understanding, mental model, human-centric design, design tool, design method, empirical research, mixed-methods research, cognitive engineering, human factors.

Acknowledgments

Going into this, and throughout, I was reminded that getting a PhD would be challenging. While I won't dispute that statement, I will add that these were some of my favourite years. It was some of the best years of my life because I got to learn and grow alongside and from a diverse group of people I would never have met otherwise, and I am grateful for that. However, W.A. Ward remarked that *"feeling gratitude and not expressing it is like wrapping a present and not giving it"*, therefore, I want to express my thankfulness to everyone making this work possible and a difference during this journey.

First and foremost, my deepest gratitude goes to MariAnne Karlsson, my principal supervisor who supported me throughout the process and beyond. Not only, was I lucky to receive the best scientific education and guidance over the past years, but also more support and encouragement than I could have ever wished for. Thank You from the bottom of my heart. Many thanks also go to Lars-Ola Bligård, my co-supervisor. I always will remember our discussions and your jokes as one of the keys for having lots of fun, while approaching complex questions.
As an industrial PhD candidate, you get twice the manpower, and I was especially lucky, that I got to work with a number of great people at Volvo Cars over the years. First, I want to thank Pernilla Krook for your insight and friendship over the years, and Mikael Gordh who believed in me and gifted me his support. Further, I want to thank Christoffer Kopp, Annie Rydström and especially Alexander Eriksson who acted in the role of my industrial supervisors, confidents, and guides during different stages of this work. You all brought your unique perspective and knowledge to our discussions. Especially you, Alex, without you, your support and believe in my work, the last bit of this thesis would likely not have happened the way it did. Casper Wickman, I cannot begin to express how grateful I am to have had you by my side throughout this journey. You made it, unlike many others, from the beginning to the end, and you have been an inspiration, mentor, champion, and true friend. For that, I am indebted to you.

Special appreciation goes also to my collaborators and co-authors. Thank You, Julia Orlovksa, for inviting me to collaborate on Study II, which ended up giving us both a lot more to learn then we set out to do. The most fun and

learning, however, I had with you Mikael Johansson. Thank You, for joining forces during Study III, always being up for another idea or discussion and letting me in on your perspective – I hope that our paths continue to cross. I am also grateful for Soyeon Kim, who with her creativity and abundance of energy brought about another spur of motivation during the last sprint of this thesis. I am so happy we got to collaborate on your endeavours and on Study IV and to have made a friend in you.
Not to forget, all the research conducted was enabled by my colleagues at Volvo Cars, who supported by providing their expertise and time in the preparation and conduction of the studies, and most importantly their interest in what I do. Thank you, Tor Guttormsen, Hanna Gerdeskans, Alvaro Alonso Bivou, Alfons Massey, Claas Wedin and especially Kaj Luukkonen† for making Study III possible and so much fun. Thanks also to Erick Hernandez, Patrik Castenbladh, Niclas Lind, Alice Nilsson and Pauline Lorin that supported Study IV in the same extent. And a very special thank you to Linnea Olsson – I really enjoyed working with you. A big thank you also to Fernando Sánchez-Ulloa, who made me an unofficial member in his team allowing me to understand the needs of my colleagues, and ultimately providing the space and time to conduct Study V. However, without your time and enthusiasm, Kevin Orende, Tatiana Choeuiri and Manu Revi, I would have never learned as much as I did. Yet my warmest appreciation goes to you, Manu, you did not only believe in the usefulness of the toolkit, and applied it, but also supported me during the year, incorporating all the feedback and improving it. Thank you, it was the most fun working with you. Finally, a special thank you to Amanda Jonell, who was not only my biggest cheerleader during the last study, but also supported with her skills as a researcher during the interviews. And last but not least, appreciation goes to Kaspar Raats, who jumped in when I needed a moderator and has been my brother in mind during these past few years, walking the same path and always ready for a good conversation and a laugh. However, none of my studies would have been possible without all the participants. Thank you, for dedicating your time, driving around with us, answering so many questions, and describing your experiences to me. You contributed to fun and insightful sessions that formed this work.

A lot of people involved, but this kind of work requires not only expertise and lots of work, but also idle time. One of the things I learned from Mari-

Anne is that good ideas need incubation time. And the motivation and ideas that enabled me to go the extra mile came to me in the days between major milestones. For that, I first want to thank each of my colleagues at the division Design & Human Factors at Chalmers. Not only have you been a second home, providing so much encouragement and support, but also endless fikas, craft meets, rock parties and skitgubbe tournaments. You are truly amazing and fun people and I count myself lucky to have had the pleasure being part of it. I am especially grateful for the exchanges with you Antonio Cobaleda Cordero, the abundance in laughter and positivity you bring, Göran Smith, for good advice and better music, and Fredrick Ekman, for always making time for a meaningful conversation. My deepest gratitude, however, goes to the wonderful women I've had the pleasure of meeting here. Siw Eriksson, Cecilia Berlin, Eva Simonsen, and Anneli Selvefors - you are all amazing and have taught me more than you might know. And most significantly, Maral Babapour and Helena Strömberg, I truly admire you, appreciate your insightful advice, and friendship - you are an inspiration I am grateful to have you in my life.

And last, but not least, I want to thank my family. I am profoundly thankful for my parents who have been the greatest role models and supporters throughout my entire life. You proved to me the value of hard work and perseverance. *Faleminderit për dashninë dhe mbështetjen. Besimi i patundshëm në mua është dhurata më e mire që do të kisha kërkuar.* Finally, Johannes, I am grateful beyond words for you. You have been the greatest support anyone could ever ask for, cooking the best meals, making sure I relax and get a laugh in at least once a day, listening to me rambling about my theories and models, making my sketches into beautiful illustrations, joining me on travels, and entertaining unsolicited educational monologues about driving automation and human cognition with patience, all the while renovating our home with me. Without you, the last years would have been only half as fun. Thank You.

Appended Publications

Paper A
Karlsson, I.C.M., & Novakazi, F. (2023). Drivers' usage of driving automation systems in different contexts: A survey in China, Germany, Spain and USA. *IET Intelligent Transport Systems*, 17(10), 2004–2019. https://doi.org/10.1049/itr2.12392
Contribution: Karlsson and Novakazi designed the survey and collected the data. Analysis, writing, and editing of the paper were carried out in collaboration between the authors.

Paper B
Orlovska, J., Novakazi, F., Lars-Ola, B., Karlsson, I.C.M., Wickman, C., & Söderberg, R. (2020). Effects of the driving context on the usage of Automated Driver Assistance Systems (ADAS) - Naturalistic Driving Study for ADAS evaluation. *Transportation Research Interdisciplinary Perspectives*, 4, 100093. https://doi.org/10.1016/j.trip.2020.100093
Contribution: Novakazi planned and conducted the qualitative study phase. Analyses, writing, and editing of the paper were carried out in collaboration between the authors.

Paper C
Novakazi, F., Orlovska, J., Bligård, L. O., & Wickman, C. (2020). Stepping over the threshold linking understanding and usage of Automated Driver Assistance Systems (ADAS). *Transportation Research Interdisciplinary Perspectives*, 8, 100252. https://doi.org/10.1016/j.trip.2020.100252
Contribution: Novakazi planned and conducted the qualitative study phase, with feedback from Bligård. The analysis of the data was carried out in collaboration between the authors. Novakazi wrote the manuscript with feedback from the other authors.

Paper D
Johansson, M., & Novakazi, F. (2020). To Drive or Not to Drive – When Users Prefer to Use Automated Driving Functions. *Proceedings of the 7th Humanist Conference*. Rhodes Island, Greece, September 2020.
Contribution: Novakazi and Johansson planned, conducted, and analyzed the study in collaboration. Johannson wrote the paper with feedback from the other authors.

Paper E
Novakazi, F., Johansson, M., Strömberg, H., & Karlsson, I.C.M. (2021). Levels of What? Investigating Drivers' Understanding of Different Levels of Automation in Vehicles. *Journal of Cognitive Engineering and Decision Making*, 15(2–3), 116–132. https://doi.org/10.1177/15553434211009024
Contribution: Novakazi and Johansson planned, conducted, and analyzed the study in collaboration. Novakazi and Johansson wrote the paper with feedback from the other authors.

Paper F
Johansson, M., Novakazi, F., Strömberg, H. & Karlsson, I.C.M. (2023, accepted with revision). Piecing together the puzzle – exploring how different information sources influence users' understanding of automated vehicles. *Behaviour & Information Technology.*
Contribution: Novakazi and Johansson planned, conducted the study, and analyzed the data. Johansson and Karlsson wrote the paper with feedback from the other authors.

Paper G
Kim, S., Novakazi, F. and Karlsson, I.C.M. (2023, in submission). Interaction Challenges in Automated Vehicles with Multiple Levels of Driving Automation - An On-Road Study. *Applied Ergonomics.*
Contribution: Novakazi planned and conducted the study, with feedback from Karlsson. Analysis, writing and editing of the paper were carried out in collaboration between the authors.

Paper H
Novakazi, F. & Bligård, L.O. (2023, in submission). Design for Perception – Co-Creation and Validation of a Design-Tool for Driving Automation Systems. *Conference of Intelligent User Interfaces, 2024.*
Contribution: Novakazi planned, conducted the study, analyzed the data, wrote, and edited the manuscript with feedback from Bligård.

Additional Publications

Johansson, M., & Novakazi, F. (2023). Action-Meaning Networks - A Novel Methodology to Identify Unsafe Usage of Driving Automation. *Proceedings of the 8th Humanist Conference.* September 21-22 Berlin, 2023, Germany.

Kim, S., Shi, E., Novakazi, F., & Oviedo-Trespalacios, O. (2023 Stakeholder-Centred Taxonomy Design for Automated Vehicles. *Adjunct Proceedings of the 15th International Conference on Automotive User Interfaces and Interactive Vehicular Applications.* https://doi.org/10.1145/3581961.3609829

Lidander, L., Novakazi, F., & Erhardsson, G. (2022). Building Blocks of Responsibility - A Conceptual Model Illustrating the Factors Influencing Perceived Responsibility Over the Driving Task when Interacting with Driving Automation Systems. *Adjunct Proceedings of the 14th International Conference on Automotive User Interfaces and Interactive Vehicular Applications.* https://doi.org/10.1145/3544999.3552524

Novakazi, F., Eriksson, A., & Bligård, L. O. (2022). Design for Perception - A Systematic Approach for the Design of Driving Automation Systems based on the Users' Perception. *Adjunct Proceedings of the 14th International Conference on Automotive User Interfaces and Interactive Vehicular Applications.* https://doi.org/10.1145/3544999.3552525

Rydström, A., Mullaart, M. S., Novakazi, F., Johansson, M., & Eriksson, A. (2022). Drivers' Performance in Non-critical Take-Overs from an Automated Driving System—An On-Road Study. *Human Factors.* https://doi.org/10.1177/00187208211053460

Johansson, M., Söderholm, M., Novakazi, F., & Rydström, A. (2021). The decline of user experience in transition from automated driving to manual driving. *Information*, 12(3). https://doi.org/10.3390/info12030126

Novakazi, F., Johansson, M., Erhardsson, G., & Lidander, L. (2021). Who's in charge? The influence of perceived control on responsibility and mode awareness in driving automation. *IT - Information Technology*, 62(2). https://doi.org/10.1515/itit-2020-0020

Orlovska, J., Novakazi, F., Wickman, C., & Söderberg, R. (2019). Mixed-method design for user behavior evaluation of automated driver assistance systems: An automotive industry case. *22nd International Conference on Engineering Design, ICED 2019.* Delft, Netherlands. https://doi.org/10.1017/dsi.2019.186

List of Abbreviations

ACC:	Adaptive Cruise Control
AV:	Automated Vehicle
BA:	Behavioural Adaptation
BASt:	Bundesanstalt für Straßenwesen
CC:	Conventional Cruise Control
CW:	Cognitive Walkthrough
ECW:	Enhanced Cognitive Walkthrough
DAS:	Driving Automation Systems
DC:	Drive Cycle
DDT:	Dynamic Driving Task
DFMEA:	Design Failure Modes and Effects Analysis
FMEA:	Failure Modes and Effects Analysis
GDPR:	General Data Protection Regulations
GPS:	Global Positioning System
HCI:	Human-Computer Interaction
HMI:	Human Machine Interface
HOR:	Hand-Over Request
JCS:	Joint Cognitive Systems
GUI:	Graphical User Interface
LoA:	Level of Automation
LCA:	Lance Centring Assist

LKA:	Lane Keeping Aid
NDS:	Naturalistic Driving Study
NHTSA:	National Highway Traffic Safety Administration
ODD:	Operational Design Domain
OEM:	Original Equipment Manufacturer
PA:	Pilot Assist (Level 2 DAS in Volvo vehicles)
PR:	Participatory Research
SAE:	Society of Automotive Engineers
SUV:	Sport Utility Vehicle
TOR:	Take-Over Request
UI:	User Interface
WOz:	Wizard-of-Oz

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Chapter 1
Introduction

CHAPTER 1

Introduction

This chapter introduces the area of research by providing a short description of the background and problem area. This is followed by a presentation of the aim and the research questions based on this description. The chapter concludes with an outline of this thesis.

1.1 Background

The development of automated vehicles (AVs) has garnered significant attention in various sectors, including industry, academia, and the general public, because of its argued potential to revolutionise transportation. However, the widespread availability of fully automated vehicles capable of operating under all situations is unlikely to occur over the next few decades, despite the rapid evolution of technology. This has resulted in a transitional phase for drivers, where the vehicle and the driver share the responsibility and control over the driving task. During this transitional phase, there is a need for clear guidelines and regulations to ensure the safe integration of driving automation systems into vehicles.

Driving automation systems (DAS) can be conceptualised as a compilation of active safety technologies designed to assist the driver. Therefore, DAS are widely recognised as effective measures for tackling issues related to traffic safety [1][2][3]. Nevertheless, while it is acknowledged that these systems are not capable of entirely eliminating accidents, research conducted by Cicchino [4][5][6] has demonstrated that they do play a significant role in reducing the occurrence of fatalities and severe injuries.
However, drivers find themselves in the situation where the capabilities and limitations of such systems vary greatly, as they become increasingly complex with the introduction of vehicles offering several levels of automation (LoA). According to the definition provided by SAE International [7] the Levels of Driving Automation range from Level 0 (No Driving Automation) to Level 5 (Full Driving Automation). Vehicles classified as Level 0 to Level 2 automation are fitted with driver assistance systems that possess varying capabilities and functions. For example, Level 1 vehicles are equipped with adaptive cruise control (ACC), and Level 2 vehicles have both lane-keeping and adaptive cruise control functionalities [8]. Vehicles equipped with Level 3 and Level 4 DAS can operate without any input or intervention from the driver in specified driving contexts. These are termed operational design domains (ODD), i.e., specific environment, scenarios, and situations in which the automated system is intended to function without human intervention. Level 5 DAS can fully automate the vehicle in all ODDs and does not require any driver input.

A number of studies have investigated different factors that impact drivers' safe utilisation of DAS. Many conclude that the utilisation of automated systems is heavily influenced by the driver's understanding of the capabilities and limitations of these systems [9][10][11][12]. However, it has been shown manifold that a significant number of drivers lack awareness or possess incomplete comprehension about the constraints associated with the automated systems in their personal vehicles [13][14][15][16][17]. Therefore, for these technologies to improve traffic safety as well as enhance the driving experience and comfort [18], DAS must be designed so that drivers accept them, understand their capabilities and limitations, and use them appropriately, without abusing them or becoming overly reliant on them.
However, the implementation of several levels of automation (i.e., driving

modes) in vehicles has brought about a level of intricacy that poses considerable difficulties for drivers in understanding the capabilities of a DAS and their own role when interacting with such systems [19]. The availability of several driving modes, which are offered depending on different ODDs, can result in a state of confusion about what the system's and what the driver's responsibility is at a given time. The state where a driver is not aware of what driving mode or automation level is currently active, is also known as mode confusion [20].
A simulator study by Feldhütter and colleagues [21] on the topic of mode confusion in the interaction with automated vehicles, found that mode confusion between two driving modes is especially an issue in transitions. Some work contends that the user interface (UI) is essential in addressing this issue. For example, Banks and colleagues [22] found during an on-road study with Level 2 vehicles that a poor design of the UI and physical controls led to a number of the observed mode confusion instances. Based on similar observations, Carsten and Martens [23], argue for the importance of the UI design when developing automated systems in order to increase the driver's awareness about the driving mode, especially in the interaction with a vehicle offering several levels of automation.
A wide range of studies has investigated how transitions effects in automated driving (cf. [24]). A literature study conducted by Kim and colleagues [25] reviewed the effects of the UI in transitions and found that there are many conflicting results as to if the UI can have a positive effect on the driver's interaction with DAS. These findings highlight that there are other factors that need to be investigated.

Therefore, it can be deduced that one of the elements crucial for the safe utilization of DAS, is the driver's mental model. It has been found that drivers' understanding of how automated systems work and how they can utilize such systems often does not match the mental model of the designers intended use. For example, Beggatio and Krems [26] conducted a longitudinal driving simulator study to examine the potential changes in a driver's mental model of their interaction with Level 1 DAS, specifically ACC, when it is consistently employed in the same situation. While the precise effects remain unknown, this investigation indicates that drivers may develop an inaccurate or incomplete mental model of the systems in use, even after prolonged use, particularly if they are not exposed to specific situations that require them to adjust their mental model. Additional research endeavours have provided evidence of the intrinsic constraints associated with trial-and-error learning [27][28], coming to similar conclusion that driver's understanding of a DAS will not evolve, if it is sufficiently developed to allow for a perceived safe usage [29]. Consequently, the experience of individuals with the systems is affected. This indicates that the driver's understanding of the systems impacts their interaction and therefore safe utilization of such systems [30][13][14][31][15]. Thus, in order for drivers to utilise the systems in a safe manner, it is essential that they have a thorough understanding of the various modes of operation and limitations associated with these systems. Failure to acquire this knowledge can result in an inability to formulate effective usage strategies and lead to hazardous situations [32][26][22][33].

There are various methods available for disseminating information to drivers on vehicle functionalities, with one such method being the utilisation of car manuals, which aim to offer insights into the underlying principles of vehicle functions. Yet, other investigations have shown that car manuals, which include information about the operation of the systems, are not successful in training drivers due to the provided information being too technical and abstract and therefore go underused [34][35][36]. As a result, drivers often encounter challenges when attempting to put the information into practical application [15][37]. Moreover, Abraham and colleagues [38] drew attention to the lack of research on dealerships' provision of DAS-related information and training to consumers. Based on the findings of their exploratory research conducted across multiple dealerships, it was determined that there is a significant lack of educational initiatives. Consequently, the study concluded that consumers may continue to have insufficient or incorrect knowledge, i.e., mismatch in mental model, regarding the automated systems installed in their personal vehicles [38].

While many streams of research have identified issues with existing taxonomies, some have proposed improvements, and attempts have been made to reduce driver confusion, including investigating how the names of DAS are associated with different levels of automation [38], rephrasing the descriptions of responsibilities (e.g., [39]), and framing the driver's responsibility in terms of "driving" and "riding" [40]. In light of this realisation, SAE has added a visual chart to the initial taxonomy to simplify and clarify the "Levels of Driving Automation" for consumers [7]. The addition describes the levels of automation through simpler language and graphical representation, illustrating what the driver must do and what the system does. However, despite the fact that the human role has been clarified, the taxonomy continues to illustrate which actor is responsible for which task and does not account for human perception of the system use and purpose. Critics continue to argue that misconceptions and lack of understanding can be traced to the technological focus during the development of these systems, based on current taxonomies, which take a task allocation approach and do not regard the driver's perception of the system's capabilities and their own responsibilities [39][41].

As DAS become increasingly complex the need for a human-centric perspective increases, relying on new and human factor driven approaches to address the increasing challenges. However, while there is a number of human factors methods applied in the automotive industry, the chosen methods are usually driven by a human error paradigm, which aims to identify and quantify human error in the interaction with a system through different Human Reliability Analysis (HRA) techniques (cf. [42]). This paradigm is driven by the perspective that humans are the root cause in the failure of a technical system, focusing on errors rather than the effects of all forms of human behaviour, and thus, not considering the complex interaction that takes place in the human-automation interaction. Therefore, currently, a notable gap exists in the automotive industry, where designers lack a human-centric approach to effectively address the development of driving automation from a human-centric perspective which clarifies cognitive processes and drivers' needs in the interaction with a DAS. Recognizing the vital role of design methods in guiding design and engineering practices, a human-centric perspective is instrumental in assisting designers to accurately identify driver needs and validate their design choices [43], especially for the development of complex driver-automation interaction.

The highlighted factors only represent a subset of the complexities involved in the complex interaction between the driver and the vehicle, and still has not fully answered the question on how this knowledge can be applied to the design of driving automation.

To the best of the author's knowledge, no prior research has endeavoured to establish a unified description of or has provided an in-depth overview of the factors that influence the driver's perception and consequent understanding of driving automation systems. Therefore, the presented work aimed to investigate the various factors that influence drivers' perception and consequently shape their understanding of DAS, with the goal of informing the human-centric design of driving automation from a human-centric perspective.

1.2 Aim and Research Question

This thesis has examined the interaction between humans and automation in the context of driving, specifically focusing on end-users of Driving Automation Systems. The primary objective was to contribute towards the systematic development of DAS from a human-centric standpoint. Given the problem description and thesis aim, the following research questions are posed:

> *RQ1: What are the factors that impact the driver's perception and subsequent understanding of driving automation systems?*

> *RQ2: How can this knowledge be applied to guide design decisions for practitioners involved in the development of driving automation systems?*

In order to support a problem-solving approach and motivate manufacturers to adopt a human-centric perspective for the design of DAS, it is imperative to comprehend the various factors that influence the drivers while utilising such systems. These research questions guide the generation of knowledge that can inform future design decisions in the development of automated driving systems from a human-centric standpoint.

1.3 Thesis Outline

The present thesis is structured into seven distinct chapters, the contents of which are briefly described below.

Chapter 1 introduces the area of research by providing a short description of the background and problem area. Based on that, the aim and the research questions are presented. The chapter ends with a brief outline of the thesis structure.

Chapter 2 details the theories through which the empirical data extracted from the four empirical studies were viewed. First, the chapter provides the reader with an overview of relevant background and where the theories originated, and it then concludes by discussing the author's perspectives and observations regarding the subject matter. The purpose is to provide a condensed version of the corpus of knowledge to the reader.

Chapter 3 provides an overview of the methodological strategy employed in the research. The paper examines the author's philosophical standpoint regarding scientific theories and explores its implications for their methodological choices in addressing the research questions. The connection between the attached papers and the research questions is illustrated, and afterwards, the methodology for conducting the cross-study analysis is explicated.

Chapter 4 provides a comprehensive overview of the synthesised findings derived from the cross-study analysis. It presents the findings in the form of a descriptive model that explains the interplay between perception and understanding. Additionally, it provides an overview of the developed design toolkit and its variants.

Chapter 5 establishes the foundation for addressing the research questions. The responses are based on a summary of the investigations that were carried out and details a summary of the results from the cross-study analysis for each of the conducted studies independently.

Chapter 6 concludes the thesis by presenting a comparison between the contribution made through this work and the current body of research, followed by a discussion of the implications for design. The chapter concludes with reflections on the research approach.

Chapter 7 summarizes the conclusions of this thesis.

Chapter 2
Frame of Reference

CHAPTER 2

Frame of Reference

At the core of this thesis lie the concepts of automation and understanding, and therefore this chapter in divided into these two sections. The purpose is to provide a condensed version of the theoretical foundations to the reader. Firstly, the chapter provides the reader with an overview of the relevant background and thus, provides the frame of reference within which the data extracted from the four empirical studies was examined. It concludes by discussing the author's perspectives and observations regarding the subject matter.

2.1 Automation

This chapter presents an overview of several theories related to automation and Levels of Automation, as well as the existing taxonomies. In addition, it examines the human factors challenges that arise when implementing a system that provides several levels of automation, particularly in the automotive domain, and how this pertains to the design of DAS.

Perspectives and Challenges

Humans continuously strive to make work easier. Automation can be defined as the process by which mechanical or electronic devices autonomously operate an apparatus, process, or system, thereby replacing human labour [44]. A household thermostat, GPS route planners, parking assistance, and automatic windscreen wipers in vehicles, as well as sophisticated industrial control room systems, are all examples of applications that fall under the umbrella of automation. Control complexity can range from straightforward on-off control to intricate multivariable algorithms. Automation is used for information gathering and analysis, decision-making, carrying out an action, system monitoring, and aiding humans in executing a range of tasks. This human-machine interaction and cooperation is described by various models. One influential attempt aiming to describe the human role in the interaction with automated systems is Fitts' list [45]. Fitts allocated different tasks or functions to either the human (detection, perception, judgment, induction, and improvisation) or the machine (speed, power, computation, replication, and simultaneous operations), based on which could perform them in the best way.

The outsourcing of demanding tasks to an automated system has been developed for functions that humans do not wish to perform or cannot perform as accurately or reliably as machines, resulting in a transition from manual to supervisory control by the operator [46]. Although Fitt's [45] goal was to adopt a compensatory strategy, seeking to determine the optimal utilisation of automation to improve human abilities, the primary driving force behind this approach is the desire for efficiency, safety, quality, and productivity.
However, it is crucial to acknowledge the intricate nature and difficulties associated with human-automation interaction. To that regard, Bainbridge [47] pointed out the paradox of automation, arguing that it may expand rather than eliminate problems with human operators. This irony derives from the deterioration of manual control skills, cognitive abilities, and the inability to stay vigilant during monitoring tasks. Consequently, human operators are often seen as a significant source of unpredictability and unreliability in system performance. This perception led many system designers to advocate for minimising human involvement in the execution of tasks. Notably, the need for a human operator stems from the inability to fully automate certain tasks due to their technical complexity, leaving operators with systems and inherent

processes that are difficult to fully comprehend and thus prone to use errors [47][48].
Additionally, Dekker and Woods [49], posited that placing emphasis on the allocation of tasks may create the misconception that automation can be effectively implemented by merely transferring human responsibilities to automated systems. This view emphasizes that a pure task allocation approach (cf. Fitt's list [45]) fails to acknowledge that the implementation of automation does not merely replace human labour but rather introduces novel responsibilities for individuals tasked with overseeing the automated processes.
Thus, for complex and unexpected systems that heavily rely on the adaptive capacity of individuals to handle unforeseen variability, it is imperative to shift the focus from a task allocation approach towards an understanding of the collaboration between humans and machines. In an attempt to address these challenges, different research streams have endeavoured to describe the human role in automated systems. For example, Kaber and Endsley [50] pointed out that the goal of human-centred automation is to create systems that retain the human operator in control loops with meaningful and well-designed tasks. One key issue they have identified in human-automation interaction is a lack of situation awareness [51], i.e., operators struggle to attend to monitoring and supervisory tasks over prolonged periods of time, loosing oversight of the system state and task progress for example. To overcome this problem, Kaber and Endsley's [50] approach on automation, focused on adaptive automation to manage operator workload through dynamic control allocation between the human and machine in collaboration. Other research findings on the search of a human-centred approach support achieving situation awareness in the interaction with complex systems, by distributing the tasks between the human and automation in a way that a team effort is achieved, which enhances the overall performance and decision-making capabilities of the operators. This approach recognizes the importance of maintaining a balance between human control and automation, allowing operators to maintain a high level of situational awareness while also benefiting from the capabilities of automation. By effectively distributing tasks and responsibilities, operators can focus on higher-level cognitive processes, such as problem-solving and decision-making, while automation handles routine or repetitive tasks [52][53].

