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User-Centered Development of Interaction Concepts for a Comfortable and Safe Use of Travel Time in the Context of Fragmented Automated Drives

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This work would not have been possible without you!

Abstract

Automated driving will fundamentally change the way car travel time is utilized. The possibility to engage in a variety of non-driving related activities (NDRAs) is perceived as a major user benefit. However, technical and regulatory restrictions will limit the availability of automated driving functions for the next decades. This will result in fragmented trips consisting of manual, assisted, and automated driving segments. The present thesis seeks to support users of such vehicles in using their drive time as comfortably and safely as possible. Different interaction concepts were developed to support users prior to a drive and during automated and assisted driving. The development followed the user-centered design process.

An introductory literature research reveals that users want to be involved in route planning when contrasted with fragmented drives. User requirements for a trip planning tool were derived in a workshop. Based on user needs like travel profiles, prioritization of NDRAs, and an easy-to-interpret visualization of route alternatives, a first prototype was designed, iteratively evaluated, and improved. Finally, a functional smartphone app was developed and evaluated in a usability study. Besides good usability and a high level of intention to use the app, users were able to plan a drive in a short amount of time. Furthermore, the user requirements were highly fulfilled. In addition to the pre-drive phase, the automated driving phase was investigated. During automated driving, NDRAs will be performed on different devices and objects. To prepare users for interruptions caused by transitions to manual or assisted driving, peripherally visible concepts were developed to communicate the remaining time in automated driving in a device-independent and non-interruptive manner. Therefore, a light-emitting diode (LED) stripe was mounted at the bottom of the windshield. In a set of two driving simulator studies, the developed concepts were evaluated positively. However, remaining time estimates will be subject to uncertainty, e.g., due to changing traffic or weather conditions, updated infrastructure information, or unforeseen route changes. Thus, a concept to communicate time budget uncertainties was developed in a small-scale user study. However, the concept using the well-known mobile phone connection icon to convey time budget prediction confidence was rated too complicated in another driving simulator study. Finally, the assisted driving phase was investigated. Users are known to quickly disengage from the monitoring task and rather engage in NDRAs, especially when using a reliable assisted driving function. Thus, a concept to counteract this effect by displaying short motivating pop-up messages was designed in cooperation with usability experts. In a driving simulator study, it was shown to have positive effects on monitoring behavior but did not improve drivers' reactions to a silent system malfunction.

In summary, concepts that can support users in their use of drive time were developed and found to increase comfort and safety in the context of fragmented automated drives. For further implementation, the actual availability and prediction capability of automated driving systems need to be considered.

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Zusammenfassung

Ein bedeutender Vorteil des automatisierten Fahrens ist die Möglichkeit, die Fahrtzeit vielseitig nutzen zu können. Aufgrund von technischen und regulatorischen Einschränkungen wird es jedoch in absehbarer Zeit nicht darstellbar sein, eine komplette Fahrt von Start bis Ziel automatisiert zu fahren. Fahrten werden daher aus manuellen, assistierten und automatisierten Streckenanteilen bestehen. Die vorliegende Arbeit geht der Frage nach, wie eine solche Fahrt trotz dieser Einschränkung möglichst komfortabel und sicher nutzbar gemacht werden kann. Im Ergebnis der Arbeit stehen verschiedene, anhand des nutzerzentrierten Designprozesses entwickelte Interaktionskonzepte.

Nutzer wollen zukünftig in die Fahrtplanung auch bezüglich der Automation eingebunden werden. Um dies zu realisieren, wurden Nutzeranforderungen an ein Fahrtplanungstool im Rahmen eines Workshops erhoben. Es werden beispielsweise Reiseprofile, die Möglichkeit, eine fahrfremde Tätigkeit zu priorisieren, sowie eine einfache Visualisierung verschiedener Routenalternativen gewünscht. Daraus abgeleitet wurde ein erster Prototyp, welcher anschließend iterativ evaluiert und weiterentwickelt wurde, sodass schlussendlich eine funktionsfähige Smartphone-App entstand. Diese wurde in einer Usability-Studie bewertet und gegen die zuvor erhobenen Anforderungen abgeglichen. Dabei zeigte sich neben einer guten Usability und einer hohen Nutzungsabsicht auch eine schnelle Bedienung und ein hoher Erfüllungsgrad der Nutzeranforderungen. Weitere Lösungen für die Mensch-Maschine-Interaktion betreffen die automatisierte Fahrt. Während dieses Abschnitts werden fahrfremde Tätigkeiten auf unterschiedlichen Geräten und mit Hilfe verschiedener Gegenstände ausgeübt. Um Nutzer auf Unterbrechungen durch Transitionen zum manuellen und assistierten Fahren vorzubereiten, wurden peripher sichtbare Konzepte entwickelt, welche die verbleibende Zeit im automatisierten Fahrmodus geräte-unabhängig und unterbrechungsfrei über eine Lichtleiste in der Fensterwurzel kommunizieren. Diese Konzepte wurden in zwei Fahrsimulatorstudien von Nutzern als hilfreich bewertet. Da solche Restzeitschätzungen jedoch einer gewissen Unsicherheit unterliegen werden, wurde außerdem ein Konzept zur Kommunikation von Ungewissheiten entwickelt. In einer weiteren Fahrsimulatorstudie wurde es von den Probanden jedoch als schwer interpretierbar eingestuft. Als letztes wurde die assistierte Fahrt untersucht. In früheren Studien zeigte sich, dass sich Fahrer schnell von der hierbei notwendigen Überwachungsaufgabe abwenden. Ein Konzept, welches diesem potenziell gefährlichen Verhalten durch kurze, motivierende Pop-Up-Nachrichten im Head-Up Display entgegenwirken sollte, zeigte in einer Fahrsimulatorstudie positive Effekte. Insgesamt konnten somit in der vorliegenden Arbeit Konzepte entwickelt werden, welche die Nutzung der Reisezeit im Kontext einer fragmentierten automatisierten Fahrt komfortabler und sicherer machen können. Für die weitere Umsetzung müssen jedoch insbesondere die tatsächliche Verfügbarkeit und Vorhersagbarkeit der Automation betrachtet werden. Zudem sind weitere positive Effekte des Fahrtplanungstools auf das Verhalten von Nutzern während einer Fahrt denkbar, hierfür sind jedoch weitere Untersuchung nötig.

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Abbreviations

ADS	Automated Driving System
ALD	Ambient Light Display
AMC	Affective Message Concept
AV	Automated Vehicle
BEV	Battery Electric Vehicle
CID	Central Information Display
DDT	Dynamic Driving Task
DMS	Driver Monitoring System
HCD	Human-Centered Design
HD	High Definition
HMI	Human Machine Interface
HUD	Head-Up Display
IC	Instrument Cluster
LED	Light Emitting Diode
LiDAR	Light Detection and Ranging
LoA	Level of Automation
NDRA	Non-Driving Related Activity
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
Radar	Radio Detection and Ranging
RtI	Request to Intervene
TUM	Technical University of Munich
UCD	User-Centered Design

1 Introduction

With a recent change of regulations by the United Nations Economic Commission for Europe (UNECE, 2022), automated driving has become one step closer to reality. A reality where drivers do not need to drive but can spend their travel time reading, working, relaxing, and with many other activities. Unlike currently available driver assistance systems, automated driving will not only support drivers in parts of the driving task but replace the driver and thus allow him/her to take hands off the steering wheel and eyes off the road (SAE International, 2021a). With this step forward in legislation, automated driving will become more widely available and its projected advantages will become more prominent. For decades, the effective use of travel time has been an exclusive benefit for passengers of busses, planes, and especially trains. Consequently, only 13% of train travelers think about their travel time as waste (Susilo et al., 2013) but 46% of car drivers consider their time as lost (AutoScout24 GmbH, 2011). Consequently, the ability to perform various non-driving related activities (NDRAs) has the potential to increase travel comfort and is perceived as a key advantage of automated driving (König & Neumayr, 2017). Naujoks et al. (2017) highlight the possibility of NDRA engagement as an important factor for acceptance and thus market success of automated driving functions. Moreover, the possibility to engage in productive NDRAs (e.g., working, reading, and communication) leads to a more positive travel time evaluation when using the train (Susilo et al., 2013) and similar effects can be expected for automated driving. Thus, the market introduction of automated vehicles (AVs) can have a positive economic impact. Leech et al. (2015, p. 21) estimate a large benefit of up to 20 billion British Pounds to the UK economy, realized through using the freed-up time productively. Similarly, Kolarova et al. (2019) expect a higher value of travel time with the introduction of automated driving, especially for commuting trips.

However, both legal and technical constraints restrict automated driving availability and will continue to do so, some even say for the next decades (SAE International, 2017). The next step in development is expected to include vehicles that cannot drive automated from start to destination but only on certain sections of a given trip (Gräter et al., 2019). The availability of automated driving will depend on infrastructure (e.g., only on highways, but not in tunnels and construction sites), weather (e.g., no snow/ice and heavy rain possible), traffic conditions (e.g., only in traffic jams), and other factors (Gräter et al., 2019; Mercedes-Benz AG, 2022). The limited availability of future automated driving systems (ADS) will result in fragmented drives. This causes several challenges to the comfortable and safe use of travel time. Information on and control over the route planning process with regard to projected automation availability will need to be increased to ensure user satisfaction and acceptance (Hecht, Kratzert, & Bengler, 2020; Lehtonen et al., 2021). Present navigation systems allow users to find the shortest, fastest, or most scenic route (Google, 2022; TomTom International, 2022) and some original equipment manufacturers (OEMs) support customers of battery electric vehicles (BEVs) with additional information on charging stations, the calculation of efficient routes, and allow to state certain needs like the state of charge at the destination (Mercedes-Benz Group, 2021). With the ongoing market introduction of automated driving, users will want to make the most use of their travel time using the new possibilities an ADS promises. Thus, planning tools incorporating automation availability will become necessary to extend current navigation systems. During automated driving, users will engage in a wide range of different NDRAs (Hecht, Feldhütter, et al., 2020). Then, information needs focus especially on system status and time budget information (Hecht, Darlagiannis, & Bengler, 2020). To avoid interrupting users during their NDRA engagement and to prepare for transitions, the human machine interface (HMI) should communicate in a non-interruptive and device-independent way. Furthermore, drivers will have to limit their engagement in most NDRAs to automated driving segments (SAE International, 2021a). However, assisted driving can appear very similar to automated driving functions but requires the driver to supervise and be reactive to sudden events. However, past research has revealed increasing NDRA engagement during assisted driving, thus potentially counteracting the positive effects of such functions on safety (Boos et al., 2020). Thus, drivers will need to be supported to keep up with the monitoring task.

The overall goal of this thesis is the design of interaction concepts to address the described challenges resulting from fragmented automated drives. The focus is on supporting users of AVs in the comfortable and safe use of travel time. The approach is oriented towards the development of digital solutions including mobile applications and in-vehicle HMI components rather than the analysis of motivational aspects or behavioral planning. Nonetheless, this work follows the user-centered design (UCD) process (DIN EN ISO 9241-210) with a close integration of users through iterative design and evaluation phases throughout the development process. The focus is on the consideration of first contact scenarios rather than on the investigation of long-term effects.

2 Theoretical Background

First, this chapter provides background on UCD. Next, the current state of sensors and vehicular communications is explained to understand the concept of automation availability and the capability of predicting it. Furthermore, the use of travel time as the central theme of this work is introduced: time use in the context of manual driving, often leading to distraction, is discussed and activities conducted in other modes of transportation are reviewed. Moreover, the user needs in connection with automated driving are evaluated and current research gaps in the field of travel time use are deduced. For a common understanding, the following terms are used throughout this thesis:

- (Dynamic) Driving Task (DDT)
  According to Geiser (1985), the manual driving task is split into three categories: primary task (navigating, maneuvering, and stabilization of the vehicle), secondary tasks (e.g., operating the indicators or wipers), and tertiary task (e.g., manipulating climate control or radio). According to SAE International (2021b, p. 9), the dynamic driving task includes the subtasks lateral and longitudinal vehicle motion control, monitoring the driving environment, object and event response execution, maneuver planning, and enhancing conspicuity (e.g., via lighting, signaling, gesturing).
- Non-Driving Related Activities
  With automated driving, NDRAs, become the new primary task. According to Petermann-Stock et al. (2013), NDRAs can be categorized according to their modality and demands:
    - Level 1: auditory (+ cognitive),
    - Level 2: visual + auditory (+cognitive), and
    - Level 3: auditory + visual + manual (+ cognitive).

  In the literature, the terms non-driving related tasks and secondary tasks are also often used (Hecht et al., 2019; Wandtner et al., 2018).
- Assisted and Automated Driving Systems
  In accordance with the definition by SAE International (2021a, p. 6), the term ADS refers to hardware and software systems that are collectively capable of performing the entire driving task. This term is valid for L3, L4, and L5 systems (see Chapter 2.2). Similarly, the term AV is used for vehicles capable of at least L3 automated driving. The term assisted driving refers to L1 and L2 systems that can perform only parts of the driving task.
- Operational Design Domain (ODD)
  According to SAE International (2021a), the ODD is defined as the "operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics" (p. 17). Thus, ODDs cannot necessarily be matched to stationary infrastructure elements or areas but may depend on other characteristics. ODDs are varied and multi-faceted and they are

necessary to accurately describe automated driving features (SAE International, 2021a, p. 33).

- Transition
  For this work, a transition is defined as a change from one LoA to another. Transitions can include both monitoring activities and motion control. They can be initiated by the system and by the driver and include both deactivation and activation.
- Human Machine Interface
  The place where information is transferred from the human to the vehicle and vice versa is referred to as the human-machine interface (HMI) (Bubb et al., 2015, p. 272). HMIs can be categorized using the HMI framework by Bengler, Rettenmaier, et al. (2020). This classification features dynamic, vehicle, infotainment, automation, and external HMI. While the dynamic HMI (dHMI) communicates both externally and internally (e.g., via trajectory), the external HMI (eHMI) is meant to communicate the vehicle's intention explicitly to other road users. According to Bengler, Rettenmaier, et al. (2020), the vehicle HMI (vHMI) shares conventional information about the vehicle's condition, whereas the infotainment HMI (iHMI) offers additional interfaces for NDRAs. The automation HMI (aHMI) is meant to communicate the system status as well as the current and future activities of the ADS. Although this work revolves around NDRAs, the concepts developed can be assigned to the aHMI, since the focus is not on creating physical space for the processing of NDRAs but on organizational aspects surrounding the possible execution of these activities in connection with the ADS (Bengler, Rettenmaier, et al., 2020).

