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Interaction between Automated Vehicles and Oncoming Human Drivers: Efficient and Safe Urban Driving in Bottleneck Scenarios

Michael Rettenmaier, M.Sc.

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Vorsitz: Prof. Dr.-Ing. Rüdiger Daub

Prüfer:
1. Prof. Dr. phil. Klaus Bengler
2. Prof. Dr. phil. Martin Baumann

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Abstract

Vehicle manufacturers, suppliers, and research institutes are currently working at full speed to introduce automated vehicles into the existing traffic system, promising benefits for traffic safety and traffic efficiency. In urban traffic, which is generally characterized by complex traffic situations and a large number of different road users, this initially leads to mixed traffic where automated vehicles will have to integrate smoothly into established interactions with pedestrians, cyclists, and conventional vehicles.

In this context, the present thesis aims to optimize the interaction between an automated vehicle and a simultaneously oncoming human driver at a bottleneck narrowed on both sides of the road. This scenario is of particular relevance since the simultaneous arrival of the interaction partners implies that the right-of-way is not regulated by law requiring the development of a comprehensible communication strategy to ensure traffic safety and increase traffic efficiency.

The body of this manuscript includes four articles, based on which this thesis develops the optimal communication strategy of the automated vehicle for safe and efficient interaction with the oncoming human driver in the aforementioned bottleneck scenario. Article 1 designs an external human-machine interface and explores the potential of explicit communication. Complementary to this, Article 2 addresses implicit communication and implements comprehensible vehicle movements to convey the intention of the driving automation system. To derive a benchmark for successful interaction at a bottleneck, Article 3 estimates the latest possible communication timing and models the encounter of both interaction partners in a time-based manner. The findings of these previous works are combined in Article 4, where the developed explicit and implicit, as well as a joint communication strategy, are compared for their potential to maintain traffic safety and to increase traffic efficiency while considering the modeled communication timing from Article 3. The results show that a combined explicit and implicit communication strategy supports human information processing most effectively, surpassing the other two strategies in terms of avoided crashes, reduced passing time, and thus traffic safety and traffic efficiency.

Based on this, the thesis combines the information flow within the driving automation system and during human information processing with the findings on external communication and the human driver’s reaction in a closed control loop. This approach includes five principles for the human-centered design of external communication, thereby setting the foundation for safe and efficient interaction in the bottleneck scenario. The automated vehicle should communicate explicitly and implicitly together in a time-based manner, taking into account the necessary period for the information processing of the human driver. Furthermore, the automated vehicle must yield the right-of-way in case of uncertainty and never change the communicated maneuver during the interaction.

Zusammenfassung

Fahrzeughersteller, Zulieferer und Forschungsinstitute arbeiten derzeit mit Hochdruck an der Einführung automatisierter Fahrzeuge in das bestehende Verkehrssystem, da dies unter anderem Potenziale in den Bereichen der Verkehrssicherheit und der Verkehrseffizienz verspricht. Im durch komplexe Verkehrssituationen und eine Vielzahl unterschiedlicher Verkehrsteilnehmer geprägten urbanen Verkehrsraum kommt es dabei zunächst zu einem Mischverkehr, in dem sich automatisierte Fahrzeuge nahtlos in etablierte Interaktionen mit Fußgängern, Radfahrern und konventionellen Fahrzeugen integrieren müssen.

In diesem Zusammenhang befasst sich die vorliegende Arbeit mit der Interaktion eines automatisierten Fahrzeugs und eines zeitgleich entgegenkommenden menschlichen Fahrers an einer gleichrangigen Engstelle. Dieses Szenario ist von besonderer Relevanz, da die Vorfahrt aufgrund der zeitgleichen Ankunft der Interaktionspartner gesetzlich nicht geregelt ist und dies die Entwicklung verständlicher Kommunikationsstrategien zur Gewährleistung der Verkehrssicherheit und zur Steigerung der Verkehrseffizienz notwendig macht.

Der Hauptteil der Thesis umfasst vier Artikel, auf deren Grundlage diese Arbeit die optimale Kommunikationsstrategie des automatisierten Fahrzeugs im Engstellenszenario entwickelt. Artikel 1 entwirft ein externes Anzeigekonzept und untersucht das Potenzial expliziter Kommunikation. Artikel 2 thematisiert implizite Kommunikation und gestaltet verständliche Trajektorien, um die Intention des automatisierten Fahrzeugs zu vermitteln. Artikel 3 befasst sich mit dem letztmöglichen Kommunikationszeitpunkt und modelliert die Begegnung der beiden Interaktionspartner zeitbasiert. Die Erkenntnisse dieser Vorarbeiten werden in Artikel 4 vereint und die implizite und explizite Kommunikationsstrategie unter Berücksichtigung des modellierten Kommunikationszeitpunktes separat und kombiniert bezüglich deren Potenzial zur Steigerung der Verkehrssicherheit und der Verkehrseffizienz verglichen. Die Resultate zeigen, dass ein kombinierter expliziter und impliziter Kommunikationsansatz die menschliche Informationsverarbeitung bestmöglich unterstützt und die beiden anderen Strategien hinsichtlich der Verkehrssicherheit und der Verkehrseffizienz übertrifft.

Darauf aufbauend kombiniert die Thesis den Informationsfluss innerhalb des automatisierten Systems und der menschlichen Informationsverarbeitung mit den Erkenntnissen bezüglich der externen Kommunikation und der Reaktion des menschlichen Fahrers in einem geschlossenen Regelkreis. Dieser Ansatz beinhaltet fünf Prinzipien zur menschzentrierten Gestaltung externer Kommunikation und setzt den Grundstein für eine sichere und effiziente Interaktion im Engstellenszenario. Das automatisierte Fahrzeug sollte zeitbasiert explizit und implizit gemeinsam kommunizieren und dabei die notwendige Zeitspanne der menschlichen Informationsverarbeitung berücksichtigen. Des Weiteren muss das automatisierte Fahrzeug im Fall von Unsicherheit die Vorfahrt gewähren und darf während der Interaktion in keinem Fall das kommunizierte Manöver ändern.