Hollnagel and Woods [54] proposed a another perspective, known as the Joint

Cognitive Systems (JCS) theory, for characterising human involvement with an automated system. The JCS theory is an approach in cognitive science and human-computer interaction that emphasizes the interaction and collaboration between humans and their tools, technologies, or environments. It focuses on understanding cognition not just as an individual process but as a distributed phenomenon between the human and the machine, in order to achieve a common objective. JCS does not aim to diminish the importance of the operator or eliminate the involvement of a human operator but examines how humans and technology collaborate and complement each other's abilities, leading to effective problem-solving and decision-making, and thus, entails the collaborative interaction between humans and machines, rather than solely focusing on its individual constituents. This perspective highlights the necessity to consider the driver's understanding of DAS, as it assumes that the human operator and the machine have shared knowledge about situations encountered. This leads to the consideration of the ongoing communication and collaboration between driver and vehicle and spotlights the perception process as a crucial component in understanding the collaborative interaction.

Levels of Automation

Discussions regarding a cooperative relationship between human and machine in the control of complex systems have been conducted under the overarching concept of Levels of Automation. The following subsections will discuss this concept and its various taxonomies.
The term Level of Automation (LoA) refers to the level of task planning and performance interaction maintained between a human operator and a complex system [55][56]. Over the years, a number of different taxonomies describing LoA have been developed (cf. [57][58][59]). However, all of these taxonomies have in common that they, similar to Fitt's List, solely determine decision-making and control authority, for a wide range of tasks, which enables an assessment of whether human or machine should be carrying out certain tasks in a system.

In an early work, Sheridan and Verplank [60] developed a hierarchy which included the allocation of decision making and action selection of various degrees. The objective of Sheridan and Verplank's LoAs was to define if the machine or the human should have the control, rather than deciding how they

share the control. Endsley [57] developed a LoA to extend the description of human decision making in the context of expert systems. The hierarchy constituted five levels ranging from 1. Manual Control, 2. Decision Support, 3. Consensual Artificial Intelligence, 4 Monitored Artificial Intelligence, and 5. Full Automation. This list concentrates on the cognitive tasks expert operators have to conduct, based on the information the system provides.
Building on foregoing efforts, Endsley and Kaber [58] developed a taxonomy for LoA encompassing wider array of aspects, including a range of cognitive and psychomotor tasks in different domains, e.g., air traffic control, aircraft piloting, and advanced manufacturing.

Throughout all the analysed domains, four generic functions were identified as common: 1. Monitoring: Taking in all information relevant to perceiving system status; 2. Generating: Formulating options or task strategies for achieving goals; 3. Selecting: Deciding on particular options or strategies; and 4. Implementing: Carrying out the chosen options. Based on these generic functions ten levels of automation were formulated, by assigning each function to either Human, Computer (i.e., automated system), or both, as can be seen in **Table 2.1**. The taxonomy serves as a means to identify decision-making and control authority and is applicable to a variety of tasks, which enables the assessment of whether a human or a computer should be responsible for certain tasks within a system, based on their performance. Parasuraman and

Table 2.1: Endsley and Kaber's [58] LoA taxonomy for human-computer performance.

Levels of Automation		Monitoring	Generating	Selecting	Implementing
1	Manual Control	Human	Human	Human	Human
2	Action Support	Human-Computer	Human	Human	Human-Computer
3	Batch Processing	Human-Computer	Human	Human	Computer
4	Shared Control	Human-Computer	Human-Computer	Human	Human-Computer
5	Decision Support	Human-Computer	Human-Computer	Human	Computer
6	Blended Decision Making	Human-Computer	Human-Computer	Human-Computer	Computer
7	Rigid System	Human-Computer	Human-Computer	Human	Computer
8	Automated Decision Making	Human-Computer	Human-Computer	Computer	Computer
9	Supervisory Control	Human-Computer	Computer	Computer	Computer
10	Full Automation	Computer	Computer	Computer	Computer

colleagues [46] provided a similar approach to LoA. However they do not provide a taxonomy, but rather a framework that aims to offer insights into the potential automation of various systems across different automation levels. The framework considers whether 1. Information Acquisition, 2. Information Analysis, 3. Decision Selection and 4. Action implementation are functions to be automated. The information acquisition, decision selection and action implementation for a function, are identical to Endsley and Kabers' [58] monitoring, selection, and implementation features, but, this framework does not include providing information as a function. Instead, it views information analysis as a separate step that needs to be automated.

The concept of LoA are still heavily discussed, and it has been suggested that the different taxonomies overlook certain key issues, or that they do not satisfactorily project a human-centred view on automation. Therefore, several studies have suggested alternative ways of categorizing automated system functions. One example is Spath and colleagues [61] who suggested a more generalized view of types of automation, and simply differentiated between a 'semi-automated' and 'completely automated' system. A system is categorized as semi-automated when the machine needs some degree of support from the human in performing the tasks at hand. For example, the start, end and succession of the functions are controlled by the human. 'Complete automation' is achieved when the machine completely relieves the human of their task to achieve higher precision, efficiency, or safety.

In a similar vein, Onken and Schulte [62] put forth a conceptual framework that delineates two distinct categories of automation: operator-controlled automation, which is typically regarded as a form of supervisory control, and built-in automation, which is seen as an inherent component of the system. In the context of supervisory control, the operator activates, monitors, and deactivates the automated function, which bears resemblance to the concept of semi-automation. The authors claim that, by engaging with the automated function, users develop a mental representation of the interaction, which then influences their use of the system.
However, an integrated automation, when built into a system, operates without direct user control. This lack of control can lead to users being unaware of the presence of automated functions or the current status of the system. The

presence of concealed operations in built-in automation runs the risk of elicit frustration among human operators, may lead to a lack of awareness about the inherent system states [63] and in certain instances, may even result in hazardous situations. This was exemplified in the case of the Boeing 737 MAX incident, wherein a malfunctioning sensor initiated a sequence of events that led to a state of perplexity and ultimately culminated in a tragic accident [64].

The airline industry, where most of this research has gathered its findings, has tried to address the aforementioned challenges since the 1970s and introduced additional training, educating pilots about the changes to their role when flying with an automation [65][66], as well as educating them about the technical and functional aspects of the automation system [67]. Through these efforts, the airline industry has managed to provide pilots with a more complete understanding of the systems and significantly reduced the number of such events [68].
The various taxonomies and different approaches proposed over the years often serve a specific domain, and sometimes one domain applies different taxonomies [69]. For instance, the taxonomies created by Parasuraman [46] and Endsley and Kaber [58] were based on the knowledge gathered in the aviation sector but were considered as a basis for the introduction of automation into the automotive sector. However, there is a disparity between the levels provided in each of the automation descriptions, showing that a unification of approaches is not an easy task and different stakeholders regard different aspects as suitable for their respective approaches and domains.

Within the context of the automotive domain, the introduction of automated technologies into vehicles appears to reintroduce similar challenges. However, one significant obstacle is the fact that the general population possesses a lesser understanding of driving automation and its many levels compared to proficient operators, such as pilots, and training possibilities for DAS are lacking [70]. Thus, the introduction of levels of driving automation presents a new set of challenges for designers, developers, and regulators of such systems.

Levels of Driving Automation and Human Factor Issues

Driving Automation Systems are designed to assist the driver and facilitate the use of numerous comfort and safety functions. These systems feature a variety of assistive functions including anti-locking systems, blind spot warning, collision aid, and emergency brakes [71][72][73]. The adoption of electronic brake and drive control technologies facilitated the introduction of partially automated driving. Partially automated driving features provide assistance to the driver by utilizing longitudinal and/or lateral control of the vehicle through the process of scanning and analysing the surrounding environment [74][75]. To capture their environment, DAS utilize radar and video technologies to enable longitudinal vehicle motion (i.e., direction of travel) and lateral vehicle motion (i.e., position of the vehicle in the lane). Cruise Control was the initial implementation of longitudinal control, which aimed to maintain a predetermined speed during long travel. The term "Conventional Cruise Control (CCC)" has been widely adopted to differentiate it from Adaptive Cruise Control (ACC) systems. ACC systems additionally incorporate forward-looking sensors that enable the system to detect and regulate the distance and closing speed of a lead vehicle [73][76]. Active lateral vehicle control is an enhancement that builds upon lane departure warning technologies, which are designed to identify events when a vehicle deviates from its designated lane. Thus, active lane positioning control systems have the capability to steer the vehicle back to the lane's centre, rather than simply alerting the driver, provided that distinct lane markings are visible. The present generations of lateral vehicle control systems are commonly referred to as Lane Keeping Assist (LKA), Lane Centring Assist (LCA), or similar distinctions, which may vary based on the specific manufacturer.

Throughout this work 'system' is defined as a collection of various components or clusters of functions that support longitudinal (direction of travel) and lateral (lane position) vehicle motion. In contrast, a 'mode' or 'driving mode' refers to the specific level of automation executed by the system.

Vehicle automation is a prominent example of a domain where LoA taxonomies are continuously discussed. Several organisations and consortiums, including the German Federal Highway Research Institute (BASt), the National Highway Traffic Safety Administration (NHTSA), and SAE International, have devised taxonomies describing levels of driving automation. The most prominent, SAE's taxonomy J3016 [7], was created with the intention of establishing a common understanding of the various levels of automation and providing a definition for the classification of driving automation in order to support regulations. See **Figure 2.1** for an overview of the taxonomy and definitions related to DAS according to SAE International.

The taxonomy describes variations in driver and driving automation task allocations. The classification ranges from level 0 (No Driving Automation) to level 5 (Full Driving Automation), with each level having distinct functional specifications for the vehicle and, consequently, a distinct task for the driver. For instance, in Level 0 solely offers alerts and temporary support through vehicle safety subsystems, such as antilock braking and stability control. Level 1 (Driver Assistance) performs the longitudinal or lateral driving task but requires the presence of a driver who supervises the system and handles the remaining dynamic driving tasks (DDT). Level 2 (Partial Driving Automation) the DAS performs the longitudinal and lateral driving tasks simultaneously, under supervision of the driver, who also performs the remaining DDT. Throughout all of these driving modes, the vehicle is regarded as an assistive system, with the driver retaining full control and responsibility for the driving task at all times.
In Level 3 (Conditional Driving Automation) and Level 4 (High Driving Automation), the driver is relieved of the driving task under certain driving conditions and for a certain amount of time but retains supervisory control. A significant differentiation between Level 3 and Level 4 or 5 DAS is in the requirement for the human driver in Level 3 vehicles to be fallback-ready to resume control of the vehicle whenever prompted by the system. In contrast, at Level 4, the human driver does not need to be alert or prepared to take over the DDT at any time. In Level 5 (Full Automation), the driver is relieved completely from the driving task and becomes merely a passenger.
The existing frameworks for describing different levels of automated driving have advantages, such as describing the task of the automation and/or human [77][19], but they have been criticised for being based on detailed technical and functional taxonomies (e.g., [39][40] or a narrow a function allocation approach (e.g., [78]. However, the more driving modes are introduced into the vehicle, the less likely is it for the driver to understand the intricate system states fully, as the increased complexity makes it difficult for drivers to understand the various driving modes the vehicle offers and, thus, it becomes more challenging to grasp how the vehicle will behave in different situations. This

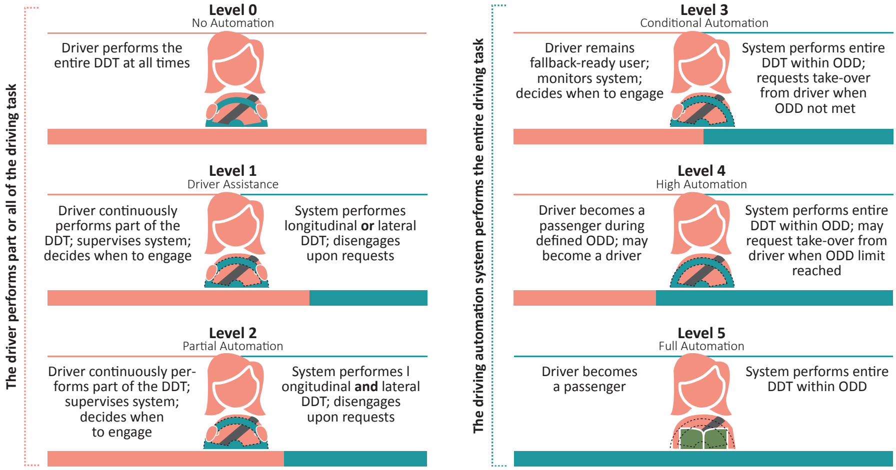

Figure 2.1: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. (Adapted after SAE International [7])

contributes to ambiguity surrounding automation modes in vehicles, reducing the driver's overall understanding of the vehicle's capabilities and their own responsibilities (cf. [20][79][69][19].

Hence, it is argued that control allocation becomes a significant issue as the driving task (e.g., steering, accelerating, braking, keeping distance to other road users, navigating, etc.) shifts from the driver to the vehicle, especially as the driving task becomes increasingly shared between the driver and the vehicle. The transfer of control authority [80] during interaction with DAS is recognised to have both direct and indirect impacts on the driver and the system's utilisation. Direct effects refer to specific system function specifications that are designed to improve performance on one or more control levels, such as improved lane keeping performance. Indirect effects refer to unintended consequences that are not intended or inferred by the designers' functional specifications.
It has been shown that the use of these technologies can lead to the driver making behavioural adaptations (BA) to the system, potentially reducing safety and comfort benefits the use of these technologies promises [76]. The phenomenon was first recognised in the 1990s and defined as 'those behaviours

which may occur following the introduction of changes to the road-vehicle-user system and which were not intended by the initiators of the change' [81]. Manser and colleagues [82] categorised BA process into three distinct time periods: immediate, which refers to the initial encounter; short-term, which spans days or weeks; and long-term, which encompasses months or years. The majority of studies focus on the immediate or short-term impacts and examine the early deviations from the mental model of interacting with the DAS. As a result, the long-term effects of these systems remain mostly uncertain [83][84]. Another stream of research on behavioural adaptation has developed a considerable body of literature on the identification of 'adverse behavioural consequences' [85] or negative behavioural adaptations. For instance, different research endeavours have long pointed out that drivers tend to have over-trust, which promotes over reliance, and misuse [86][87][88][22] [33], the effects of automation on situation awareness and the connected 'out-of-the-loop'-problem [89][90][91][92][93], fatigue through the monotony of supervising the vehicle [94][84] or that drivers simply use the systems in ways and in ODDs that were not intended by designers [95], leading to unsafe usage practices.
Multiple studies indicate that the driver's understanding of the capabilities and limitations of driving DAS, their awareness of the available and currently active driving modes, and ability to maintain the appropriate level of engagement and intervention in crucial scenarios is a matter of worry [32][13][14]. These concerns are widely based on evidence about driver misconception of the relevant functions, or over-confidence in the systems' capabilities and limitations.

Some research streams attempted to tackle the problem of informing the driver about the intention of the automation through the application of user interface design guidelines for automated vehicles (e.g., [23]). Nonetheless, the irony of automation lies in the perception of increased capability of such systems, which leads to a range of issues, extending beyond the user interface. Other research streams, in search of alternative explanations for the observed human factor issues, have indicated that the existing design of DAS lacks adequate attention to the driver's mental model of interacting with a DAS (e.g., [26][15]. The introduction of several driving modes into one vehicle only exacerbates the existing problems (e.g., [21][19]. Driver's struggle to understand feedback received from the vehicle about the different mode changes or are confused

about information received from the vehicle, and what they are supposed to do [22][96]. A survey conducted by Seppelt and colleagues [40] revealed that the taxonomy proposed by SAE International [7] led to confusion regarding the roles and responsibilities of drivers, for example, that drivers could distinguish between driver assistance and full automation but had difficulty distinguishing between the levels in between. Similarly, Abraham et al. [38] demonstrated that the design of DAS affects the driver's perception of the system and the expected levels of accountability. Furthermore, Homans and colleagues [97], concluded based on a survey, that drivers' understanding of automation levels does not align with the taxonomies. This ambiguity may result in misuse or even non-use of the system, thereby diminishing the potential benefits that automation support can provide [46].
Furthermore, Yang and colleagues [39] argue that the extant levels of driving automation taxonomies are technology-centred and presented from the perspective of vehicle technology development or policy development, which is problematic as this approach may impact the design of the driver-vehicle interaction and might not address the ways drivers comprehend such systems. Seppelt and colleagues [40] noted that classifications are written by engineers for engineers. Smith [98] further argues that the established taxonomies influence the way designers think about the system, resulting in design decisions driven by technological instead of driver-centric viewpoints. Consequently, a technology-centred taxonomy may result in design decisions that disregard crucial driver perspectives, such as how drivers perceive and comprehend the systems.

Overall, research indicates that there are numerous factors that impact the driver's interaction with a DAS. Although DAS have the potential to greatly improve safety and comfort, the existing challenges highlight the importance of designing these systems to assist drivers in developing an accurate understanding of what driving modes the vehicle offers, what the currently active driving mode is and what the driver's role in the interaction with and use of an automated system is. Thus, in order to create a positive driving experience and prevent the misuse of DAS due to overreliance and misaligned mental models, designers must carefully consider the implications of various variables, such as cognitive, behavioural, and contextual aspects, and how they influence the driver's perception of and consequent interaction with DAS.

2.2 Understanding

This section presents an overview of the principles governing human perception of information and the cognitive process involved in understanding driving automation. It concludes with an explanation of the author's perspectives and definitions of these key concepts.

Perception

Our comprehension of the world is based on the information we perceive through our senses from the environment. In other words, perception is the process by which objects, events and relationships become phenomenally here, now, and real [99]. The five senses that comprise perception are visual, auditory, gustatory, olfactory, and tactile. Beyond this, perception includes proprioception, which is the ability to determine one's body's position in space, and vestibular senses, i.e., balance and motion.
In contemporary research, there is a prevailing consensus that the existing theories pertaining to perception do not offer comprehensive explanations for the intricate processes involved. Consequently, it can be inferred that the field of study pertaining to perception is an ongoing endeavour. To date, there are opposing views concerning the concept.
One of those, is the 'bottom-up'-theory of perception, which was coined by James Gibson [100]. He stated that the sensation of stimuli is perception and that there is no need to process incoming information because it is analysed in a single direction; in other words, the unprocessed data from our senses enables a direct interpretation of the environment. Thus, bottom-up processing of information is frequently referred to as data-driven processing because it is assumed that perception is directly influenced by stimuli generated by the sensory system. The contrasting approach, is the 'top-down' theory of perception, described by Richard Gregory [101]. He described perception as a process that is based on integrating higher cognitive information, like previous experiences, and knowledge. Thus, top-down processing of information is a goal-driven process, supported by recognizing patterns and categorizing them in the context in which they are perceived.
This means that, the 'bottom-up' approach requires no learning, as a percept[1] is solely based on stimuli that are currently being experienced from the envi-

[1] the mental representations formed as a result of perception

ronment, whereas the top-down approach recognizes that previous knowledge, experiences, and expectations are essential in order to recognize a percept.

Other work suggests that perception is determined by the experiences and previous knowledge we have. Jerome Bruner [102] stated that, "all perceptual experience is necessarily the end product of a categorization process", and that perception, therefore, is a process of categorization of stimuli from merely cues to meaning. Further, he believed that the values we hold, and our needs and goals determine how we perceive the world, down to the lowest levels of the visual system. From this, one can infer that perception is the result of a combined bottom-up and top-down process, and hence, that we perceive the world in categories and patterns, guided by our needs, expectations and beliefs. This mental predisposition or readiness to perceive sensory stimuli in a particular way based on previous experiences, expectations, beliefs, and context, is also called 'perceptual sets' [103]. Perceptual sets regulate choices between competing alternative activities and, therefore, influence the outcomes of the perception process. This means, at a fundamental level, that perceptual sets influence what in the available sensory data we perceive and what we ignore. This is also in line with expectation theory [104], which asserts that a person will act in a particular manner based on their personal frame of reference, motivations, and interests, resulting in that decisions are based on the individual's estimation of how closely the anticipated outcomes of a given behaviour correspond to the desired outcomes. Similarly, an individual's interpretation of an event or adjacent stimuli is influenced by subconscious blinders such as lack of awareness and similarity of stimuli. Consequently, ambiguous information is interpreted based on a person's perceptual sets, which influence how they process presented information [104].

Nevertheless, in the literature there is ongoing controversy regarding this matter. However, according to a widely accepted definition, perception is defined as "the process or result of becoming aware of objects, relationships, and events through the senses, which includes activities such as recognising, observing, and discriminating" [105]. In other words, perception is the process of receiving sensory information, and then organising it into patterns, and recognizing or interpreting its meaning, in order to plan and execute an action. According to this interpretation, one can infer that top-down and bottom-up processing occur simultaneously during the perception process and that attention is guided by either of them at any given moment, depending on the strength of the stimulus or the individual's objectives. For instance, when interacting with a machine interface, changes in the focus of attention will be influenced by the individual's knowledge or expectations regarding the location of the desired information (top-down process) and/or the inherent characteristics of the stimuli (bottom-up process). In the case of DAS, visual signals regarding the status of the DAS are sought in the instrument cluster, while an audible cue associated with the system status can direct or draw attention when necessary.

Thus, throughout this work, the operational definition of perception pertains to the cognitive process by which individuals evaluate and derive meaning from sensory stimuli in their surrounding environment. This process encompasses the identification of sensory stimuli, which will, throughout this work, be referred to as *sensory information*, as well as the readiness to receive stimuli and interpret information, relying on previous experiences or expectations, which will be referred to as *perceptual sets*.

Mental Models

The role of prior knowledge and cognitive processes (top-down perception) in the interpretation of sensory information (bottom-up perception) is also referred to as 'apperception' [106]. The term, more specifically, refers to the process by which the content of information obtained from sensory experiences is synthesised with the knowledge obtained from previous experiences and brought into consciousness. Thus, apperception is the process that assigns meanings to experiences and phenomena and integrates them into concepts and categories (i.e., mental representations) that assist us in navigating and understanding the world, e.g., understanding how to interact with a machine or product.

However, the concept of understanding is complex and without a unified definition. Gijsbers [107] defines understanding as the knowledge of which connections exist between various phenomena. Further, he argues that understanding enables us to successfully classify events, and thus comprehend and apply that knowledge.

Within the area of system design, this knowledge is commonly referred to as a ‘mental model’ (cf. [108]). In this context, the mental model of a system represents the user’s understanding of the system’s contents, operations, and underlying logic [109]. Thus, the mental model contains sufficient knowledge of the system’s purpose, explanations of how it functions and the system states, as well as predictions on future states [110]. Mental models, although subject to development and evolution through experience, primarily consist of static knowledge related to the product or system. This includes its prominent features, operational mechanisms, interrelationships among different components, and the anticipated behaviour of its components when exposed to various external conditions [51].

Within the research community, mental models have been recognised as a significant element in ensuring the safe utilisation of DAS. Many investigations address different aspects of the topic. For instance, how do drivers construct a mental representation of a DAS operation? What is an adequate mental representation that facilitates safe utilisation? In what ways might Human-Machine Interface design contribute to the formation and development of a mental model? How do faulty mental models emerge, and how can they be avoided?
While ongoing attempts are being made to address these enquiries and others of a similar nature, it is well recognised that addressing the mental model during the design of a DAS can aid drivers in their understanding the vehicle’s capabilities and limitations [111][14]; information and feedback received from the vehicle is relevant for drivers to be able to develop a mental model [112][113][16]; and that the ability to anticipate potential hazards and make effective decisions and responses on the road is impacted by the ability to forma a sufficient mental model [26][114][115]. Other work has investigated how exposure and use of a system impacts the driver’s mental model of it [27][28], or how training can aid the development of a sufficient mental model for better utilization of a DAS [116].

The existing research recognises that mental models are constructed based on diverse ideas and perceptions originating from several sources. However, there is a dearth of knowledge regarding the specific components that comprise a driver’s mental model of a DAS, as well as the sources that shape these

components.
By investigating these various components, this thesis aims to shed light on the concepts of perception and understanding in the context of driving automation.

2.3 From Perception to Understanding: A Unified Model

While there are opposing views on the concept of perception, it is the author's belief that a unified view of the perception process is the answer to understanding the user's perception of a system. Therefore, the author refers to the concept of perception as an integrated top-down and bottom-up process, which is the synthesis of sensory information and perceptual sets leading to the development of a 'mental model' of a product or a system. This mental model is referred to throughout this thesis as 'mental representation' or 'understanding'. Therefore, the process of understanding incorporates the process of apperception – a combined top-down and bottom-up process of perception – as a crucial component in answering the question of how users understand their interaction with a product or system.

Figure 2.2 exemplifies the author's position regarding how the mental representation is formed through apperception, i.e., perceptual sets, and sensory input, and how this affects the user's overall understanding of a product (or system) in a conceptual illustration. The depicted feedback loops emphasize the distributed and adaptive joint cognition at play in the interaction between driver and vehicle.
During the use of a DAS the driver will recall the knowledge that they have about the system, i.e., a mirror of the mental representation of the system that helps them navigate their interaction with it. During use, the driver's apperception will synthesise retrieved stimuli into information that informs their next action, based on the knowledge (mental representation) they have of the system. This means that, during use, the driver will – subconsciously - continuously assess the sensory information retrieved and weigh it against the perceptual sets, which will influence how they will perceive the feedback from and interaction with the vehicle, and consequently how they will interact with it. While that mental representation is largely static, new information that

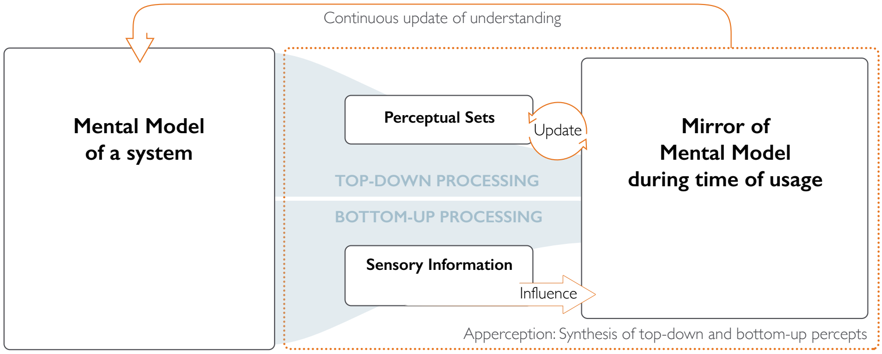

Figure 2.2: Conceptual model of how apperception and understanding interact.

is encountered, for example during an unfamiliar situation, will be fed back through a continuous loop and can alter the driver's understanding of the system, or simply reinforce already known information, and thus the current mental model. This will also cause the reassessment of the perceptual sets and may cause the driver to update these with regard to the newly encountered knowledge.