2.1 User-Centered Design

UCD has its origins in the work of Norman and Draper (1986). However, user orientation already started to achieve attention in product development in the 1940s (Rothstein & Shirey, 2004). UCD is generally characterized by an integration of the users' perspective in all stages of a design process and by the iterative execution of processes (DIN EN ISO 9241-210). The approach relies upon the application of usability knowledge and techniques to make interactive systems more usable (DIN EN ISO 9241-210). Research has acknowledged the integration of users in the product development process as leading to more efficient, safer, and easier-to-use products with higher user experience (DIN EN ISO 9241-210).

Although a distinction can be made between UCD and human-centered design (HCD), the terms are often used interchangeably (DIN EN ISO 9241-210). Moreover, expressions like human-computer interaction (HCI), user experience (UX), usability, and interaction design are used in a similar context (Da Silva et al., 2011). While HCD aims to include all humans as possible users, UCD focuses on a target audience (DIN EN ISO 9241-210). According to Locke (2021), targeting all users requires the inclusion of a wide range of users to uncover every imaginable need throughout the process to design accessible and inclusive outcomes. Furthermore, HCD and UCD are linked to the design thinking approach (Burmester, 2022). However, according to Burmester (2022), design thinking is focused on the development and early evaluation of visions and creative approaches and starts at an earlier stage and with a more general approach than HCD and UCD. In 1999, the ISO Standard 13407 on the "Human-Centered Design Processes for Interactive Systems" was first published (DIN EN ISO 9241-210). After years of refinement, today's ISO 9241-210 is the norm for HCD principles and activities throughout the life cycle of computer-based interactive systems. It is described as human- rather than user-centered as it also focuses on a set of stakeholders who are usually not regarded as users.

HCD is an iterative process that has to be planned first (Figure 2-1). Then, it is necessary to understand the context of use by describing users and other stakeholders and their characteristics and goals as well as the system's surroundings. Thereby, information on problems, expectations, and restrictions is gathered. Next, user requirements shall be specified based on the context of use, relevant guidelines, and organizational aspects. Based on the first steps, design concepts can be developed and evaluated. Concepts are refined and improved from step to step (DIN EN ISO 9241-210).

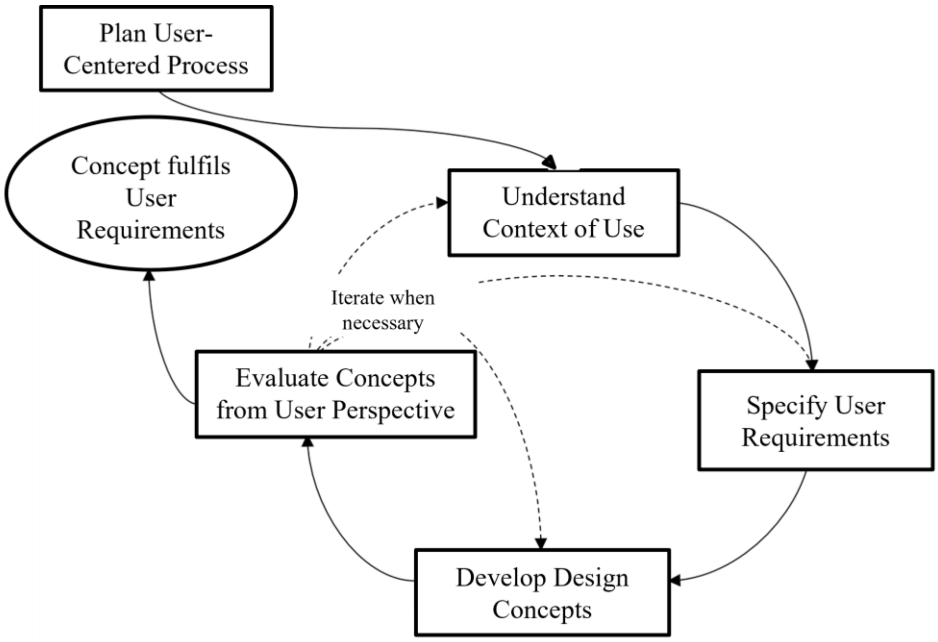

Figure 2-1 Overview of the HCD (DIN EN ISO 9241-210)

For the success of the UCD approach, the accurate use of methods is of great importance (DIN EN ISO 9241-210). In general, a growing and diverse mix of qualitative and quantitative methods is available (Rothstein & Shirey, 2004). For instance, personas, scenarios, use cases, surveys, focus groups, usability testing, heuristic evaluations, usage analytics, and eye-tracking are applied (Vora, 2021). In a survey by Vredenburg et al. (2002), iterative design, usability evaluation, task analysis, informal expert review, and field studies were found the most common methods among usability practitioners.

Despite the positive impact of UCD, there are still barriers to business implementation and its integration into agile development processes (Salah et al., 2014). A lack of time for upfront planning activities necessary for UCD, the difficulty of modularization and of prioritizing UCD activities, difficulties between developers and UCD practitioners, the effort required for usability testing, and a lack of documentation in agile processes were identified as the main challenges (Salah et al., 2014).

2.2 Automated and Assisted Driving

The development of automated driving functions is expected to yield manifold advantages: higher safety levels for road traffic, reduced congestion through more efficient use of traffic infrastructure, the provision of individual mobility to people currently not allowed or not able to drive, and more comfort through freed-up driving time (ACEA, 2019). There are several taxonomies classifying different LoAs according to the allocation of roles between user and system, e.g., by the German Federal Highway Research Institute BASt (Gasser, 2012) or the US-American National Highway Traffic Safety Administration (NHTSA, 2022). The SAE International, formerly known as the Society of Automotive Engineers, has published the standard J3016 which is the industry's most-cited taxonomy

(SAE International, 2021b). It distinguishes six different levels ranging from no (L0) to full driving automation (L5; Figure 2-2).

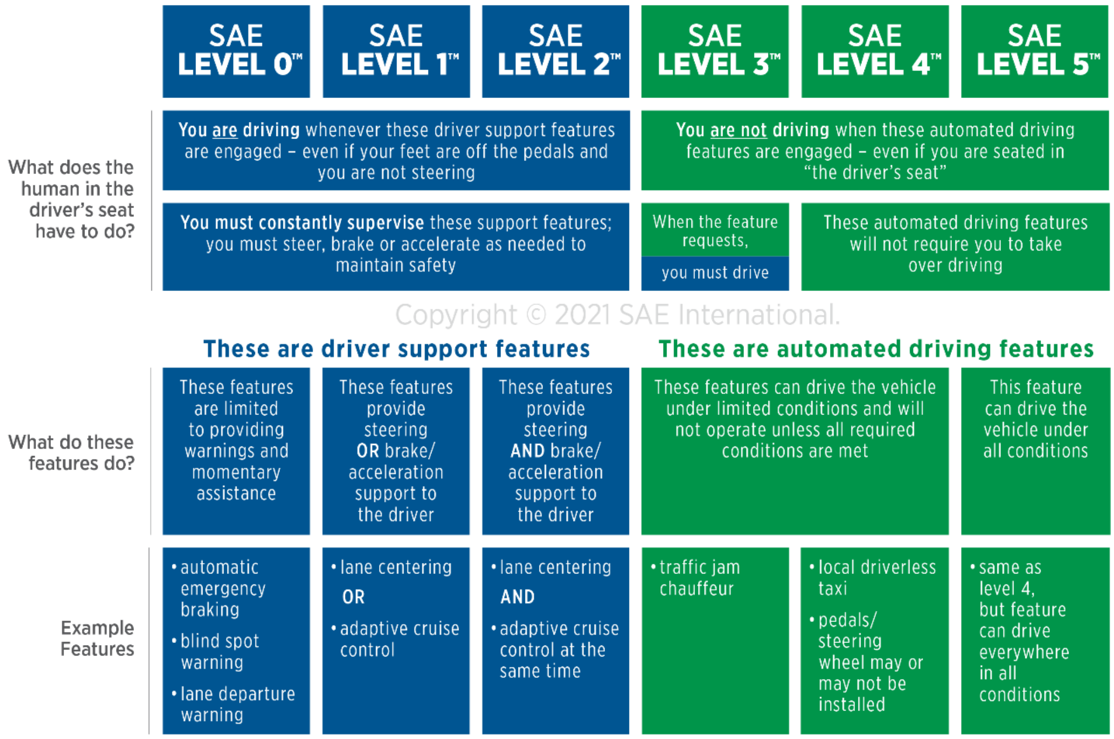

Figure 2-2 SAE J3016 Levels of Automation (SAE International, 2021b)

The LoAs L1 and L2 refer to cases in which the driver continues to perform parts of the driving task while the assistance system is active. Starting from L3, the system performs the entire driving task within a specific area, the ODD. The user needs to be receptive to system-initiated requests to intervene (RtI) but no longer needs to monitor the system. With L4, the ADS additionally takes over the fallback feature to achieve a minimal risk condition (if the user fails to respond). Lastly, L5 automation is capable of sustained and unconditional performance of the driving task (SAE International, 2021a). In contrast to the SAE International (2021a) and other rather technical taxonomies, BASt (2021) has recently published a taxonomy of only three levels: First, there is the assisted mode, where the system supports the driver in parts of the driving tasks, but the driver is fully responsible and needs to supervise the system at all times. Second, in the automated mode. The driver can engage in NDRAs but needs to be ready to take over manual control with a sufficient time budget. Third, there is the autonomous mode. The system is capable of driving throughout a given trip and passengers do not have a driving task at all.

2.2.1 Automated Driving Technology

As the availability of automated driving functions and its prediction is a key component of the present work, this chapter provides an overview of the current technology necessary to realize ADS, as well as its capabilities and limitations. From a functional perspective, there are four primary functional blocks in an ADS (Figure 2-3)

(Velasco-Hernandez et al., 2020). In the perception stage, the main goal is to receive data from sensors and other sources to generate a representation of the vehicle's status. In the planning and decision stage, the ADS receives external information like a goal or a travel mission, as well as traffic information and map updates, to develop a long-term and a short-term plan. These plans are then executed in the motion and vehicle control stage. Lastly, all aspects of the vehicle are monitored in the system supervision stage. A malfunctioning of hardware or software should not result in any harm to people, environment, or property (Velasco-Hernandez et al., 2020).

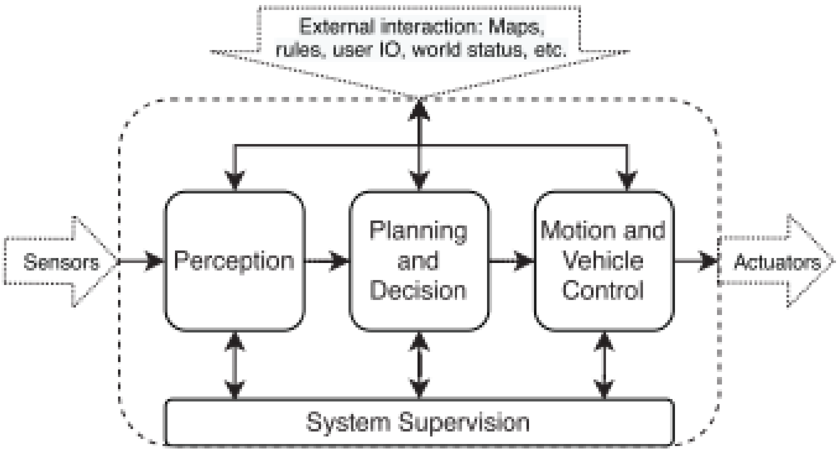

Figure 2-3 Functional architecture for an ADS (Velasco-Hernandez et al., 2020)

From a technical perspective, an ADS consists of hardware and software components to realize the functional blocks (Velasco-Hernandez et al., 2020). Sensors can be categorized into proprioceptive and exteroceptive sensors and are key components for automated driving (Yeong et al., 2021). A combination of three principal sensor technologies for exteroceptive perception is necessary to sense the surroundings of the ego-vehicle (Marti et al., 2019): First, cameras are essential for object detection, such as vulnerable road users, traffic signs, and other objects on the road and surroundings (Marti et al., 2019). Multiple cameras can be used to retrieve depth information (Marti et al., 2019). Besides the wide range of information, cameras are advantageous due to their relatively low costs (Marti et al., 2019; Yeong et al., 2021). However, varying light and visibility conditions complicate the implementation of artificial vision algorithms (Marti et al., 2019). Moreover, scenes with a high dynamic range (dark and strongly illuminated areas in the same frame, e.g., when entering or exiting a tunnel) can cause a loss of information (Marti et al., 2019).

Second, radar (Radio Detection and Ranging) sensors are used. They emit electromagnetic waves that are reflected on objects. Based on their round-trip time, distance can be determined (Y. Zhang et al., 2021). Unlike camera-based systems, radars work independently of light and weather conditions and are reliable and precise (Yeong et al., 2021). A limitation of the technology is the angular resolution that restricts the ability to separate distant targets (Marti et al., 2019). Furthermore, different target reflectivity makes it difficult to process and interpret radar data, meaning that e.g., metals amplify radar signals, but materials like wood do not reflect them (Marti et al., 2019). This can cause false positives (detection of a non-existing object) and false negatives (not detecting an actual object) (Marti et al., 2019). Furthermore, radar sensors depend on a precise mounting position and orientation, as any angular misalignment could have fatal consequences for the operation of the vehicle (Rohde & Schwarz, 2022).