Contents

Nomenclature

Acronyms

AV	Automated Vehicle
ADS	Automated Driving System
CRT	Choice Reaction Time
DDT	Dynamic Driving Task
dHMI	Dynamic Human-Machine Interface
eHMI	External Human-Machine Interface
HD	Human Driver
HMI	Human-Machine Interface
RQ	Research Question
TTA	Time to Arrival
V2V	Vehicle-to-Vehicle Communication

Symbols

Variable	**Unit**	**Description**
a	m/s²	Deceleration
$D_{AV-bottleneck}$	m	Distance of the AV to the Bottleneck
$D_{bottleneck}$	m	Length of the Bottleneck
D_{brake}	m	Braking Distance
$D_{HD-bottleneck}$	m	Distance of the Human Driver to the Bottleneck
$D_{sensory}$	m	Minimum Sensory Range Required
D_{stop}	m	Stopping Distance to the Bottleneck
TTA_{HD}	s	Time to Arrival of the Oncoming Human Driver
T_{AV}	s	Processing Latency of the Automated Vehicle
T_{CRT}	s	Information Processing Time of the Human Driver

$T_{lat.}$	s	Time Period from Steering Angle Input to Maximum Yaw Angle
$T_{long.}$	s	Time Period from Applying the Brake until the Braking Force is Fully Built Up
T_{Total}	s	Time Period from External Communication to Measurable Human Response
v_{HD}	m/s	Speed of Human Drive

1 Introduction

"Self-driving cars are the natural extension of active safety
and obviously something we should do."
~ Elon Musk

1.1 Urban Traffic: Potentials and Challenges of Automated Driving

Research offers the opportunity to create fundamental knowledge for society by analyzing and enhancing everyday situations, thus improving the daily lives of many people. This also applies to this thesis, as it studies the interaction at bottlenecks in urban road traffic, a scenario that most people are familiar with or even encounter daily due to the clear global trend towards urbanization and the growing urban population. With 30% of the global population living in urban areas in 1950, this share increased to 55% by 2018 and is estimated to grow to 68% by 2050 (United Nations, 2018a, 2018b). While 82% (Urmersbach, 2020) of the population in North America lived in urban areas in 2018, this was 74% in Europe and only 50% in Asia (United Nations, 2018a, 2018b), where urbanization is still estimated to increase to a level greater than 74% in half of the countries in 2050 (United Nations, 2018a). In Germany, about 77.4% of the population lived in urban space in 2019 (Rudnicka, 2020), which is characterized by a large number of medium-sized cities complemented by several major cities (Hipp, Bengler, Kressel, & Feit, 2018),

Due to the growing level of urbanization, the self-organized, chaotic traffic system (Färber, 2015) and the associated problems become increasingly important. The high number of complex heterogeneous traffic situations (Hipp et al., 2018) results from diverse infrastructure consisting of different signalized and unsignalized intersections or roundabouts, which are connected by a wide variety of road types, such as arterial roads, distributor roads, high streets, or local streets (Parkin, Clark, Clayton, Ricci, & Parkhurst, 2016). Pedestrian crossings and bicycle lanes, and a large range of traffic regulations further complement this diverse infrastructure. Moreover, conventional cars, buses, trucks, and vulnerable road users such as pedestrians and cyclists (Litman, 2019; Parkin et al., 2016) occupy this traffic space simultaneously leading to high temporal dynamics, short decision times among all actors, a lot of stimuli and information, and thus increased stress on road users (Hipp et al., 2018). Road traffic can be seen as a social environment with a multitude of interactions (Litman, 2019), where road users communicate with each other (Stanciu, Eby, Molnar, St. Louis, & Zanier, 2017) to reach their destinations safely and efficiently.

Within this environment, the integration of intelligent transportation solutions such as driving automation systems, shared mobility services, or demand-responsive transportation (Butler, Yigitcanlar, & Paz, 2020) is currently being driven by technology companies and traditional car manufacturers (Faisal, Yigitcanlar, Kamruzzaman, & Currie, 2019) in order to generate a more sustainable transportation system. These technologies offer the potentials to increase traffic safety, traffic efficiency, energy consumption, environmental impact, and accessibility (Butler et al., 2020) by sustainably reducing accident rates, travel times, and vehicle emissions while being accessible by everyone (Papa, Gargiulo, & Russo, 2017; Tomaszewska & Florea, 2018). In this regard, this thesis addresses driving automation systems from the pool of smart transportation solutions and analyzes their potentials in terms of traffic safety and traffic efficiency in the road bottleneck scenario (Section 1.2).

Regarding traffic safety, human errors are considered to be the main reason for 90% to 95% of road traffic accidents (Lajunen, Parker, & Summala, 2004) in the sense that the last event in the causal chain leading to the crash was an error of the human driver (Singh, 2015). In this context, human errors can be classified into recognition errors, decision errors, and driver performance errors (National Highway Traffic Safety Administration, 2008) and could be caused by inattention, distraction, excessive speed, or misjudgments which increase the likelihood and severity of accidents (Fagnant & Kockelman, 2015; Thomas, Morris, Andrew, Talbot, Rachel, & Fagerlind, 2013). By relieving the driver from the driving task driving automation systems are considered to have the potential to increase traffic safety by avoiding human errors (Arbib & Seba, 2017; Greenblatt, 2016; Marti, Miguel, Garcia, & Perez, 2019). Compared to human drivers, automated vehicles (AVs) are better at detecting objects (Millard-Ball, 2018), react more quickly to their surroundings, and could consequently prevent collisions (Parkin et al., 2016). Additionally, AVs behave according to the applicable traffic regulations, adhere to speed limits, and maintain safe distances from other road users (Chaloupka & Risser, 2020). For these reasons, AVs have the potential to reduce crash rates by up to 90% as their market penetration increases (Fagnant & Kockelman, 2015; McKinsey&Company, 2016). However, until this goal can be achieved, a wide variety of safety engineering disciplines need to be coordinated to guarantee the safety of AVs in real-road traffic (Koopman & Wagner, 2017).