All in all, this conceptual model represents how the process of apperception and the building of a mental representation of a product occur – the process of understanding. This conceptual model is the foundation of the work presented here, which seeks to shed light on how drivers perceive and consequently understand DAS.

Chapter 3

Research Approach

CHAPTER 3

Research Approach

This chapter outlines the methodological approach to the research. The author's personal context and philosophical perspective is discussed, as well as how this affects their methodological decisions when approaching the research questions. The relationship between the attached papers and the research questions is demonstrated, and finally the procedure for the cross-study analysis and the development of a design tool are subsequently explained.

3.1 Personal Context

The research was conducted during the author's tenure in the automobile industry, balancing academic and industrial commitments. The positioning of this thesis within an industrial setting has significant implications not only for its foundational epistemology but also for the choice of design examples. Rooted in the author's extensive industry experience, the work is grounded in a pragmatic approach. This approach involved selecting methods that were considered to be most effective for addressing the research questions. Further, a pragmatic approach prioritises real-world implications in the design process, emphasising the practical applicability of knowledge. The author's background has fostered a spirit of curiosity, driving the exploration of innovative techniques that extend beyond the conventional design tools commonly employed in daily industrial practice.

The aim of this research was to generate knowledge that enables automotive developers to make more informed design decisions when creating DAS. Laozi formulated the dictum: “Those who have knowledge, don’t predict. Those who predict, don’t have knowledge”, that describes the author’s aspiration to approach their research and development practices in a methodological and structured way. This distinctive perspective enriches the research, infusing it with practical relevance and a forward-looking ethos.

With a background in Information Science and Information Technology, coupled with a specialised focus on Human-Machine Interaction, the author inherently recognises the profound interconnections between human users and machines as pivotal elements in technical system design. The author’s educational journey has nurtured a perspective where knowledge is gleaned through the scrutiny of artefacts and their practical application in real-world contexts, underpinned by a Human Factors Engineering approach. Moreover, the author brings substantial expertise as a practitioner in the realm of human factors engineering, specifically in designing and evaluating automobile user interfaces.

The primary objective of the work was to investigate and comprehend the driver’s understanding when engaging with a vehicle offering several levels of automation. Therefore, a research approach that is both applicable and focused on people should be at the centre of the development process. Further, the author’s practical experience highlighted the significance of approaching the development of DAS from a human-centric perspective, as opposed to a purely technological or safety-driven one.

Thus, the author’s reflections and interpretations have been shaped by the acknowledgement that the human and the machine are two equal partners involved in a collaborative accomplishment of a shared task, and thus strive to highlight the human operator as a central factor for the design of technical systems. This viewpoint, shaped by Joint Cognitive Systems Theory [54], delves into the intricacies of human information processes, exploring how the user's understanding and perception are influenced or enhanced by technical solutions. Ultimately, this approach merges the comprehension of technological systems with human perception, enabling the identification of cognitive states, processes, and the intricate interplay between humans and their environment. This perspective is the main contributor to the answering of the research questions that have guided the development of this body of work.

3.2 Methodological Approach

This work is consistent with a pragmatic worldview, and it makes use of methods that are both practical and outcome oriented. These approaches are founded on action, and they lead iteratively to additional action, which supported the answering of the research questions at hand. To put it another way, the pragmatism that was used took an openly value-oriented approach to the research that was conducted (cf. [117]). The pragmatist viewpoint acknowledges the existence of meaning not just within a person but also within an object. This is to say that our reality is continuously being renegotiated, disputed, and renegotiated in the light of its usefulness, with reference to the breadth of the issue. Because of this, information is seen to be both generalizable and contextually specific, and the nature of newly acquired information is thought to be best understood in terms of how it may be applied in real-world situations [118].

Thus, a combination of qualitative and quantitative research methods have been applied because pragmatism holds the belief that the approach to learning that is most effective is the one that results in the solution to the problem. Creswell and Clark [119] define mixed methods research as a paradigm in which the investigators collect, analyse, and integrate qualitative and quantitative approaches within a study or programme of inquiry, with the objective of gaining both a depth and breadth of understanding of the topic under investigation.
Therefore, a sequential, mixed methods [120] research design has been adopted and integrated throughout the course of this work. The sequential and embedded use of qualitative and quantitative methods aims to facilitate an integrated interpretation of the collected data by applying a hybrid analysis approach (inductive and deductive). The primary characteristic of sequential mixed methods design is the sequential execution of two phases, wherein the outcomes of the qualitative phase guide the structure of the quantitative phase (or vice versa). This iterative method enabled the author to leverage the insights acquired and triangulate the data throughout the design of the research approach to generate knowledge and develop theories that provide answers to the research questions.

An inductive approach, when combined with quantitative and qualitative research approaches, paves the way for the generalisation of specific phenomena into plausible theories, the grounds for which led to the comprehension of the researched scope and provided support for verification through the triangulation of data. Subsequently, the present research has been based on the utilisation of inductive and exploratory methodologies in combination during the initial stages, specifically employing online surveys and naturalistic driving studies to gather empirical observations. These observations have been instrumental in identifying recurring patterns and developing a comprehensive understanding of drivers' behaviours and potential challenges for drivers when utilising DAS. Further, the author's objective has consistently been to incorporate in-depth interviews as a means of augmenting the scope and depth of the findings, thereby achieving a deeper understanding of observed patterns and phenomena. From there, the knowledge corpus was systematically expanded through the utilisation of deductive analysis approaches, enabled by on-road driving studies, in conjunction with qualitative data collection techniques, e.g., observations paired with think-aloud methods and in-depth interviews.

These combined approaches facilitated the contextualization of the research findings and the identification of underlying factors and rationales behind specific observations. This led to enhanced interpretation of the collected data and enhanced validity of the identified patterns and observed phenomena.

Organisation of Research

This work relies primarily on the author's applied and empirical research which aimed to identify factors influencing the driver's perception and their consequent understanding of DAS by utilizing a series of five studies. The following **Figure 3.1** illustrates the process of the different studies, their goals, their associated publications, and the synthesised output representing the theoretical and practical contributions made by this work.

Studies I, II and III built the foundation for the theoretical contribution presented in this work, which was a tentative model describing the different aspects constituting the driver's perception and consequent understanding of DAS. The associated papers all addressed different aspects of the underlying goal, which was to shed a light on how driver's utilise DAS, and from there to gain deeper knowledge about how they perceive and consequently understand such systems.

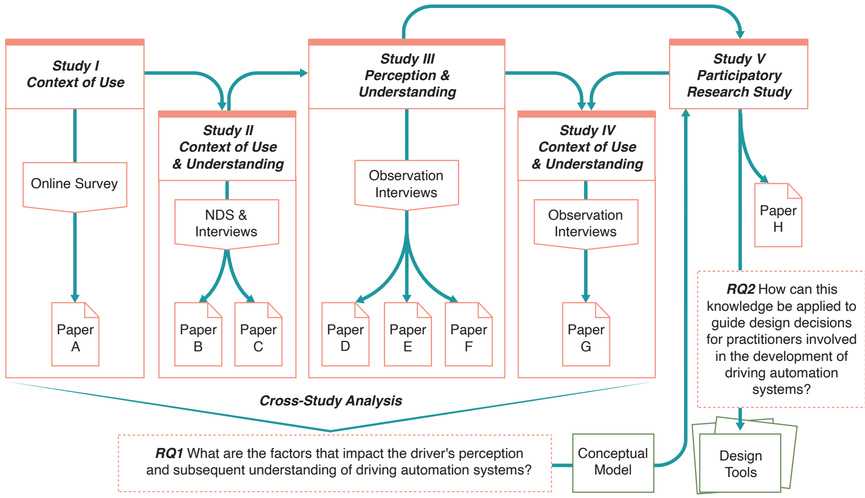

Figure 3.1: Organisation of Research.

The knowledge acquired in Studies I-III was built on to address RQ2, "In what ways may this knowledge be utilised as a means of providing design guidance for practitioners?". The aim was to propose a tool intended to support a more user or driver-centred design of DAS. Subsequently, a co-creation study (Study V) was undertaken to go deeper into the second research question. Study V employed a use case within the co-creation study to develop a user interface. This interface was then used in Study IV to acquire a more thorough understanding of driver's perception and understanding of DAS.

Finally, all four empirical studies (Studies I-IV) were analysed in a cross-study analysis by utilizing a framework analysis approach to finalise the tentative model, which consequently addressed RQ 1, "Which factors influence the driver's perception and consequent understanding of DAS?". The synthesis of the results from these four empirical studies constitutes the theoretical contribution – a conceptual model describing how perception shapes understanding (presented in 5.1). The development of the design tool and the outcome of Study V represent the practical contribution provided by this work – a design toolkit called the Design for Perception toolkit for designers and developers of DAS (presented in 5.3).

3.3 Overview of Studies

To ensure consistency across datasets, each of the selected studies investigated driver understanding of DAS. The section that follows provides a summary of the four study designs, including a description of the data collection method(s), number of participants, context and assessed level of automation (according to SAE [7]). An overview of the conducted studies is presented in **Table 3.1**.

Table 3.1: Overview of the Studies, describing data collection method, assessed level of automation, number of participants, and context.

	Method of Data Collection	Level of Automation	Number of Participants	Context	Paper
Study I	Online Survey	Level 1 Level 2	Completed Questionnaires: 568 Germany; 532 Spain; 516 USA; 504 China	China, Germany, Spain, USA, 2018	A
Study II	Naturalistic driving study, 7-month data collection; consecutive semi-structured interviews	Level 1 Level 2	NDS: 132 vehicles, 7 months of data collection Interviews: 12 participants from identified usage groups	Gothenburg, Sweden, 2018-2019	B, C
Study III	Wizard-of-Oz, on-road driving study; observations, and semi-structured interviews	Level 2 Level 4	20 participants, novice users	San Francisco, USA, 2019	D, E, F
Study IV	Wizard-of-Oz, on-road driving study; A/B GUI test; observations, and semi-structured interviews	Level 2 Level 3	16 participants, novice users	Gothenburg, Sweden, 2022	G
Study V	Co-Creation; Workshops and Feedback Sessions, and semi-structured interviews	n/a	6 AD/ADAS Designers and Developers; Author as facilitator, 1 User Researcher supporting facilitation	Gothenburg, Sweden, 2022	H

Study I (Paper A): Context of Use. The aim of this study was to investigate the application of Level 1 and Level 2 DAS, in a variety of driving contexts. In the course of the study, an online questionnaire was administered to individuals in the United States of America, China, Germany, and Spain. The survey aimed to compare usage Level 1 and Level 2 systems in personal vehicles, in nine distinct driving contexts. The objective of conducting this study through an online questionnaire was to achieve a wide-reaching sample of drivers from various nations who possess access to the system in question, and thus, allowed for the collection of self-reported data regarding real-world user experiences with the systems in various driving contexts, enhancing the validity of the collected data.

Study II (Papers B and C): Context of Use and Understanding. The aim of this study was to acquire a more in-depth understanding of the drivers' reasons for using Level 1 and Level 2 DAS, as well as the drivers' understanding of the capabilities and limitations of these systems. Building upon Study I the contextual effects on the utilisation of the systems were also investigated.
This study was broken up into two distinct phases, a quantitative data collection and a qualitative data collection phase. A Naturalistic Driving (ND)[1] study was employed to acquire the quantitative data. In this analysis, the ND study provided a time-efficient and trustworthy method for conducting quantitative evaluations of system and driver performance, in conjunction with sensor-based data providing information such as weather conditions, road conditions, and data indicating traffic conditions on the roads. In order to shed a light on the sensor-based findings, in-depth interviews were conducted with a subset of the study participants in order to identify and explain the effect that driver's perception has on the use of DAS.

Study III (Papers D, E and F): Perception and Understanding. The aim of this study was to gather insights into first-time users' perception and understanding of a vehicle that offers several levels of automation, specifically Level 2 and Level 4. This aim was accomplished through conducting a semi-controlled on-road study in the San Francisco Bay Area, USA, where the participants experience two different DAS, in a Wizard-of-Oz[2] vehicle. The

[1] ND study typically refers to a study in which data collection is not constrained by a strict experimental design [121]) This enables data collection in a natural driving context and under a variety of driving conditions, in real-world driving situations, and over prolonged periods of time.

[2] Wizard of Oz - The WOz technique, as described by [122]), entails the use of a human who assumes the role of a machine, all while keeping the participant unaware of this fact. In the application domain of driving automation, a WOz vehicle enables the simulation of different automation levels and conceptual user interfaces, thus enabling testing in

study facilitated the elicitation of insights by means of observation during the driving sessions, collection of think-aloud data, as well as in-depth semi-structured interviews before and after the driving sessions.

Study IV (Paper G): Perception and Understanding. The aim of this study was to analyse the dynamics of human-machine interaction in a vehicle that incorporated several levels of automation, specifically Level 2 and Level 3. This was accomplished by making use of a semi-controlled Wizard-of-Oz (WOz) driving study that was conducted on-road, in Gothenburg, Sweden. During the driving sessions, the participants experienced two alternative graphical user interfaces (GUIs) designed to enhance drivers' mode awareness in a vehicle offering several levels of automation. Data was collected through recordings of participants' behaviour and think aloud comments. Additionally, in-depth semi-structured interviews were conducted after the driving sessions to further enhance the insights gathered. The results were then contrasted and compared, with the end goal of gaining insights into the factors that influence drivers' perception of a vehicle offering several levels of automation.

STUDY V (Paper H): Co-Creation of a Design Tool. The goal of this study was to utilize an initial version of the design tool and continue developing it further throughout a participatory design study, and by means of co-creation[3] and other collaborative feedback methods. This study was structured around a series of workshops which enabled the domain experts, i.e., designers and developers who were also the target users, to use the tool within a defined use case. Thus, the workshops provided a setting for collaboration in which the participants could get to know the tool and share their experiences with it and requirements on it. Subsequently, the participants were interviewed, using a semi-structured approach to gain insights into the toolkit's efficacy and limitations, as well as utilisation. The result of the co-creation study was the Design for Perception toolkit, which has of two variants: A Heuristic Checklist in Excel, and a Card Deck.

early development phases.

[3]Co-design is a method, that is part of the Participatory Research (PR) approach, and is characterized by an iterative design process that includes consumers in the design of products intended for them [123]

Ethical Considerations

In the realm of research involving human participants, a paramount ethical consideration revolves around ensuring the well-being, confidentiality, and informed consent of the individuals involved. Online surveys, interviews, naturalistic driving studies, and on-road driving studies are valuable methods employed in various disciplines, but they demand meticulous ethical scrutiny. In all these methodologies, researchers bear the responsibility of upholding the dignity and rights of participants, ensuring their voluntary participation, and guaranteeing that the data collected is utilised responsibly and ethically. Thus, efforts were made for each of the conducted studies to adhere to the guidelines provided by the Swedish Research Council [124].

In the digital age, online surveys are convenient but necessitate stringent data protection measures to safeguard participants' privacy. Thus, the retrieval, storage, and processing of the collected survey responses for **Study I** rigorously adhered to the General Data Protection Regulations (GDPR) of the European Union. The participants were reimbursed for their time through a third-party recruitment agency that provided access to the different markets.

Naturalistic Driving Studies, capturing real-world driving behaviour, require transparent consent processes and anonymization techniques to protect participants' identities. Therefore, prior to the collection of the data for **Study II**, an internal ethical review board reviewed the data collection plan and assessed the potential risks and benefits for participants. This ensured that the study complied with ethical guidelines and protected the privacy of the individuals involved. Even though all participants were part of a co-development fleet that already had mechanisms for data collection in place, they were provided with clear information about the purpose of the study, their rights, and how their data would be handled to ensure informed consent and their agreement to participate in this particular study. Further, the retrieval, storage, and processing of the collected vehicle data and interview responses rigorously adhered to the General Data Protection Regulations (GDPR) of the European Union. The participants who joined the interviews were reimbursed by a cinema voucher for two tickets.

Studies III and IV applied Wizard-of-Oz driving observations in a real-traffic environment. This demanded careful supervision and adherence to safety protocols to prevent any harm to the participants and the test crew. Thus, the preparation for the studies included meticulous training of the WOz-drivers and HMI-wizards (see **Chapters 4.3** and **4.4** for details), as well as an assessment of the test procedure using a risk catalogue. This risk assessment was conducted prior to each study and assessed potential risks that could occur on the designated test route. Each anticipated or potential risk had to be addressed, solutions found, or the approach adjusted in order to ensure the safety of all participants. Further, local authorities and traffic management organisations evaluated and approved the routes, and regular communication within the research team took place in order to address identified issues. This comprehensive approach allowed for a smooth and safe execution of the experiments on public roads. Additionally, all participants were informed prior to the study about the test setup and the data collected during the session in order to ensure informed consent. The data collection, which included the collection of data by means of vehicle-signals, video- and audio-recordings, was conducted in accordance with the General Data Protection Regulations (GDPR) of the European Union. Finally, since both studies utilised a WOz-approach enabling the simulation of technical solutions that were not yet developed, all participants were informed after their driving session about the details of the set-up and had the chance to ask questions and share their experience with the test leaders. Local recruitment agencies paid all participants for their time.

During **Study V**, colleagues of the author were recruited to participate in the co-creation study. All participants participated on a voluntary basis, out of interest and support for the topic. Due to the study taking place during working hours, the participants were reimbursed through their salaries. The acquisition and analysis of data during the co-creation stage and subsequent interviews were conducted with the explicit consent of all participants, adhering to the guidelines outlined in the EU General Data Protection Regulation (GDPR).

3.4 Analysis and Evaluation

The following sections describes the steps taken during the cross-study analysis in detail, and how the collected knowledge was turned into actionable insights in form of a design toolkit.

Cross-Study Analysis

The empirical studies were followed by a cross-study analysis that synthesised the results of the four empirical studies into a summary of the process by which the driver's perception influences their understanding of DAS. The cross-study analysis primarily depends on the driver's verbal accounts and observed behaviours while using a driving automation system, as well as their descriptions of the systems and their usage gathered during the conducted interviews.

The 'Framework Approach' [125] was utilised to approach the large and complex dataset. The framework approach, also referred to as framework analysis, is an inherently comparative form of thematic analysis that uses an organised structure of inductively and deductively derived themes (i.e., thematic framework) to conduct cross-study analyses by combining data description and abstraction [125][126]. These methods facilitate the identification of similarities and differences in qualitative data prior to focusing on the relationships between the various data components and attempting to draw descriptive and/or explanatory conclusions. The defining characteristic of framework analysis is that it follows explicit steps to generate a structured output in a matrix or table (cases, codes, and summarised data), which is then used to systematically reduce the data [125]. Since the overall objective of framework analysis is to identify, describe, and interpret critical patterns across themes within the phenomenon of interest, it was chosen as the method to address *RQ1: "What are the factors that impact the driver's perception and subsequent understanding of driving automation systems?"*.

The data analysis was divided into five stages in accordance with the framework methodology:

Data Familiarisation: Immersion into the collected data and becoming familiar with the raw information. The purpose of this step was to gain a deeper understanding of the data's contents and context.

Framework Identification: Identifying an appropriate analytical framework. A first step in the framework identification was the mapping of data into concept maps, allowing to organise the data. The purpose of this step was to establish a structured approach for categorising and understanding the large amount of collected data and its nuances.

Indexing: Systematic coding and labelling of segments in the data set. The codes represent themes, which were later categorised into different aspects and factors, enabling to identify recurring patterns across all the four studies and data types, allowing to triangulate the data.

Charting: In this step, the indexed data was condensed into matrixes, summarising and facilitating an overview of the identified categories, which aided in the identification of relationships and hierarchies.

Mapping and Interpretation: Finally, the matrixes were analysed deeper, and its contents compared in order to identify overarching themes with regard to the driver's perception or understanding. The purpose of this step was to interpret and synthesise the data into tables, organised by the different categories and typologies.

The final stage was conducted iteratively and yielded a combination of key learnings that summarise the factors describing the driver's perception and the aspects comprising the driver's understanding of DAS. In addition, the structured approach generated typologies and enabled the mapping of connections between and within the identified aspects.

This, ultimately led to the development of a model illustrating the process of how perception shapes understanding, including the identified factors of perception, and aspects of understanding associated with DAS. This model developed through an iterative process, and by conducting a workshop with colleagues who are experts in the area of automation and cognition and scrutinizing the iterated ideas in discussions and thought experiments.
The result was a unified descriptive model, incorporating all identified factors, describing how user's perception shapes, through a top-down and bottom-up process, the understanding of a DAS. The unified descriptive model is presented in detail in **Chapter 5**, and constitutes the theoretical contribution made in this work.

Development and Evaluation of the Design Toolkit

Since the results of the cross-study analysis were already structured into tables, these tables were transferred into Excel and organised into two different sheets: (i) aspects of understanding and (ii) factors of perception. The table containing the aspects describing the driver's understanding was further provided with supporting questions and columns allowing the user (e.g., the designer assessing a design solution) to add information about the technical specifications of the desired solution, as well as a column where usage scenarios could be described. The table containing the aspects describing the driver's perceptions was similarly structured and provided with supporting questions. Additional columns aimed to foster a deeper discussion around possible failures and effects of the provided design solutions.

This initial version was used as a starting point for the co-creation study, which was organised around a use case study and a series of workshops. The purpose of the workshops was to build a new user interface for DAS applying the Design for Perception toolkit. When creating the interface, the toolkit provided a systematic framework that led the participants to address crucial aspects and factors. The workshops offered a cooperative environment in which participants could share their experiences with and requirements on the design tool, with the purpose of contributing to the design process for the design toolkit. The following sections briefly describe the development activities and the evaluation of the toolkit.

Developing the Toolkit

Throughout the development of the toolkit, the author implemented multiple iterations and feedback cycles to ensure that the toolkit aligned with the feedback and requirements of the team. This approach continued throughout the duration of the co-creation project, running in parallel with the workshops.
The aim of this was to gather input from the workshops and engage the designers during the prototyping stage to elicit their feedback and foster their active involvement in designing the toolkit. Further, the author analysed the outcomes of the workshops, discussed them with colleagues, and formulated solutions throughout the project with the aim of identifying and implementing solutions that could effectively tackle the requirements and obstacles mentioned by the designers. In order to ensure the effectiveness of this collaboration, a system of regular meetings and communication channels was implemented. This facilitated continuous collaboration and the exchange of ideas between the author and the designers, thereby promoting a sense of ownership and shared responsibility in the design process.

The collaboration was shaped by a range of activities, such as designers offering input on the author's proposed solutions and actively engaging in the conceptualization and creation of solutions. This collaboration typically cen-

tred on the various variants of the toolkit and the structuring of information and contributed to the development and design of a card deck variant of the toolkit, with the goal of making the use of the toolkit more accessible and easier to incorporate into the designers' daily tasks. Additionally, there were frequent discussions pertaining to the integration of the toolkit within existing processes and its potential to improve or optimize such processes. The objective was to guarantee the seamless integration of the toolkit into the current workflow without introducing any new stages or complexities.
After the conclusion of the workshop series, the prototyping co-creation was continued. As a group representative, one of the designers worked closely with the author over an extended period of time, concentrating predominantly on the card deck (physical and digital) variant of the toolkit. Evaluating the Toolkit

To gather thoughts and comments on the efficacy, limitations, and possible enhancements of the design toolkit, a series of semi-structured interviews were conducted with the participants in Study V. The purpose of the interviews was to assess the results from the workshops and evaluate the perceived value of the toolkit among the designers, as well as identify areas for potential further enhancements.
The interviews were held after a period of three months had passed. During these months, the participants had been granted unrestricted access to the toolkit and its variants, enabling them to apply it in a manner they deemed suitable. Hence, it was considered an opportune moment to assess the utilization and application of the toolkit.
The author created a topic guide for the interviews, which was organized into three main areas: (i) the daily activities and challenges faced by designers, (ii) the toolkit's utilization and perceived usefulness, and (iii) the positive and negative aspects of the toolkit. The interview guide was not exhaustive and allowed for additional questions. The interviews were carried out by a colleague acting as an impartial third party in order to mitigate bias and guarantee that the respondent's answers were not affected by the author's affiliation with the team. The conducted interviews yielded significant insights into the potential challenges and benefits associated with the integration of the toolkit into established design workflows. Further, the panel of experts offered recommendations for further additions and optimizations to optimize

the toolkit's efficacy in practical design situations.
The interviews were transcribed verbatim. Subsequently, the transcriptions were subjected to coding and analysis. Due to the fact that the structure and content of the interviews were based on a topic guide, a deductive thematic coding strategy was used in the first phase (cf. [127]).
The codes underwent a process of revision, refinement, and validation after the first coding phase. During the thematic organization of the codes, statements pertaining to the usage scenarios, strengths and limitations, potential enhancements, and additional value of the toolkit were discerned. From the findings, it became evident that the designers held the belief that the various versions of the toolkit could be employed in distinct ways. Consequently, significant emphasis was placed on the particular representation and its usefulness when consolidating the gathered insights, despite the fact that the contents of the toolkit remained unchanged.

Chapter 4
Summary of Studies

CHAPTER 4

Summary of Studies

This chapter lays the groundwork for solving the research questions. The responses are based on a summary of the investigations that were carried out in Studies I-IV, and details the results from the cross-study analysis for each of the conducted studies independently. Only relevant results are reported in the dedicated sections. It concludes with presenting the co-creation approach applied during Study V that enabled the development of a design tool, based on the key findings.

4.1 Study I: Context of Use

The study's objective was to gather insights into drivers' usage of DAS in different driving contexts, by means of an online survey. The survey was exploratory in nature and relied on the driver's self-assessment of their use of Level 1 and Level 2 driving automation system in their personal vehicles. A detailed description of this study can be found in Paper A.

Aim

The aim of this study was to understand the extent to which drivers use DAS. Most studies have addressed Level 1 DAS, particularly Adaptive Cruise Control. To the author's knowledge, no study has compared the use of Level 1 and Level 2 DAS. Additionally, few studies have studied how context, specifically the traffic environment and traffic circumstances, affect DAS use. Thus, this study compares driver's use of these systems in different driving contexts by means of an international online survey.

Method

The survey was administered to 2,000 drivers in Germany (DE), Spain (ES), the United States (US), and China (CHN) and covered their usage and experience with Level 1 and Level 2 DAS. The ages of the respondents ranged from 18 to over 65. The majority of respondents reported annual mileage between 5,001 and 20,000 kilometres, a smaller proportion between 20,0001 and 30,000 kilometres, and a very few between 5,000 and 30,000 kilometres. The driving contexts in all countries were mainly urban areas, followed by motorways or highways, and then the countryside, with a fairly even distribution between these, with the exception of China, where the majority of participants drove primarily in urban areas, with close to no driving in the other driving contexts.
The responses were collected via an online survey which was sent out via email by a third party with access to the various markets. There were a total of 36 questions, and it took participants between 10 and 15 minutes to complete the survey. The majority of the questions were Likert-type [128], scenario-based statements querying the participants on their use of the DAS in their personal vehicles in different driving contexts, e.g., road types, weather and light conditions, road conditions and the drivers' physical and mental condition.

Findings

The key findings of this study concentrate on the different driving contexts drivers report when utilizing DAS.