Third, LiDAR (Light Detection and Ranging) technology has continuously evolved over the last decades and is one of the core perception technologies for AVs (Yeong et al., 2021). Contrary to radar, LiDARs emit pulses of infrared beams or laser light which reflect off target objects. These reflections are detected and the round-trip time is used to calculate the distance to objects (Marti et al., 2019). Typically, LiDARs used in the automotive industry make use of an array of emitters to generate a 360° 3D point cloud representing the environment (Marti et al., 2019). LiDARs are as good as radar for distances and relative speeds, but deliver a much higher accuracy for objects and angles and are thus able to display pedestrians and small objects in 3D (Wildemann, 2022). A drawback associated with LiDAR systems is high costs, especially for high vertical resolutions (Marti et al., 2019; Wildemann, 2022). Furthermore, dark and specular objects can appear invisible to LiDARs, and small objects are difficult to detect (Marti et al., 2019). Moreover, near-infrared LiDARs commonly used in the automotive sector are affected by rain and fog (Marti et al., 2019; Yeong et al., 2021). LiDAR sensors do not provide color information (Yeong et al., 2021).

To sense the vehicle state, also proprioceptive sensors are relevant for automated driving (Velasco-Hernandez et al., 2020). Position, movement, and odometry information is gathered using sensors like Global Navigation Satellite Systems, Inertial Measurement Units, Inertial Navigation Systems, and encoders (Velasco-Hernandez et al., 2020). Furthermore, high definition (HD) maps are highly accurate and detailed 3D maps that provide globally referenced road networks and, in contrast to conventional maps, lane-level accuracy including landmarks or the whole surrounding environment to estimate the current vehicle position (R. Liu et al., 2020; Mihalj et al., 2022). According to Mihalj et al. (2022), HD maps deliver redundancy for onboard sensors, extend their field of view and allow more precise path planning. They can be provided via the cloud or can be stored directly within a vehicle (Mihalj et al., 2022). Cloud solutions are updated via crowdsourcing, which uses data from public and private vehicles automatically and thus delivers real-time information about the road and traffic ahead (Tchuente et al., 2021). However, generating HD maps requires a large effort; thus, HD maps currently tend to be restricted to research purposes (Mihalj et al., 2022).

The overall performance of an ADS is largely influenced by the chosen sensor setup (Fayyad et al., 2020). It can be improved by using different modalities (visual, infrared, radio waves) operating at different ranges and bandwidths and by incorporating the outputs of each sensor in a fused output to overcome the particular sensors' shortcomings and thus improve the efficiency and reliability of the overall system (Fayyad et al., 2020). Thus, multi-sensor calibration and fusion are important fields of research (see Fayyad et al. (2020) and Yeong et al. (2021) for an overview). Sensor fusion integrates data from multiple sensing modalities to reduce detection uncertainties and develop a consistent model to perceive the surroundings accurately in various environmental conditions

(Fayyad et al., 2020). As the different sensors used in AV systems produce a large volume of data and require a complex computational pipeline with multiple servers, a very high amount of computing and electrical power is necessary and the resulting cost is an important barrier to automated driving's market penetration (S. Liu et al., 2017).

While in L2 systems, the driver is still responsible, L3 to L5 systems need to be highly reliable. However, current infrastructure, originally designed for human perception, can lead to recognition failure by ADS due to ambiguous traffic signs, design patterns, insufficiently maintained infrastructure, and non-harmonized appearances of traffic signs and road markings (Mihalj et al., 2022). High reliability is supposed to be achieved by sensor redundancy, e.g., through the aforementioned sensor fusion, digitalization of the road network, vehicular communication (V2X), and HD maps (Mihalj et al., 2022). According to Mihalj et al. (2022), road infrastructure and vehicular communication play an important role in achieving the desired level of reliability. Vehicular communication is a collection of different communication types such as vehicle-to-pedestrian (V2P), vehicle-to-network (V2N), vehicle-to-vehicle (V2V), and vehicle-to-infrastructure (V2I). V2N (sends and streams information from the cloud) and V2I (communication with infrastructure) are of high importance, e.g., to communicate traffic light states, road works, road obstacle objects, congestion and queue warnings, as well as offering merging support, and communicate adverse weather (PIARC, 2021). However, high data precision and data transfer rates, as well as low latency are required (Mihalj et al., 2022). Different vehicular communication protocols are used, but high vehicular densities still pose a threat to performance for short-range communication (Mihalj et al., 2022). For long-range communication of around 2000 m, cellular communication is used. However, 4G and LTE do not fulfill latency and speed requirements (Mihalj et al., 2022). This is improved with 5G, that is, however, still rather restricted in its availability (Mihalj et al., 2022).

2.2.2 Legal Situation and Market Readiness

Market-available L1 and L2 systems are in accordance with current regulations based on the Vienna Convention on Road Traffic from 1968; the driver is liable for potential accidents (Gasser, 2012). The first L3 system available in Germany is the Mercedes Drive Pilot, available for purchase since 2022 (Duff, 2022). This became possible with amendments to the Road Traffic Act which entered into force in 2017 and 2021; these regulatory changes established the framework for L3 and L4 systems in Germany (BMDV, 2021). However, ADS like the Mercedes Drive Pilot are still limited to highways and driving speeds of up to 60 km/h. Furthermore, automated lane changes are not yet covered (BMDV, 2021). Moreover, Mercedes' system requires high traffic densities, lead vehicles, and can only be operated during the daytime (Mercedes-Benz AG, 2022). It does not work in tunnels and construction sites and only with temperatures above 3°C and dry surfaces. Furthermore, lane markings are necessary, and highways need to be saved on an HD map (Mercedes-Benz AG, 2022). A regulatory extension of the maximum speed for ADS for passenger cars and light-duty vehicles up to 130 km/h on motorways is expected for 2023 and will additionally allow lane changes (UNECE, 2022).

Besides market available systems, several test and research projects are currently ongoing, e.g., by Waymo in California (C. Metz, 2022), GM Cruise in San Francisco (Herger, 2021), and Lyft Motional (Hyundai + Aptiv) in Las Vegas (Hawkins, 2022). Despite the progress of ADS in the US, routes in US cities are usually less complex than in European and Asian cities, the weather is more predictable, and pedestrians are few (Boggs et al., 2020). In general, the introduction of automated driving functions to urban areas is more challenging than on highways. The variety of different road users including bicyclists, pedestrians, and other manual and automated driving vehicles, the diversity of infrastructure elements such as narrow lanes, complex intersections, and difficult lane marking quality make it hard for AVs to reliably act in the environment (Capallera et al., 2019). Test projects for ADS in complex European cities can rather be seen in approaches for shuttles operating within limited ODDs, e.g., by the technology companies EasyMile, Baidu, or Navya (Iclodean et al., 2020). In conventional passenger vehicles, there are L2 systems that work in urban areas (see e.g., Kim et al. (2022)) and research projects are aiming at introducing L3 and L4 for cities (e.g., @CITY (2018)). However, according to a survey by SAE International (2017), industry experts do not expect L5 vehicles to become widely available before the 2050s. In line with this, Gräter et al. (2019) state that the availability of L5 private vehicles on all public roads is "not yet foreseeable" (p. 15).

To overcome deficits encountered with current ADS and consequently help AVs through difficult situations they cannot handle on their own, remote control solutions became an important topic in research and industry (T. Zhang, 2020). Furthermore, safety approval of ADS is still under discussion and valid proof of automation safety remains challenging. Present approval methods are not economically and practically feasible (so-called approval trap, Winner (2015)). Thus, research is looking into virtual testing of ADS (Dona & Ciuffo, 2022), as well as into approaches considering the entire system of humans, machines, and other road users from a risk assessment perspective using tools like the Functional Resonance Analysis Method (Grabbe et al., 2020).

2.2.3 Transitions

In L2 driving, the driver is continuously required to monitor the driving environment, the system performs longitudinal and lateral vehicle motion control. In case of system or vehicle malfunctions, the driver is expected to intervene immediately and perform the entire driving task (SAE International, 2021a, p. 25). Past human factors research has focused on both silent malfunctions (without notice, e.g., Boos et al. (2020), Feierle et al. (2021), Pipkorn et al. (2021)) or communicated take-over situations (with short time budget; e.g., Naujoks et al. (2015)).

In L3, the driver is called fallback-ready user who is receptive to RtIs and needs to respond by performing the manual driving task in a timely manner (SAE International, 2021a, p. 26). Unlike L1 or L2 driver support features, L3 (and L4) systems are designed to monitor and enforce their ODD limitations while engaged to prevent engagement or operation outside their ODD (SAE International, 2021a). The transition to manual is seen as crucial for the safety and comfort of L3 automation and consequently past human factors research has heavily focused on non-predictable transitions in L3 automation (see

B. Zhang et al. (2019) for an overview). Take-over performance is quantified in timing aspects (take-over time, time-to-collision) and qualitative measures (maximum lateral and longitudinal acceleration) (Gold & Bengler, 2014). Furthermore, industry and research have investigated driver state and situational aspects influencing take-over performance (see B. Zhang et al. (2019) for an overview), as well as approaches to quantify the driver state (see Hecht et al. (2019) for an overview), and the design of HMI concepts for safe, efficient, and comfortable transitions (e.g., Petermeijer et al. (2017)). Furthermore, the influence of different NDRA characteristics on drivers' ability to regain manual control was investigated in many studies (B. Zhang et al., 2019).

In L4, when approaching an ODD (or in case of an ADS failure), the driver is prompted to take over the manual driving task if a sufficient time budget is available. In case of missing interventions by the driver, the vehicle performs a maneuver to achieve a minimal risk condition. The minimal risk condition is defined as a "stable, stopped condition in order to reduce the risk of a crash when a given trip cannot or should not be continued." (SAE International, 2021a, p. 15)

2.2.4 Automation Availability and Prediction

Assisted and automated driving systems function within their specific ODD. Based on the ODD, several driving automation system features can be available during a given trip. Consequently, the ERTRAC working group "Connectivity and Automated Driving" pictures fragmented drives to be realized in the 2020s (Gräter et al., 2019, p. 13). Figure 2-4 visulizes an imaginary drive from Garching to Lake Starnberg. The exemplary ADS only becomes available on the highway, the "first mile" needs to be driven manually. In addition, a transition to manual or assisted driving is necessary when changing the highway. Furthermore, ADS availability is limited due to a construction site and adverse weather. During the final part of the drive on rural roads, the ADS is not applicable.

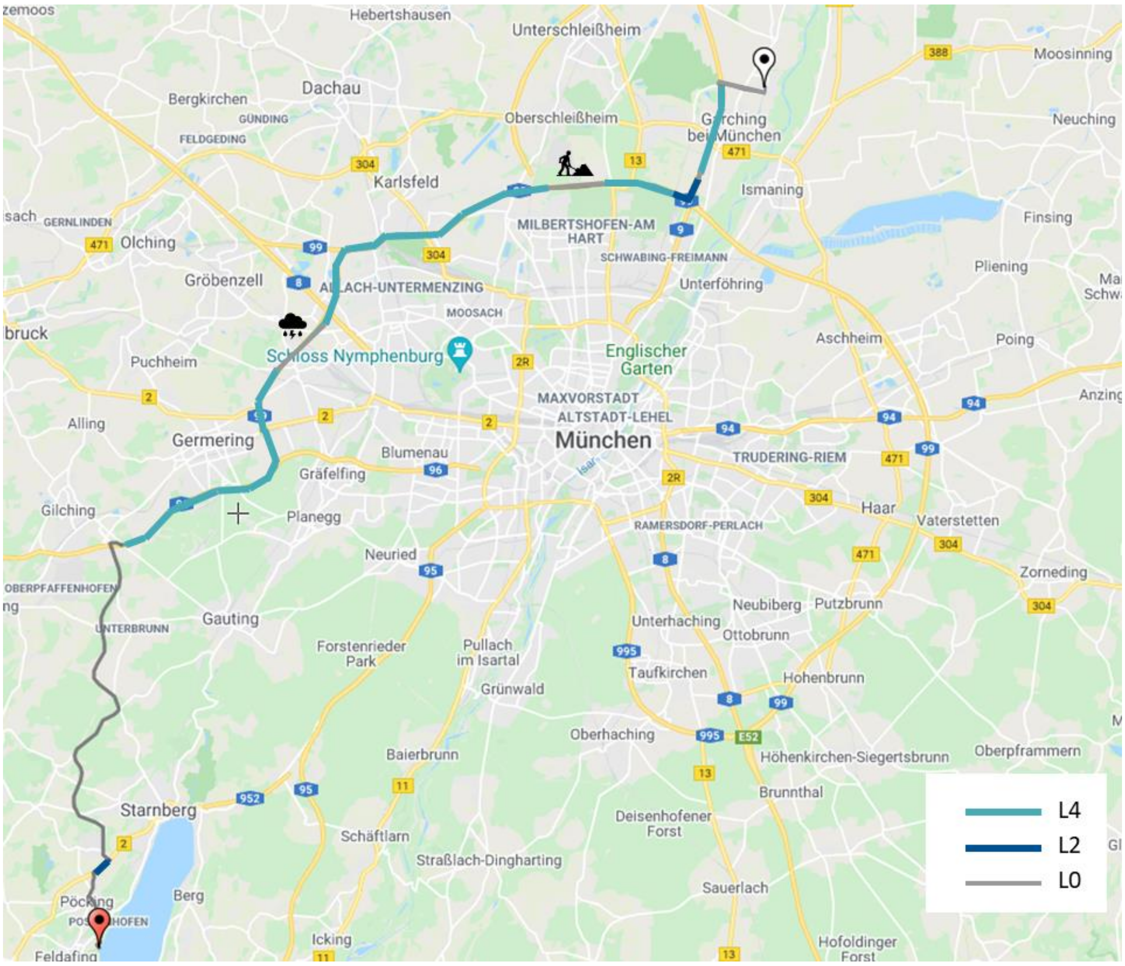

Figure 2-4 Example of a fragmented drive with manual, assisted, and automated driving segments (Google Maps, editing by author)

ADS monitor their ODD in order to adapt longitudinal and lateral control in response to infrastructural and environmental requirements and to eventually ask the driver to take over the execution of the driving task if the requirements of the DDT are about to leave the ODD of the function (SAE International, 2021a, p. 28). Transitions can be predicted based on infrastructure information (e.g., highways, tunnels, low radius curves), vehicular communication, and weather forecasts (see Chapter 2.2.4). However, as these information sources include uncertainties, such predictions will be prone to errors. In case of sudden unforeseeable events (e.g., defective vehicle in a standstill on ego lane, unknown construction sites, hard- or software issues, sudden adverse weather events) the ADS will request the driver to take over manual control or execute a minimal risk maneuver (see Chapter 2.2.3). According to Holländer and Pfleging (2018), the majority of transitions will be predictable. This assumption is supported by Capallera et al. (2019) who have analyzed owner manuals of market-available L2 systems: most limitations in longitudinal and lateral control stem from road (e.g., shape and slope) and lane (lane markings and road surface) issues, followed by environment (weather, temperature), external human factors (behavior of humans outside the ego vehicle), vehicle alteration (obstructed or damaged sensors, unauthorized modifications), and obstacles (static or mobile objects on the road). Currently, the most common causes for disengagements among vehicle companies testing in California are planning discrepancies, hard-/software discrepancies, perception discrepancies, environmental/other road user, and control discrepancies (Boggs et al., 2020). According to Boggs et al. (2020), the number of disengagements is higher on streets/roads than on freeways/highways.