Regarding traffic efficiency, travel time in 15 German cities and regions was on average more than 20% longer in 2020 compared to congestion-free traffic (TomTom International BV, 2020). The implementation of AVs may reduce these time losses (Chaloupka & Risser, 2020) since smoother braking maneuvers and speed adjustments result in a harmonic traffic flow (Hipp et al., 2018), reduce traffic-destabilizing stop-and-go waves (Fagnant & Kockelman, 2015; Sivak & Schoettle, 2015), and avoid traffic congestion (Gasser, Schmidt, Bengler, Diederichs, & Flemisch, 2015).

Since this thesis focuses on the effects of AVs on traffic safety and traffic efficiency, additional potentials are only briefly summarized. In addition to an increase in driving comfort (Gasser et al., 2015), the more efficient traffic flow offers environmental benefits by reducing vehicle emissions in addition to saving time (Stern et al., 2019; Tate, Hochgreb, Hall, & Bassett, 2018; Wadud, MacKenzie, & Leiby, 2016). Furthermore, AVs offer new mobility options to individuals who currently face mobility limitations (Beza & Zefreh, 2019).

All these positive aspects suggest that Elon Musk is right in his quote at the beginning of this chapter and that there are no arguments against the introduction of AVs in road traffic. However, it is important to bear in mind that, in contrast to the potentials created by traffic automation, several challenges need to be solved before AVs can be successfully introduced on a broad scale. The aforementioned large number of diverse and differently behaving road users in the complex, highly dynamic traffic environment complicates perception and sensory recognition. Weather conditions such as rain, fog, or snow can lead to perception errors and consequently to accidents. In addition, AVs must operate during varying light and visibility conditions at day, at night, or in partial sunlight. They must cope with visual obscurations, shadows, and reflections. (Fagnant & Kockelman, 2015; Marti et al., 2019)

Additionally, motorized vehicles have long lifetimes before they are replaced and it will take decades for AVs to prevail over conventional vehicles (Lavasani, Jin, & Du, 2016; Litman, 2019). Therefore, the introduction of AVs will initially lead to mixed traffic consisting of conventional human road users and AVs with different levels of automation (Chaloupka & Risser, 2020; Gasser et al., 2015). The challenge arising is to integrate AVs smoothly into existing traffic for example by mimicking the behavior of human drivers (Juhlin, 1999) and by communicating with the surrounding road users in a comprehensible manner. However, this endeavor is only possible to a limited extent, as the driving automation system takes over longitudinal and lateral vehicle guidance which may lead to a driving style that differs from that of human drivers (Chaloupka & Risser, 2020; Färber, 2015). Furthermore, from a certain level of automation, passengers may engage in non-driving related activities such as reading the newspaper or playing on their smartphones and are no longer available for communication with other road users (Hecht, Darlagiannis, & Bengler, 2019; Klingegard, Andersson, Habibovic, Nilsson, & Rydstrom, 2020; Körber, Gold, Lechner, & Bengler, 2016). The deviating driving behavior and the distracted passengers may result in changes in the interaction and therefore create the need for new interaction concepts. This is particularly relevant where road users will occupy the same space in the course of the interaction and therefore one partner needs to offer space to the other (Haddington & Rauniomaa, 2014; Heymann & Degani, 2019; Markkula et al., 2020). In this context, typical scenarios for researching the interaction of AVs and human road users include intersections (Imbsweiler, Stoll, Ruesch, Baumann, & Deml, 2018), pedestrian crossings (Clercq, Dietrich, Núñez Velasco, Winter, & Happee, 2019; Fuest, Michalowski, Träris, Bellem, & Bengler, 2018), merging on motorways (Kauffmann, Winkler, Naujoks, & Vollrath, 2018; Potzy, Feinauer, Siedersberger, & Bengler, 2019; Potzy, Feuerbach, & Bengler, 2019), and road bottlenecks (Habibovic, Andersson, Lundgren, Klingegård, & Englund, 2018; Kaß et al., 2020b), with the latter being largely unexplored and therefore investigated in this thesis.

1.2 The Bottleneck Scenario: Relevance, Rules, and Assumptions

A bottleneck in road traffic is defined by the extent and duration of the narrowing. According to German law, a bottleneck is present if an obstacle narrows a limited section of the roadway for a limited period of time (Heinrich, 2006) where otherwise there would be sufficient space for oncoming traffic. With this definition, a roadway narrowed along its entire length due to double-parked vehicles or a permanent construction site that is separated from the roadway is not considered a bottleneck. However, this section also includes findings of permanent constrictions extending over a limited distance because the interaction of road users is the same in these scenarios.

This thesis focuses on bottlenecks caused by stopping and double-parking vehicles for example due to delivery traffic (Yannis, Golias, & Antoniou, 2006), as these are most frequent in reality (Heinrich, 2006). Around the globe, double-parking is a common problem, especially in big cities. In New York City, double-parking was present with over 500,000 violations and an amount of 5% of all parking violations in 2014 (Gao & Ozbay, 2016). In Athens, parking shortage causes 8,000 parking violations including double-parking (Kladeftiras & Antoniou, 2013). In Lisbon, full parking spaces lead to the fact that double-parking is not a marginal phenomenon and there is often more than one double-parking vehicle on the same stretch of road (Lu, B. and Viegas, & J., 2007).