In summary, the results indicate that system usage was context-dependent and that the systems were not utilised in the same manner across all con-

texts. Overall, respondents utilized Level 2 systems slightly more than Level 1 systems. In variable traffic conditions, the Level 2 system was used in both less congested and heavy traffic situations. This result may be explained by the fact that the vehicles were equipped with both systems and users had the option to use the Level 2 system, which incorporates all the capabilities of the Level 1 system plus a Lane Keeping Aid (LKA). As the system relieves the driver of a portion of the driving task, the additional support function may also explain why drivers reported a greater reliance on the Level 2 system when they were fatigued or when the driving was monotonous. The respondents utilized the Level 2 system over the Level 1 system when driving in urban areas. On the highway, however, both systems were utilised frequently, which may be attributed to the overall assistance they provide, such as sustaining a speed and maintaining a safe distance from other vehicles.
However, the results also indicate that in adverse weather conditions or at night, when visibility is poor, a greater proportion of drivers preferred to drive themselves rather than rely on automated systems. Under certain weather conditions, this decision can be attributed to the limitations of the Level 2 system, which relies on visible lane markings and unobstructed lines of sight for sensors and cameras, as well as the driver's lack of trust in the system's ability to handle adverse weather conditions in daytime driving conditions. Finally, there were preferences for using both systems, but especially the Level 2 systems, when the driving was deemed monotonous, and generally a tendency to use the systems when the drivers were tired, which can be assumed to be due to the assistive features of the systems.

Summary of Insights

- ◇ The driving context and thus the question "When can I use the system?" appears essential for the driver's understanding of the DAS's capabilities and limitations – irrespective of the automation level.
- ◇ The context includes both driving situations and a driver's physical or mental condition.
- ◇ Aspects falling under driving context are road types, traffic conditions, weather conditions and time of day.
- ◇ Aspects falling under personal the driver's physical or mental condition are boredom or monotony, and tiredness.

◇ While DAS are not designed to handle all traffic, weather and road conditions, the results from this study showed that participants did not always use the systems as the manufacturer intended. On the contrary, frequent usage occurred outside of the intended operational design domain (ODD).

4.2 Study II: Context of Use and Understanding

The second study was exploratory in nature and employed a sequential mixed-methods research design to investigate the use of Level 1 and Level 2 DAS. This study's aim was to investigate the factors influencing the drivers' utilisation and understanding of DAS by triangulating data from a Naturalistic Driving (ND) study with clarifications and reflections from in-depth interviews with selected participants. Additional comprehensive findings are documented in the appended Papers B and C.

Aim

Drivers must have a solid understanding of the various modes of operation and inherent limitations of DAS in order to utilise them safely and effectively, as well as gain the benefits they provide. Failure to acquire this knowledge will hinder the development of appropriate trust and the formulation of effective usage strategies. Hence, the aim of this investigation was to examine the motivations behind drivers' usage strategies when utilizing Level 1 and Level 2 DAS and determine the factors that impact their understanding of the investigated systems.

Method

This was accomplished by adopting an Explanatory Sequential Mixed Methods [120] methodology, combining data from a naturalistic driving (ND) study with insights and reflections obtained through in-depth interviews with a select group of participants. The sequential application of quantitative and qualitative approaches (see **Figure 4.1**) was intended to facilitate an integrated interpretation of the effect of driving context on DAS utilisation. The ND study was conducted over a period of seven months, collecting data from 132 vehicles. Driver behaviour and system performance were categorised and measured in order to evaluate them independently and investigate their relationship. To evaluate driving contexts, the evaluation incorporated vehicle speed, driving distance, time of day, GPS data, wiper sensor status, road conditions data, and other sensor data. This analysis allowed for the identification of the driving conditions (e.g., road, traffic, and weather) in which the driver utilised the systems or decided to disable them.

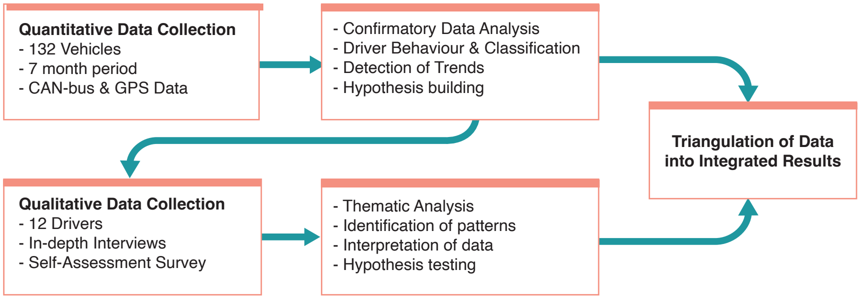

Figure 4.1: Explanatory Sequential Mixed-Methods Design.

Subsequently, using in-depth, semi-structured interviews, an investigation and validation of the quantitative data were conducted to investigate the individual driver experience and understanding of the systems. The interview consisted of four sections: Contextual Information, System Usage and Scenarios, Perception and System Experience, and Information Display and Controls. Accordingly, a series of open-ended questions were formulated based on the four major themes. The structure of and questions in the interview were based on the preliminary findings of Study I and the learnings from the ND study.

Findings

The key findings of this study concentrate on insights as to when drivers utilize DAS, and the factors affecting the usage and the driver's perception of the systems.

According to the interviews, the majority of interviewees concurred that using the systems on long trips (over 50 kilometres) was preferable to short trips, where the majority of drivers did not use them. Adaptive Cruise Control (ACC) was highlighted throughout the interviews as a significant aid in managing speed, safety, and comfort on long trips. This demonstrates that the length of the journey was an important factor in system utilization and provides an explanation for the preference for use on highways over city driving (something that was also found in Study I). In urban environments, the infrastructure or other traffic required frequent deceleration and driver engagement, causing the driver to need to activate and deactivate the systems with excessive frequency. Several participants preferred the Level 2 DAS in slow-moving or congested traffic due to its more stable steering assistance. Rural roads were also deemed as inappropriate for system activation. The interviewees reported that rural roads frequently lack visible or distinct lane markings, causing the system to switch between active and standby, particularly in poor weather or low light. In extreme conditions, the systems may not function at all; therefore, participants preferred to drive manually rather than engage the DAS.

From the narratives of the drivers, one can conclude that perceived system performance affected whether and when the DAS was utilised. The Level 2 system's steering support was unstable, especially on country roads, so the majority of drivers were hesitant to use it. In variable traffic conditions with a large number of vehicles, participants chose to drive themselves, indicating a preference for control over the driving task. Others felt relieved when DAS assumed some driving responsibilities. These contradictory statements demonstrate that perceived control influences the driver's understanding of the system's authority over the driving task. Some believe advanced support means they can let go of the driving task, whereas others recognise they must always be involved and ready to intervene, but still appreciate the additional support. Overall, the system performance seemed to affect how much control drivers perceive they have over the system, which reflects their understanding of their responsibility for the driving task and their willingness to use the systems. Nevertheless, the majority of drivers found both automated driving systems to be useful. The systems were easy to use and supported them during the drive and were particularly useful for primary driving tasks such as accelerating, decelerating, and maintaining a safe distance or speed limit. This was frequently mentioned in connection with long-distance travel and highway monotony. All drivers who were regular DAS users reported feeling more physical and mental relief and at ease as a result of the enhanced comfort. When utilising the system, all drivers reported following the traffic flow rather than overtaking and setting their own tempo, which was perceived as safer and less aggressive driving behaviour. Numerous interviewees valued the enhanced safety they associated with the systems. Participants viewed PA as an additional pair of eyes or quick reflexes that assisted them in focusing on a phone call or driving while fatigued.

Further, the interviews revealed that the driver's preconceptions about the systems influenced their learning and their mental representations of the system's capabilities and limitations. Previous usage appears to generate assumptions when encountering unfamiliar systems. When asked what was anticipated from the system, responses ranged from convenience and safety features to more advanced systems that took over driving for a certain amount of time. Depending on the driver's expectations and prior usage experiences, the outcome was either disappointing or beneficial. Thus, these expectations shaped the driver's perception of the system. However, the drivers' statements demonstrate that the system's capabilities differ from their expectations. The technology lacks situational awareness, but drivers appeared to expect a more intelligent system that would read traffic conditions such as traffic signals and other road users, as well as predict their behaviour. Some participants were more hesitant, stating that they did not know what to expect; consequently, their experience was positive. Those whose expectations were met or exceeded during the learning period had a lower threshold during testing and learning how to use the system, resulting in greater acceptance. Users with high hopes were dissatisfied with the systems and ceased using them. The causes of dissatisfaction were often linked to feelings of uncertainty and inadequate feedback provided by the system.
In numerous instances, drivers expressed their lack of awareness regarding system status changes, specifically noting that lateral control was unavailable while longitudinal control remained active. This phenomenon resulted in confusion and, in certain instances, hazardous situations, as the drivers failed to notice the change in the automation status and continued to rely on the lane keeping aid. Their failure to notice these inherent mode changes was ascribed to a lack of auditory feedback. A status indication solely on the displays failed to notify drivers, showing that drivers expected to have clearer indications and feedback about the system status.

Another commonly noted occurrence was the issuance of a hands-off alert by the system while drivers were not actively engaged in steering. The comments revealed that the perceived purpose of the driving automation differed significantly from the actual purpose of the system. Numerous drivers ex-

pressed their annoyance over the persistent prompts from the system, which consistently reminded them to keep their hands on the steering wheel. This frustration stemmed from the assumption, derived from the system's performance, that it was a hands-free system.
This shows that the drivers made assumptions about the system's capabilities that ascribed to them capabilities beyond what was intended by the manufacturer.

However, the feedback they got from the systems did not succeed in clarifying their responsibility for the driving task, causing frustration and in some cases the drivers ceased using the systems.

Lastly, trust was discussed as a result of the learning experiences. One of the most significant aspects of interviewees' trust in the system was its consistency. The drivers provided multiple clarifications, including about system performance. There were examples of functions that did not perform as anticipated, placing drivers in uncomfortable situations. The majority of drivers characterised the system as a support function, but they wanted it to mimic human driving behaviour and adapt to changing conditions. This suggests that some drivers have exaggerated expectations of the capabilities of the systems. The drivers also indicated that they had to develop trust in the system over time. There appears to be a learning phase in which the driver either gains sufficient trust to accept what the system can do and use it or encounters too many negative situations or inconsistencies that they cannot explain and therefore never accepts or uses the system. Further, it was indicated that their trust in the system varied depending on the driving context. They indicated that they chose a function or drove themselves based on the road type, the weather, and the amount of light. This implies that the greater the user's understanding of the system's capabilities and limitations, the more effectively expectations can be met, and trust can be established.

Summary of Insights

- ◇ The driving context and thus the question "When can I use the system?" appears fundamental for the driver's understanding of the DAS's capabilities and limitations – independent of the automation level.
  - ◇ The driving context includes aspects like road types, traffic condi-

tions, weather conditions, time of day and trip types.

  - ◇ Aspects that fall under personal conditions are monotony, tiredness, physical and mental stress from the driving task.

- ◇ The vehicle's capabilities and limitations were crucial in understanding many aspects of the interaction, thus the question "What does the vehicle do?" emerged as another central guide for drivers.
  - ◇ Vehicle behaviour and how drivers perceived the system's performance influenced how capable they perceived the systems to be and their inclination to use them – this too was context-dependent.
- ◇ The question of what the driver's tasks were when using the systems emerged as "What do I do (now)?" and appeared to guide the driver's understanding of how much attention they needed to pay to the DAS and who was responsible and in control of the driving task at what time.
- ◇ Preconceptions seemed to play a significant role with regard to accepting and using the systems.
  - ◇ The system's capabilities, its usefulness and consequently the purpose of the system guided the drivers in their assessment.
- ◇ Previous experiences with other or similar systems set the driver up for how they would perceive a new system when they encountered it.
- ◇ Feedback with regard to the automation status was found to be relevant to understanding the system's purpose. However, their perceptions of the system performance could contradict and misguide drivers in their interpretation of feedback.
- ◇ Trust was closely connected to the driving context and the learning experience. The level of trust varied as well as the driver's perceptions of in which situations the systems could be trusted.

4.3 Study III: Perception and Understanding

The third study utilized a Wizard-of-Oz (WOz) driving study on actual roads and was exploratory in nature. This study's aim was to assess the driver's perceptions, and subsequent understanding, of the interaction with a driving automation system that offers multiple modes of operation, with the focus being on a level 2 partial automation function and a level 4 high automation function. For a greater level of detail, please refer to the findings presented in Papers D, E and F.

Aim

As a division of responsibilities between the driver and the vehicle in the driving task becomes more prevalent, there is a possibility that the driver will encounter instances where the assumed system mode differs from the actual driving mode, resulting in incorrect actions and uncertainty regarding the driving mode and the driver's responsibility. One potential factor contributing to this lack of understanding regarding automation levels and forms of engagement could be the driver's perception of the relationship and division of responsibilities between themselves and the automated system. Therefore, the aim of this study was to investigate the driver's understanding of vehicles equipped with multiple levels of automation in a real-world setting.

Method

This was achieved by gathering insights from an empirical road study conducted in the San Francisco Bay Area, California, United States, in June 2019, with 20 participants: 11 females and 9 males ranging in age from 22 to 62 years (Mean=42, SD=14). During the study, participants encountered two different driving modes (levels of automation) in a Wizard-of-Oz (WOz) vehicle: a Level 2 partial automation system and a Level 4 high automation system [7].

Equipment

Vehicle. The WOz vehicle was a prototype based on a Volvo XC90 platform that was modified to facilitate testing of the two levels of automation. The modified platform suggests to the driver that the vehicle is performing

some or all of the driving task, simulating an authentic user experience for the participants. The simulation was made feasible by installing a steering wheel, instrument cluster, and pedals in the rear seat, allowing the vehicle to be driven from this position by the driving wizard. The human machine interface (HMI) prompts were orchestrated by an HMI wizard via a tablet according to a set of pre-defined rules. The installation was concealed and could be seen by those seated in the front seats.
The vehicle was modified in accordance with all applicable road permission standards and audited and approved for road testing by the local authorities, allowing for the investigation of drivers' experiences with automated driving in a real-world driving context. **Figure 4.2** exemplifies the setup in the vehicle, including all wizards, the test leader, and the participant.

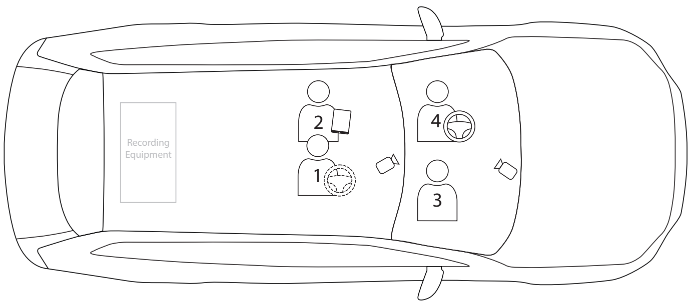

Figure 4.2: The Wizard-of-Oz vehicle, with video cameras facing the UI, and (1) driving wizard, (2) HMI wizard, (3) test leader and (4) participant.

Automated Driving Systems. The Level 2 system was capable of automatically adjusting the vehicle's speed in relation to other moving objects in front, or sustaining a set speed, as well as providing lane-keeping assistance, but lacked advanced steering capability. This driving mode could be activated at any time by the driver and was considered a supervised driving system. This is because, even though the system provided both lateral and longitudinal support, the driver remained fully in charge and responsible for the driving task.

The Level 4 system was an unsupervised driving mode that operated within a specified operational design domain (ODD), i.e., under certain conditions.

Since traffic congestion was a daily occurrence in the region where the study was conducted, it was decided to limit the context of this system to a congested traffic scenario. It was necessary to have dense traffic with other vehicles in front of the vehicle for the mode to be available. Upon encountering such a circumstance, the driver could activate the system, and the vehicle would assume full control of the vehicle as long as the conditions were met. If this was no longer the case, for example, if the congestion cleared, the driver was prompted to retake control with a visual and auditory cue and a one-minute preparation time. However, while the Level 4 system was engaged, the driver was free to engage in other activities than the driving task.

Human Machine Interface (HMI). For this study, a graphical user interface (GUI) concept was developed and embedded into a prototype that offered various means of feedback to the driver, i.e., visual, auditory, and haptic feedback. In the context of this study, the term HMI pertains to a multi-modal user interface, while GUI specifically pertains to the visual concept and associated auditory elements. The different sequences and states of each of the developed GUI are presented in comparison in **Figure 4.3**.

The HMI wizard controlled the HMI from the rear seat via a tablet, and various graphics were displayed based on the vehicle's status. When the availability conditions were met, an offer to be driven by the system was displayed in the visual displays of the vehicle (i.e., instrument cluster and centre display) along with an auditory alert. To activate or deactivate the system, the driver was required to press two buttons on the left and right sides of the steering wheel for a prolonged time until the system activated or deactivated. During automated driving, the instrument cluster displayed graphics depicting the vehicle's current intent. When the system's availability conditions were no longer met, participants were instructed to resume manual driving, by first receiving a tug from the seatbelt, and then auditory and visual cues about what they were supposed to do.

Procedure

All twenty participants experienced both modes during the driving session. Participants could use the Level 2 system whenever they wished, but they

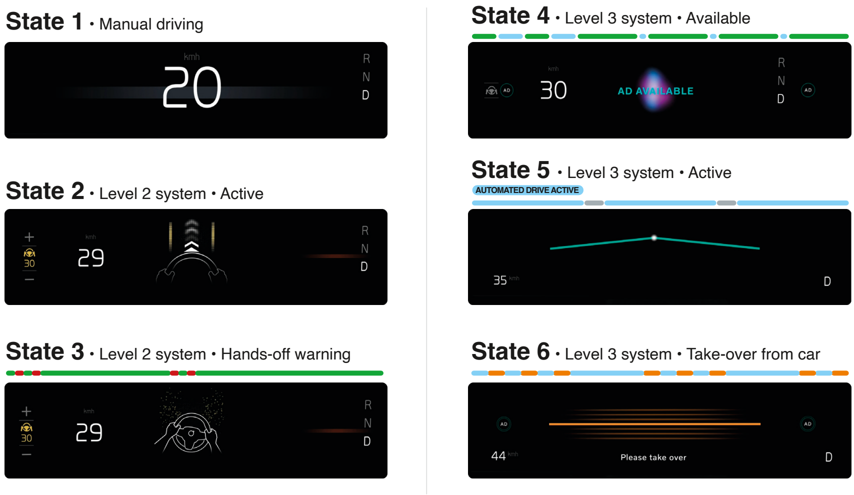

Figure 4.3: Visual and Auditory description of GUI sequence and states for each of the driving modes.

could only use the Level 4 system when they received a prompt indicating that the necessary contextual conditions had been met and the system was available. Before each session, participants received information in written form during the test's introduction, as well as in the car prior to the driving sessions, and they were given the opportunity to ask questions. The information the participants received about the two systems is summarised in **Table 4.1**.

The introduction of the systems was comparable to what a new car customer would receive when purchasing a vehicle from a dealership. This decision was made in order to provide a high level of realism, as the purpose of the study was to investigate the driver's understanding of a vehicle with multiple levels of automation and intensive driver training is typically not provided when a vehicle is delivered.

Driving Observations. To satisfy the two distinct conditions for the operational design domain of the system, a route with multiple instances of slow or halted traffic and a section with free-flowing traffic was required. Based on

Table 4.1: Description of DAS capabilities and limitations and information participants received prior to the driving session in Study III.

System	Description	ODD	Limitations	Interaction
Level 2	- Maintains speed - Adjusts speed to vehicle in front - Lane keeping support	-Always available	-Clear view of lane markings	- Driver in control of steering - Driver responsible at all times - Activation/deactivation via steering wheel button
Level 4	-Takes over the driving task completely under congested traffic conditions	- “Bumper to bumper”/slow moving traffic	- System prompts when available - Clear view of lane markings	- Vehicle in full control - Driver does not need to supervise and can engage in secondary tasks while system is active - Activation/deactivation via long press of steering wheel button

the collected traffic data and the results of several test drives, a round-trip route including various road types was selected.
Thus, the driving sessions were conducted on highways (US highway 101: 6-lane partially controlled access road, speed limit = 70mph, LOS E-F; Interstate 280: 8-lane full access road, speed limit = 70mph, LOS C-D) and urban areas (State Route-84: 4-lane, speed limit 25-50mph, LOS B-C) in the San Francisco Bay area (see **Figure 4.4**). All trips were conducted during rush hour, in the morning and in the evening, with the intention of observing the interaction between the two modes the participants experienced. During the test drive, the participants were encouraged to test and experiment with the systems as much as they wanted, and asked to verbalise their thoughts so that their thought processes during interaction with the system could be documented.

Post-Interviews. After the drive, the session concluded with an interview focusing on the participant’s understanding of the two systems they had experienced and their comparison. The participants were asked to describe and explain the various systems they encountered during the driving session. In particular, they were asked to describe the distinctions between the two

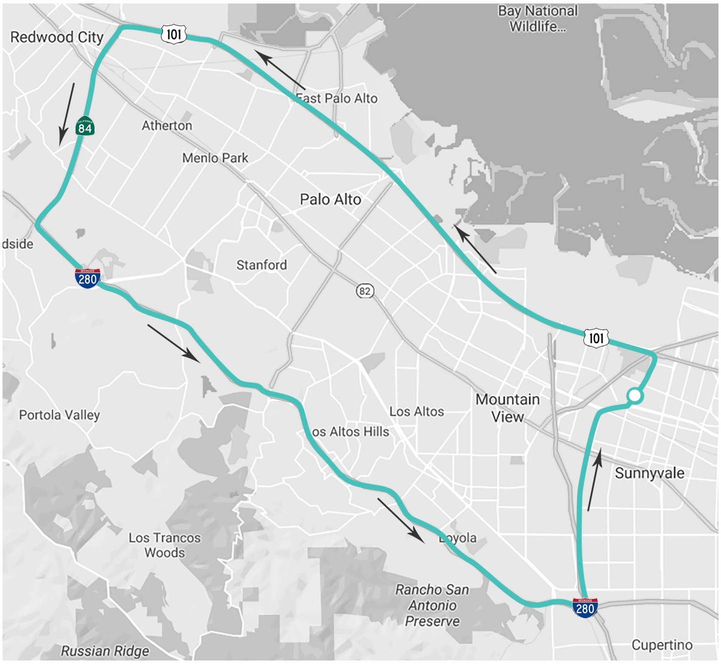

Figure 4.4: Route for the observation study in the San Francisco Bay area.

modes, and their perception of the systems during the different phases of the trip.

Findings

The key findings of this study concentrate on identifying how drivers perceive and consequently understand DAS, specifically in the interaction with a system offering several levels of automation. The following section summarizes the findings from the study.

Prior to the driving sessions, participants were questioned regarding their expectations of a highly automated system. All participants agreed that it would have a positive effect on their stress levels because they would be able to delegate driving tasks to the vehicle when they did not wish to drive. Thus, commuting to and from work, particularly during rush hour and congested traffic, was one of the most frequently mentioned situations. Similarly, participants anticipated being able to use the system on lengthy highway journeys, such as when travelling in the vehicle for extended periods. While both systems were believed to be useful on long journeys, it was determined that the Level 2 system was superior in free-flowing traffic, whereas the Level 4 system was superior on highways and in congested traffic.

After the driving session, in addition to what they believed prior to the driving session, participants indicated whether the Level 2 system would be a beneficial to use when they were fatigued or unable to focus due to personal conditions, such as being tired. The participants further stated that the system lowered their perceived stress levels and helped them to feel more relaxed. Moreover, some participants indicated that the system would enable them to be more productive or socialize with passengers, as they would be liberated from the driving task and could engage in other activities, such as day planning, email writing, and phone calls. In addition, it appeared to the participants that the system made driving simpler by relieving them of physical and mental workloads such as accelerating, braking, and maintaining a predetermined distance between vehicles. Furthermore, it was believed that having a system that takes over part or all of the driving is particularly useful when commuting to and from work, but also on longer trips, such as travel with the family (see also Paper D). However, the participants primarily emphasized that having a DAS would contribute to safer driving and, as a result, reduce the number of traffic accidents. The two systems experienced were referred to as an additional pair of eyes and were valued for their assistance in maintaining speed limits. Nevertheless, some participants were unsure of what the Level 2 system provided and were dissatisfied with the system's performance because they felt that too much interaction was required (for instance, irritation that they had to be constantly engaged in monitoring and steering) and therefore did not see how they benefited from using it, indicating that they misunderstood the system's purpose.

When discussing the purpose of the system, control was a frequent theme. Participants perceived the driver to be in control of the vehicle or to be receiving assistance from or sharing control with the vehicle when using the Level 2 system. As a result of the presumed shared control, several participants expressed confusion regarding control allocation when the system was operational, resulting in ambiguity regarding their actual responsibilities. Some participants believed they could disengage even though the Level 2 system does not perform the driving task for the driver but merely assists them. The Level 4 system was characterized as completely taking over control of the driving task, requiring minimal human input, and making the driver feel like a passenger in the vehicle. However, with the ability to retake control of the vehicle at any moment by deactivating the system, the majority of participants did not feel out of control, with only a few participants feeling uncertain about how much responsibility they could delegate to the vehicle. As they had activated the system and were seated in the driver's position however, many participants still felt responsible for monitoring the vehicle. Ultimately, control assignment during the various operating modes led to confusion, particularly when using the Level 2 system. Such confusion is risky because it can lead to difficulties for drivers to understand how much responsibility they must assume for the driving task and when they can disengage.

Beyond the aspects of perceived control, which seem partly related to the driver's expectations of the systems and partly to the haptic feedback they perceived from the vehicle, other information sources were also considered relevant when trying to understand the vehicle's behaviour. Obvious sources are the visual and auditory cues the vehicle gave the participants, such as indications in the vehicle's instrument cluster and infotainment system, as well as haptic feedback received from the seat belt retraction of the vehicle. However, more factors could be observed influencing the driver's perception of the vehicle.

During the interview, participants were asked if they trusted the systems they had encountered. All participants noted that, over time, they developed a measure of trust in the system and a desire to continue using it. Initial apprehensions were due to a lack of familiarity with the capabilities of the systems, as all participants had only ever used a Level 1 system in their personal vehicles. As a result, one of the reasons they gained trust in the system was because they witnessed the vehicle managing a variety of situations, such as matching their speed to that of the vehicle ahead or reacting to merging traffic. Thus, vehicle behaviour was interpreted as indicating that the vehicle had situational awareness comparable to that of a human driver, being able to anticipate the behaviour of other road users, and therefore was viewed as more intelligent and trustworthy than a system that only reacts to what it encounters. Comments like this were also frequently noted during the driving sessions.

Finally, the vehicle brand was cited multiple times as a reliable brand with a reputation for producing safe vehicles, prompting the participants to place trust in the unknown systems. However, different brands and their reputations were also discussed in light of recent technological developments, and information sources identified were various media outlets and social circles. In addition, the current legislative status of automated vehicles was considered and debated when discussing the Level 4 system, and whether drivers should relinquish control to engage in other tasks. Consequently, these secondary sources (i.e., non-experienced but otherwise learned information) influenced the drivers' expectations and the perceived safety of the systems experienced, as well as their willingness to use them.