2.2.5 Summary and Implications

As the technology for assisted and automated driving systems is evolving, more driverless test fleets and shuttles run on closed or public streets and more assistance and automation systems become available in conventional passenger vehicles. However, legislation and technical restrictions lead to limited ODDs. For privately owned vehicles, driving fully automated on a given trip from start to destination is in the far future. Fragmented drives with manual, assisted, and automated driving in the course of a trip are the most likely scenario. Infrastructure elements can predict the availability of automated driving, but also weather forecasts, traffic information, and V2X information can help estimate automation availability.

2.3 Use of Travel Time

The possibility of being able to use travel time freely is an important benefit for train travelers (Ettema & Verschuren, 2007; Lyons et al., 2007; Wang & Loo, 2019). Consequently, the introduction of ADS has the potential to change the way car travel time is utilized. While in manual and assisted driving, only a limited range of activities other than driving is legal and distraction has consequently been an important field of research for decades (Ranney et al., 2001; Young & Regan, 2007), the driver becomes a passenger in an AV. In the following, past research on driver distraction in the context of manual and assisted driving is briefly summarized, and users' expectations of NDRA engagement in automated driving are tackled, as well as activities during train rides.

2.3.1 Travel Time as Driver

Driver distraction and its causes and consequences have been an issue in the context of manual driving for decades (see Young and Regan (2007) for an overview). Nonetheless, there is no universally agreed-upon definition of driver distraction (Young & Regan, 2007). During manual driving, drivers engage in a variety of activities like talking to other passengers, using wireless devices like mobile phones or tablets, drinking, eating, and manipulating in-vehicle infotainment and navigation systems (Neale et al., 2005). According to Young and Regan (2007), the engagement in tertiary tasks can be explained by the fact that many aspects of the driving task become automated with experience and that drivers are often capable of dividing their attention between concurrent tasks without serious consequences. Furthermore, drivers can adapt their driving to meet the demands of the driving environment, for instance by decreasing speed, increasing distance to surrounding traffic, and changing attention allocation (see Young and Regan (2007) for an overview). However, any activity that competes for drivers' attention has the potential to degrade driving performance. When drivers no longer allocate sufficient attention to the driving task, serious consequences for road safety can be the result (Young & Regan, 2007). According to Young and Regan (2007), the potential of an NDRA to distract depends on numerous factors, including task complexity, current driving demands, driver experience and skill, and the willingness of the driver to engage in the task. NDRAs are known to impair driving performance on several safety critical measures, e.g., impaired lateral and longitudinal vehicle control, increased reaction times in critical events, as well as an increased risk of being involved in a vehicle crash (Drews et al., 2009; Neale et al., 2005).

In assisted driving, drivers are still considered an integral part of the driving task. However, assisted driving can appear very similar to automated driving, especially in the case of reliable H-off systems. With such systems, drivers tend to disengage from their monitoring task easily and rather engage in NDRAs (Banks et al., 2018; Boos et al., 2020; Llaneras et al., 2013). However, decreasing visual attention to the road ahead was found to increase crash probability since the likelihood of appropriate intervention in critical scenarios is significantly reduced (Boos et al., 2020; Louw et al., 2019). In line with that, Mole et al. (2020) predict a high rate of unsafe outcomes in plausible L2 failure scenarios. Like in manual driving, drivers adapt their NDRA engagement to the situation: Naujoks et al. (2015) found a strong relation between task execution and driven velocity; tasks were mainly conducted at lower speeds.

2.3.2 Travel Time as Passenger

Research on travel behavior modeling has widely assumed that travel is a source of disutility that individuals seek to minimize (Susilo et al., 2013). However, more recent investigations revealed that engagement in activities during travel can make trips more enjoyable and productive: next to listening to music, also working/studying (Ettema & Verschuren, 2007; Lyons et al., 2007) and entertainment (Wang & Loo, 2019) positively influence the value of travel time. However, this depends also on the trip's purpose (Wang & Loo, 2019). According to Mokhtarian and Salomon (2001), the positive utility of travel time is thought to have three components: the act of travel itself, the utility of engagement in the activity at the destination, and the utility of activities that can be conducted while traveling.

With automated driving, there is a paradigm shift. Users are allowed to spend a longer time on NDRAs before switching to an interrupting task (e.g., taking over manual control). Consequently, the likelihood of NDRA engagement was found to rise with LoA (Llaneras et al., 2013; Naujoks et al., 2016). Based on a meta-analysis, Winter et al. (2014) predict an increase in task engagement by 261% from manual to L3 automated driving. Because the first L3 ADS has only recently been introduced (see Chapter 2.2.2), it can be helpful to take a closer look at passenger activities during train rides. Moreover, surveys, simulator studies, and first on-road studies were conducted to better understand drivers' NDRA engagement.

With the help of passenger observation, Pfleging et al. (2016) found the majority of subway passengers do nothing, read newspapers, talk to passengers, look out of the window, and read or type on the phone. In additional interviews, subway passengers answered to mainly text, talk to passengers, use social media, make use of phone apps, listen to music/radio, and do phone calls when taking public transportation. Similarly, in a survey by Thalys (2013), participants answered to preferably read newspapers and magazines, relax/do nothing, read a book, listen to music, sleep, play games, work, or watch a movie during long-distance train rides. Unsurprisingly, business travelers tend to work more, but read, relax, and sleep less (Thalys, 2013). To better understand what people will do in future ADS, Pfleging et al. (2016) also conducted an online survey. Participants answered that they will most frequently listen to music, talk to other passengers, watch out of the window, text, browse the internet, eat & drink, and do phone calls. Similarly, Fraedrich et al. (2016, p. 71) found gazing out of the window, conversing with other passengers, and relaxing to be most attractive based on an online survey. In line with that, listening to music/radio, talking to other passengers, and conducting phone calls were rated as the most likely activities in an online survey by Sommer (2013).

These activities appear similar to activities currently conducted during manual driving (see Chapter 2.3.1). Visually engaging activities were rated less appealing in surveys on future activities during automated driving. However, in simulator studies, Hecht, Feldhütter, et al. (2020) and Large et al. (2017) found participants to quickly begin with visually engaging NDRAs. Moreover, NDRAs were found more similar to activities conducted during train rides: reading an article or magazine, social networking activities, web-browsing, and watching movies (Large et al., 2017), respectively browsing the mobile phone, reading books and magazines, browsing the tablet, and watching videos (Feldhütter et al., 2018). Klingegard et al. (2020) were able to confirm these driving simulator study results in an on-road study using a Wizard of Oz L4 AV. Results show that drivers shift their attention to a great extent from the road to visually and cognitively demanding activities. Moreover, participants were able to perform the NDRA equally well as in an office. Thus, online surveys and interviews are possibly influenced by the lack of experience with automated driving. Hecht, Darlagiannis, and Bengler (2020) conclude that future activities conducted in AVs will be diverse, involve a large range of items (phone, tablet, book, food, drinks, etc.), and most of the conducted tasks will be visually engaging. Furthermore, the chosen activities will be prone to inter- and intra-individual differences and the choice of NDRAs during travel will be influenced by many factors: besides available time budget, additional passengers, vehicle interior design, users' age, and trip purpose will likely influence the attractiveness of NDRAs (Hecht, Feldhütter, et al., 2020; Large et al., 2017).

2.4 User Needs in the Context of Fragmented Drives

For this work, a drive is deconstructed into three parts: the pre-drive phase, the automated driving phase, and the assisted driving phase. In the following, resulting user needs and approaches to addressing them are investigated.

2.4.1 Pre-Drive

In general, human planning is hierarchical. It starts with a rough mental sketch of goals that should be achieved and is then iteratively refined into a detailed sequence of sub-goals and sub-sub-goals, down to the actual sequence of bodily movements (Tomov et al., 2020). Interdependent decisions about what to perform where, at what time, for what duration, with whom, and in what sequence lead to an activity schedule that impacts travel behavior (Doherty & Miller, 2000). From research on train travel, it is known that especially business travelers do advance planning. The longer the journey, the more likely people are to plan in advance. Moreover, the more people plan, the more they consider their time worthwhile (Lyons et al., 2007). According to Wandtner et al. (2018), also NDRA engagement is planned on a higher level.

To plan ahead, information is required. For specific use cases in the mobility sector, information and planning tools have been developed to improve user experience and user control. For instance, the French railway company SNCF supports travelers of the high-speed train TGV with information on the Wi-Fi quality during train rides with a map-based visualization (see Figure 2-5) (Chicheportiche, 2016). This allows users to plan their activities according to internet connection availability.

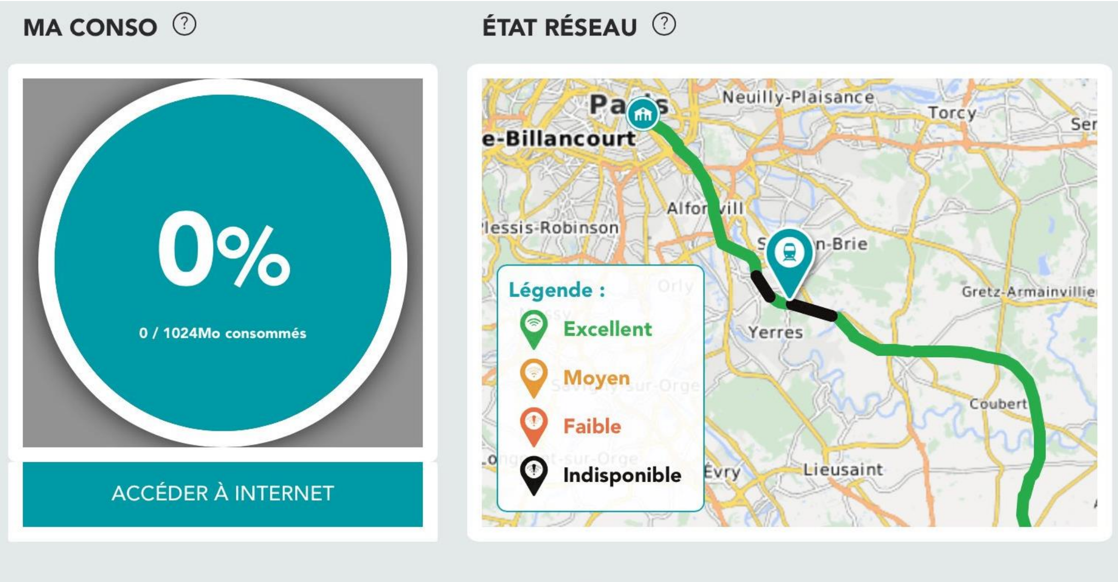

Figure 2-5 Overview of projected Wi-Fi quality during a TGV trip (Belkaab, 2016)

As a day is full of scheduling tasks next to route planning, other domains can also be incorporated into vehicle HMIs to ease day and work planning for users through a holistic approach. A first step can be seen in the integration of personal calendars, e.g., Tesla's Autopilot connects with the calendar to calculate the route to a meeting (Tesla, 2022) and BMW's Intelligent Personal Assistant automatically searches for parking lots at the destination, informs about traffic jams on the route, and reminds drivers to start their drives on time (BMW, 2018).

To improve user information, refining user control has been researched in recommender systems, a technology that proactively suggests items of interest to users based on their objective behavior or stated preferences (Pu et al., 2012). User control, defined as "the range of ways to manipulate the content" (IGI Global, 2022), can positively influence user satisfaction (Pu et al., 2012). Furthermore, perceived output quality is improved (Harper et al., 2015), cognitive load decreased, and user acceptance increased (Jin et al., 2018).

Current navigation systems for car drivers, no matter whether built-in or on mobile devices, already grant some possibilities for user control and advanced planning. The tools provide options such as finding the shortest or fastest route, or avoiding toll roads and ferries (Google, 2022; TomTom International, 2022). Another example of user information and increased user control is the improvement of current navigation systems for BEVs to deal with drawbacks of the technology (e.g., short range, long charging durations). For instance, Mercedes equips their vehicles with advanced navigation systems that are able to calculate the most energy-efficient route and automatically include charging stops (Mercedes-Benz Group, 2021). In addition, topography and temperature can be taken into account and the route is continuously updated during the drive (Mercedes-Benz Group, 2021). It is also possible to define a certain state of charge on arrival to include a buffer or to have enough battery capacity for a follow-up drive (Mercedes-Benz Group, 2021). Some apps and tools also include settings like the minimum amount of charging spots at a charging station, preferences regarding the amount and length of charging stops, exclude certain operators of charging stations, and search for restaurants or supermarkets close to the charging point (see Bönnighausen (2022) for an overview). In addition, some apps learn from users' preferences and automatically adapt their route suggestions (Bönnighausen, 2022). The need to further extend route planning for fragmented automated drives has been expressed by Hecht, Kratzert, and Bengler (2020) and Lehtonen et al. (2021): while the first revealed a positive attitude towards accepting longer drive durations in exchange for fewer transitions, Lehtonen et al. (2021) found that users are willing to accept longer travel times if this increases the share of automated driving.