Conflicts and critical situations arise in road traffic predominantly in areas that will be occupied simultaneously by two or more road users in the course of the encounter (Markkula et al., 2020). This fact also applies to bottlenecks. Simulations support this finding and show that the probability of incidents and accidents increases near double-parking vehicles (Lu et al., 2007). However, real accident data at road bottlenecks are rarely available and, to my knowledge, have only been collected by Gerlach, Breidenbach, and Rudolph (2011). The study considered traffic events at 300 selected constructional bottlenecks in cities with less than 30,000 inhabitants. The data were obtained from police-registered accidents at 63 bottlenecks from 2005 to 2007. During this period, accidents were recorded at 24 bottlenecks, which corresponds to an average accident rate of 7.6 accidents/million km. Moreover, 92% of accidents involve only minor damage to vehicles crashing predominantly in longitudinal traffic with vehicles traveling in the opposite direction due to misjudgments of the drivers regarding the smaller lane width or rear-end collisions during increased traffic volumes. In conclusion, passing through bottleneck scenarios is safe in conventional road traffic due to the low accident probability and the low severity in the event of an accident. (Gerlach et al., 2011)

In addition, double-parking has a negative impact on traffic efficiency that is not only limited to the area around the bottleneck but could also be transmitted to other roadways (Lu et al., 2007). Double-parking contributes to traffic congestion on urban streets and reduces road capacity (Galatioto & Bell, 2007; Gao & Ozbay, 2016; Portilla, Oreña, Berodia, & Díaz, 2009). Moreover, it leads to a reduction in the average vehicle speeds, causes traffic delays (Gao & Ozbay, 2016; Kladeftiras & Antoniou, 2013), and consequently results in an increase in travel time (Gao & Ozbay, 2016; Guo, Gao, Yang, Zhao, & Wang, 2012; Portilla et al., 2009). In this context, traffic delays due to double-parking even increase with increasing traffic volume (Gerlach et al., 2011; Lu et al., 2007). Accompanying this, the high stopping rates at bottlenecks lead to an increase in pollutant emissions compared to free driving (Galatioto & Bell, 2007; Gerlach et al., 2011). Avoiding frequent stop and go would reduce emissions of carbon dioxide, carbon monoxide, and hydrocarbon and thus would be beneficial for the environment (Kladeftiras & Antoniou, 2013).

Considering the presented findings, the relevance of the bottleneck scenario due to double-parking vehicles and its negative consequences for traffic efficiency is evident. On this basis, the question arises of how AVs should be implemented to increase traffic efficiency in the bottleneck scenario while maintaining or even enhancing the high level of traffic safety that is already present today.

A key factor in achieving these goals and successfully integrating AVs is the type of bottleneck and the associated traffic regulations that must be adhered to by the driving automation system. At bottlenecks where only one lane is narrowed due to a double-parked vehicle, the driver on the side with the obstacle has to yield the right-of-way to oncoming traffic following §6 of the German road traffic regulations. According to §8, yielding the right-of-way must be communicated with sufficient lead time using the driving behavior, for example by moderate speed. The bottleneck may only be passed if the driver who has the right-of-way is neither endangered nor significantly impeded. (Straßenverkehrs-Ordnung, 2013)

In bottleneck scenarios with one double-parked vehicle on each side of the road §6 is not applicable (Heinrich, 2006). In these cases, a distinction must be made as to whether the available street is wide enough to allow both encountering vehicles to pass through the bottleneck at the same time. If a simultaneous passage is not possible, the driver who does not have to use the oncoming lane has priority. If both interaction partners have to use the oncoming lane, the one who reaches the bottleneck first obtains the right-of-way (Heinrich, 2006). However, if both road users arrive at the bottleneck virtually at the same time, the right-of-way is not regulated and the drivers must agree on it according to §11 (Straßenverkehrs-Ordnung, 2013). In any case, §1 applies in bottleneck scenarios narrowed on both sides, which states that caution and mutual consideration are required and all road users must behave without harming, endangering, or impending others (Straßenverkehrs-Ordnung, 2013).

Due to the potentially higher communication needs, this thesis analyzes the interaction between the AV and the human driver at unregulated bottlenecks narrowed on both sides of the road. All studies integrated in this thesis (Section 4-7) refer to the bottleneck scenario in Figure 1. The bottleneck is located on an urban link road with one lane in each direction, with a cross-section and layout based on a residential street in the center of Munich (Viktoriastraße 15-21, 80803 Munich). This street type allows parking on the roadway, which increases the probability of bottlenecks, and generally has a speed limit of 30 km/h (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2006). The bottleneck consists of one double-parked vehicle on each side of the road, placed at the same level. Due to the simultaneous arrival of the AV and the human driver, the right-of-way through the bottleneck is unregulated. In order to increase traffic efficiency and ensure traffic safety, the AV communicates the right-of-way to the human driver, who responds by adjusting the driving behavior.

The bottleneck scenario of this thesis seems to be artificially designed and less relevant since it does not cover the variety of real road traffic. However, the exact definition of the parameters in the scenario was deliberately chosen for methodological reasons. The restriction to only two interaction partners with exactly simultaneous arrival at the bottleneck allows gaining fundamental insights regarding the basic mechanisms of interaction and the sequence of actions during the encounter and based on this to derive recommendations for the communication of AVs.

To complete the scenario specification, a definition of both interaction partners is necessary to specify the capabilities of the AV and the demands on the human driver due to the dynamic driving task in the present bottleneck scenario.

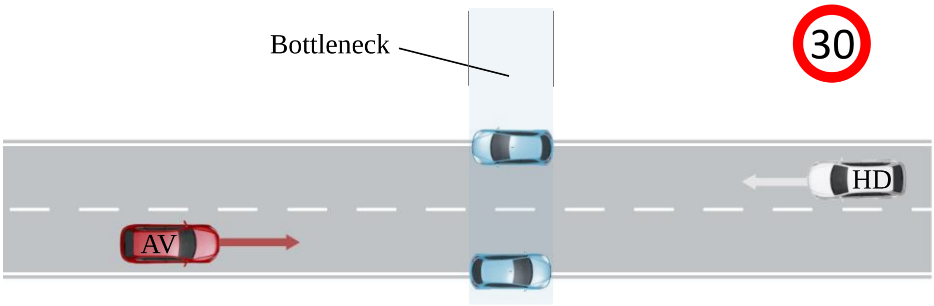

Figure 1: The bottleneck scenario narrowed on both sides due to double-parked vehicles. The automated vehicle (*AV*) and the human driver (*HD*) arrive simultaneously.

Human Driver (HD):

The oncoming human driver approaches the bottleneck in a conventional vehicle with automation level 0 (SAE International, 2018) (see Section 2.2.1), perceives the external communication of the automated vehicle, processes it, and adjusts the human driving behavior accordingly.