Summary of Insights

- ◇ Also in Study III, the driving context and thus the question "When can I use the system?" appears essential for the driver's understanding.
  - ◇ The driving context included aspects like road types, traffic conditions, weather conditions, time of day and trip types.
  - ◇ Aspects that fall under personal conditions are monotony, tiredness, physical and mental stress through the driving task.
- ◇ The vehicle's abilities were prominent in understanding many aspects of the interaction, thus the question "What does the vehicle do?" emerged here too as another central guide for drivers.
  - ◇ Vehicle behaviour and how drivers perceived the system's performance influenced how capable they perceived the systems to be.
  - ◇ The less human involvement was required, the smarter and more capable the system was perceived to be.
- ◇ Trust was closely connected to the learning experience and seemed to be affected (either positively, or negatively) by observing how the systems

handled different driving situations.

- Previous experiences with other or similar systems were named as a benchmark and used to compare capabilities, in order to gain an understanding of the systems experienced.
- The question “What do I do (now)?” emerged as well, especially when trying to make sense of the different driving modes encountered.
  - The system performance and haptic feedback seemed to influence the driver’s perception of who was in control in which driving mode.
- Preconceptions were relevant with regard to using an unknown system.
  - Information received through other sources than actual usage, including the media, social circles, and legislation, influences the driver’s perception of the systems and their willingness to use them.
- Information about the vehicle’s capabilities and intentions was received through multiple sensory channels.

4.4 Study IV: Perception and Understanding

The fourth study was exploratory-comparative in nature and utilised the Wizard-of-Oz (WOz) method as well as an A/B HMI test. This study's objective was to investigate the driver's understanding and interaction with a driving automation system that offers multiple modes of operation, with a focus on the Level 2 partial automation function and the Level 3 high automation function. For more insights, please refer to the findings presented in Paper G.

Aim

With the introduction of several driving modes into vehicles, the significance of developing efficient ways of communicating a vehicles capabilities and limitations with the driver is growing. The driver's perception of the division of responsibilities between themselves and the DAS may influence their understanding and cause uncertainties about the currently active and available driving modes in a vehicle. One potential way of addressing uncertainties is through the HMI. Therefore, the aim of this study was to investigate what influences the driver's perception and consequent understanding of vehicles equipped with multiple levels of automation (i.e., Level 2 and Level 3 DAS), by contrasting two different graphical user interfaces (GUI) concepts, in a real-world setting.

Method

This study was an empirical road study conducted in Gothenburg, Sweden, in September 2022, with 16 participants (7 female and 9 male), ranging in age from 23 to 70 years old (M = 44, SD = 13.48). During the study, participants encountered two different modes (levels of automation) in a Wizard-of-Oz (WOz) vehicle: a Level 2 partial automation system and a Level 3 high automation system [7]. Furthermore, the study utilized an A/B UI test in order to compare the influence of different UI elements on the driver's understanding and interaction with each of the systems.

Equipment

Vehicle. The test vehicle was a modified Volvo XC90 that utilised a WOz approach to simulate the two DAS, as well as to control the UI via controls in the back seat that were concealed from the driver in the front. In this configuration, a driving wizard was in charge of operating the simulated Level 3 DAS, while an HMI wizard was responsible for controlling the prompts and feedback to the driver received from the UI. In addition, cameras facing the UI and interaction were installed behind the driver to capture observational data regarding the driver's interaction with the vehicle's systems.
The vehicle was modified in accordance with all applicable road permission standards and audited and approved for road testing by the local authorities, allowing for the investigation of drivers' experiences with automated driving in a real-world driving context. Refer to **Figure 4.5** for an illustration of the configuration.

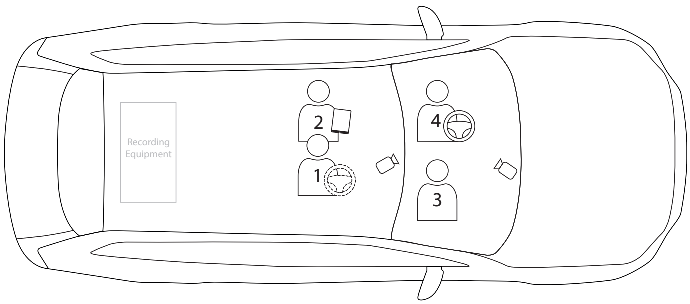

Figure 4.5: The Wizard-of-Oz vehicle, with video cameras facing the UI, and (1) driving wizard, (2) HMI wizard, (3) test leader and (4) participant.

Automated Driving Systems. During the driving sessions, participants had the option of engaging a supervised (Level 2 Partial Driving Automation) or unsupervised (Level 3 Conditional Driving Automation) DAS.
The Level 2 DAS was the Volvo Cars Pilot Assist system that was already present in the vehicle and was described to the participants as having the ability to maintain a set speed, modify the distance between them and the vehicle in front, and provide steering assistance. Nevertheless, the driver remained

in charge and accountable for the driving task. This system was always accessible, and drivers were encouraged to utilise it as frequently as they desired.

The Level 3 DAS was designed to operate autonomously within an operational design domain (ODD). The system was described as one that alerts the driver when available. Upon activation, it would assume full control of the driving task until the conditions were no longer met. The availability conditions depended on the external traffic environment and were defined as follows: (i) partially controlled access roads with up to 80kph speed limits; (ii) free-flowing traffic (LOS A-B), meaning that the system would prompt takeover when merging traffic was approaching; and (iii) clear view of lane markings. When these conditions were met, the driver could activate the system and the driving wizard would take control of the vehicle. When the conditions were no longer met, the driver would be prompted to resume control of the vehicle.

Human Machine Interface (HMI). This study presented two different HMI concepts. Both concepts were developed to support the driver in the interaction with a vehicle offering several driving modes: (i) manual driving, (ii) Level 2 Partial Automation, and (iii) Level 3 Conditional Driving Automation. The two concepts differed mainly in their graphical representation, while interaction schemes and technical solutions remained the same. Thus, in the context of this study, the term HMI encompasses a multi-modal user interface (i.e., employing visual, auditory and haptic feedback), while GUI specifically pertains to the visual concept and associated auditory elements of the various concepts.

The intention of **GUI A** (developed for and used in Study III) was to provide the driver with only the pertinent information in each driving mode. The designers' intention was to be clear about the vehicle's intentions and the driver's responsibilities at all times by providing only the necessary information at any given time and removing other information that could confuse the driver about the driving modes they encountered.

The **GUI B** was developed during a series of workshops where the Design for Perception toolkit was utilised as a design tool (see Paper H). This GUI's underlying concept was derived from a conceptual model describing the factors that influence the driver's perception and, as a result, affect their understanding of a DAS and their interaction with it. This was addressed primarily by attempting to answer the following three questions throughout all design phases, and for each driving mode the driver would encounter: When can I use the system for? What can the vehicle do? What should I do?

During the driving sessions, the HMI wizard controlled the HMI from the rear seat via a tablet, and various graphics were displayed based on the vehicle's status. When the availability conditions were met, an offer to be driven by the system was displayed in the visual displays of the vehicle (i.e., instrument cluster and centre display) along with an auditory alert. To activate or deactivate the system, the driver was required to press two buttons on the left and right sides of the steering wheel for a prolonged time until the system activated or deactivated. During automated driving, the instrument cluster displayed graphics depicting the vehicle's current intent. When the system's availability conditions were no longer met, participants were instructed to resume manual driving, by first receiving a tug from the seatbelt, and then auditory and visual cues about what they were supposed to do. The different sequences and states of each of the developed GUI are presented in comparison in **Figure 4.6**.

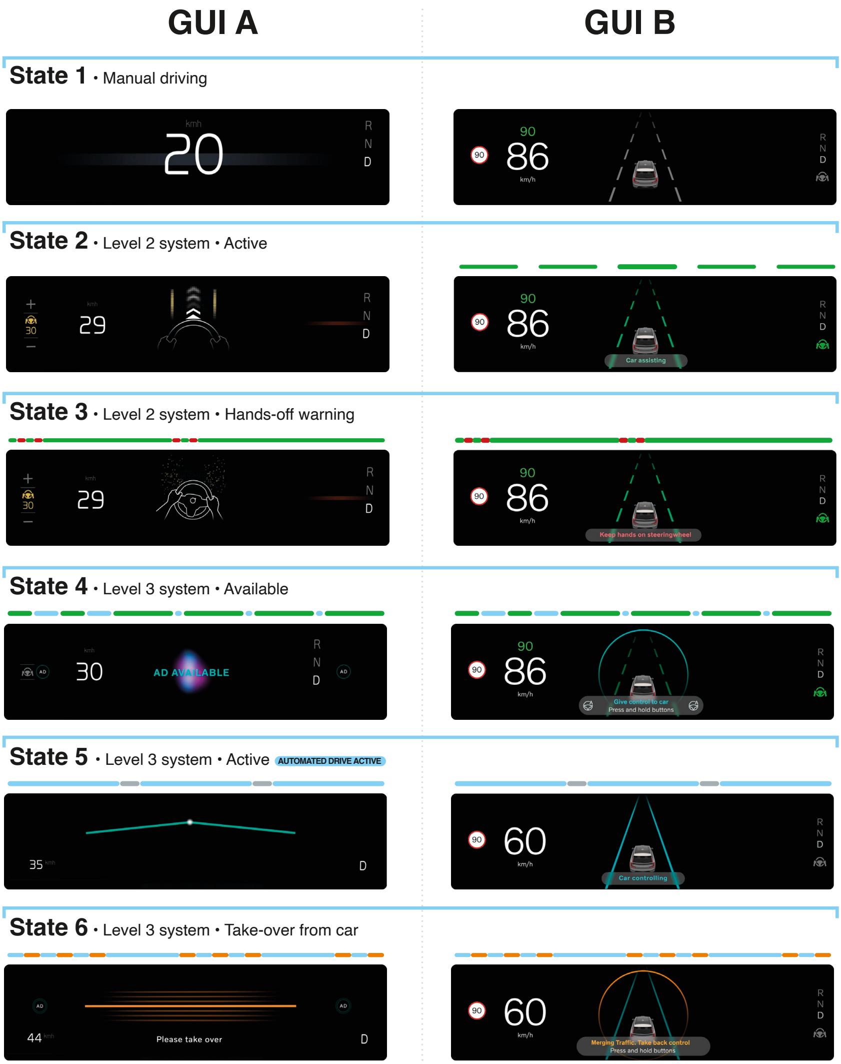

Figure 4.6: Visual and auditory description of GUI sequence and states for each of the DAS and comparison of concepts GUI A and GUI B.

Procedure

The data collection strategy for this study involved two stages: the first was an on-road driving session, and the second was a semi-structured interview.

Introduction. Before the driving session, the participants were given a quick introduction to the structure of the study, after which they were led to the test vehicle, where they were given a brief introduction to the two DAS and how to interact with them.
The information that drivers were provided with in advance of the driving session is outlined in **Table 4.2**, which also gives an overview of the two systems. The introduction to the systems was carried out within the vehicle itself in a manner that was analogous to the orientation that one would receive at a car dealership upon picking up a brand-new vehicle. In order to create a driving experience that was as realistic as possible, the decision was made to give the drivers only a relatively small amount of information. Following the introduction, the participants were given some time to familiarise themselves with the environment and get comfortable in it. It is important to note that the drivers were unable to observe the configuration of the driving or GUI wizard in the back seat because all of the necessary equipment was hidden from view.

Table 4.2: Description of DAS capabilities and limitations and information participants received prior to the driving session in Study IV.

System	Description	ODD	Limitations	Interaction
Level 2	- Supervised driving automation - Maintains speed - Adjusts speed distance to vehicle in front - Lane keeping assistance	-Always available	-Clear view of lane markings - Driver responsible at all times	- Activation/deactivation via steering wheel button
Level 3	- Unsupervised driving automation - Maintains speed	- Partially controlled access roads - Speeds up to 80kph	- Clear view of lane markings	- Activation/deactivation via a long press of the steering wheel button

On-Road Observations. The driving session took approximately 60 minutes and was conducted on a partially controlled access city highway with speeds up to 80 kph. The route led from the Volvo Cars Torslanda office to a southern section of Gothenburg (Slingan South) where a brief stop was made to swap interfaces. At this juncture, drivers were asked to exit the vehicle with the test leader and fill out a questionnaire based on the same framework used to create GUI B.
This questionnaire was designed to assess the driver's understanding of the two systems experienced. After the switch, the driver returned to the car and drove the same route back to the beginning of the driving session (Slingan North), where they were asked to fill out the same questionnaire regarding the second drive and GUI B.

Figure 4.7 depicts the route taken, including the beginning, and ending points and the point at which the GUI was changed. In addition, it emphasises the predefined stretches where Level 3 driving automation was available, as well as the duration of their availability, which resulted in approximately eight minutes of automated driving in each direction.
Post-Driving Interviews. After returning to the starting location, the test leader and participant would enter the Volvo Cars office and retreat to a separate room for the interview. The purpose of the roughly 30-minute semi-structured interview was primarily to gain insight into how the driver perceived the two distinct DAS, their capabilities, and their limitations. In addition, a comparison of the two GUIs experienced was made by presenting screenshots of the sequences and states (as seen in **Table 4.6**), and the driver was asked to elaborate on what aided them in understanding the systems and what aspects were unclear.

Participants

A total of 16 people, seven of whom were female and nine of whom were male, ranging in age from 23 to 70 years old (mean = 44, and SD = 13.48), were recruited and compensated by means of a recruitment agency. The recruiter was provided with a screener as well as criteria for excluding candidates, and all of the participants met the following criteria: (i) have a valid driver's licence, (ii) drive a vehicle that has an automatic gearbox, and (iii) possess a car with adaptive cruise control (which is considered Level 1 Driver Assistance

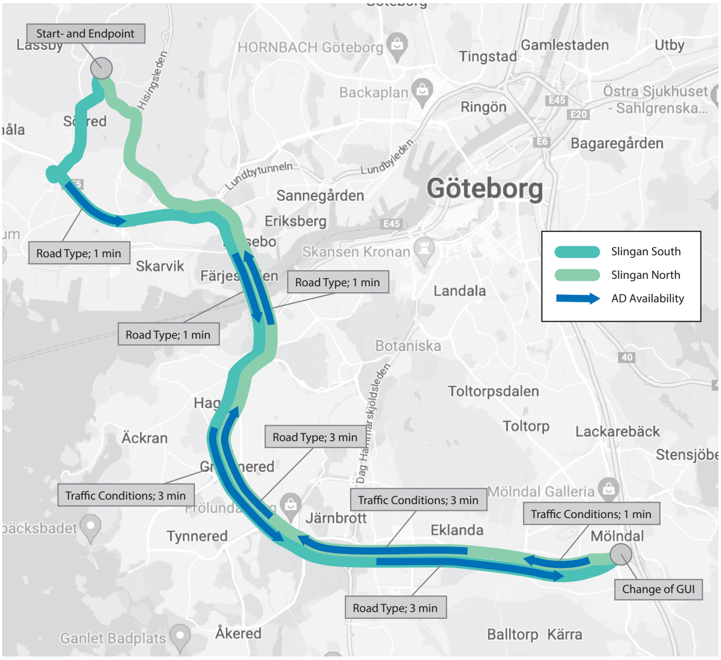

Figure 4.7: Route for driving session highlighting stretches for Level 3 DAS availability and exposure time.

by SAE). Every single participant was a seasoned driver who routinely drove to and from their job in their own vehicle. Nobody who took part in the study worked in the automotive industry or for a company that was involved in vehicle research and development.

Findings

The primary focus of this study is to examine the driver's perceptions and understanding of DAS, particularly in relation to their engagement with a multi-level automation system.
Overall, participants agreed that the implementation of automated features provides enhanced assistance and facilitates a more seamless driving experience, hence contributing to increased safety. For example, the inclusion of indicators, such as blind spot warnings, is regarded as useful. Still, participants

agreed it would be beneficial to incorporate information about the surroundings and other road users inside the visual displays. However, the participants believed that the DAS possesses a level of intelligence and can be effectively employed in instances of long-distance driving, but also saw potential benefits for drivers experiencing stress, particularly in congested traffic scenarios, due to the belief that the system has situational awareness. Nevertheless, while the DAS was perceived to be smart and aware of its surroundings, participants were divided about the vehicle's ability to consistently maintain its performance, e.g., speed control or the detection of red lights. Thus, the statements conveyed a degree of uncertainty about the vehicle's ability to perceive its surroundings, underlining the need for contextual information. It appears that drivers sought contextual information in order to assess the vehicle's capabilities and limitations, and thus in order to decide if it was trustworthy.

However, the drivers also believed that the more they utilize the systems, the more comfortable they will become with them, and referred to their experiences learning to use Adaptive Cruise Control (Level 1 DAS) in their personal vehicles. This was underlined by different situations experienced during the driving session, where participants explained that observing how the vehicle would handle a traffic merge, for example, would give them confidence in the vehicle's abilities and an indication of what traffic scenarios it could handle.
Notably, while participants only experienced the two driving modes in free-flowing traffic, they believed that the DAS was capable of managing slow traffic scenarios. While its applicability in city traffic with a high pedestrian presence remains questionable for most participants, a few believed the system was able to adapt to complex traffic scenarios and city traffic.
Upon further inquiry, it was revealed that this idea was based on preconceptions obtained from media coverage and automobile magazine reporting on DAS that were already on the market.
This indicates that the participants did not seem to distinguish between the different brands and even though they were experiencing a prototype that had little in common with the systems on the market, the technology was perceived to be the same.

This confusion about the technology was also observed in their lack of mode awareness within the driving modes they experienced. The drivers frequently experienced confusion regarding the active driving mode, expressing ambiguity about the distinction between the two driving modes, despite receiving an introduction to the differences prior to the driving session. This also revealed that, no matter the active driving mode, the participants always felt responsible for the driving task. Further inquiry showed that they also felt responsible when the Level 3 DAS was active even though, according to the taxonomies and the introduction by the test leader, they were allowed to engage in other activities. The prevailing viewpoint was that the driver is always accountable for the actions of the vehicle, and the lack of clarity surrounding legal and insurance issues further reinforced the sense of this.

Nevertheless, the participants enjoyed the experience of handing over the driving task to the vehicle, even though they remained vigilant, throughout all the driving sessions, in observing the driving behaviour. Notably, in this study too the vehicle's driving behaviour was used as an information source in order to understand the vehicle's capabilities. However, a curious effect could be observed. Although the driving behaviour remained consistent, it was observed that the UIs had an impact on the driver's perception of the DAS. The findings from the post-interviews indicate that when GUI B was activated, the DAS was perceived as more adept and smoother in its driving performance than when GUI A was activated. Furthermore, there was an overall preference for GUI B because it offered more information throughout the various driving modes, which indicates that an interplay between the UI and the perceived performance of the DAS influenced the driver's perception of the system.
However, a consensus existed about the general user-friendliness of both systems, mostly attributed to their high level of intuitiveness. It is worth noting, however, that some initial struggles were observed, particularly in relation to the activation and deactivation processes of the Level 3 DAS. The participants further appreciated the auditory and haptic feedback of both UIs by announcing their availability or the tug of the seatbelt when their attention was required. However, the use of symbols and text was seen as more helpful in their understanding of the system's intention, what was expected of them, and how they could interact with the system, even though at times the drivers would have liked more input. The participants recognised that the absence of essential feedback from the vehicle hinders their sense of complete control in evaluating situations. Additionally, they emphasized the importance

of explicit communication between the driver and the vehicle in order to understand the vehicle's intentions, e.g., the availability status of the DAS and reasons why. This was seen as another indicator of the participants' reluctance to relinquish control over the driving task to the vehicle and engage in other tasks.

Summary of Insights

- Also in Study IV, the driving context and thus the question “When can I use the system?” appears essential for the driver’s understanding.
    - The driving context includes aspects that are discussed, especially road types and traffic conditions, even though there were no differing conditions experienced.
- The vehicle’s abilities were prominent in understanding many aspects of the interaction, thus the question “What does the vehicle do?” emerged here too as another central guide for drivers.
    - Vehicle behaviour and how drivers perceived each system’s performance influenced how capable they perceived the systems to be but were also strong indicators of the system’s limitations.
    - The less human involvement was required, the smarter and more capable the system was perceived to be.
    - Capable systems were ascribed situational and predictive capabilities and assigned greater trust.
- Trust was closely connected to the learning experience and was calibrated by observing how the systems handled different driving situations but was also connected to the information received from the vehicle.
- Previous experiences with other or similar systems were frequently mentioned in order to explain expectations of the DAS capabilities and possible interactions with it.
- The question “What do I do (now)?” emerged as well, especially when trying to make sense of the different driving modes encountered.
    - Many drivers struggled to understand the purpose of the two systems, as they were perceived to have the same capabilities.
    - Drivers overall saw themselves as always responsible for supervising and monitoring the system, no matter the automation level.
- Preconceptions were relevant with regard to using an unknown system.
    - Information received through other sources than actual usage, including the media, social circles, and legislation influenced the driver’s perception of the systems and their willingness to use them.

- ◇ Legislative status and current social discourse surrounding automated vehicle technologies seemed to inspire greater distrust in the vehicle's capabilities.

4.5 Study V: Co-Creation of a Design-Tool

The fifth study was a participatory design study. The study was structured around a series of workshops in which experts in the field utilised the Design for Perception Toolkit to design a user interface for a DAS. The goal of the study was to utilize an initial version of the toolkit and continue developing it further throughout the participatory design study by means of co-creation and other collaborative feedback methods. The detailed process and steps taken during the workshops and co-creation activities are described in Paper H.

Aim

The aim of this study was to apply the knowledge gathered and represented in the Design for Perception Toolkit in a use case study with the goal to gather insights for the development of the toolkit, which was subsequently done through a co-creation approach with the participants in the study.

Method

This study was structured around a series of workshops using the Design for Perception Toolkit to facilitate a participatory design methodology. Throughout the duration of the study, a co-design approach was utilised to further develop the toolkit in collaboration with the practitioners who were the target demographic. At the conclusion of the study, interviews were conducted to gather information regarding the utilization and the strengths and weaknesses of the toolkit. The subsequent sections describe the methodology employed in this study and conclude with a summary of the interview findings.

Co-Design Activity

Using an initial version of the Design for Perception Toolkit, the purpose of the workshops was to develop an interface for driving automation systems. When designing the interface, the toolkit provided a systematic framework that prompted participants to consider crucial factors and aspects regarding the driver's understanding of such systems.
In order to contribute to the design of the toolkit, the workshops provided a setting of collaboration in which participants could share their experiences

with and requirements for the design tool. Subsequently, the project utilised a co-design approach to achieve the stated aim.

Post-Interviews

The participants in the use case study were interviewed using a semi-structured approach to gain insight into the design tool's efficacy, limitations, and future enhancements. After the workshops, the participants had complete access to the toolkit and all of its versions and were free to employ it as they saw appropriate. Thus, the interviews determined if the practitioners liked the toolkit and where it could be improved.

The interview topic guide consisted of three sections: (i) the designer's routine responsibilities and obstacles; (ii) tool utilisation and perceived utility; and (iii) the toolkit's strengths and weaknesses. The interview guide was not exhaustive and allowed for additional questions. A colleague of the author conducted the interviews as a neutral third party to reduce bias and ensure that the author's team affiliation did not influence the responses of the experts. The interviews discussed the pros and cons of integrating the toolkit into the existing workflows and other possibilities of usage.

Setup and Participants

Practitioners participated in an iterative use case study during the workshops. Among the practitioners were four interaction designers, one design researcher and a software developer, as well as the author facilitating the workshops, and one user researcher supporting and conducting the subsequent interviews. All participants worked in the field of driving automation, and as such, they are representative of the knowledgeable users who are the design toolkit's target audience. The purpose of the use case was to create a user interface for a vehicle with multiple driving modes and increase the driver's mode awareness.

However, the designers had to refrain from using any currently available concepts under development and were instructed to construct a new user interface (UI) from scratch. The purpose of the toolkit was to encourage exploration and innovation, thereby facilitating the inclusion of features and functionalities that could potentially improve the user experience. In addition, they were given the latitude to experiment with various design elements, such as colour schemes and layout options, to create a visually appealing user interface – without any design guidelines other than those provided by the Design for Perception Toolkit. While the author facilitated the use case, the workshops and subsequent feedback sessions and co-design activities concerning the toolkit, she did not involve herself in the design of the two GUI concepts, but merely observed the working sessions.

Process

This project's application of participatory design research can be broken down into several phases, with each phase delineating specific activities that occurred during that phase. This project's phases were guided by Spinuzzi's [129] participatory design methodology and are referred to as (i) work exploration, (ii) the discovery process, (iii) prototyping, and (iv) evaluation, respectively. These phases can occur sequentially, concurrently, or iteratively, making them flexible and adaptable to the requirements of the project.

Figure 4.8 provides an illustration of the process that was applied during the participatory design study, outlining all activities along with the participants. It also demonstrates the iterative and simultaneous character of the process's activities.

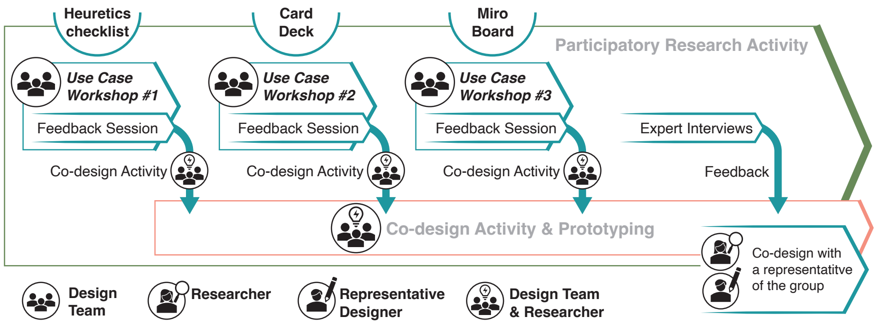

Figure 4.8: Participatory design research process indicating activities and participants during the project.

The design of the use case and the review workshops were used to gain insight into the concept development, with the workshops also serving as a forum for the team to discuss the positive and negative aspects of the toolkit with the researchers. Notably, design review sessions are a common way for a practitioner to receive feedback from team members and stakeholders during a project, which is why this configuration was chosen. This process enabled the team to revise the toolkit based on the received feedback. Involving the team in closed-loop review sessions ensured that the toolkit was effectively utilized and that any issues or areas for improvement were promptly addressed.

The workshops provided a forum for team members and stakeholders to discuss their ideas and suggestions in an open manner, fostering a collaborative environment for progress. In addition, the co-creation activities allowed for hands-on exploration of the toolkit, ensuring that it met the precise needs and requirements of the project, which were later assessed through interviews with the participants.