2.4.2 Automated Drive

While previous research on the planning phase of a fragmented drive is limited, user information needs before and during an automated driving phase were already investigated. In line with findings on NDRA engagement, information needs during active ADS concern system status and time budget information, maneuvers, and environmental information, as well as navigation, speed, and speed limits (Beggiato et al., 2015; Feierle, Danner, et al., 2020; Hecht, Darlagiannis, & Bengler, 2020). Moreover, engaging in a visual NDRA was found to lower the importance of most information items, especially situation-related items like speed, maneuvers, and detected surrounding elements lose importance. Simultaneously, time budget information remains equally desired by participants, no matter if engaged in an NDRA or not (Hecht, Darlagiannis, & Bengler, 2020). Additionally, the importance of time budget information that helps to prepare for interruptions through transitions is highlighted by previous research on interruption effects. Transitions from automated to manual driving can interrupt the user in his primary activity, the NDRA. Interruptions were found to worsen primary task performance by additional time required to finish the primary task, by a higher load on the working memory, and through higher error rates (Altmann & Trafton, 2004; Edwards & Gronlund, 1998). Moreover, discomfort is induced by increasing subjectively experienced annoyance and anxiety (Bailey & Konstan, 2006). Especially when interrupting a complex task, the total workload is increased (Speier et al., 1999; Weigl et al., 2012). Also, it is known that interrupting requires self-control. However, human self-control capabilities are limited and decrease over time (Muraven et al., 1998). Thus, interruptions can lead to task perseveration (i.e., the continuation of the primary task), especially when engaged in complex tasks which are close to completion (Heath et al., 1999; Kivetz et al., 2006). Task perseveration in take-over situations can have negative effects on the take-over quality (Wandtner et al., 2018).

Due to the importance of time budget information, several studies have investigated ways of communicating the remaining time until a system limit. Richardson et al. (2018) evaluated both time- and distance-based predictive HMIs and found them to lower workload and higher acceptance and usability compared to a baseline HMI. Holländer and Pfleging (2018) found that not displaying a planned transition leads to lower usability scores. Wandtner et al. (2018) have revealed a positive impact of an overview of an entire drive with automated and manual driving segments on the ability to choose a suitable NDRA. However, if the predictive HMI element is not integrated into or displayed close by the NDRA, positive effects seem to diminish (Hecht, Kratzert, & Bengler, 2020). If time budget information is not directly or peripherally visible, the driver has to direct attention to the display and thus interrupts the primary activity or misses the information.

Furthermore, time budget predictions will be prone to changes, e.g., due to updated infrastructure, traffic, or weather information, as well as through route changes (see Chapter 2.2.4). The visualization of uncertainty information has been an important field of research in aviation (McGuirl & Sarter, 2006) and recommender systems (Shani et al., 2013). In addition, weather forecasts quantify the likelihood of rain in percent to convey the confidence of the forecast (Sillin, 2022). Moreover, communicating uncertainties has recently been implemented in the context of assisted and automated driving, e.g., to convey the confidence of an ADS to drive in a certain situation in automated driving mode (Beller et al., 2013; Helldin et al., 2013; Large et al., 2017). Even though these studies show promising effects of confidence displays, no approach enriches time budget information with prediction confidence.

2.4.3 Assisted Drive

While users can engage in a variety of NDRAs during automated driving, L2 assistance requires the user to monitor the system and surroundings. However, L2 and L3/L4 can appear very similar. Past research found that users increasingly neglect this obligation and engage in NDRAs instead (see Chapter 2.3.1). Thus, current L2 H-on and H-off systems use different driver monitoring systems (DMS) to ensure users' compliance with supervision requirements: H-on DMS are based on the steering wheel torque or capacitive sensors to detect drivers' hands on the wheel (Schweber, 2021a, 2021b). H-off systems use cameras to detect drivers' visual attention allocation (e.g., Cadillac (2022)). However, DMS are prone to misuse and can be bypassed (Alvarez, 2021; Bindley & Elliott, 2021).

The reasons for the observed violations were investigated by Boos et al. (2020). In a driving simulator study in the context of drives with both L2 and L3, reliance, physical tiredness, and higher attractiveness of NDRAs compared to the monitoring task were found central factors. Lack of mode awareness, i.e., the general knowledge of levels and currently engaged LoA, was not the main cause of the observed violations (Boos et al., 2020). It can be concluded that users are aware of their obligation but prefer to engage in NDRAs due to a lack of motivation and self-regulation. Potential countermeasures to such rule-breaking behavior were investigated in the past. Tice et al. (2007) proved that inducing a positive mood or emotion can help regain the capability of effective self-regulation. A common approach to implementing emotion regulation is to deliver information via facial expressions by using smiley faces. In a naturalistic driving study by Rattenbury (2020), the idea of emotion regulation via facial expression has been implemented with smiley faces on road speed signs and was found to decrease average speeds and the number of speed violators. Similarly, the Affective Intelligent Driving Agent by Williams et al. (2014) was found to promote safe driving behaviors and reduce cognitive load. Another approach to address driving safety is message framing. Different strategies of message formulation influence behavior adoption rates and their efficiency (Lewis et al., 2008). According to the protection motivation theory, a social cognitive model, the intention to engage in an activity is influenced by the cognitive response to maladaptation (e.g., speeding) and alternative behaviors (e.g., driving within the speed limit) (Maddux & Rogers, 1983). Glendon and Walker (2013) found anti-speeding messages based on the protection motivation theory to be of higher effectiveness than previously used messages in France. Chaurand et al. (2015) discovered gain-framed anti-speeding messages to be more efficient than loss-framed messages.

3 Objectives and Research Questions

The use of travel time is an important aspect for train travelers and mobility providers. For good reason, car drivers are currently restricted in their ability to utilize drive time. The introduction of automated driving opens new possibilities but also challenges for car manufacturers and users. The possibility to engage in a wide variety of NDRAs during automated driving is an essential advantage of such systems. However, current technical and legal limitations restrict automated driving functions to certain ODDs. Given infrastructure can be used to predict the availability of automated driving, but also weather forecasts, traffic and V2X information. Past human factors research has focused on different aspects of NDRAs but not on the support of travel time use. Thus, the central aspect of this thesis is to develop interaction concepts that support users in the context of fragmented automated drives with their comfortable and safe travel time use.

Based on the state of research, this work aims to answer the following research questions (RQs):

RQ1 (pre-drive): How can the predicted automation availability be integrated into the route planning process?

a. What are user needs concerning route planning?
b. How can these user needs be transferred in a route planning tool?
c. Does a route planning tool increase user control over the route planning process?

RQ2 (automated drive): How can the HMI for an ADS be supplemented with peripheral visibility of system status and time budget information?

a. Does peripheral visibility of time budget information increase usability, acceptance, and trust in automated driving?
b. What is the best way to visualize system status and time budget information peripherally?

RQ3 (automated drive): How can the HMI for an ADS be supplemented with uncertainty information?

a. Does offering additional information on the prediction quality of time budget information increase the subjective evaluation of the system?

RQ4 (assisted drive): How can drivers be supported in carrying out their monitoring task during L2 assisted driving?

a. Does adding pop-up messages in the HUD using message framing and affective elements help drivers refrain from NDRA engagement and improve the reaction to a system malfunction?
b. Does the additional information yield negative effects like increased workload or distraction?

4 Methodology

This work followed the HCD design approach (DIN EN ISO 9241-210) for the development of interactive systems for all three researched segments of a fragmented drive. However, as the focus is on users rather than on other stakeholders, the term UCD is used in the following.

4.1 Context of Use

Parts of this work were realized within the @CITY project. As this project aimed at introducing automated driving features for privately owned conventional vehicles in urban environments, the present thesis focused on evaluating the developed interaction concepts in city environments. Such complex conditions pose high demands to the perception, planning, and vehicle control capabilities of ADS. Thus, transitions are expected to occur more frequently than in highway conditions.

Based on the current and projected stage of technical and legal development (see Chapter 2), the following assumptions were formulated for this work:

- Fragmented drives: automated driving is available only on sections of a given route, not for a complete trip from start to destination.
- Predictable fragments: automated driving segments are mainly predictable, e.g., based on maps, weather forecasts, and V2X communication.
- Levels of automation: besides automated driving, vehicles will also feature manual and assisted driving.
- Conventional vehicle interior: vehicles are designed to be operated by an in-vehicle driver and are thus equipped with steering wheels and pedals.
- Malfunctions and transitions: During assisted driving, system limits and malfunctions may appear without any warning. During automated driving, there are sufficient time budgets and minimal risk maneuvers.

Users of future vehicles with assisted and automated driving functions are expected to cover a wide age range and include all genders. However, manual driving will still be necessary, the possession of a driving license and the unrestricted ability to do so is presumed.

4.2 Tools and Apparatus

Based on the UCD, several tools were chosen to fulfill the formulated research goals efficiently and effectively:

- Understand the context of use and user requirements:
    - Literature review
    - User workshop
- Develop design concepts:
    - Click dummies

  - Simple prototypes in reduced environments
  - Interaction concepts with a reduced feature set
- Evaluations from a user perspective:
  - Small-scale user studies
  - Expert evaluations
  - Driving simulator studies

Design and evaluations of interaction concepts were carried out depending on the development stage. Small-scale user studies and expert evaluations were part of the evaluation process, as five users are known to be good enough to uncover 85% of all usability issues (Nielsen, 2000). In the studies on assisted and automated driving phases (Hecht, Danner, et al., 2020; Hecht, Weng, Kick, & Bengler, 2022; Hecht, Zhou, & Bengler, 2022), driving simulator studies were conducted in a dynamic seat box at the Chair of Ergonomics at the Technical University of Munich (TUM). It was equipped with pedals and a steering wheel, three 55” ultra-HD monitors creating a 120° field of view, two displays for the side mirrors, and a 13” monitor behind the steering wheel to display the instrument cluster (IC). The IC displayed was based on the adaptive concept by Feierle, Bücherl, et al. (2020). Furthermore, the seat box featured a motion platform to induce pitch and roll motions and a LED stripe positioned on the dashboard. The latter was connected to the driving simulator software to display information depending on the current driving situation. The simulator was run with the software SILAB, allowing to create different driving environments, traffic flows, and levels of automation freely. In driving simulator studies where gaze behavior was assessed (Hecht, Weng, Kick, & Bengler, 2022; Hecht, Zhou, & Bengler, 2022), the head-mounted eye-tracking system Dikablis by Ergoneers was applied.

5 Summary of Publications

The present work is divided into three parts (Figure 5-1): first, the pre-drive phase is examined. Two publications (Hecht, Sievers, & Bengler, 2020; Hecht, Weng, Drexl, & Bengler, 2022) describe the iterative process of designing an app-based route planning tool for fragmented drives, taking the automation availability on a given route into account. The goal is to thereby enable users to plan a route according to their current needs. The final concept is evaluated in a usability study.

Two publications (Hecht, Danner, et al., 2020; Hecht, Weng, Kick, & Bengler, 2022) describe user information needs during the automated driving phase and how they can be addressed. The first paper targets the design of an HMI element to inform users of the available time budget and the system status in a non-interruptive and device-independent manner. Building upon previous research, different color-coded LED stripe concepts are iteratively developed and evaluated in two driving simulator studies. In the second publication, communication of time budget prediction uncertainties is tackled. Based on previous research on confidence displays, an HMI concept using the well-known mobile phone connection symbol is developed and evaluated in a driving simulator study.

The third part of this work addresses the assisted driving phase and the driver monitoring task (Hecht, Zhou, & Bengler, 2022). The goal is to design an HMI solution that motivates users to continue their supervision task. An HMI concept using message framing and affective elements is designed and assessed in a driving simulator study.

Figure 5-1 Outline of the present work

5.1 Investigating User Needs for Trip Planning with Limited Availability of Automated Driving Functions

Hecht, T., Sievers, M., & Bengler, K. (2020). Investigating User Needs for Trip Planning with Limited Availability of Automated Driving Functions. In C. Stephanidis & M. Antona (Eds.), *HCI International 2020 - Posters* (pp. 359–366). Springer International Publishing.

The objective of this work was to understand user requirements for a tool for route planning with regard to automation availability. To efficiently use the automated driving time, avoid unnecessary interruptions, and schedule activities in advance, a new feature to currently available route planning tools was suspected to become necessary. An initial literature research proved the general user need and the inexistence of such concepts at present. A participatory design workshop with two usability experts and three naïve users was conducted. This resulted in several user needs that were clustered into the two categories "user inputs" and "system responsibilities" (Table 5.1).

Table 5.1 User requirements for a route planning tool (Hecht, Sievers, & Bengler, 2020)

User inputs: the user would like to …	System responsibilities: the system should …
R1) … configure the general priorities for the current trip, e.g., on-time arrival or maximization of uninterrupted automated driving sections.	R7) … provide the user with a comparison of key data on the various route options, such as the arrival times or an overview of the available LoAs.
R2) ... set a minimum continuous period that a trip segment offering a certain automation level must last for it to be accounted for in the route planning process.	R8) ... provide the user with a reliable prediction on the available levels of driving automation throughout the trip.
R3) … set the uninterrupted completion of an important NDRA as an absolute priority irrespective of the consequences on travel time.	R9) … take real-time data into account to improve the accuracy of the predicted travel times and the available LoAs on various route options, such as data on traffic congestion, route closures, or weather conditions.
R4) … choose from a customizable selection of standard destinations with preconfigured trip priority settings.	R10) … adapt its general route planning behavior to match the user's overall, long-term preferences.
R5) … choose from a customizable selection of standard travel priority settings when selecting a destination.	R11) … adapt its trip-specific route planning behavior to best suit the user's current priorities, NDRA requests as well as mental and physical state.
R6) … invest as little time as possible in planning the trip while still finding the route that best suits their needs.	R12) … proactively warn the user about unusual circumstances affecting travel time or NDRA possibilities.
	R13) … always await the user's consent before changing the route during a trip, unless the user has given the system explicit permission to continuously optimize the route for a certain priority, such as achieving the shortest possible travel time.