Automated Vehicle (AV):

The automated vehicle is capable of automatically driving through the bottleneck scenario. It detects all relevant objects, predicts the future course of the situation, and communicates the right-of-way to the human driver. The driving automation system is specified based on its capabilities in the bottleneck scenario and not according to a specific automation level. The necessary automation skills are available from automation level 2 (SAE International, 2018) (see Section 2.2.1).

1.3 Thesis Outline

Figure 2 illustrates the interaction (Section 2.1) between the AV and the human driver in the bottleneck scenario in a closed loop and additionally indicates the structure and content of this thesis. During the interaction, the human driver and the AV are affected by the driving environment, which mainly consists of the characteristics of the bottleneck scenario (Section 1.2). The AV approaches the road bottleneck at a certain automation level (Section 2.2.1) determining the extent to which the driving automation technology (Section 2.2.2) can perform the dynamic driving task automatically. Given a certain automation level, the sensory system of the AV detects the bottleneck and the oncoming human driver, and the software components predict the encounter and decide whether to yield right-of-way or to insist on it. The actuators of the AV execute this decision in the form of implicit (Section 5 & 7) and explicit (Section 4 & 7) external communication (Section 2.2.3). The human driver performs all parts of the human driving task that are necessary to pass through the road bottleneck (Section 2.3.1) and perceives, processes, and reacts (Section 2.3.2) to the AV's external communication by adapting the longitudinal and lateral dynamics of the conventional vehicle (Section 4, Section 5, Section 7) which in turn is detected by the AV's sensory system. The studies included in the main part of this thesis (Section 4-7) show how the interaction can be described in sufficient detail and how the communication of the AV should be designed to optimize the interaction with the human driver in the bottleneck scenario. Based on these findings, this thesis resumes the concept of the AV-HD control loop (Section 8.2), integrates the study results, and offers a guideline expressed in five principles for optimal external communication design (Section 8.2.1-8.2.5).

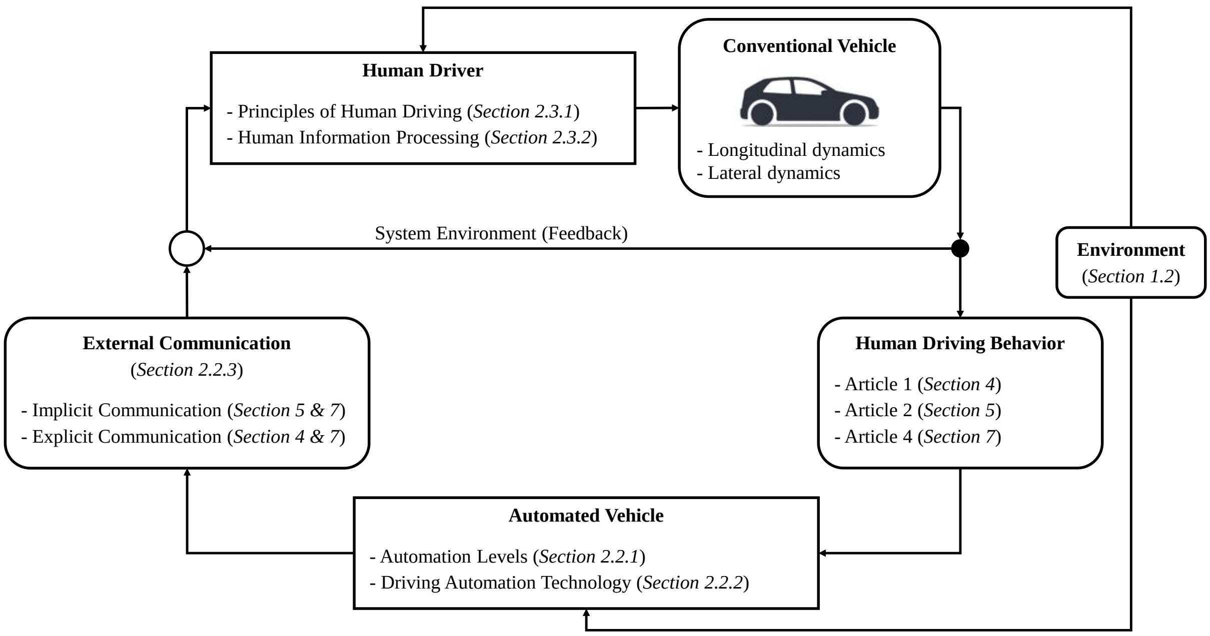

Figure 2: Closed loop of AV-HD interaction in the bottleneck scenario including the thesis structure.

2 Interaction at Bottlenecks: Negotiation between Human and Automation

"The gadget-minded people often have the illusion that a highly automatized world will make smaller claims on human ingenuity than does the present one ... This is palpably false."
~ Norbert Wiener

2.1 Principles of Interaction in Road Traffic

Communication and interaction share several definition characteristics and are often used synonymously (Risser, Zuzan, Tamme, Steinbauer, & Kaba, 1991). Furthermore, communication has been defined in more than 160 different terminologies (Merten, 1977a, 1977b). For these reasons, it is essential to define the terminology used in this thesis right from the start.

Communication: (VandenBos, 2015, p. 215)

"The transmission of information, which may be by verbal ... or nonverbal means"

The term communication considers the unidirectional intentional transmission of information (Bentele, Brosius, & Jarren, 2013) between the two systems AV and human driver. Communication does neither consider how the receiver of the message reacts to its content nor the mutual interdependence between both systems. In today's road traffic, communication between road users helps to resolve potential conflicts (Stanciu et al., 2018) and maintain the flow of traffic (Chaloupka & Risser, 2020).

"Who says what in which channel to whom with what effect?" (Lasswell, 1948). This quote structures communication into its elements communicator, message, medium, recipient, and effect (Maletzke, 1998) and thus describes the basis of the classic transmitter-receiver communication models. These models are suitable for reducing the complex relationships in communication processes to the mentioned essential elements and for analyzing communication in detail (Röhner & Schütz, 2016; Zwicker, Petzoldt, Schade, & Schaarschmidt, 2019). The communication model according to Shannon and Weaver (Shannon, 1948) (Figure 3) originates from communications technology and considers communication to be the exchange of information. The model is used in the following to illustrate the communication processes in the bottleneck scenario.