Findings

The experts, who participated in the use case study and subsequent interviews, concurred that the toolkit is a useful instrument for validating interfaces and comprehending user perspectives. It can be used individually or in a group setting, streamlining the process of generating ideas and evaluating subsequent proposals. It was agreed that the tool may elicit questions that would not ordinarily be considered and could be useful in the early design phases, whereas when used in a group it can generate more conversations and a variety of perspectives. It facilitates the screening and interpretation of the initial round of ideation, the determination of the results of the initial conceptualization phase, and a structured approach to specific tasks and design solutions. However, it was also noted that implementing a structured group discussion requires time and preparation. In addition, the tool addresses the fundamentals of what must be considered, making it effective for presenting concepts during a final review. In such settings, the tool was regarded as a useful backup for decision support and can demonstrate traceability, because it provides the possibility to trace design decisions and, when necessary, substantiate them using the underlying data.
Thus, using the Excel variant of the toolkit as a checklist at the conclusion of

a design iteration can ensure thoroughness and identify overlooked opportunities, according to the experts. Furthermore, the Excel variant was compared to heuristic checklist aiming to reduce errors and omissions during the design phase. It was mentioned that using heuristics can also foster creativity and promote alternative thinking, thereby facilitating the identification of overlooked opportunities or mistakes. The Card Deck variant on the other hand, was seen as more of a tool that offers support during phases of ideation and helps to review design solutions in groups, leaving more room to discuss and engage, in a structured and guided manner through the supporting questions.

Based on the responses to the interview questions, it can be inferred that the representation variant of the tool appears to influence the stage of the design process where each variant is deemed useful. Furthermore, the application area was closely linked to the tool and its variants, as different methods were employed to make use of it in diverse tasks. The discussion among the experts centred on the function of the toolkit in providing a structured framework for evaluating and reviewing design concepts and ideas. Due to the nature of the applied processes, the significance of being able to relate the contents of the toolkit to each other at different stages of the design process and how these activities are interconnected was emphasised. Thus, the tool provided a methodical approach to comprehending and addressing complex design challenges, as well as tracking these activities throughout the duration of a project. In summary, designers saw the toolkit's as being useful especially in three application areas: (i) Explore: this area addresses the initial phases of a project when trying to scope solutions and identify gaps; (ii) Design: this area focuses on utilising the toolkit to ideate new ideas, and at the conclusion of design iterations and during design reviews; and (iii) Test: this area of application focuses on using the toolkit as a validation and risk assessment tool.

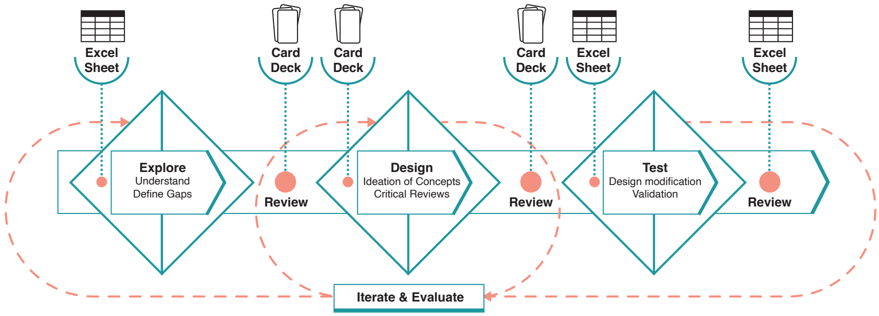

Figure 4.9: Illustration of the toolkit's application during different activities during the design process.

Figure 4.9 depicts the implementation of the toolkit's variants during a design process based on the triple diamond method [130], according to the findings of the interview. It demonstrates that there were three distinct application areas (Explore, Design, and Test) and that two toolkit variants were utilised at various phases of the process.

It is notable that, despite the fact that the toolkit's content remained unchanged irrespective of the representation, the designer's utilisation preferences varied depending on whether the data was presented as an Excel Sheet or a Card Deck. **Table 4.3** summarises the various scenarios and tasks for which each variant was deemed useful.

Table 4.3: Overview of application areas for the different variants (Excel Sheet vs Card Deck) of the tool.

	Explore		Design			Test	
	Exploration of Solutions	Identification of Gaps	Ideation	Concept Development	Decision Tracking	Review Activities	Validation and Evaluation
Excel Sheet	x	x			x	x	x
Card Deck		x	x	x		x	

In conclusion, the toolkit was seen as valuable for designers in the automotive industry, as it provides insights into driver's needs when interacting with a DAS. Further, the tools foundation in empirical data was considered to give it credibility. In addition, it provided a structured framework for collaboration and communication among team members, thereby potentially saving time and aligning different perspectives. During the design process, the concise layout of the toolkit facilitated easy reference and swift decision-making. However, the large amount of information that the toolkit provides was seen as an obstacle for new users, since thorough reviews necessitate a considerable investment of time and effort.

Summary of Insights

- The toolkit can be used as ideation and design support (Card Deck variant), but also as a heuristic's checklist (Excel variant).
- The toolkit offers a structured approach for design reviews and decision making based on empirical data.
- The toolkit helps establish a common baseline between stakeholders and enables designers to understand the driver's needs and factors influencing their use of DAS.
- A limitation of the toolkit is the large amount of information that is provided to the user, which creates a steep learning curve for new users of the toolkit, and the application requires a commitment of time by the teams.
- Despite this shortcoming, the toolkit's concise format enables improved communication among stakeholders and facilitates quick decision-making and the traceability of design decisions.

Chapter 5
Synthesis

CHAPTER 5

Synthesis

This chapter presents the synthesised results from the conducted research studies. It presents the findings from the cross-study analysis, answering RQ1 by presenting a unified descriptive model illustrating the process of how perception shapes understanding, and discussing the implications for the design of driving automation systems. It concludes with answering RQ2 by presenting the developed Design for Perception toolkit and its two variants.

5.1 Factors Impacting the Driver's Perception and Consequent Understanding

The results of the cross-study analysis suggest interdependencies between the driver's understanding and their perception of the driving automation in their vehicle. This process is presented as a descriptive model of how perception shapes the understanding of a DAS (**Figure 5.1**). In the context of the presented work, the term 'perception' refers to the cognitive process by which individuals assess and interpret information they receive from their surroundings; and the term 'understanding' refers to the capacity to construct a mental representation that facilitates the interaction with a DAS.

The presented model illustrates that, irrespective of the degree of automation, users of DAS understand the systems by reference to three distinct components: the Context, the Vehicle, and the Driver. Further, the cross-study analysis revealed eleven recurring characteristics that constitute the driver's understanding of an automated system. The various aspects and connected sub-aspects have been found to collectively form the elements that contribute to a driver's understanding, or mental model, of a DAS. Moreover, a total of six factors that exert an influence on the driver's perception were found, ultimately impacting and shaping the driver's understanding. These factors were further categorised as perceptual sets and sensory information, which subsequently modify and/or impact the driver's mental representation of the DAS. The illustrated process cycle in **Figure 5.1** can be characterised as

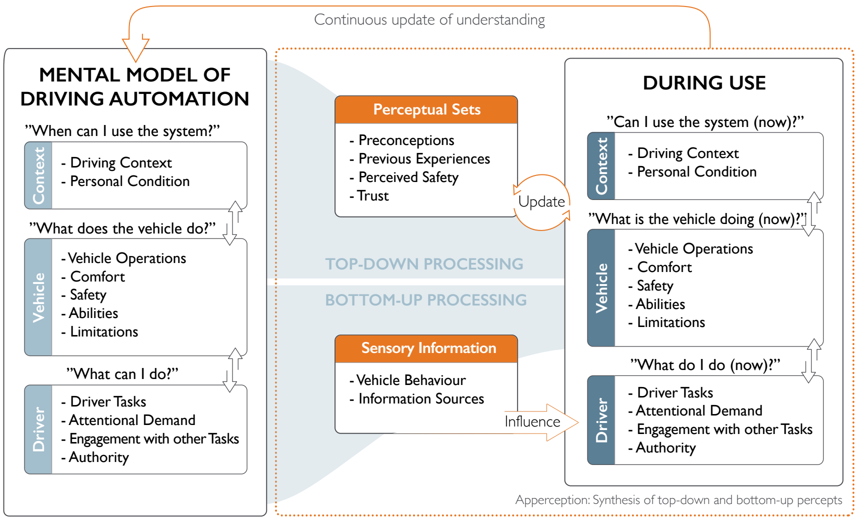

Figure 5.1: Descriptive model of the process of how the driver's perception shapes their understanding of DAS.

continuous – a feedback loop that integrates the information received through a top-down and bottom-up process, as well as a feedback loop updating the driver's mental representation of the DAS. The process can be conceptually divided into three distinct parts: (i) the mental representation, (ii) the perception during engagement with a DAS, and (iii) the dynamic process through which perception shapes understanding.

Mental Representation. This element of the process entails the driver's understanding of the system's characteristics and interaction strategies. It consists of all the aspects and components that comprise the driver's understanding and can be considered the starting point for all interactions. This part of the model represents a static image of the driver's mental representation of the driving automation. This image remains unchanged unless new information is received about the system.

Perception During Use. This block is a mirror of the driver's mental representation of the system. This part of the model demonstrates how the interaction is affected by the perceptual sets and sensory information they receive while driving, operating the vehicle in real-time, and during interaction with a DAS, or when the driver is presented with information about a DAS (e.g., reading about it, or talking to someone about a DAS). Here, the driver's existing knowledge and received information about the DAS is synthesised into a mental representation during use, enabling the driver to assess an interaction or plan and execute an action.

Shaping Understanding. This part of the process is a feedback loop that connects the driver's perception of the system during use with their mental representation of the system. The perception of the system during use is continuously evaluated and the results of that interaction and evaluation have the capacity to change the driver's mental representation based on what they perceive while using the DAS. This can lead to the reinforcement of existing knowledge about a DAS, or when encountering new information, the evaluation of such information and subsequent revision of the driver's understanding of the DAS.

Furthermore, the results from the cross-study analysis suggest that the driver's understanding of a DAS is structured in layers (Context, Vehicle, Driver) that are in continuous interaction (illustrated by the arrows in the model). This means that, for example, the driver's understanding of when they can use the

system, and what the vehicle does, will affect their assessment of what they are supposed to do. Likewise, if the driver believes they are allowed to let go of control over the driving task, this will influence their expectations of what the vehicle will do. Each aspect contributes to the overall understanding of how the system operates and how it affects the driver's role. Thus, when a driver is asked to explain how the DAS in their vehicle functions, they will recall the knowledge organised in their mental representation. Similarly, in the moment of using the system, the driver will ask themselves: "When can I use the system?", "What does the vehicle do?" and "What do I do (now)?". During use however, their mental representation of the DAS is accessed and facilitates their interaction with the encountered system. As long as the system works as expected by the driver, their mental representation will be confirmed by what is perceived during use. However, should the driver encounter a new scenario, this may prompt them to reassess their assumptions about the system and update their mental representation and all the connected aspects.
The subsequent sections will elaborate on the aspects of the driver's understanding and perception of DAS, as depicted in **Figure 5.1**.

The Driver's Understanding

The findings indicate that regardless of the level of automation, drivers of such systems discussed driving modes by reference to three distinct elements: the Context, the Vehicle, and the Driver. In addition, the thematic analysis identified eleven recurring aspects: Driving Context, Personal Condition, Vehicle Operations, Comfort, Safety, Abilities, Limitations, Driver Tasks, Attentional Demand, Engagement in Other Tasks, and Authority. According to the findings, the identified aspects, along with their sub-aspects, constitute the driver's knowledge of a DAS. The proposed classification suggests that the driver's understanding consists of a layered structure in which the different elements (Context, Vehicle and Driver) interact (see also Paper E).

Context

On the highest level of the structure is the Context, which describes when and where the DAS can be used, including aspects traffic conditions and road types, but also the driver's personal constitution. In order to make sense of the automation's availability, the driver's understanding is guided by the question "When can I use the system?" and will typically be answered by for example: *"Since we didn't use it in city traffic or so, I can't speak about it, but it works on bigger roads and [...] free-flowing traffic."*; (P08[1], S4[2]), or when referring to their personal condition: *"[...]if I drive early in the morning, so maybe not fully alert or there is some... you have a meeting you have to fall into or I mean if they are like, you know that there are distractions around you, then I put in the pilot assist functionality as sort of an extra safety."* (P02, SII). Descriptions of each aspect in the Context layer and its associated sub-aspects are presented in **Table 5.1**.

Table 5.1: Context. Description of aspects and sub-aspects.

Element	Aspect	Sub-aspect	Description	Identified in Study
Context When can I use the system?	**Driving Context** Different driving situations when the driver can use the system	Traffic Conditions	The traffic conditions needed for the system to be operational, e.g., density or speed of traffic	I, II, III, IV
		Road Types	The road types that the system can operate on, e.g., freeways or urban streets	
		Weather Conditions	The weather conditions under which the system is operational, e.g., sunny, dry, snow, rain, slippery surface	
		Time of Day	Time of day the system is operational, e.g., daylight, night-time	
		Trip Type	Trip types on which the system is used, e.g., long or short trip, commute to work, leisure activities, traveling	
	Personal Condition The driver's physical or mental state at a given time	Tired	The physical and mental shape the driver is in, e.g., tired, less attentive, bored, or in a state of stress	I, II, III
		Bored		
		Stressed		

[1]P = Participant; in this case 08
[2]S= Study; in this case Study IV

Vehicle

The next layer of the structure is represented by the Vehicle or the DAS. The driver's understanding here is guided by the underlying question "What does the vehicle do?" or "What is the vehicle capable of?" and represents the vehicle operations like performing the driving task to different degrees, the comfort and safety it provides, the limitations of the system, as well as any underlying abilities that the driver assumes the vehicle has, such as situational awareness.
Typical impressions that drivers have when describing vehicle operations and abilities are, for example: *"[...] it does all the functions for acceleration, deceleration and including steering"*; (P05, SIII) or *"[...] it would actually notice the car and slow down"* (P04, SIV). When talking about comfort, statements like the following were identified: *"It's relaxing, because I don't need to take care of certain rather annoying parts, like keeping a safe distance to the car in front of me, and so on. It definitely helps, it takes away certain...maybe no responsibility, but a certain burden."* (P12, SII). **Table 5.2** provides descriptions of each aspect in the Vehicle layer and its associated sub-aspects.

Table 5.2: Vehicle. Description of aspects and sub-aspects.

Element	Aspect	Sub-aspect	Description	Identified in Study
VEHICLE What does the vehicle do?	**Vehicle Operations** The parts of the driving task the vehicle performs	Maintaining the Speed	Driving tasks performed by the systems, e.g., accelerate, brake, or steer	II, III, IV
		Keeping a safe distance from other road users		
		Keeping within the lane		
	Comfort The ways in which the vehicle supports the driver	Physical and Mental Relief	The operations the vehicle performs that support the driver, e.g., relaxation and stress relief	II, III, IV
		Stress Relief		
	Safety The ways in which the vehicle contributes to a safer driving experience	Extra Set of Eyes	The enhanced safety the vehicle offers, e.g., seeing when I am distracted, less aggressive driving by following the traffic flow	II, III, IV
		Smoother Driving Style		
	Abilities The underlying capabilities the driver assumes that the vehicle has	Situational Awareness	The perceived capabilities of the vehicle to perform the driving task, e.g., understanding traffic situations, seeing other road users	II, III, IV
		Predictive Capabilities	The ability to predict traffic development and the actions of other road users, e.g., other road users might pull in/out in front of the vehicle	
		Environment Awareness	Reading traffic and road signs, lanes	
	Limitations The activities a vehicle is not able to perform		The functional limitations of the system, e.g., not being able to switch lanes, drive in city traffic, or read traffic signs	II, III, IV

Driver

The last layer of the structure represents the Driver and their responsibilities, thus the underlying guiding question is "What can I do?" or "What should I do?". This layer represents aspects that the driver associates with their responsibilities during driving, e.g., who is in charge of the driving task and which ones, how much attention they need to pay to the driving as well as more fundamental questions regarding the interaction with the displays and controls.

Table 5.3: Driver. Description of aspects and sub-aspects.

Element	Aspect	Sub-aspect	Description	Identified in Study
DRIVER What can I do?	**Driver Tasks** The tasks the driver can or needs to perform	Interaction with Displays and Controls	The interaction needed from the driver to operate the system, e.g., how to activate the system or manipulate the interface	II, III, IV
		Operation of Vehicle	What the driver needs to do to operate the vehicle, e.g., accelerate, brake, and steer	
	Attentional Demand The amount of attention the driver must pay to the driving activities	Supervise the System	The attention needed from the driver for different driving modes, and the information required from the vehicle	II, III, IV
		Take-Over Ready		
		No Attention		
	Engagement with other Tasks What the driver can do when not driving	Relaxation	The possibility to engage with other tasks than driving, e.g., reading, movies, emails, chatting with passengers	II, III, IV
		Productivity		
		Socialising		
	Authority The power and responsibility over the driving task	Responsibility	The allocation of control and awareness of driving modes, i.e., who is in charge of the driving task, e.g., shared control or vehicle taking over control	II, III, IV
		Control		
		Mode Awareness		

Typically, statements regarding the interaction with the displays and controls included: *"[. . .] you put it in self-driving mode with these buttons, and you see the blue line"* (P01, SIII), describing the steps they take in the interaction and feedback they receive. Further, aspects regarding their involvement in the driving task are described as follows in the case of partial automation: *"I don't release the steering wheel fully. I still have my hand there, so I still drive the car."* (P03, SII), where who has the authority over the driving task is described as *"[...] it's kind of ambiguous to me exactly how much responsibility it's going to take"* (P17, SIII). Detailed descriptions of each aspect in the Driver layer and its associated sub-aspects are presented in **Table 5.3**.

The Driver's Perception

The cross-study analysis of the data from the four studies (I-IV) identified six factors that influence how drivers perceive driving automation during usage. The six factors are Preconceptions, Previous Experiences, Perceived Safety, Trust, Vehicle Behaviour and Information Sources, which have been further split into different aspects. These factors together with their respective aspects describe how a driver perceives driving automation in the moment of use, but also aspects influencing the driver's perception prior to use, which in turn influences their understanding and therefore usage strategies. The driver develops from this a mental representation of the system, describing when it can be used, what tasks it will take over and what responsibilities the driver has when engaging with the system. The identified factors have been categorised further into two groups: Perceptual Sets and Sensory Information.

Perceptual Sets

Preconceptions, Previous Experiences, Perceived Safety and Trust belong to the category of top-down processing factors, i.e., Perceptual Sets, as they comprise contextual information. The perceptual set is the tendency to perceive objects or situations from a specific frame of reference. Existing schemas, mental representations, and concepts frequently serve as a guide for perceptual sets. Top-down processing begins with the most general perceptions and progresses to the more specific ones. Such perceptions are significantly influenced by prior knowledge and expectations, such as schemas and mental models. In the case of a driver interacting with an automated driving system, the driver's perception will be influenced by preconceived notions, previous interactions with other DAS (not exclusive to a specific level of automation), perceived safety, and trust in the system's capabilities. Thus, the driver's perception of the system is influenced by what they expect to perceive.

Preconceptions

Preconceived ideas or expectations about the DAS are organised under Preconceptions. This factor influences the driver's understanding significantly, as it typically harbours the driver's ideas about the system and their anticipations of it, be they current ones or those concerning its unrealised potential. This includes the driver's notion of the system's purpose and their relationship to it: *"It does some driving for you, [...] makes sure you don't get a ticket and go above speed limit. This is more assisting you."* (P07, SIII), as well as anticipations about the system and the benefits of using it. This can include anticipated usefulness and/or expected gains prior to experiencing the system, as described by one participant: *"I think every car should have it. If you could install it in an older car that doesn't have the system, that would be something for traffic security, for safety. Because I do think it will help you to drive smoother, keep you a little bit more comfortable."* (P11, SIV). Expectations will influence how drivers interact with the system; however, these expectations cannot always be met, which consequently led to one participant not using the system: *"I had higher expectations than I could receive from the system, so to say. But on the other hand, I also knew about it, kind of. But I still wanted to test it. I just thought 'OK, I will not use it'."* (P08, SII). **Table 5.4** describes the aspects categorised under Preconceptions in detail.

Previous Experiences

Previous experiences include the driver's experienced situations and learning process with the current system, but also those involving previously encountered DAS. This factor also incorporates knowledge obtained through social discourse, e.g., topics debated in the news and on social media, marketing campaigns, or discussions in social circles. Their experience of usage with any automated system will influence the driver's usage of the currently experienced DAS, and this experience is used as a means to understand encountered systems, like a participant comparing the system in their personal car to their experience of the Level 2 system in Study III: *"The adaptive cruise control was very, very different from regular cruise control, a little bit more...it's a more complicated version of cruise control"* (P15, SIII). Besides comparison to other experiences, the learning experience and the way the driver learned

Table 5.4: Perceptual Sets (Top-Down Processing Factors): Preconceptions.

<table>
<tr><th>Factor</th><th>Aspect</th><th>Sub-aspect</th><th>Description</th><th>Identified in Study</th></tr>
<tr><td rowspan="13">Preconceptions
Mental representation of the vehicle's capabilities, based on expectations</td><td rowspan="2">Purpose of the System
The extent to which the system is supposed to support the driver with executing the driving task</td><td>Assisting the Driver, Collaboration</td><td rowspan="2">The driver's understanding of how the system is supposed to assist them, e.g., by assisting or taking over parts of the driving task</td><td rowspan="2">II, III, IV</td></tr>
<tr><td>Take over the Driving Task</td></tr>
<tr><td rowspan="3">Capabilities
The capabilities the drivers expect the system to be able to execute</td><td>Situational Awareness</td><td rowspan="3">The impression that the system is capable of executing complex driving tasks, e.g., seeing other road users, acting on cut-ins, predicting the behaviour of other road users, reading traffic signs and lights</td><td rowspan="3">II, III, IV</td></tr>
<tr><td>Predictive Capabilities</td></tr>
<tr><td>Environmental Awareness, e.g., reading traffic signs</td></tr>
<tr><td rowspan="2">Anticipation
Excitement and aspirations about an event or interaction, e.g., capabilities and future development</td><td>Social</td><td rowspan="2">Technology development and future values are discussed within social circles and also based on media information or information from regulatory authorities, as well as the impact of sudden AD-related accidents in the media and/or hopes for development.</td><td rowspan="2">II, III, IV</td></tr>
<tr><td>Technology</td></tr>
<tr><td rowspan="4">Anticipated Usefulness
The benefits the driver expects to gain from using the system</td><td>Driving Support</td><td rowspan="4">The ability of the vehicle to take over parts or all of the driving task, thereby increasing safety and the possibility to perform secondary tasks, and relieving the driver of stress and the effect on their personal condition</td><td rowspan="4">II, III, IV</td></tr>
<tr><td>Enhanced Safety</td></tr>
<tr><td>Free Time</td></tr>
<tr><td>Stress Relief</td></tr>
</table>

to use the system have also been shown to make a difference to learners - from drivers trying on their own to drivers who learned under supervision: *"I had a colleague who knew a lot. So, it was learning by doing with some support."* (P08, SII). This enabled the driver to feel confident in using the system. Further, discussions in the media and social circles influence how drivers perceive and talk about the systems, even if they have no prior experience with them. These information sources tend to inform the drivers in a way that might misinform them. For example, a participant in Study IV believed they knew details about a system which was, in fact, a prototype built solely for the study: *"I'm really interested to drive the second system in the city because I've read about it, and I think it works good even in the city."* (P02, SIV). Further details for each aspect are found in **Table 5.5**.

Table 5.5: Perceptual Sets (Top-Down Processing Factors): Previous Experiences.

Factor	Aspect	Sub-aspect	Description	Identified in Study
Previous Experiences Experienced situations and learning processes and their influence on the mental model	**Experience of Usage** The skill or knowledge gained from the use of prior systems or the current one, resulting in the overall experience	Prior Usage of Similar Systems	Driver's comparison to a system they have used before, and key events that influence the driver's perception of the system	II, III, IV
		Positive and/or Negative Experiences		
	Learning Experience How the driver learned to use the system	Trial and Error	The ways that drivers learn about or use the system, e.g., by reading manuals or tutorials, or through supervision and guidance	II, III, IV
		Reading the Manual		
		Under Supervision/ Guided Learning		
	Social Discourse Everything said or written in society about the topic	Media	Written, verbal, or other representative communication about automated vehicles in the media, or social circles, e.g., marketing campaigns, news reports, discussions with other people	III, IV
		Social Circles		

Perceived Safety

The factor Perceived Safety incorporates a range of aspects describing the driver's subjective assessment of how safe it is to use the system. Aspects like the system's performance and its consistent and predictable behaviour influence whether the driver assesses the system to be safe, but also their awareness of the system's technological and legislative situation influences the driver's perception, and their willingness to risk usage. In many cases, participants' awareness of the legislative status influenced their perception of who would be liable when driving with a fully automated system, which in turn influenced their perception of safety and the usefulness of the system: *"I need to stay focused. I think it's a false sense of security. And when it comes to if* *it becomes a court case and I run over someone and the car was steering, there have been many such cases. Then, of course, it's my car. I've chosen to buy it with that system, and I chose to activate it. [...] So, I don't see this system as helpful or yeah, legally speaking."* (P06, SIV). Further, the impression of the system being intelligent and able to execute tasks without human intervention seemed to be associated with the safety perception, as in this example, where the driver stated that the car had *"[...] good predictive capacity on how to engage with other vehicles"* (P03, SIII). Generally, it seemed that the smarter the system appeared to the driver, the higher the perceived safety was. A detailed description of Perceived Safety and its assigned aspects can be seen in **Table 5.6**.

Table 5.6: Perceptual Sets (Top-Down Processing Factors): Perceived Safety.

Factor	Aspect	Sub-aspect	Description	Identified in Study
Perceived Safety The subjective risk assessment the driver makes of the vehicle's behaviour and capabilities	**Awareness** The awareness a driver has about the technology, the years before it was approved by the authorities, and its current status	Awareness of Technology	Knowledge about the system, its capabilities, and limitations, as well as historical knowledge about its development and current level of safety and the standpoint of the authorities	II, III, IV
		Awareness of Legislative Status		
	System Performance The execution of system functionality and how the driver perceives the vehicle's reliability	Predictability	The possibility for the driver to successfully foresee the result of an interaction with or action of the system, and consistent system behaviour, leading to the driver perceiving the vehicle as reliable	II, III, IV
		Consistency		
		Transparency		
	Anthropomorphism Humanisation of vehicles by drivers through ascribing human characteristics to the system and empathising	Intelligence	The technological capabilities to act on behalf of humans without direct human intervention and control. Agency to execute tasks, and perception of the vehicle being intelligent enough to execute complex tasks	II, III, IV
		Autonomy		

Trust

Under Trust, aspects that describe trust at different levels of abstraction are found. On a basic level, a driver's appreciation of a brand will influence whether, even before engaging with it, the driver will trust the system. Although, drivers will also choose when to trust the system and to what extent. Hence, while a brand's reputation can help drivers overcome initial hesitations about trying DAS, *"I trust the car. [...] I mean, I know [brand] is very good like it's a very reliable car. So, yeah, it has a very strong reputation."* (P13, SIII), the context of use will guide users to build trust in the system in different situations. For example, participants make distinctions between traffic and weather conditions when deciding in which situations to trust the system: *"Uh, the clearer the road is, the better the road is, the less traffic it is, the more you can trust the system. But, as soon as you get something in front of you, something where you need to pass a car or whatever it is, the less you can trust the system."* (P4, SII). These assessments help drivers to calibrate their trust level and therefore, hopefully, not over-trust and misuse the systems, like a participant who did not see any limitations for the use of the system: *"As long as you trust the car, I think you can use it almost anywhere."* (P09, SIV), which could potentially end fatally. A detailed list of all factors and connected aspects of Trust can be found in **Table 5.7**.