While these findings confirm prior results obtained by Hecht, Kratzert, and Bengler (2020) and Lehtonen et al. (2021) on the importance of increasing user control in the route planning process of fragmented automated drives, they also form the basis a first lowfidelity prototype. This was designed for an in-vehicle touch navigation system using the wireframing tool Balsamiq. The prototype included user and trip profiles to save preferences for the route calculation and provided users with different route alternatives which can be visualized in an abstract manner to focus on the automation availability. It marked an intermediate state that needed to be iteratively evaluated and improved upon.

My personal contribution to this article included the definition of the research questions, processing and analysis of data, design of the Balsamiq prototype, writing of the manuscript, and involvement in the preparation and execution of the participatory design workshop.

5.2 User-Centered Development of a Route Planning App for Fragmented Automated Drives

Hecht, T., Weng, S., Drexl, A., & Bengler, K. (2022). User-Centered Development of a Route Planning App for Fragmented Automated Drives. In H. Krömker (Ed.), *Lecture Notes in Computer Science. HCI in Mobility, Transport, and Automotive Systems* (Vol. 13335, pp. 134–150). Springer International Publishing. https://doi.org/10.1007/978-3-031-04987-3_9

Based upon the first prototype described in the previous article, three small-scale user studies were performed to subsequently improve the route planning tool. First, the in-vehicle Balsamiq prototype was evaluated in a study with five naïve users and consequently transferred into a mobile phone format using the more elaborated tool Adobe XD. Two follow-up studies revealed further improvements, e.g., concerning the travel profile settings and the need for additional information. In consequence, a disclaimer was created to draw attention to possible deviations from planning and reality. Then, an Android app using the widespread software development kit Flutter was developed. With a link to google maps, the app allowed to calculate routes from and to every point in Germany. As no actual data on automation availability was public during the development process, the automated driving segments were randomly generated following certain rules. While some simplifications were necessary to ease the implementation (e.g., no intermediate stops and no exchange of start and destination), the app covers all relevant functions drafted in the final Adobe XD prototype. To eliminate errors that stem from the Flutter implementation or the limited functionality of the prototypes, an expert evaluation was conducted after the implementation phase. Once again, improvements concerning the visualization of automated driving segments, design simplifications, and help texts were derived from the three usability experts that were part of this study. Next, the fully functional mobile phone app was evaluated regarding the fulfillment of previously derived user needs, usability, acceptance, and further options for improvements. For this purpose, 23 participants executed six different tasks supposed to be representative of future use cases. Results in both quantitative and qualitative metrics revealed that the tasks were well handled and user requirements were fulfilled to a high degree. While there were ideas for the improvement of both the design and functional aspects of the app, a high overall usability score was yielded and participants stated a high intention to use.

The developed app can be seen as a possible extension to existing mobile phone tools that already allow one to plan a route on a mobile phone (Audi AG, 2022). However, the usefulness of the proposed app concept will depend on the future automation scenario and yield the largest benefits in cases with high reliability of automation prediction and medium automation coverage. Furthermore, the additional functions need to be included without overwhelming the user.

My personal contribution to this article included the definition of the research questions, processing and analysis of data, writing of the manuscript, involvement in the preparation and execution of the small-scale user and expert studies, and concept and app development, as well as preparation and execution of the usability study.

5.3 How Users of Automated Vehicles Benefit from Predictive Ambient Light Displays

Hecht, T., Weng, S., Kick, L.-F., & Bengler, K. (2022). How users of automated vehicles benefit from predictive ambient light displays. *Applied Ergonomics*, *103*, 103762. https://doi.org/10.1016/j.apergo.2022.103762

While the first two papers target the pre-drive phase, this article deals with the provision of time budget information during an automated drive. Users of AVs will conduct a variety of NDRAs using various items and devices (Hecht, Feldhütter, et al., 2020). While it is simple to support users conducting NDRAs on in-vehicle devices like the central information display (CID) with relevant time budget and mobile phone apps can be implemented to ensure communication with phone users, it becomes difficult to establish a direct non-interruptive line of information with users who read books or magazines.

This work's approach was to implement a light-based HMI concept realized with an LED stripe mounted at the bottom of the windshield. The ambient light display (ALD) concept was chosen because of its ability to unobtrusively raise awareness (Müller et al., 2013). Furthermore, no direct attention is needed and foveal vision is not influenced by peripheral view (Matthews et al., 2004). ALDs can already be seen in today's vehicles: VW ID.light, an LED strip in the bottom of the windshield, supports the driver with intuitive signals, e.g., on navigation, incoming phone calls, or state of charge (Volkswagen, 2021).

First, a simple traffic light color-coded concept was developed to convey different remaining times to predictable system limits. Results of a driving simulator study with 21 participants suggest that the ALD with three discrete time steps leads to improved usability and lower workload compared to a baseline interface without any ALD. The results on usability are in line with Richardson et al. (2018) and Holländer and Pfleging (2018). While also workload was decreased in this work's study, this was not the case for Holländer and Pfleging (2018) and Richardson et al. (2018). This highlights the potential of peripheral information presentation for a non-interruptive communication. Beyond that, no significant effects on trust, attention ratio, and travel time evaluation were found, but the majority of participants favored the ALD. Due to the positive results and based on the outcome of this study, the traffic light ALD was subsequently improved and compared to an elapsing concept. The latter was developed in a small-scale user study and was supposed to be easier to integrate into a setting with multiple LoAs. Results of a second driving simulator study with 32 participants did not show any significant differences between the two ALD concepts in subjective ratings, but advantages of the traffic light concept can be found in terms of its intuitiveness and the level of support experienced.

The positive results of this study set are in line with previous research on the use of ALDs in the context of automated driving (Dandekar et al., 2022; Feierle, Holderied, & Bengler, 2020) and extent these findings to the use case of time budget information. Future studies need to take the communication of uncertainties of time budget predictions into account, as well as the impact of the developed ALD concepts on safety measures.

My personal contribution to this article included the definition of the research question, the processing and analysis of data, the writing of the manuscript, and involvement in the experimental design.

5.4 Does a Confidence Level for Automated Driving Time Estimations Improve the Subjective Evaluation of an Automation HMI?

Hecht, T., Danner, S., Feierle, A., & Bengler, K. (2020). Does a Confidence Level for Automated Driving Time Estimations Improve the Subjective Evaluation of an Automation HMI? *Multimodal Technologies and Interaction*, *4*(3), 36. https://doi.org/10.3390/mti4030036

The previous article highlights the positive effects of a predictive HMI concept in a setting that represents an optimum in prediction quality with no time leaps triggered by a deviation from planning and reality. This paper targets the communication of uncertainty information in addition to time budget projections. Forecasts on automated driving times will be prone to errors: changing weather and light conditions can make a L4 ADS unavailable, changing traffic conditions can prolong or shorten parts of a given drive, accidents may necessitate bypasses where no automation is available, and updated information on construction sites or road conditions can additionally alter availability forecasts. This causes leaps in the time forecast that make it impossible for the user to maintain his/her original activity schedule.

In order to address this issue, a pre-study with future users was conducted. Based on relevant literature on the design of uncertainty information (Shani et al., 2013) and previous uncertainty concepts in the domain of assisted and automated driving (Beller et al., 2013; Helldin et al., 2013; Kunze et al., 2018; Large et al., 2017; Stockert et al., 2015), four different concepts were developed and subsequently evaluated with five naïve participants. The final concept included a four-stage horizontal bar resembling the well-known icon for a mobile phone connection to abstract the confidence level of a time budget estimation.

In the conducted driving simulator study, 32 participants experienced three time leaps in both directions. All possible confidence levels were displayed at least once. As a result of the study, the integration of the developed uncertainty element as part of the automation HMI cannot be recommended. While there was no significant impact of the concept on the subjective measures usability, trust, acceptance, and frustration, most participants preferred the baseline HMI without any confidence display. This contrasts with previous positive results (Beller et al., 2013; Helldin et al., 2013; Kunze et al., 2018; Stockert et al., 2015). However, prior studies' uncertainty information relates to the ability of an assistance or automation system to handle a situation and might thus be easier to interpret than a confidence level for time budget information. Furthermore, previous studies mainly revealed a positive impact on take-over performance measures in a system failure scenario. However, that was not investigated in the present work. In our first contact scenario with no explanation and no free choice of NDRAs, the concept was not intuitively understood and was rated rather confusing than helpful. Thus, such a concept can only be helpful in certain scenarios and with additional explanations of the way it works.

My personal contribution to this article included the definition of the research question, the processing and analysis of data, the writing of the manuscript, and involvement in the experimental design.

5.5 How to Keep Drivers Attentive during Level 2 Automation? Development and Evaluation of an HMI Concept Using Affective Elements and Message Framing

Hecht, T., Zhou, W., & Bengler, K. (2022). How to Keep Drivers Attentive during Level 2 Automation? Development and Evaluation of an HMI Concept Using Affective Elements and Message Framing. *Safety*, *8*(3), 47. https://doi.org/10.3390/safety8030047

The sustained engagement in visually demanding NDRAs during assisted driving poses a serious threat to road safety due to missing or delayed driver reaction to (silent) system limits and malfunctions (Boos et al., 2020; Louw et al., 2019). The goal of this work was to develop an HMI concept that motivates drivers to refrain from engaging in NDRAs and consequently improve monitoring as well as reactions to silent system malfunctions. In traffic psychology, different approaches to motivating humans to follow rules can be found. Amongst others, inducing a positive mood or emotion can help regain the capability of effective self-regulation (Tice et al., 2007), Moreover, message framing is a common approach to improve drivers' behavior adoption rate, e.g., used in anti-speeding messages (Lewis et al., 2008). Based on these ideas, two concepts were developed and evaluated in an expert study with four usability professionals. This led to the integration of the concept in the HUD rather than a speech-based integration. Messages and emoticons used during L2 driving were designed to induce a positive mood and a coping appraisal. Seven messages were displayed following a time-based approach rather than taking into account the current driver state. Finally, a driving simulator study with 32 participants was conducted to assess the concept's effectiveness regarding monitoring behavior, NDRA engagement, driver reaction to a silent system malfunction, user experience, and workload.

The results of the study suggest that the developed affective message concept (AMC) is helpful in motivating drivers to continue their supervision task rather than engaging in NDRAs. Furthermore, it was well-rated as a reminder to keep engaged and does not higher subjective workload. However, no impact on crash rate and take-over time in a silent malfunction scenario was found. The high crash rate in the researched urban scenario is in line with the results obtained by Feierle et al. (2021). In addition, high rates of unsafe outcomes in malfunction scenarios were found in Boos et al. (2020), Othersen (2016, p. 238), and Victor et al. (2018). Over-reliance was mentioned as a reason by this study's participants and was also highlighted by Boos et al. (2020). In our study, there was no effect of the AMC on the user experience ratings. Additional research will need to further investigate the long-term effectiveness and the concepts' actual impact on driver reaction in more detail. Furthermore, a driver state-dependent design might sustain or even improve its effectiveness.

My personal contribution to this article included the definition of the research question, the processing and analysis of data, the writing of the manuscript, and involvement in the experimental design.

6 General Discussion

Overall, the present thesis aims to develop HMI solutions that support users in utilizing their travel time in the context of fragmented automated drives. Based on infrastructure, vehicular communication, and weather forecasts, most transitions are expected to be predictable, but predictions are subject to error and fuzziness. For this work, the vehicle interior was assumed to be conventional, featuring a steering wheel and pedals. In assisted driving, system limits and malfunctions may appear without any warning. In automated driving, there are sufficient time budgets for transitions to manual and minimal risk maneuvers are executed by the system if necessary. HMI solutions were developed and evaluated following the UCD process (DIN EN ISO 9241-210) and for the three phases pre-drive, automated drive, and assisted drive. Throughout the process, different methods were used, including a workshop, small-scale user studies, expert evaluations, driving simulator studies, and a usability study. The derived interaction and information concepts include an app-based route planner and different in-vehicle HMI concepts using HUD, IC, and ALD. Overall, most solutions were proven beneficial for the specific challenges associated with the three phases. They were found to aid users to plan and use their time safely and comfortably.

With regard to the first RQ ("How can the predicted automation availability be integrated into the route planning process?") and its sub-questions concerning the pre-drive phase, it can be concluded that user requirements include the desire to configure priorities for a drive. For instance, on-time arrival or maximization of uninterrupted automated driving time was requested, as well as a minimum continuous period a drive segment must last for it to be accounted for in the route planning process. Users want the opportunity to set the uninterrupted completion of an important NDRA as a priority. Moreover, standard destinations with preconfigured travel settings were required. A customizable selection of travel profiles was seen as useful. Different route alternatives calculated by the system should be easy to compare and not only be displayed on a map but also be visualized in an abstract manner. Real-time data should be taken into account, as well as users' overall long-term preferences. In general, users want to invest as little time as possible while still find the route best suited to their needs. These user needs were transferred into a route planning tool (Hecht, Sievers, & Bengler, 2020). After several small-scall user studies and incremental improvements of the design, a functional route-planning tool for mobile phones was developed as an Android app. This route planner features travel profiles to save preferences such as the optimization of a route to be fast, have a high share of automated driving, or have as few transitions as possible. Additionally, the tool is designed to support the uninterrupted execution of NDRAs by allowing to request time slots to be driven automated. In a final usability study, the tool yielded a high usability rating, a high degree of fulfillment of previously derived user needs, and a high intention to use. Furthermore, complex route-planning tasks can be accomplished in a short amount of time (Hecht, Weng, Drexl, & Bengler, 2022). The results obtained during the development process support findings by Hecht, Kratzert, and Bengler (2020) and Lehtonen et al. (2021) on the need for route planning.