The information source produces a message and sends it to the transmitter, which converts the message into a signal. This signal is transmitted to the receiver via a medium or channel. The receiver decodes the signal, extracts the original message, and forwards it to the destination. (Shannon, 1948)

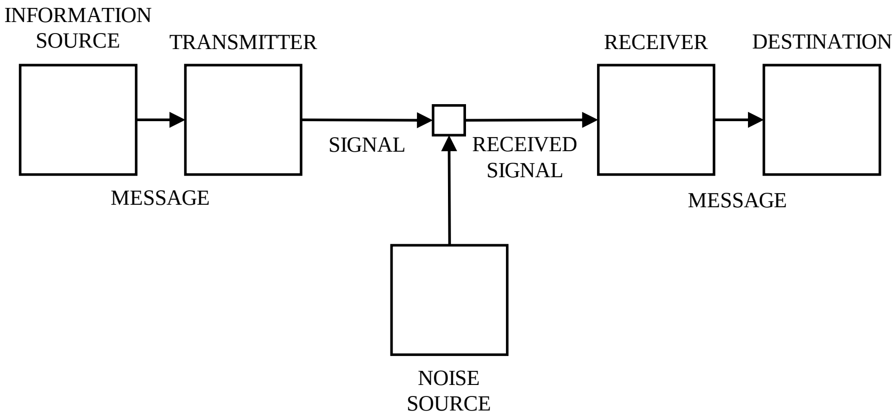

Figure 3: Communication model according to Shannon (1948)

In the bottleneck scenario, the software of the driving automation system acts as the information source, since it plans the message to yield the right-of-way or to insist on it and forwards it to the actuator system (transmitter) to transmit the message. There, the external human-machine interface (eHMI) or the driving dynamics actuators encode the AV's message into its external communication (signal) and send the stimuli via the visual channel to the receiver. When generating the signal, the software module of the driving automation system (information source) has to consider the capabilities and limitations of external communication (signal) and the perceptual limitations of the human driver (Maletzke, 1998). The driver's eyes and brain (receiver) receive the signal and extract the original message from external communication. The message reaches the human driver (destination), who in turn communicates to the AV. During the transmission process to the receiver, visibility obstructions or weather conditions may degrade the signal perceptibility and other road users may divert attention from the signal and prevent signal transmission. All these factors act as noise sources in the bottleneck scenario that may irrecoverably distort the signal.

In road traffic, signals could be transferred using formal and informal communication (Hölzel, 2008). Whereas formal traffic-specific communicational means are defined by road traffic regulations and include the turn signal to indicate direction or the brake light to saliently communicate vehicle deceleration, informal communication is socially regulated, contains the use of gestures, facial expressions, or speed changes, and is interpreted due to road users' experiences (Portouli, Nathanael, & Marmaras, 2014). On the one hand, informal communication is especially prominent in negotiation situations (Färber, 2015), such as the bottleneck scenario, and enables efficient and safer behavior on the road (Müller, Risto, & Emmenegger, 2016). On the other hand, the characteristic of informal communication is highly situational (Färber, 2015), may change quickly in complex situations, and may lead to misunderstandings due to its partly ambiguous usage (Risser, 1985). Following Merten (1977b), Färber (2015) classified the informal communication channels into the categories schema formation, non-verbal communication, and anticipatory behavior which implies that road user actions indicate their future behavior. In conventional traffic, this category prevails during interactions in the bottleneck scenario where human drivers communicate predominantly by implicit means (Imbsweiler, Ruesch, Palyafári, Deml, & Puente León, 2016; Rettenmaier, Requena Witzig, & Bengler, 2019). Provided a driver enters the bottleneck scenario first, the driver takes the offensive role and accelerates or maintains speed to insist on right-of-way (Rettenmaier, Requena Witzig, & Bengler, 2019). The driver who arrives second acts defensively by decelerating or braking to a standstill to yield the right-of-way. This mutual communication between both human drivers is designated as interaction.

Interaction: (VandenBos, 2015, p. 549)

"*A relationship between two or more systems, people, or groups that results in mutual or reciprocal influence*"

Interaction is based on the principle of reciprocity, in which the activity of one system influences the activity of the other systems (Goffman, 1959; Risser et al., 1991). Interaction between the AV and the human driver is understood as a cyclic process (Thalya, Kovaceva, Knauss, Lubbe, & Dozza, 2020) including the communication of one interaction partner and the subsequent reaction of the other partner or the ongoing reciprocal interaction of both systems. In this context, road traffic interaction bases on experiences and expectations of road users (Röhner & Schütz, 2016; Swan & Owens, 1988) and is characterized by their anonymity, short interaction periods, and limited communication options (Šucha, 2014).

The concept of reciprocity is also included in the HMI-framework (Figure 4) which visualizes the complexity and interdependencies of different human-machine interfaces (HMIs) of future AVs. The model represents the interaction as a closed loop between the AV and its interaction partners and additionally entails factors influencing the selection of HMI types and their content. The AV consists of the components of internal and external communication and contains the five different HMIs (ISO, 2019) that are affected by the characteristics of the influencing factors. The internal communication includes the vehicle HMI (vHMI), the automation HMI (aHMI), and the infotainment HMI (iHMI) and is not considered further in this thesis. External communication is used to communicate the right-of-way to the human driver. It consists of the dynamic HMI (dHMI) representing implicit communication via the AV movement and the explicit communication via external HMIs (eHMI). The influencing factors include the static infrastructure in the bottleneck scenario (Section 1.2), the functional capabilities of the driving automation system (Section 2.2.1), and the dynamic elements consisting of the weather and light conditions, the double-parked vehicles representing the bottleneck, and the oncoming human driver as an external communication partner. (Bengler, Rettenmaier, Fritz, & Feierle, 2020)