Table 5.7: Perceptual Sets (Top-Down Processing Factors): Trust.

Factor	Aspect	Sub-aspect	Description	Identified in Study
Trust The trust the driver has in the vehicle's capabilities	**Level of Trust** The amount of trust, the driver has in the system	No Trust Appropriate Trust Over-Trust	Trust calibration towards the system, ranging from no trust, resulting in disuse, and over-trust, resulting in misuse	II, III, IV
	Situational Trust The contexts in which the driver trusts the system's capabilities. Distinctions between situations when the driver trusts the vehicle	Driving Context Personal Condition	The driving contexts that the driver deems the system capable of handling, e.g., traffic conditions, and the physical or mental state in which the driver is comfortable using the system	II, III, IV
	Brand Perception The culmination of all a customer's thoughts and feelings about the brand, and its products and services		The sum of the driver's experiences and anticipations expectations about what a brand represents	III, IV

Sensory Information

The factors Vehicle Behaviour and Information Sources are classified as bottom-up processing factors because they pertain to sensory data in terms of environmental stimuli and occur in real-time. The vehicle's behaviour is perceived in real-time via several sensory channels such as visual, auditory and haptic feedback. This means that the driver considers the vehicle's driving behaviour as information from the vehicle to the driver, which will inform their evaluation of the vehicle's capabilities, for example in terms of comfort, reliability, and even the vehicle's ability to communicate.

Vehicle Behaviour
The driver's understanding of the vehicle's capabilities and their inclination to trust it are closely related to the vehicle's driving style and behaviour. If the vehicle's driving style is not in accordance with the expectations of the driver, it can lead to negative experiences, as was the case for one participant who was bothered by the vehicle's placement in the lane when driving through curves: *"I think I feel a bit unsafe when I'm in a curve. I don't know if it can handle this curve or not."* (P01, SII).

Table 5.8: Sensory Information (Bottom-Up Processing Factors): Vehicle Behaviour.

Factor	Aspect	Sub-aspect	Description	Identified in Study
Vehicle Behaviour How the driver perceives the vehicle's actions and driving performance	**Driving Style** Judgement expressed by the driver on a scale ranged from aggressive to cautious, e.g., "drives like me", aggressive, defensive, etc.	Longitudinal Movement	The vehicle's ability to communicate with the driver through its behaviour, capabilities, efficiency, and consideration for other road users through performance factors like acceleration, frequency of speed shifts, lateral placement, and frequency of change in distance to objects	II, III, IV
		Placement in Lane		
		Distance to Objects		
		Consideration of Driving Context		

However, the driving style can also be perceived as considerate and aware by the drivers, for example, in a case of merging traffic: *"I think the system was much, much better because when a car came out on the highway, it saw the car [...] it was slowing the speed to let them pass and it also took notice of* *this car behind me, because it wasn't braking it just slowed down and made it so smooth. It was like a school example. It was a very good experience."* (P05, SIV). This shows that the vehicle's driving style influences the driver's perception of its capabilities but can also foster positive experiences and encourage use. A further description of the included aspects is found in **Table 5.8**.

Information Sources
The factor Information Sources concerns all input that the driver perceives through their senses. This includes multimodal feedback stemming from visual, auditory and tactile sources, but also kinaesthetic aspects like the perceived motion of the vehicle.

Table 5.9: Sensory Information (Bottom-Up Processing Factors): Information Sources.

Factor	Aspect	Sub-aspect	Description	Identified in Study
Information Sources The information sources the driver uses to make sense of the vehicle operations and their own responsibilities	**Visual System** The information perceived through the eyes, including elements such as colour, light, proximity, patterns, similarity, and so on	Graphical Elements	Visual feedback that the driver receives from the vehicle, for example, from displays in the form of text, icons, and graphics, but also information drawn from the environment outside the car	II, III, IV
		Text		
		Environment		
	Auditory System The loudness, frequency, and meaning of auditory information	Non-Speech Sound	Auditory feedback that the driver receives from the vehicle, such as warning sounds (ping or beep) or verbal instructions	
		Speech Sound		
	Tactile System The input of messages about pressure, vibration, texture, and temperature through the skin	Steering Wheel	Haptic feedback that the driver receives through their tactile sensory system, like vibrations through the seat or steering wheel, and tug of the seat belt	
		Seat		
		Seat Belt		
	Kinaesthetic System The feeling of motion, like position, force and movement	Seat	The information the driver infers from the vehicle's motion, such as acceleration and deceleration or braking behaviour	
		Vehicle Motion		

For example, the driver deduces information about the car's actions through what they perceive from its acceleration and braking behaviour: *"I can feel it braking, I can see that it is going faster and slowing down when it needs to."* (P02, SIII). However, traditional sources of information such as in-vehicle displays and auditory interfaces are still a primary source of information with regard to understanding a system's status, *"When I'm in my car, I can choose the distance, and then if there's a car in front of me, it even displays that car. [...] Green kind of tells me that everything is fine. And then I have the acoustic signal and the hand symbol. And I think there it is even ... that I should put my hands on the steering wheel."*; (P11, SII), or what they as a driver are supposed to do. *"It was super clear because it was both saying that the system is ready and the text. Two things that make you understand, all right, it's ready."* (P09, SIV). Especially in the case of the Information Sources, all aspects work in a multi-source fashion when it comes to helping the driver understand the system's behaviour and capabilities, and it is not possible to consider them in isolation. **Table 5.9** provides detailed information about the factor and its specific sub-aspects.

5.2 The Process of how Perception Shapes Understanding

To provide further clarification of how the driver's perception influences their understanding of a DAS, a hypothetical scenario will be introduced, exemplifying how the different aspects shaping the driver's understanding and factors influencing their perception are affected through the use of a DAS and their encounters with different driving situations.

If a person has a system in their personal car that supports the dynamic driving task (DDT) by (i) keeping the vehicle at a set speed, (ii) at a set distance from other moving vehicles, as well as (iii) taking over the steering, as long as there are (iv) visible lane markings. The driver would make sense of the automated system's use by searching for answers to the aforementioned questions that correspond to the aspects of each layer in their understanding. They would do this in order to make sense of the information received from the vehicle or to understand the interaction required. In this scenario, a driver is travelling to work from a residential location, passing through countryside and some highway segments into an urbanised area. When they are driving, they will wonder: "When can I use the system?". In this instance, that would be on well-established roads with good lane markings (Driving Context). The driver might not use the system in the suburbs, but he or she may attempt to use it in the countryside and on the highway. However, the driver could also deduce the wrong specifics, leading them to create a faulty understanding of the DAS and its capabilities and limitations. Considering the same system has certain inherent technical limitations, such as the system performance being unstable when driving on roads with high curvature (Limitations), as are often experienced in the countryside. If the driver further assumes that all that is needed are clear lane markings, they might assume that they can use the DAS on any type of road, while the manufacturer has primarily intended it to be used on highways, where road infrastructure is more controlled and streamlined. This could lead to a situation where the driver experiences the DAS as acting in an unstable way, and may even leave the road, impacting what the driver assumes the benefits of using the system are (Comfort and Safety).

Next, they will ask the question "What does the vehicle do?". The answer is that it maintains the predetermined speed and distance from other moving vehicles, as well as assisting with the steering (Vehicle Operations). Finally, when utilising the system, they might ask "What do I do (now)?" which, depending on the level of the steering assistance, may imply that the driver does not need to steer or control the speed (Driver Tasks), but must supervise the system (Authority). In such cases, the driver must remain attentive and ready to take over control of the vehicle if necessary (Attentional Demand). Assuming that the vehicle automation has another inherent limitation in its technology. While the DAS is able to detect and keep a safe distance to other moving objects, it is not able to do this with objects that are stationary (Limitations). If the driver does not understand this important limitation (which is often only mentioned in a manual), they might wrongly assume that the vehicle will come to a halt when approaching a red light, and that it does not need their intervention. However, since the system is not capable of processing that an object is stationary, it would require the driver in those moments to act by braking and resuming full control over the driving task (Driver Tasks and Authority). Otherwise, this situation could well result in a crash.

This demonstrates that the answers to these questions are reflected through the different aspects and are interrelated with and inform each other. In this way, a comprehensive understanding of the automation while in use is created by the driver.

However, the driver's understanding and consequent use of such systems might not always be the one the designers and developers of such systems intended, which can be explained by introducing the driver's perception into the interplay. For example, the driver's preconceptions about a DAS could influence their perception and understanding while using the DAS in a way that might obscure the intended use of the system. In the case of our hypothetical system, the driver does not need to steer, but still has to pay attention and supervise the system.
To illustrate, the system performs the driving task to a very high degree of satisfaction according to the driver's perception (System Performance). This might lead the driver to perceive the system as more capable than it is and assume that they do not need to pay attention (Purpose of the System). Their

willingness to relinquish control and even take up other activities would indicate a high Level of Trust. While previous experiences can influence the driver's expectations as to what the systems are capable of, also other sources like news articles or a chat among friends (Social Discourse) can influence their expectations and consequent use of these systems. These expectations can sometimes be misinformed and lead to negative experiences and unexpected interactions (Learning Experience). For example, the driver might use the DAS in a way that the designers did not intend. These experiences can result in confusion about what the system is doing, which can cause frustration and mistrust, leading the driver to reject the systems (Perceived Safety) – or in the worst case to fatal incidents.

To illustrate further, the hypothetical system is able to keep a set speed and safe distance to other road users. While the technical specification in itself only describes the task the vehicle takes over, the vehicle's behaviour when the driver is using the systems will influence the driver's judgement about its performance. For example, if a system keeps a set distance to other road users and the driver perceives it to accelerate and decelerate too fast in relation to the other vehicles, it may be judged as too aggressive in its Driving Style and thus uncomfortable to use.
Other communication from the system to the driver falls under information sources that are perceived through the in-vehicle user interface(s). This can include visual, auditory, and haptic cues and feedback. For instance, the system might run into limitations and not be able to steer for the driver any longer. It might then send a take-over request (TOR) through a visual and auditory prompt in the in-vehicle interfaces, e.g., displays and speakers. If the driver does not act on the prompt, the vehicle might send a warning by intensifying the signal and adding vibration in the seat, in order to get the driver's attention. All these are ways that the driver can receive information about what the vehicle is doing or what is expected of the driver, and this in turn, will influence their perception of the system's capabilities and limitations.

5.3 Implications for the Design of Driving Automation

Finding an adequate framework that explains the problem area and guides design solutions is a significant challenge for designers, especially in the context of driving automation. In order to enhance system design and the user experience, it is crucial that designers have tools to support their design decisions when developing solutions for DAS. The absence of such support or frameworks can result in solutions that are not understood by users or do not serve their needs. The model presented here seeks to support designers by providing theory; however, in answering the second research question, it became essential to transform the model into a design toolkit to make it applicable to practitioners and their daily challenges, thus addressing a practical need.

The process depicted in the model (**Figure 5.1**) illustrates that the driver's perception and understanding of DAS are influenced by various factors. For example, the driver's preconceptions about the purpose and capabilities of the system can shape their perception and understanding during usage. Additionally, more abstract ideas, such as previous experiences and social discourse, play a significant role in shaping the driver's expectations and subsequent use of such systems. This has important implications for the design of DAS. Although the levels of automation may be well-defined within the industry, the drivers of vehicles with such capabilities lack an understanding of the associated expectations of them as drivers and their responsibilities (cf. [15][33]).

However, the inherent intricacies underlying the allocation of responsibility for the driving task at all times, and the limitations of vehicles offering such capabilities, fall under the expertise of professionals. Another challenge that drivers face is that, while the taxonomies provide general guidance on technical specifications surrounding the vehicle's capabilities for each level, the implementation of these systems is not standardised, and manufacturers provide different solutions with different feedback and interaction strategies. Further, a widely recognised paradox in the realm of automation pertains to the phenomenon wherein the increasing proficiency of a system in being automated leads to a decrease in the motivation for the human operator to sustain their attention, especially with increased vehicle performance [131]. Therefore, it is crucial for designers to consider the influence of the driver's perception on their understanding of the DAS when designing the system's functionalities and capabilities. Clear communication and education about the system's purpose and limitations can help align the driver's understanding with the intended use of the system, and possibly bridge the gaps between different manufacturers' solutions by taking the driver's perspective.

However, as illustrated by the hypothetical scenario, while there are factors that designers and developers can and must consider during the design of a DAS, there is a range of factors that one cannot directly influence, but nonetheless has to account for. These external factors include unpredictable weather conditions, road infrastructure, and the behaviours of other road users, as well as information that is not published by the manufacturers themselves.

Despite not being directly controllable, designers and developers must anticipate that these variables will influence the driver's interaction with the system – often not in the intended ways.

Hence, for designers and developers of such systems, it is imperative to comprehend the impact of these factors on the driver's perception in order to develop DAS that are in line with the users' mental models and facilitate safe and effective interactions. Thus, the Design for Perception toolkit, which incorporates the knowledge established in the model (**Figure 5.1**), is an important contribution towards a user-centric approach in the design of DAS.

5.4 The Design for Perception Toolkit

The Design for Perception toolkit aims to offer a framework that facilitates the systematic review of potential design solutions and the identification of areas needing improvement. In this context, one can identify requirements for a technical solution from the driver's perspective, as well as specify technical requirements and scenarios that must be addressed through design solutions like the graphical user interface, the vehicle's behaviour, and specific functionalities of the systems. Further, the toolkit addresses a range of usage scenarios that can aid in the assessment and examination of potential solutions. By taking a driver-centric approach to the design of DAS, it enables a thorough examination of user requirements and preferences, enabling the development of a solution that addresses the driver's needs.

The Design for Perception toolkit has two distinct variants, each presenting the same information in different formats, and tailored to correspond to various aims within a project. The contents of the toolkit represent the different components of how the driver's perception shapes their understanding of DAS (**Figure 5.1**). The two components represented in the model are: (i) the aspects of the driver's understanding, including the context, the vehicle, and the driver; and (ii) the driver's perception, including perceptual sets and sensory information. A third part of the toolkit provides guiding questions corresponding to the different aspects and factors and aims to trigger a discussion and critical review of proposed design solutions. The two developed variants can be utilised either independently or in conjunction with one another throughout the entirety of the design phases.

DESIGN FOR PERCEPTION

Figure 5.2: QR Code to the Design for Perception repository

The subsequent sections will describe the different variants and components of the toolkit, as well as their respective applications. A repository where the toolkit materials can be downloaded is found under the following link https://doi.org/10.5281/zenodo.10116149 or via the QR code in (**Figure 5.2**).

The Toolkit's Variants

The Design for Perception toolkit consists of two variants: a Heuristic Checklist in Excel format and a Card Deck. The two variants are presented in the following sections.

Variant 1: Excel - Heuristics Checklist
The Excel variant of the toolkit was identified as specifically useful as a checklist and structured approach to identifying solutions for given technical specifications. The checklist consists of two tables: *Table 01 Understanding*, which supports the development process and provides aspects to consider when designing and ideating around solutions; and *Table 02 Perception*, which supports the review of design solutions and aids decision-making and backtracking.

Moreover, the Table allows the designer the option to incorporate the technical specifications of the system that is being developed, that align with the various aspects (e.g., at what speeds the DAS operates, which tasks it will take over), alongside usage scenarios (e.g., describing a driver's activity and context when using the specified functionality) that elucidate the functioning of the system. Additionally, it provides the opportunity to describe design solutions and ways for effectively conveying the associated elements to the driver. **Figure 5.3** shows a section of *Table 01 Understanding* for illustration purposes for how it could be utlized.
The structure of *Table 01 Understanding* is determined by the different elements and aspects that comprise a driver's understanding of a DAS. The goal of this table is to support the exploration and ideation of design solutions by using the driver's mental representation of a DAS as a basis. Thus, the table consists of three parts and their guiding questions: 1. Context – "When can I use the system?"; 2. Vehicle – "What does the car do?"; and 3. Driver – "What do I do?". Each of the sections contains the different aspects and sub-aspects, with descriptions.

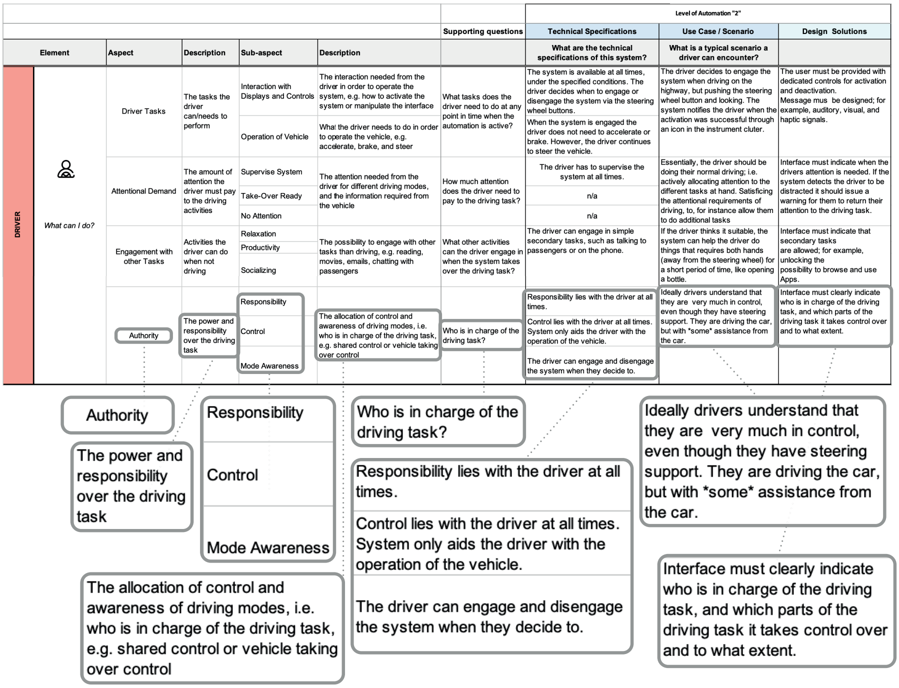

Figure 5.3: Table 01 Understanding. Section illustrating the structure of the checklist with example contents for a Level 2 DAS.

The structure of *Table 02 – Perception* is similar to that of Table 01, and is determined by the different factors that affect the driver's perception of a DAS. The goal of this Table is to review and validate the design solutions in focus. As a result of this, the Table is further divided into the top-down processing factors, i.e., Perceptual Sets, and the bottom-up processing factors, i.e., Sensory Information. Each of the factors and its sub-aspects are described in detail and supported by guiding questions which aim to facilitate a discussion around their corresponding aspects. **Figure 5.4** gives an overview of a section of *Table 02 Perception* for illustration of how it could be utilized.

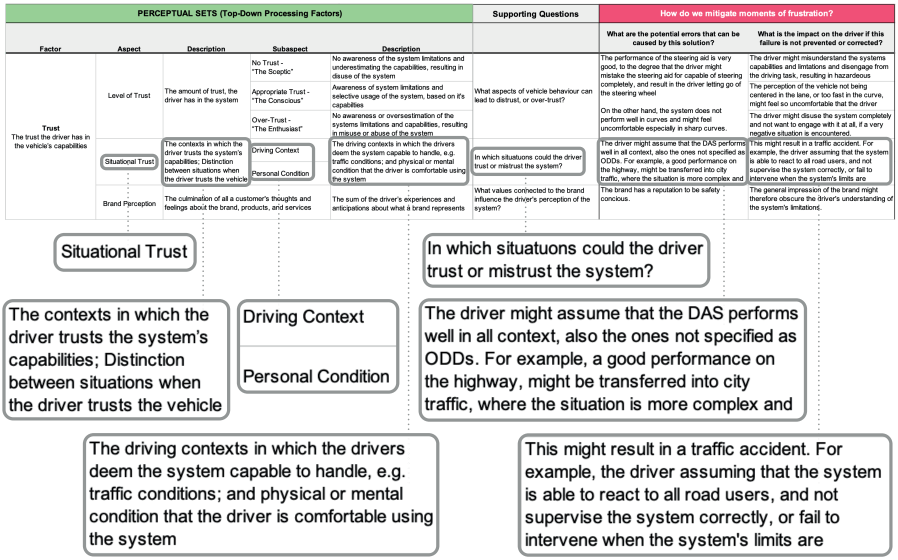

Figure 5.4: Table 02 Perception. Section illustrating the structure of the checklist with example contents for a Level 2 DAS.

Additionally, Table 02 introduces a third component called 'Impact', which addresses the design solutions through critical discussion. It does so by introducing, on the one hand, questions that aim to identify the failures and effects of the discussed solution, and on the other hand, by challenging the designer to think of ways to improve the user experience.

Variant 2: Card Deck – Ideation and Validation

The Card Deck variant of the toolkit has been recognised as particularly valuable for facilitating workshops, as well as for individual use in scenarios that require a creative approach, but also when aiming to facilitate a structured review of design solutions within a team. Similar to the Excel variant, the Card Deck is split into three parts: *Deck 01* Understanding, *Deck 02* Perception, and *Deck 03* Impact.

Deck 01 Understanding – Explore and Ideate
The first Card Deck covers the driver's understanding of DAS and facilitates a guided exploration and ideation around possible solutions. **Figure 5.5** shows a selection of cards from Deck 01.

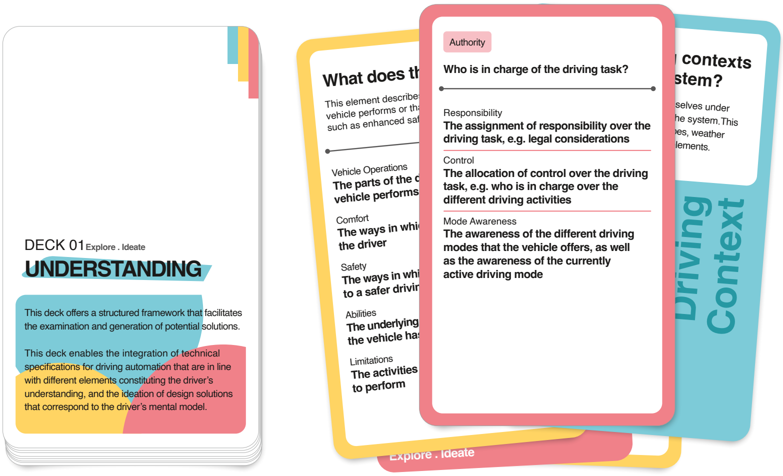

Figure 5.5: Deck 01 Understanding. Selection of cards from the deck.

The cards can be played in any order, and the designer is free to use all of them, or just the cards representing the areas they want to focus on. With this deck, the designer can incorporate the technical specifications of a system that align with the various aspects and ideate around design solutions corresponding to the driver's mental representation or identify areas in need of improvement and create strategies to address these.

Deck 02 Perception – Review and Validate]
This deck supports the review and assessment of design solutions through a guided approach. **Figure 5.6** shows a selection of cards from Deck 02.

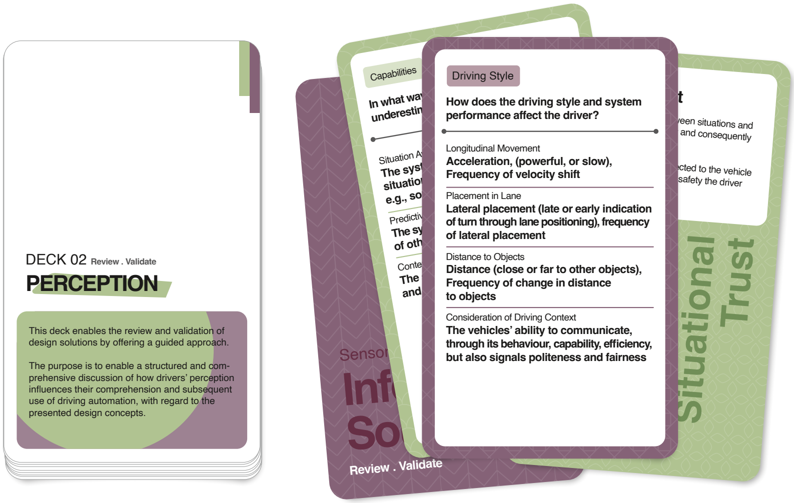

Figure 5.6: Deck 02 Perception. Selection of cards from the deck.

With this deck, one can critically review the developed design solutions and discuss the effect of the driver's perception on their understanding and consequent usage of the driving automation. Further, it enables the validation of existing or created solutions from a driver-centric standpoint by challenging the designers and developers to discuss guiding questions corresponding to the factors influencing the driver's perception. The cards provide the flexibility to be utilised in any order, granting the freedom to use all of them or selectively choose those that pertain to the areas of focus.

Deck 03 Impact – Mitigate and Delight
This deck supports the in-depth review of design solutions. With the help of the included cards, questions are introduced which aim to identify the possible failures of a design solution and their effects on the driver in order to mitigate them. In addition, the deck includes cards which aim to challenge design solutions in order to create moments of delight that can have a positive impact on the user experience. **Figure 5.3** shows the cards included in Deck 03.

Figure 5.7: Deck 03 Impact. Selection of cards from the deck.

This deck is special in the sense that its cards can be played on any other card and at any point during the design process. While Deck 02 already offers guiding questions to discuss design solutions critically, this Deck 03 aims to prompt a deeper discussion about the impact of the provided solutions. The impact can be seen as any positive or negative effect on the driver's perception of the system that consequently leads to acceptance and willingness to use a DAS or not.

Chapter 6

Discussion

CHAPTER 6

Discussion

The aim of the present research was to investigate the factors that impact the driver's perception and consequent understanding of driving automation systems (RQ1) and to investigate how this knowledge can be applied to guide design decisions for practitioners involved in the development of driving automation systems (RQ2). This thesis provides both theoretical and practical contributions by addressing these research questions. This chapter presents a comparison between the contribution made through this work and the current body of research, followed by a discussion of the implications for design. The chapter concludes with reflections on the research approach.

6.1 Contributions

The primary objective of the thesis was to address two research questions: (RQ1) What are the factors that impact the driver's perception and subsequent understanding of DAS? and subsequently (RQ2) How can this knowledge be applied to offer design recommendations for practitioners involved in the development of DAS?

In order to address the research questions, a mixed-methods methodology was utilised, employing a range of methods, such as surveys, field observations, and interviews. This work makes contributions to both the theoretical and practical aspects of the research area. The subsequent sections will discuss and compare the contributions with previous research, followed by a discussion on the implications for the design of DAS.

Theoretical Contributions

The theoretical contribution of this thesis lies in the identification of the aspects that shape the driver's understanding of DAS, as well as the factors that influence the driver's perception of such systems, which also answers the first research question (Papers A - G). Additionally, the work integrates the discovered aspects constituting understanding, and factors influencing perception, into a unified conceptual model that elucidates the process by which the driver's understanding of a DAS is shaped by their perception.
Consequently, by providing a comprehensive and unified overview, this work addresses a gap in the existing literature: the lack of a holistic understanding of how the driver's perception influences their mental model of DAS.