To answer the second RQ ("How can the HMI for an ADS be supplemented with peripheral visibility of system status and time budget information?"), two ALD concepts were developed. In order to evaluate whether this way of peripherally communicating time budget information improves the evaluation of, amongst others, usability and acceptance, a set of two driving simulator studies was conducted (Hecht, Weng, Kick, & Bengler, 2022). It can be stated that ALD concepts conveying time budget and system status information are beneficial for users when the ADS is engaged. A peripheral visible concept using the well-known traffic light color scheme to convey remaining time budgets was found to improve usability and lower workload, while no significant effects on trust, attention ratio, and travel time evaluation were found. In an iterative improvement, a second concept using elapsing colors was also found suitable, while the intuitiveness was rated slightly worse than with the first concept. However, despite the advantages of the developed concepts and user preferences, no impact on safety aspects was found in the studies; only three cases of task perseveration occurred. Possibly, this can be explained by the setting that focused on free naturalistic NDRAs without a definite goal or extrinsic motivation. Furthermore, the early first acoustic information on the upcoming system limit has proven sufficient for the chosen tasks. Settings as in Wandtner et al. (2018) with controlled and complex NDRAs which are then interrupted close to finishing might lead to higher interruption costs and additional insights on the safety benefits of the proposed ALD. In general, the set of studies highlighted the importance of time budget information. In summary, peripheral visibility of time budget information is favored by users over exclusively using the IC, it increases usability and has positive effects on workload. Both, elapsing and discrete concepts have proven suitable. However, despite the rather short period communicated via ALD, the concepts are also challenged by possible time leaps in the time budget prediction.

The third RQ ("How can the HMI for an ADS be supplemented with uncertainty information?") resulted in a driving simulator study. It was evaluated whether offering additional information on the prediction quality of time budget information increases the subjective evaluation of an automation HMI (Hecht, Danner, et al., 2020). Following a pre-study, an HMI concept using a bar resembling the well-known mobile phone connectivity icon was developed to convey a confidence level for time budget estimations. The driving simulator study revealed no impact on the subjective evaluation (usability, trust, frustration, acceptance) of the system. The baseline concept without a confidence display was favored by the majority of the subjects. These results contrast previous positive findings on confidence displays in the domain of assisted and automated driving (Beller et al., 2013; Helldin et al., 2013; Kunze et al., 2018; Stockert et al., 2015), but add to critical results obtained by Shani et al. (2013). It can be stated that, based on these findings, a confidence display cannot be recommended for use in connection with time budget information.

Regarding the last RQ ("How can drivers be supported in carrying out their monitoring task during L2 assisted driving?"), an HMI concept featuring pop-up messages in the HUD using message framing and affective elements was developed following an expert study. The approach was driving time-based rather than driver-state-dependent. It can be deducted from the results that the developed concept supports users in their monitoring task while at the same time, the workload is not increased and drivers are not annoyed. However, even though monitoring was stable and subjects mostly refrained from NDRA engagement during assisted driving, no effect could be shown on drivers' performance in a silent malfunction scenario. While the AMC can be recommended for further use and investigation, possibly in connection with a driver state-based empathetic assistant, the results obtained on driver reaction in malfunction scenarios are in line with previous research (e.g., Feierle et al. (2021) and Boos et al. (2020)) and support the requirement for a fallback level in reliable assisted driving, especially in a complex urban context.

6.1 Automation Availability and Prediction

The setup used by OEMs to realize ADS will restrict automation availability in connection with infrastructure, light, weather, and traffic characteristics (see Chapter 2.2). However, the actual automated driving availability and the system's ability to predict it will impact this work's HMI solutions. In general, more system-initiated transitions are associated with a higher workload and decreased acceptance of an ADS (Hecht, Kratzert, & Bengler, 2020). Shorter automated driving segments will make fewer NDRAs possible or require more interruptions and thus potentially have a negative impact on the perceived value of travel time and the usefulness of the ADS. Further studies are required to assess whether the usefulness of the developed route planner is influenced by the degree of automation coverage; especially very low and very high automation coverage might diminish its usefulness. The concepts concerning the automated and assisted drive are probably not influenced by the degree of automation availability.

In addition, the quality of automation availability prediction can only be roughly estimated at present. The following error cases can be anticipated:

- Duration of an automated driving segment changes, e.g., due to dissolving or building up congestion.
- Interruption of an automated driving segment, e.g., due to an accident or adverse weather conditions.
- Incomplete or unavailable automation, e.g., due to route changes, adverse weather, or technical problems.

It can be expected that the prediction quality decreases with increasing time to start. The closer the start, the more precise are weather, light, and traffic forecasts and the more reliable are infrastructure information (e.g., on construction sites or lane marking quality). Different error cases with regard to automated driving availability impact users to a different degree (order according to the expected impact on user satisfaction, from most positive to most negative case):

1. A shortened automated travel time with early arrival time will on the one hand decrease the usefulness of drive time but allow one to arrive earlier. Thus, no negative impact is expected, except the user has scheduled a certain NDRA with a set time budget that is then interrupted due to the shortened segment.

2. A prolonged automated driving time and a delayed arrival time will let users benefit from more automated driving time but suffer from a delayed arrival. However, the additional drive time can be used.
3. A short interruption of an automated driving segment with no impact on the arrival time may lead to an interruption of the current NDRA. The negative impact on the user depends on the time to prepare for the interruption and further NDRA characteristics.
4. Incomplete or unavailable automation with manual or assisted driving instead and a delayed arrival time represents the worst scenario since usable drive time is minimized while arrival time is delayed.

Obviously, combinations of the described cases are possible and changes may also affect manual and assisted driving segments. The complexity of a given trip and its different parts will make predictions on the consequences for users difficult. However, it can be assumed that prediction quality influences frustration and thus usefulness and acceptance of the route planning tool and the predictive HMI element. Unreliable predictions will be perceived as annoying and will lead to rejection and an increased likelihood of task perseveration. Consequently, messages used by the AMC that hint at the future availability of automated driving (e.g., "Stay attentive now, use your phone in 5 minutes") should not be displayed in case of high prediction uncertainty as it could lead to the opposite effect. Furthermore, the implemented ALD concept informing users on the remaining time budget will change in case of time leaps and rather confuse users. These examples also highlight the necessity to continuously update the user on the driving schedule and grant additional control during the driving phase by extending the route planner to the driving phase. The latter was also requested by participants of the workshop described in the first article, as well as the wish to have a system that learns from users' decisions and proactively suggests necessary changes accordingly (Hecht, Sievers, & Bengler, 2020). The multitude of conceivable cases in connection with the variety of possible NDRAs and the factors influencing the attractiveness of the same will make it difficult to estimate the necessary reliability of such a route planner to be perceived as useful. Further investigation is needed to assess whether an affective assistant available throughout the drive is a suitable method of communicating and realizing route changes in relation to the learned patterns of a specific user.

Since an additional uncertainty display for a time budget estimation during an automated drive was rejected in article 4 (Hecht, Danner, et al., 2020), other options to convey uncertainty to users of a pre-drive planning tool need to be assessed. The evaluated app only featured a brief disclaimer that highlighted possible discrepancies between planning and reality but did not distinguish between different prediction qualities that can be expected based on the above-discussed factors. Concepts could include color coding, smileys, periods, limited features (e.g., no option to schedule segment until a set time in advance), decreased granularity (e.g., delete minutes, just provide abstract view), or offer only map- or distance-based visualization.

6.2 Overarching Effects of Pre-Drive Planning

The developed route planning tool allowed users of future ADS to schedule their meetings in accordance with the automation availability. Furthermore, personal preferences such as the avoidance of transitions or the optimization of a route for automated driving could be incorporated into the route planning process. This ability to plan a fragmented automated drive ahead will potentially impact people's behavior during a journey. The improved user information and increased user control potentially lead to a better system understanding by users and a higher acceptance of transitions and manual or assisted driving sequences. Thus, intentional violations can probably be reduced. Also, continuing a visual-manual activity despite the need to take over manual control (i.e., task perseverance) after an automated driving segment can potentially be avoided by a good planning and information concept. However, data gathered in the presented studies is not sufficient to answer the question of whether the route planning tool has an impact on user behavior during a drive. In addition, past and current safety-related human factors research has largely focused on take-over situations rather than targeting a complete drive. Thus, further research is needed to support the risk assessment of future AVs with insights into user behavior in connection with a pre-scheduled drive. In a first step to evaluate the impact of the route planner, data on drivers' behavior during fragmented drives need to be gathered and compared to a non-planning scenario. In a driving simulator study with a prior planning phase, worst-case assumptions can be considered by using high time pressure and complex activities and a high share of reliable H-off L2 driving. The number of observed violations in both planning and non-planning scenario can be used to calculate the probability. It is to be discussed whether a DMS should be part of the investigation. In the case of L3 automated driving (i.e., no minimal risk maneuver), the possibility to plan NDRAs before the drive can also influence the likelihood of a successful transition. In addition to task characteristics and time spent with an activity, the characteristics of upcoming transitions (e.g., timing as planned) can influence the take-over performance. Overall, the concepts designed in this thesis show additional potential regarding safety-relevant issues, but further investigation is required to quantify them.

While the route planning app has singularly addressed the automation availability, future improvements will need to include current navigation features (exclude toll roads, scenic routes, etc.), as well as BEV options (plan charging stops and providers, etc.) without overwhelming the user with a multitude of options. Furthermore, the developed route planning app currently covers only the route planning process; it does not support users during the drive with necessary information on possible or inevitable changes of the route, traffic information, or alterations to the automated driving time slots (see also Chapter 6.1). According to Danner et al. (2021), context-adaptive notifications can be a feasible way of informing the driver of changes in automation availability.

6.3 User-Centered Design Process

This work followed the UCD approach and integrated users into the development process. Following the iterative idea of UCD, different tools including literature reviews, workshops, small-scale user studies, expert evaluations, usability, and driving simulator studies were applied to design highly usable and safe interaction concepts for users of future automated vehicles. During each stage in the development process, diverse user feedback was received. As suggested by Nielsen (2000), small-scale user studies were very good to uncover a multitude of usability issues. In addition, user behavior and information on their intention to use was obtained and has led to improvements in the concepts. Furthermore, qualitative and quantitative user feedback helped to focus on relevant improvement directions. In addition, the impact of the UCD within this work can be seen in the fact that almost all concepts (except the uncertainty display) received positive feedback in the final evaluation. An advantage of the process undertaken was the continuous integration of users throughout the development process without a cut between concept design and implementation. Thus, knowledge gained in the early stages could also be used in later stages. However, although the prototypes reached high maturity, they were developed in a research context that differs from common industry practice. More iterations are necessary to develop the concepts to market maturity, including design refinements and release tests. The presented studies were conducted at the Chair of Ergonomics at TUM. Thus, the samples rather allow user- than human-centered design. The participants represent to a large extent people associated with the university. In consequence, the samples are rather young, male, and show a high technology affinity. Furthermore, most subjects are German (including fewer international students). These factors can limit the generalizability of the obtained results and do not allow the assessment of cultural differences. Moreover, the high prior knowledge of and positive attitude towards automated driving and the observation by the experimenter can influence the results. Overall, participants lack experience with ADS and might exhibit different use patterns when using ADS in their everyday life. For future improvements, samples used need to be adopted to future users and more market research is required to identify the same.

Furthermore, the driving simulator studies were conducted in a dynamic seat box. The moving system induced pitch and roll motions but did not simulate accelerations. The seat box is not a full vehicle with windows, passenger seats, etc. but a rather simple composition with limited immersion compared to a full vehicle driving simulator. Thus, the results obtained in the seat box need to be discussed critically. Moreover, driving simulator studies pose no risk of physical harm to participants. Thus, engaging in NDRAs during assisted but also during automated driving might be more appealing to users than it would be in an on-road study. However, the results of Klingegard et al. (2020) suggest that drivers also engage in visual-manual NDRAs when driving in a L4 Wizard of Oz vehicle in real traffic. Furthermore, previous test track studies by Llaneras et al. (2013) and Victor et al. (2018), as well as on-road observations by Reagan et al. (2021) confirm results obtained in driving simulator studies regarding gaze behavior and NDRA engagement in L2 assisted driving. Moreover, a high relative validity (describes how well the relative size or direction of an effect measured in the simulator corresponds to real driving (Kaptein et al., 1996)) of driving simulators was found by Eriksson et al. (2017). Nonetheless, the obtained results should be confirmed in more realistic settings. According to Bengler, Omozik, and Müller (2020), Wizard of Oz setups where humans simulate the behavior of the system yield promising results in the context of automated driving. Furthermore, a penalty or reward system as proposed by Hock et al. (2018) can be introduced as consequence for driving behavior to yield a more realistic behavior.

In general, the studies with naturalistic NDRAs aimed at producing realistic behavior with regard to the choice and execution of NDRAs. However, artificial settings can never fully picture a real situation where there are different motivations to conduct travel, different levels of time pressure, preparations, and varying underlying schedules. However, factors like trip purpose or time pressure are known to influence the choice of activities (Hecht, Darlagiannis, & Bengler, 2020) and NDRA engagement in turn has an influence on the evaluation of travel (Susilo et al., 2013). Therefore, one might try to create more realistic and comparable scenarios by further instructing participants. Future studies should evaluate the results of this work in on-road studies, especially to consider different lighting conditions (Hecht, Weng, Kick, & Bengler, 2022) and to assess drivers' gaze behavior and the impact of an AMC in a more realistic scenario (Hecht, Zhou, & Bengler, 2022). Furthermore, more representative samples can help OEMs by introducing new future features.

For UCD, it is important to find and plan suitable methods ahead. Due to the constantly growing number of methods, finding suitable tools takes a significant amount of time and getting familiar with the tools is necessary to derive valid findings. This effort needs to be considered when planning the UCD process. Furthermore, interdisciplinary knowledge is helpful or even necessary to perform the UCD process over the complete development cycle. In line with this, difficulties in integrating UCD into business processes, especially in agile methods can be observed (Salah et al., 2014). UCD uses different approaches to how resources are allocated: while agile methods try to deliver small sets of software features to customers as quickly as possible and in short iterations, UCD requires a considerable effort in research and analysis before development begins (Da Silva et al., 2011). Rosenbaum et al. (2000) found resource constraints, resistance to UCD, and a lack of knowledge about usability to be major obstacles to creating a greater strategic impact. Moreover, Vredenburg et al. (2002) discovered that some common characteristics of an ideal UCD process including tracking customer satisfaction and a focus on the total user experience are not used in practice. In the end, a multidisciplinary approach to UCD appears to be closely related to perceived UCD effectiveness (Vredenburg et al., 2002).