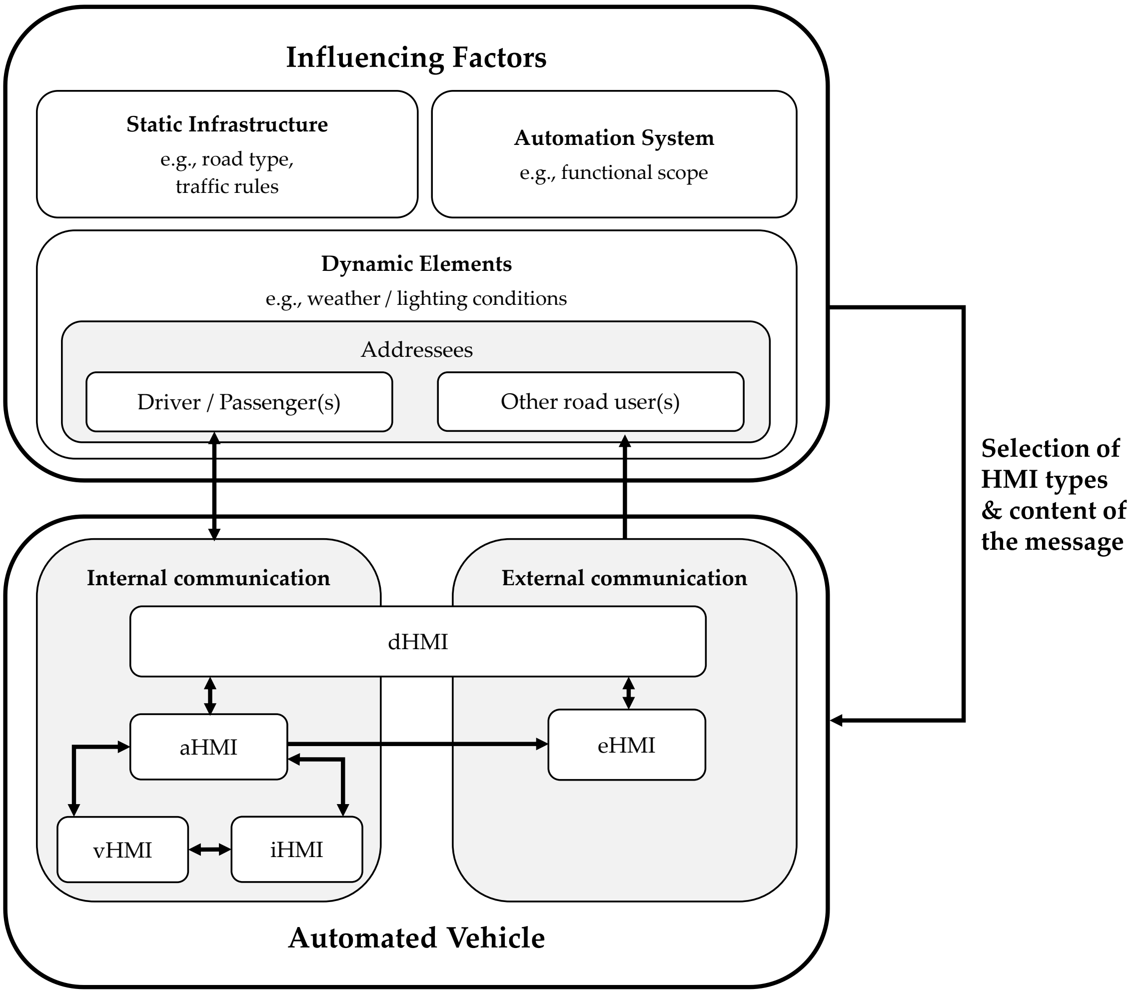

Figure 4: The HMI framework structures the relationship between the AV including its different HMIs and the factors influencing the communication of the AV in a closed loop. (Bengler et al., 2020)

Cooperation: (VandenBos, 2015, p. 251)

"A process whereby two or more individuals work together toward the attainment of a mutual goal or complementary goals"

According to Hoc (2001), the following two minimum requirements must be met for cooperation. (1) "Each one strives towards goals and can interfere with the other on goals, resources, procedures, etc." (Hoc, 2001, p. 515). In the road bottleneck scenario, the AV and the human driver compete for the resource of traffic space when passing through the bottleneck area. (2) "Each one tries to manage the interference to facilitate the individual activities and/or the common task when it exists." (Hoc, 2001, p. 515). This second requirement of achieving a common task or goal coincides with other cooperation definitions from the literature (Argyle, 2014; Bengler, 2019; Schmidtler, 2018; VandenBos, 2015). The authors state that a common understanding is a basic prerequisite for the common goal achievement and the success of the cooperation (Grice, 1975; Marwell & Schmitt, 1975; Vanderhaegen, Chalmé, Anceaux, & Millot, 2006). For the bottleneck scenario, this would mean that the human driver and the

AV each understand the other's communication, predict the other's intended behavior, and thus cooperate.

The title of this thesis mentions the term “interaction”. This terminology was chosen deliberately because the studies included in this thesis investigate the communication of the AV and the resulting changes in human driving behavior, in other words, the mutual exchange of information. In my opinion, cooperation does not apply for two reasons. First, it cannot be assumed that the AV, its passenger, and the oncoming human driver share common goals such as an efficient passage through the bottleneck. For some, it would probably be sufficient to pass the bottleneck themselves first regardless of the needs of the interaction partner. Second, the human interaction partners did not equally understand the communication strategies of the AV (Rettenmaier & Bengler, 2021). This shared social knowledge of symbols and meanings, however, is seen as a basic prerequisite for the joint achievement of goals and thus for cooperation and must be present in all interaction partners (Röhner & Schütz, 2016) to make their actions mesh smoothly and reduce accidents (Swan & Owens, 1988).