Earlier research efforts have investigated a range of variables that have been deemed important for the driver's interaction with an automated driving system. These studies have most frequently investigated the topic of safety and take-over requests, trust and complacency, acceptance of and attitude towards automated vehicles, situation awareness, workload and stress, and drowsiness and fatigue, among other factors. For a comprehensive summary, please refer to the literature review conducted by Frison and colleagues [132]. The review emphasises that the existing research on the driver's interaction with DAS often concentrates on a limited range of variables and methodologies, without considering the interplay between variables in the complex environment of the dynamic driving task, or a triangulation of data for a deeper understanding of the driver-automation interaction [132].
However, in order for drivers to understand and interact with DAS in a safe manner, it is crucial for designers to consider the driver's mental model and how their interaction with a DAS influences it. Consequently, numerous authors call for a more human-centric classification of automation levels (cf. [41][133]) than provided by the currently prominent Levels of Driving Au-

tomation provided by the Society of Automotive Engineers [7]. While there are advantages to utilising established taxonomies that categorise levels of automation (cf. [19][77]), studies show that the driver's mental models do not align with the technically driven taxonomy (cf. [40][39]). Further, studies show that the SAE taxonomy is not only ambiguous to drivers, but also to practitioners and researchers, who struggle to find a unanimous interpretation of the provided LoA (for an overview, see [134]). Thus, over the years, different approaches have been sought to identify variables relevant to the driver's interaction with DAS.

For example, various works have attempted to describe the driver's interaction with a vehicle through behavioural models. Michon [135] conducted a review of driver behaviour models and identified four different types of models along two dimensions: (i) behavioural models, representing behaviour, vs. (ii) psychological models, representing cognitive processes, vs. (iii) taxonomic models, representing an inventory of facts and their relationships, vs. (iv) functional models, containing components which interact dynamically. Based on his analysis, he remarks on the absence of driver-related factors such as cognitive functions, beliefs and emotions in most models, as they are behavioural-functional and concentrate on specific characteristics of the driving task and driver behaviours. Thus, they do not answer the question as to why the driver behaves in a certain way. He emphasises the need for additional research in the area of cognitive processes to gain a better understanding of driver behaviour and driver motivation [135]. To date, this circumstance has not changed.

Building on Stanton and Young's [136] psychological model of driving automation, Heikoop and colleagues [137] conducted a literature review in order to propose a consensus-based psychological model. Their model aimed to describe the interrelations between identified psychological constructs from the research body. However, their model is solely based on a limited literature search, and only includes nine different variables (i.e., mental model, situation awareness, attention, trust, mental workload, stress, feedback, task demands and fatigue) which represent the consensus in the literature and are critiqued as being highly biased through construct proliferation [137]. Notably, the authors acknowledged the need to extend the model with a range of psychological constructs (e.g., ability, authority, responsibility, amongst others, as well as the identification of further variables), and the empirical investigation of the identified variables and interrelations.

The aforementioned approaches collectively indicate an underlying issue: current research efforts lack a cognitive and holistic approach to the driver's understanding of DAS. In an effort to address this, several studies have examined the difficulties associated with designing DAS and have reached the consensus that numerous difficulties may emerge in the initial phases of development. These challenges are primarily attributed to the adoption of technology-centric taxonomies, which tend to overlook the human driver and prioritise task allocation strategies (cf. [39][40][98]), as well as the lack of variety in methodologies, and no triangulation of data. Moreover, it has been established through additional research that the user's understanding of automation levels does not align with the existing taxonomies [97].

Instead of a single automation level and task-allocation perspective, the research presented in Chapter 5 shows that the driver makes sense of the interaction with a driving automation system by asking themselves the questions 1. "When can I use it?" 2. "What does the vehicle do?", and 3. "What do I do?", each of which additionally contain numerous aspects that they seek answers to, and factors influencing their perception of every interaction with the automated system.

To the best of the author's knowledge, the present work represents the first attempt to thoroughly investigate and develop a model elucidating the process shaping the driver's understanding of DAS through their perception of the DAS. Several key aspects set the proposed model (**Figure 5.1**) apart.

In contrast to prior studies undertaken in the field of driving automation, the present model, and its associated aspects and factors presented in this thesis, provide a holistic examination of variables pertinent to the driver's interaction with DAS. In contrast to theoretical frameworks suggested previously, the present model is firmly grounded in empirical evidence derived from drivers in real world driving environments. In order to enhance the model's robustness, data from four distinct empirical studies (Study I-IV) was triangu-

lated through a structured analysis approach. Further, the conducted studies utilized multiple methodological approaches (e.g., surveys, naturalistic driving studies, in-depth interviews, field observations) capturing a wide array of driver behaviours and impressions, from first time drivers and long term drivers, over prolonged periods. As a result, these studies provided valuable insights into how the driver's understanding of DAS is shaped through their perception.
Through the triangulation of various data points, a comprehensive list of aspects shaping the driver's understanding and factors influencing their perception was identified, allowing for a nuanced approach to the driver's interaction with DAS. Finally, the variables that were identified were systematically classified, enabling the author to analyse patterns and relationships. The comprehensive categorization presented illuminates the intricate interplay between several variables, providing useful insights into the perception and understanding of DAS by drivers.
The proposed model is notable for its attention to the driver's perception and consequent understanding of DAS, as it thoroughly addresses the criticisms put forward by other researchers. These criticisms revolve around the lack of varied and empirical methodologies and data triangulation, as well as the neglect of a wider range of factors and their interrelation (cf. [136][72][137][132][138], in the attempt to identify a holistic driver-centric perspective.

In conclusion, the model illustrates the cognitive process by which perception influences the driver's understanding and subsequent interaction with driving automation, through which the model aims to support a holistic perspective on the driver's understanding and subsequently, on the design of DAS.

Practical Contributions

The developed and presented Design for Perception Toolkit is a significant practical contribution because it is based on broad and deep empirical evidence describing the driver's perception and consequent understanding of DAS, and thus addresses one of the most important needs of the designers and developers of such systems – understanding and applying the driver's perspective. Therefore, this practical contribution aims to address the second research question (Paper H), since the toolkit, being specialised for the automotive community, addresses a gap in the methodological toolbox for designers and developers of DAS, namely the lack of a specific and structured, user-centric tool that enhances the process of designing DAS through an empirically based and guided approach.

With the toolkit, designers can utilize the specified questions: When can I use the systems? 2. What does the vehicle do? and 3. What do I do? and ask themselves questions that drivers will ask when interacting with the systems. In addition, the model defines which factors influence the driver's perception of the system, its capabilities and limitations and, consequently, how they understand its utilization. The provided information is further equipped with guiding questions, which aim to facilitate a critical review and discussions. Thus, the model can be used as a design aid to include the relevant aspects that drivers identify during their interaction with a DAS, as well as the factors affecting them.

This approach can be compared to a Cognitive Walkthrough (CW), which is an inspection method linking an user interface walkthrough to a cognitive model of a user [139]. However, since its first version, the CW has evolved and been refined to imagine and address specific scenarios for each action that a user has to take with the help of guiding questions [140]. One of the main benefits of CW is considered to be its ease of use for developers without specialised knowledge of cognitive theory [141]. However, due to its limited focus on identifying the usability problems of a particular solution, it has been criticised for lacking a high-level perspective, prioritisation of failure-and-success effects, and a complex overview of identified results [142]. While attempts have been made to modify and improve the CW [143], the improved CW has been criticised for remaining limited in its analysis and being tedious, complex and time-consuming to implement [142].

The Design for Perception Toolkit addresses these concerns by providing a comprehensive and structured analysis approach to the effects of the design on perception. Further, it provides a high-level perspective by analysing the overall effect of design decisions on the perceptions and experiences of users. In addition, it streamlines the analysis process, making it more effective and user-friendly, thereby addressing the limitations of previously mentioned method.

The tool does, however, require an initial investment of time, due to the vast quantity of information it provides. However, the designers using the toolkit concurred that this initial threshold diminished as they gained familiarity with it.

The additional critical review support that the toolkit offers, which is loosely based on Design Failure Modes and Effect Analysis (DFMEA), is another important component. Historically, an FMEA seeks to prevent the possibility that a new design, process or system fails to meet the proposed requirements in whole or in part under certain conditions. The purpose of the DFMEA is to identify and prevent design-related failure modes of products in order to validate the established design parameters for a specific functional performance level. The most important function of this type of FMEA is the identification of potential failure modes in the early stages of design development in order to eliminate their effects, select the optimal design variant and develop a documentation base to support future designs [144]. Consequently, by employing a DFMEA-based strategy for the toolkit, designers and developers evaluate the severity, frequency, and detectability of each potential failure mode for the proposed design solutions. An additional component of the toolkit is the identification of prospective areas of delight. This not only enables the designers of DAS to prioritise and mitigate the most significant risks but also aids in ensuring that the final product meets or exceeds driver expectations. In addition, this process encourages cross-functional collaboration between teams in order to collectively mitigate potential effects and improve product reliability overall.

Further, the flexibility of the toolkit to use different variants at different points of the design process, as well as in different settings, i.e., in a group or individually, supports easy implementation into everyday activities. As also stated by the designers during the evaluation of the toolkit, they do not wish to add a new step to their current processes but would prefer it to be a seamless addition.
This notion was also discussed by Gericke and colleagues [145], who concluded that for a method to be successful in the industry, it needs to add value to the operation through effectiveness and efficiency, as well as have the ability to be combined with existing processes within the company, without distracting

from the work that needs to be done. Consequently, the toolkit facilitates the identification of design, evaluation, and training approaches to promote appropriate usage strategies and the development of the driver's understanding of DAS that aligns with the intended use promoted by the manufacturers.

Design for Perception

Numerous automotive manufacturers have signalled their intent to introduce highly automated vehicles to the market in the near future, indicating a massive push for automated driving functionality. The motivation is manifold and ranges from heightening comfort and traffic safety to introducing the possibility of engaging in non-driving-related tasks while travelling in the vehicle, thus offering a distinct user experience [75][18].

Nevertheless, it is anticipated that in the near future, there will continue to be a range of driving automation systems available, each with different degrees of automation, that will continue to be widely used on roadways. This implies that the human driver will assume the responsibilities of monitoring, supervising and serving as a backup fo the automation in instances where the automated driving system is unable to execute its tasks. However, as discussed widely ever since the introduction of automation, humans are not cut out for these types of tasks (cf. [47][47]). Different work has shown that drivers become bored, fatigued and unalert [146], lose track of what the automation is doing, or even what the surrounding circumstances are [89][147]. Further, they may not understand what their tasks and responsibilities are, or even simply forget which driving mode the automation is engaged in [33]. Therefore, the successful implementation of DAS relies on effective cooperation between the driver and the vehicle. This requires designers to view them as a joint cognitive system, wherein both must work in cooperation to guarantee a safe and enjoyable driving experience, and thus they must take a more human-centric approach to the design of DAS.

Hence, during the development of DAS, designers must take into account that the driver's perception extends beyond the system's functionalities and their own tasks. And while the HMI can play an important role in communicating crucial information about needed actions from the driver [22][23], the driver's understanding of the DAS is not just impacted during its utilization or solely by the HMI. Rather, their knowledge is shaped by various factors and influenced by variables that extend outside the realm of user interface design. This implies that designers' understanding of the system, including its limitations, capabilities, and feedback, may not align with the driver's perception, rendering the use of technology-centred taxonomies problematic as they do not account for a comprehensive view of the complex interaction between the driver and the vehicle. Therefore, it is imperative to adopt a human factors engineering approach in addressing this issue. The human factors approach encompasses the cognitive, physical, and social dimensions of the driver's engagement with the vehicle. This approach recognises that variables such as the driver's experience, emotions and context influence their perception and behaviour. By integrating these variables into the design methodology, a human-centric and effective interface can be developed that more closely corresponds to the requirements and expectations of the driver.

However, the transfer of academic knowledge and methods into industry has proven challenging [148][149][150]. Many variables within the industrial sector, including time constraints, stringent quality criteria, and the intrinsic characteristics of existing processes, present challenges to the effective implementation and incorporation of novel methods, strategies, and tools [151][152]. It is argued that developed methods need to be developed to a degree that industry can use them in conjunction with existing methods, and that efforts in this regard should strive to amplify existing knowledge and extend existing methods instead of creating new methods to replace the existing ones [153][145]. Thus, for a method to be adapted for use, one must take into account that the users of the method need to understand and accept the method, which depends on the use contexts, their needs, and the opportunity to improve established practices meaningfully [154].

The Design for Perception toolkit prioritizes humans and their perception as the focal point of technological advancement, enabling a human-centred approach to determining the requirements for the design of a DAS. At the core of this lies the empirical knowledge, presented in the conceptual model (**Figure 5.1**), describing the process of how perception shapes understanding. However, while the model describes crucial aspects and relevant processes about the driver's perception and consequent understanding of the DAS, a the-

oretical model retains a high threshold when it comes to the applicability in industrial processes and design activities.
To bridge this gap, a practical framework was needed that could translate the theoretical knowledge into applicable insights [155][152]. This framework had to not only consider the driver's needs and identify their potential impact, but also its application in the industrial context as a design tool. This was achieved by developing and evaluating the toolkit within the desired context and with its target users. The involvement of the designers in the development of the tool permitted two crucial contributions to its success: (i) adoption of the knowledge gained into applicable representation variants that could be used with great flexibility (cf. [156]); and (ii) the transfer of knowledge and a mindset, empowering the adaptation of the tool (cf. [157][158].
As described in the results, the Design for Perception toolkit has the potential to be employed in conjunction with already established methods and processes. It can be utilised to investigate and broaden the scope of the problem area, as well as act as a catalyst for generating design solutions. Further, it can be employed as an assessment tool at different phases of the design process, fulfilling both evaluative and generative purposes. Therefore, it can serve as a checklist to systematically evaluate and define design solutions. It can also be utilized in workshops to facilitate collaboration and generate ideas among various stakeholders. Additionally, it can function as a comprehensive analysis tool to identify weaknesses and areas for improvement in existing solutions.

In summary, the driver's perspective on driving automation differs fundamentally from the technological perspective that currently guides the design and development of these systems. In order to improve the user experience, we must reframe our perspective in order to design products that align with the driver's mental models and facilitate their development of a sufficient understanding of the DAS. The Design for Perception mindset applies a systematic approach based on a human-centric perspective that accounts for the driver's perception. As a result, it can help practitioners to: (i) explore possible solutions using a systematic approach; (ii) identify areas for improvement from the user's perspective; and (iii) ideate and critically evaluate design decisions using a structured process. Thus, the toolkit has the potential to act as common ground, aligning the objectives and motivations of developers, designers, and strategists with those of regulators and most importantly, the drivers.

6.2 Reflections on the Approach

The technique discussion is categorised into distinct sections, each dedicated to a certain approach and concluding observations on the chosen embedded mixed-methods research design for this project. It is crucial to acknowledge that the results of the studies presented in **Chapter 4** are intrinsically linked to the selected methodology. The methodological decisions, encompassing the selection of data collection methods, sampling strategies, and analysis methods, significantly influence the findings and interpretations. Acknowledging this interdependency is crucial for a comprehensive understanding of the research findings.

Study I – International Online Survey

Due to the lack of information regarding when drivers prefer to use DAS, it was decided to conduct a global online survey to collect information from end-users. Online surveys are a quick and inexpensive method for collecting information from a large population, particularly when targeting a specific subset of respondents, regardless of their geographical location. The aim of Study I was to gain insights into when drivers use existing (Level 1 and Level 2) systems in various driving contexts, and to understand if there are any correlations between the use of one system in a situation and the use of the other system in the same situation. The use of an online survey made it possible to reach a targeted group in larger numbers, and to include diverse countries. While the use of online surveys allowed access to a unique population, it was difficult to more precisely target individuals whose vehicles were equipped with both types of systems. As a consequence, only a small sample size of the original group of respondents remained for analysis. This highlights a second issue, which is self-reported data (cf. [159]), thus being the respondents' own evaluations of their utilization strategies. In addition, there is no assurance that respondents provided accurate demographic or other information about the systems available in their cars, which is problematic in the case of DAS given that previous research indicates that many drivers are unaware of the systems installed in their vehicles [35]. In addition, interpretation of the data can be difficult because there is no way to follow up on responses or obtain additional insights beyond the survey questions, which is why the exploration phase was continued with a mixed-methods approach as a next step.

Study II – Naturalistic Driving Study with Subsequent In-Depth Interviews

Naturalistic Driving Studies permit the accumulation of sensory-based vehicle data (such as GPS data, data indicating traffic and road conditions, and data about the use of apps and DAS) over an extended period of time and in the context of natural driving. Since vehicle data is typically collected and processed through unobtrusive technologies, it is possible to monitor driver usage patterns at all times without interfering with their daily lives or the natural environment [121].

Using a longitudinal mixed-methods design, Study II was able to collect a large amount of data from 132 vehicles, allowing for the identification of distinct user groups who employed various strategies when using the DAS available in their vehicles (Level 1 and Level 2). The subsequent interviews with drivers from the identified user groups enabled validation and an in-depth understanding of the collected sensory data, resulting in greater comprehension of the situational usage of the systems and the motivations behind those choices. In addition, initially, emergent usage patterns from Study I could be analysed in depth, and points of interest could be pursued in the interviews, permitted a focused investigation of the driver's motivation for usage and the factors influencing their understanding of the systems. Lastly, the subsequent interviews with the various user groups permitted an in-depth investigation of the drivers' prior experiences and learning processes with the systems, which supported the development of a number of DAS-related aspects pertinent to driver's understanding.

However, one of the limitations of the research was that only Volvo vehicles and Volvo Cars employees were used in the tracked vehicle fleet. Even though only employees who were not engaged in the development of DAS were included in the study and invited to the interviews, one cannot exclude a bias towards the vehicle brand and their equipped systems. In addition, an ND study does not account for possible car-sharing scenarios, and the lack of a driver recognition unit on board could contribute to the problem of driving patterns from one user being indistinguishable from those of another, obscuring data based on the amount of sharing. Even though this was screened for, the self-reported car-sharing habits of the participants should be viewed with caution. A further limitation of the study is the participants' varying degrees of familiarity with the two systems. While all participants had access to the NDS vehicle for approximately three weeks, some participants had prior experience with Level 1 and/or Level 2 systems. However, prior experience was not taken into consideration in the NDS study and could only be assessed through in-depth interviews to determine learning experiences and levels of knowledge. In addition, six distinct vehicle models were included in the study, which may have affected the system performance and driving behaviour of the vehicles, such as sedan versus SUV. Despite indications to the contrary, there are no definitive data regarding the impact of vehicle type on perceived system performance.

Study III and Study IV – Woz Driving Study with Observations and In-Depth Interviews

As the objective of the third and fourth studies was to examine the driver's understanding of a vehicle with multiple levels of automation, a quasi-experimental study design employing a Wizard-of-Oz vehicle was implemented. The semi-controlled study design made it possible to account for a number of variables, including the participants, the driving route, and the levels of driving automation that were evaluated. Despite the meticulous selection of the route and session hours based on collected traffic data, the quasi-experimental design does not permit control of the traffic conditions. This variable could therefore vary in density and exposure periods for the different participants and is regarded as a possible limitation. Nonetheless, all participants had comparable exposure periods and encountered the necessary traffic conditions for the DAS to function. An alternative to conducting on-road studies would have been the use of driving simulators to shed light on the driver's interaction with the DAS (as in studies by [26][160][161][162]. However, the use of simulators was abandoned, as a simulator study does not necessarily provide an accurate depiction of how drivers react to real-world traffic and the encountered scenarios when using driving automation. Due to the incorporation of real-world interventions, a quasi-experimental design has a higher level of external validity [163].

Regarding the sample, it was advantageous for the study to conduct the experiment with novice users because they were likely to engage in more conscious reflections during the think-aloud procedures than more experienced drivers and thus provide greater insight into how they constructed their understanding of the systems. However, a disadvantage of this is that novice users may be overly enthusiastic about using a self-driving vehicle, which may lead to a bias in their behaviour [164]. Nevertheless, the adoption of a similar study design in different locations and time periods, as well as inviting novice users to participate, has proven beneficial, as participants' comments in Study IV were significantly more concerned with safety and legal issues than in Study III, indicating a correlation between mood shifts and political and social events at the time, and providing consistency and validity in the findings. Hence, the implementation of a quasi-experimental mixed-methods study design can be deemed successful because the results of the studies were comparable and also provided new insights into user motivation for using DAS and their perception of such systems.

Nonetheless, certain factors, such as vehicle behaviour, were acknowledged as being crucial to the driver's perception of the system, although the nature of this phenomenon is poorly understood. Thus, to acquire a deeper understanding, it may be necessary to examine this phenomenon in a different, and possibly more controlled setting. However, a deep dive into specific factors during the course of this research was not possible due to time restrictions.

Study V – Co-Creation

For the development and evaluation of the toolkit, the author applied a participatory research approach utilising co-design activities with practitioners in an industry setting. Participatory Research (PR) is an approach that aims to bridge research and action by directly involving stakeholders in the process, taking in their feedback, and feeding back to them [165][166]. PR encompasses a broad range of research designs and methods, employing systematic data collection and analysis, in collaboration with the goal to instigate action [167][168]. Therefore, participatory research approaches hold a key role in facilitating an exchange between researchers and users, or individuals possessing expert knowledge in the field [169]. They actively engage individuals outside the research community as close collaborators instead of as 'subjects', to improve innovation, or the quality or speed of the design process, and ultimately user satisfaction [170]. As iterated by Kujala [170], the direct involvement of product stakeholders, i.e., designers and developers of DAS, through co-design

techniques during the development process has manifold benefits.
However, the most striking benefits when designing with users are that users are invited and empowered to actively shape the outcome of the design process [123][171], as well as the contribution of specific expertise regarding the usage and use context through the involved stakeholders [172]; with regard to Study V, these were designers, and developers of driving automation systems. Subsequently, the project applied the framework of User-Centred Research (UCR) in order to address the aforementioned aim. UCR is a form of co-design that is characterized by an iterative design process that involves users in the design of products that are intended for them [173][174][175].
Thus, the co-creation workshops and activities offered a cooperative environment in which the practitioners could share their experiences with and requirements for the design toolkit, with the purpose of contributing to the design process and shaping the toolkit according to their needs. The subsequent interviews supported this validation of the toolkit and an assessment of the outcome regarding its utility, strengths, limitations, and potential improvements.
However, the approach was constrained by the time and resources available for this use case study. Since all participants were primarily engaged in the development efforts of the company, carving out time for consecutive workshops and activities alongside the workshops was at times challenging, even though the participants were participating voluntarily and with great engagement. However, their pressing workload made it necessary to make concessions with regard to the study's duration and iterations. Nevertheless, despite the fact that there are details of the toolkit that could be improved or further developed, the toolkit has already proved useful to the participants, resulting in them becoming independent advocates for the toolkit.

Concluding Remarks on the Research Approach

The facilitation of empirical research is of utmost importance in order to gain a comprehensive understanding of complex phenomena [176]. Further, recognising the end-users of DAS as valuable sources of information, innovation and adaptability while striving to create and enhance DAS, is a choice that is critical to the success of the designed solution [54][114][177], and thus should be seen as the focus of attention. Numerous research endeavours pertaining to the assessment of DAS primarily rely on simulator studies. While these studies provide valuable insights into the utilisation of such systems [178][179], their limited realism undermines the ecological validation of the results. Consequently, these findings fail to provide genuine insights into the user's strategies and perception of the driving automation, as the presence of a safety net in simulated environments obscures the true experiences and challenges encountered during real-world driving scenarios [180][181][182][183].

The decision to employ a mixed-methods study approach enabled an examination of the driver's utilization, perception, and understanding of driving automation technologies, hence providing valuable insights. The integration of quantitative and qualitative data yielded a more comprehensive awareness of the subject matter compared to relying just on one method, as the different approaches typically possess distinct characteristics and explore different facets of the same issue. The utilisation of both qualitative and quantitative methodologies was additionally advantageous due to the exploratory and inductive nature of the chosen research methodology, since it facilitated the gathering of primary quantitative data from both the survey and the ND study that pertained to when and how drivers make use of DAS in their personal vehicles. Subsequently, this prompted a more comprehensive examination employing a hybrid approach of quantitative and qualitative methodologies by utilising observational techniques paired with in-depth interviews and triangulating the qualitative data with quantitative data points. This was done to acquire a broader and deeper understanding of the driver's perception and consequent understanding of DAS.

Chapter 7
Conclusions

CHAPTER 7

Conclusions

In conclusion, this thesis has made significant contributions to the understanding of the driver's perception and consequent understanding of driving automation systems and its implications for design. The research addressed two main research questions: (RQ1) What are the factors that impact the driver's perception and subsequent understanding of DAS? and (RQ2) How can this knowledge be applied to offer design recommendations for practitioners involved in the development of Driving Automation Systems? The first research question was answered by identifying a large number of aspects constituting the driver's understanding and factors influencing their perception of a driving automation system and describing the process shaping the mental model of a driver. The second research question led to the exploration and development of a method aiming to turn the gathered theoretical knowledge into an applicable tool for industry professionals.

The contributions of this thesis can be succinctly summarized as follows:

(i) *The theoretical contributions of this thesis identified critical aspects shaping the driver's understanding of Driving Automation Systems and factors influ-*

encing their perception.
By integrating these aspects into a unified conceptual model, this work addressed a gap in the existing literature—a lack of a holistic understanding of how the driver's perception influences their mental model of DAS. Existing research efforts often focused on limited variables and methodologies, neglecting the complexity of the dynamic driving task and the interplay between various factors. This research bridged this gap by providing a comprehensive overview grounded in empirical evidence derived from real drivers. The proposed model, developed through rigorous empirical studies and data triangulation, presents a holistic examination of variables relevant to the driver's interaction with driving automation.

(ii) *The practical contributions of this thesis are manifested in the development and evaluation of the Design for Perception Toolkit.*
Based on deep empirical evidence, the toolkit provides a structured, user-centric approach to designing DAS. It addresses the limitations of existing methods by offering a high-level perspective, comprehensive analysis, and a flexible application. The toolkit not only enhances the design process but also aids designers in critically reviewing and discussing design decisions. By incorporating critical reviews, it enables the ideation and evaluation of design solutions and the identification of areas for improvement. Finally, it addresses the existing gap in the automotive industry: A systematic tool or approach to effectively address the development of driving automation from a human-centric perspective which clarifies cognitive processes and drivers' needs in the interaction with a DAS.

(iii) *This thesis advocates for a shift in perspective—a Design for Perception mindset. It emphasizes the human-centric approach necessary for the successful implementation of Driving Automation Systems.*

By understanding the driver as part of a joint cognitive system with the vehicle, this approach aligns the objectives of developers, designers, strategists, regulators, and, most importantly, drivers. The Design for Perception mindset enables a JCS perspective by understanding the cognitive demands placed on the driver, when interacting with a DAS, and recognizing that cognition is not confined to the individual, but distributed between the driver, the vehicle, and the environment in which the collaboration takes place. Thus, the Design for Perception toolkit provides a systematic approach to exploring solutions, identifying user perspectives, and evaluating design decisions driven by a human-centric perspective of driving automation. It acts as common ground, fostering collaboration and facilitating the development of DAS that aims at facilitating a safe and enjoyable driving experience to users of DAS.

In summary, this research has significantly advanced the understanding of driver perception and interaction with DAS. By providing a comprehensive theoretical model and a practical toolkit, this work equips practitioners with a valuable approach to the design of driving automation systems that reflects the driver's mental model of such systems from a human-centric perspective.

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