7 Future Work

Through increasing market penetration, a wide range of experience with assisted and automated driving functions can be expected in the future. In addition, car sharing will further increase the diversity of experiences with ADS and corresponding HMI concepts. While prior experience potentially affects user behavior and information needs (Beggiato et al., 2015; Feierle, Danner, et al., 2020), studies also reveal that inter- and intraindividual differences exist with regard to user information needs and preferences (Beggiato et al., 2015; Danner et al., 2020; Feierle, Danner, et al., 2020). However, all studies conducted in this work simulated the initial contact of participants; only little introductory information was provided, no or little prior automation experience was prevalent, and the overall driving duration per study did not exceed 45 minutes. Based on the findings described above, two implications for this work arise. First, the developed interaction concepts will most likely have to adapt to changing user needs and behavior which arise due to changing experience and trust (i.e., long-term effects). Second, the HMI concepts will have to adapt or be adapted to individual differences to account for users' preferences. As both aspects implicate a better knowledge of the user than current systems allow, they are discussed together in this chapter. Implications of long-term effects can already be seen in today's market available L2 systems. For instance, Kim et al. (2022) report approaches to outwit the DMS, enabling users to take their hands off the steering wheel or their eyes off the road. Thus, necessary restrictions of a L2 system are bypassed with potentially dangerous consequences. Next to tiredness and higher attractiveness of NDRAs, over-reliance was found to be one driver of misuse associated with long-term effects in the context of assisted driving (Boos et al., 2020). Misuse in L3 systems is also conceivable, such as sleeping or leaving the driver's seat.

Based on the concept of mental models, it can be expected that prior experience also changes information needs (Feierle, Danner, et al., 2020). For instance, Beggiato et al. (2015) expect that users require more information in an early phase due to a lack of trust in ADS. With growing experience, trust potentially increases and information needs regarding transparency decrease (Beggiato et al., 2015). While Feierle, Danner, et al. (2020) did not find a clear influence of prior experience with ADS on information needs, they emphasize methodological restraints and recommend further investigation in an improved setting to further investigate trends observed in their study (e.g., experienced participants rated system status higher than other information items). However, Feierle, Danner, et al. (2020) found that individual participants exhibited great differences in information requirements. Thus, a single HMI design with a specific range of driving- and automation-related information will not be a perfect solution for every user due to individual differences and long-term effects.

For future research, two main approaches can be followed to respond to these challenges and in consequence avoid misuse and reduced acceptance. First, information content can be personalized by users. User profiles and standardized information displays can be utilized to establish standardized information layouts across different vehicles and allow to use the same layout in different vehicles (even across companies). Thus, information content can be tailor-fit to individual needs. However, settings must not be too complex and/or be explained by a tutorial to ensure correct use.

However, the impact of such solutions to avoid misuse is probably limited. Thus, the second approach is based on the enhanced knowledge of the user. Extended DMS can assess the current driver state in a way that enables the system to communicate in a suitable manner. In order to use the input of a DMS effectively, long-term effects need to be better understood. However, there are only isolated findings in this field (e.g., B. Metz et al. (2020) and B. Metz et al. (2021)), although the need for research has been addressed and does not only cover the development of acceptance and use of ADS but also travel behavior and land use implications (Milakis, 2019). In addition, the effort needed to retrieve results on long-term use must be kept in mind to carry out human factors studies efficiently and validly.

Knowledge of long-term effects and input from DMS can be used to convey information in a suitable manner. The AMC developed in this work can potentially not only improve monitoring behavior but also regulate trust in the system by realizing an emotional bond between the user and ADS. System trust is considered key to the acceptance of automation systems (see Ghazizadeh et al. (2012) for an overview). If trust in automation is not present or only weakly developed, technology is often used differently than intended or not at all (Parasuraman & Riley, 1997). Mood was found to affect initial trust formation (Stokes et al., 2010). Thus, the AMC can be further improved in its effectiveness to avoid misuse during L2. Studies show that the bond to an assistant (e.g., in the form of an avatar) is particularly strong when the assistant shows corresponding emotions and behaviors. Bailenson and Yee (2005) show that this effect can be achieved or enhanced by imitative behavior (mimicry; so-called chameleon effect). Emotion regulation can also be used for long-term adaption to avoid misuse by incorporating the driver state (Braun et al., 2022). Additionally, the theory of nudging can be used to further improve the efficiency of the affective messages to ensure intended use. Nudging approaches steer people in particular directions but also allow them to go their own way (Sunstein, 2014). According to Sunstein (2014), examples of nudges include graphic warnings for cigarettes, labels for energy efficiency, nutrition facts on foods, etc. Default rules, simplifications, use of social norms, increases in ease and convenience, disclosure, warnings, pre-commitment strategies, reminders, eliciting implementation intentions, and informing people of the nature and consequences of their own past choices are nudging categories (Sunstein, 2014). However, the effect of nudges varies considerably across studies, some studies have found nudges to be inefficient or even backfire (see Hummel and Maedche (2019) for an overview of the effectiveness of nudges). Thus, the potential for increased use of nudging in addition to those already implemented in the AMC needs to be carefully evaluated. Also, in connection with long-term adaption in a driver state-based approach, gamification or rewards (see e.g., Feinauer et al. (2022)) may be used to avoid maladaptive behavior.

8 Conclusions and Recommendations

Past research on travel time use in the context of automated driving has focused on the attractiveness of different NDRAs for passengers of ADS and different but isolated effects of NDRAs. The focus of this work was on the development of interaction concepts for comfortable and safe travel time use in the context of fragmented automated drives. Rather than analyzing motivational aspects or behavioral planning of car users, the focus was on the design of digital solutions. For each researched segment, namely pre-drive, assisted, and automated drive, user needs were analyzed and suitable interaction concepts were designed. The present work contributes to the ongoing development of internal HMI concepts for users of ADS. It extends existing findings by a specific view of user needs associated with travel time use. Most developed HMI solutions have proven beneficial and support users with planning and utilizing their travel time in a safe and comfortable manner. Based on the study results, the following recommendations can be formulated:

- Users should be granted additional control over the route planning process with regard to automation availability.
    - A mobile phone application including travel profiles and the option to request scheduled automated driving segments represents a suitable tool for this purpose. Further research is necessary to investigate the effects of travel planning on driver behavior during the drive.
- When L4 automation is active, users should be informed about the remaining time until an upcoming system limit in a device-independent and non-interruptive manner.
    - Using peripheral communication via a color-coded ALD at the bottom of the windshield represents a suitable approach. Future research is necessary to investigate the effects of this concept on safety measures.
- When L4 automation is active, users should not be informed about the prediction uncertainty of automated driving time budgets.
- When L2 assistance is active, users should be supported and motivated to continue their monitoring task.
    - A combination of short text messages and affective elements displayed in the HUD represents an effective way of reducing drivers' off-road glances. Future research is necessary to assess the long-term effectiveness of this approach.

Additional research is required to understand the long-term effects when interacting with the developed concepts. The future development of ADS will show their suitability and will potentially make it necessary to reevaluate and rework parts of the proposed solutions, for instance depending on the actual driving and prediction capabilities of future ADS. Furthermore, the actual impact of people being able to utilize drive time might be limited by effects like motion sickness (Milakis, 2019). Nonetheless, the present work's concepts have the potential to positively influence the usefulness and thus market success of future ADS.

9 Complementary Studies

In addition to the five publications that form the present thesis, additional studies have been conducted. Those were not the focus of the work but nevertheless contribute to the issue of travel time use in the context of fragmented automated drives. Two studies evolve around future users' NDRA engagement and associated user needs, one deals with the impact of a predictive HMI element and different transition frequencies on NDRA engagement, gaze behavior, and subjective evaluation of the system. In addition, information needs regarding an ADS while it is not available and the design of an adaptive IC concept were targeted, as well as a review of driver state constructs and assessment methods.

Hecht, T., Feldhütter, A., Draeger, K., & Bengler, K. (2020). What Do You Do? An Analysis of Non-driving Related Activities During a 60 Minutes Conditionally Automated Highway Drive. In T. Ahram, R. Taiar, S. Colson, & A. Choplin (Eds.), *Advances in Intelligent Systems and Computing: Vol. 1018, Human Systems Engineering and Design II. IHSED 2019. Advances in Intelligent Systems and Computing*. Springer International Publishing. https://doi.org/10.1007/978-3-030-27928-8_28

To understand user needs in the context of automated driving and travel time use, it is necessary to evaluate their NDRA engagement. Thus, this study focused on the analysis of video data from a driving simulator study originally designated to assess the impact of free naturalistic activity engagement during L3 automation on the driver state component fatigue and its influence on the take-over performance. During a 60 min monotonous highway ride, the subjects spent most of the time watching videos on the CID, monitoring the surroundings, listening to music, and using their mobile phone for multiple activities. Furthermore, many participants read books or magazines. Also, playing games on the CID and working on a personal laptop was observed. Both the total time spent and the mean duration of activity showed a high variance, highlighting individual differences in subjects' motivation. On average, the analyzed participants were found to engage in a visually engaging NDRA about 2 min after switching on the ADS. Older participants were found to spend significantly more time monitoring the surroundings and less time using their phones or playing video games.

Hecht, T., Darlagiannis, E., & Bengler, K. (2020). Non-driving Related Activities in Automated Driving - An Online Survey Investigating User Needs. In T. Ahram, W. Karwowski, S. Pickl, & R. Taiar (Eds.), *Advances in Intelligent Systems and Computing: Vol. 1026, Proceedings of the 2nd International Conference on Human Systems Engineering and Design II. IHSED 2019. Advances in Intelligent Systems and Computing (pp. 182–188).* Springer International Publishing. https://doi.org/10.1007/978-3-030-27928-8_28

The goal of this study was to better understand the diversity in chosen NDRAs. In an online survey, privacy, vehicle interior design, trip purpose, trip duration, and users' age were found to influence the chosen activities. Furthermore, the most important information needs for an urban automated drive were found to be the reliability of the ADS, remaining time budget, and system status. Engagement in an important work-related and visually demanding NDRA especially lowers the importance of information items like maneuvers, surrounding traffic, and current speed. Reliability, system status, and remaining time budget remain equally important. This finding and the fact that available time spans influence the choice of NDRAs highlight the importance of a predictive HMI.

Hecht, T., Kratzert, S., & Bengler, K. (2020). The Effects of a Predictive HMI and Different Transition Frequencies on Acceptance, Workload, Usability, and Gaze Behavior During Urban Automated Driving. *Information*, 11(2), 73. https://doi.org/10.3390/info11020073

The study concentrated on the influence of different transition frequencies and HMI concepts on gaze behavior, NDRA engagement, and subjective evaluation of ADS. The transition frequency was found to negatively influence workload, acceptance, and system usability. No effect on trust in automation was revealed. Gaze behavior suggests the use of the researched predictive HMI element, as well as participants' statements in a post-drive questionnaire. However, no effect of displaying the remaining time until a system limit was found. Most attractive NDRAs were monitoring the surroundings, chatting, phone use, and reading magazines. Descriptively, reading magazines and playing games gained attractiveness with decreasing transitions, while the opposite was the case for watching surrounding traffic and chatting. Further results suggest a positive attitude towards a route planning tool that allows accepting a longer travel time in exchange for fewer transitions.

Danner, S., Hecht, T., Steidl, B., & Bengler, K. (2021). Why is the Automation Not Available and When Can I Use It? In N. L. Black, W. P. Neumann, & I. Noy (Eds.), *Springer eBook Collection: Vol. 221. Proceedings of the 21st Congress of the International Ergonomics Association (IEA 2021): Volume III: Sector Based Ergonomics* (1st ed., Vol. 221, pp. 623–632). Springer International Publishing; Imprint Springer. https://doi.org/10.1007/978-3-030-74608-7_76

Previous research has mainly focused on the period when the ADS is active. This study addressed information needs regarding an ADS while it is not available. In a driving simulator study, displaying the time until the automation will be available as well as reasons for non-availability increased perceived system understanding but did not yield effects on subjective ratings as usability, acceptance, and workload. Furthermore, participants ranked HMI concepts containing additional information higher than the baseline. As a result, displaying additional information during the non-availability of automated driving functions can be recommended for future use.

Feierle, A., Bücherl, F., Hecht, T., & Bengler, K. (2020). Evaluation of Display Concepts for the Instrument Cluster in Urban Automated Driving. In T. Ahram, W. Karwowski, S. Pickl, & R. Taiar (Eds.), Advances in Intelligent Systems and Computing: Vol. 1026, *Proceedings of the 2nd International Conference on Human Systems Engineering and Design II. IHSED 2019. Advances in Intelligent Systems and Computing* (pp. 209–215). Springer International Publishing. https://doi.org/10.1007/978-3-030-27928-8_32

In the context of automated driving, the relevance of different information items changes with the LoA (Beggiato et al., 2015). The IC is the primary driver-vehicle interface for driving-related information. Evolving from small displays in between the circular elements like a tachometer and speedometer, the use of freely programmable ICs marked a change in the use of this central HMI element. Thus, the goal of this work was to design an adaptive HMI concept applicable to multiple LoAs. In an evaluation, the developed concept performed significantly better than the conventional baseline concept. As a result, the adaptive IC serves as the basis for the driving simulator studies conducted in the present thesis.

Hecht, T., Feldhütter, A., Radlmayr, J., Nakano, Y., Miki, Y., Henle, C., & Bengler, K. (2019). A Review of Driver State Monitoring Systems in the Context of Automated Driving. In S. Bagnara, R. Tartaglia, S. Albolino, T. Alexander, & Y. Fujita (Eds.), *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018)* (pp. 398–408). Springer International Publishing.

The purpose of this literature review was to provide an overview of driver-state models and monitoring systems in the context of automated driving. Based on three different driver state models, the review focused on the driver state constructs fatigue, attention, and workload. It became apparent that the driver state and its constructs lack a common definition. Regarding the assessment of the constructs, eye-tracking seems to be the technology with the highest potential but further improvement is needed to increase reliability. EEG as another assessment method lacks practicability and often used self-assessment techniques are prone to misjudgment and may counteract extreme levels of fatigue.

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