2.2 Automated Vehicle: Acting within the Limits of Technical Feasibility

2.2.1 Automation Levels

The automation of system functionalities involves a computer taking over parts or the entirety of tasks that previously had to be performed by a human operator (Parasuraman, 2000; Parasuraman & Riley, 1997; Parasuraman, Sheridan, & Wickens, 2000; Seppelt et al., 2018). In the context of automated driving, vehicle automation takes over parts of the vehicle guidance, which in conventional vehicles is performed by the human driver. The automation of individual tasks varies not only between the two extremes of full human performance and full automation (Flemisch, Kelsch, Löper, Schieben, & Schindler, 2008). By dividing the task to be automated into individual subtasks and assigning them to the human operator or the technical system (Seppelt et al., 2018), different levels of automation emerge that differ in the degree of automated task execution (Hoc, Young, & Blosseville, 2009). Consequently, a spectrum of different automation levels spans between the two extremes of full human performance and full automation (Parasuraman et al., 2000).

Sheridan (1992) breaks down task automation into ten levels by folding together various relevant dimensions (Sheridan, 1998), where the degree of automation increases from level 1, full human task performance, to level 10, full automated performance (Figure 5). However, since it is difficult to merge all relevant dimensions of different tasks (Sheridan, 1998), the scale of degrees of automation is only applicable to decision-advising functions concerning actions to be performed by humans (Wickens, 2018). For this reason, Parasuraman (2000) structures automation according to the different stages of human information processing (information acquisition, information analysis, decision and action selection, action implementation) (Section 2.3.2), where each stage can be automated to different degrees (Parasuraman, 2000; Wickens, Li, Santamaria, Sebok, & Sarter, 2010) by adding Sheridan's

(1992) automation levels as a second dimension (Figure 5). This creates a framework that allows describing the automation of one stage of information processing, the combination of different degrees of automation at multiple stages, or the automation of all four stages. Consequently, a system can be automated to varying degrees within each of the four stages of information processing which in tum defines the four automation types of *acquisition*, *analysis*, *decision*, and *action* automation (Parasuraman et al., 2000). Acquisition automation corresponds to the first stage of human information processing and refers to the acquisition of input data. In the context of automated driving, the acquisition of relevant objects from the environment by the vehicle sensor system and their visualization for the AV's passengers can be assigned to acquisition automation. In analysis automation, algorithms are applied to the incoming data to enable the prediction of the future course of the task. In automated driving, for example, the system predicts and plans its possible future trajectories based on the sensory input data. In decision automation, the best option is selected from the predicted alternatives. In this case, the driving automation system partially supplements or completely replaces the human decision-making process. In the bottleneck scenario, the AV selects the best trajectory and decides to yield or insist on the right-of-way. In the final stage, action automation, the selected option is executed. The software component of the driving automation system transfers the selected trajectory to the actuators, which implement it on the road.

With the automation of individual functions of vehicle guidance in advanced driver assistance systems and the development of higher driving automation systems, there have been several approaches to apply the idea of the automation spectrum to the vehicular context (Flemisch et al., 2008; Gasser, 2012; Hancock et al., 2020; Hoeger et al., 2008; National Highway Traffic Safety Administration, 2013; Noy, Shinar, & Horrey, 2018; Reilhac, Millett, & Hottelart, 2016; SAE International, 2018; Shi, Gasser, Seeck, & Auerswald, 2020). Distinct automation levels between the two extremes of fully manual and fully automated guidance were introduced, firstly to describe the distribution of tasks between the human and automation during the trip and thus to define their respective roles. Secondly, these taxonomies

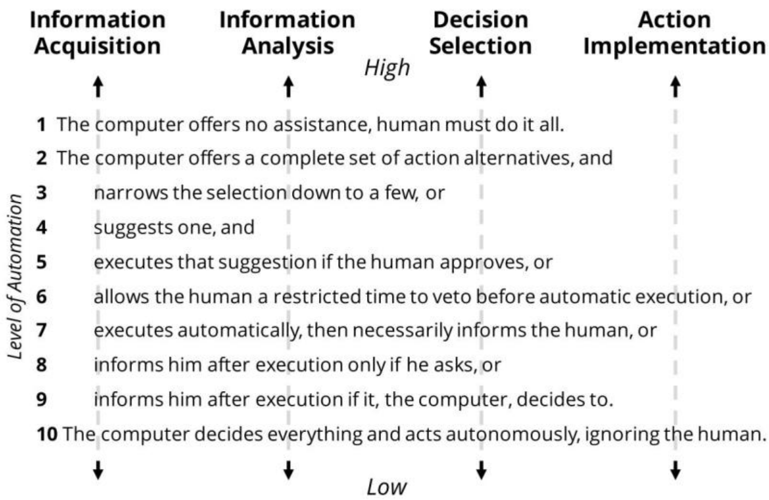

Figure 5: Types of automation according to Parasuraman (2000) in combination with the automation levels of Sheridan (1992). The illustration of this combined approach originates from Körber (2018).

allow to specify the capabilities of the driving automation system (Flemisch et al., 2008), for example in the bottleneck scenario. Although users of AVs have difficulties in distinguishing between the commonly used five to six different levels of automation within the mentioned spectrums and behaving according to their role (Homans, Radlmayr, & Bengler; Noy et al., 2018; Seppelt et al., 2019), this thesis applies the widely used taxonomy of SAE International (2018) (Table 1). This approach allows to define the necessary capabilities of the driving automation system and thus the minimum technical requirements for the interaction in the bottleneck scenario.

SAE International divides the range of vehicle automation into 6 levels (Level 0 - Level 5). With an increasing automation level, the amount of the dynamic driving task (DDT) that can be performed independently by the driving automation system increases.

In Level 0, the driver performs the entire DDT and is thus responsible for lateral and longitudinal vehicle motion control. The driver monitors the environment, detects and classifies obstacles and other road users, and reacts appropriately. In this level of automation, the driver is also the fallback in the event of critical situations. In Level 1, the driving automation system performs either the longitudinal or lateral vehicle motion control. All other components of the DDT remain with the driver, who also

Table 1: Levels of automation according to SAE International (2018)
(DDT: dynamic driving task; OEDR: object and event detection and response; ODD: operational design domain)

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

acts as a fallback level. However, automated functionalities are not available everywhere without restrictions. In Level 2, the AV performs the entire motion control. However, the driver still has the task of monitoring the vehicle guidance and the environment, since automation failures can occur at any time. Consequently, the driver is still the fallback level. From Level 3, the Automated Driving System (ADS) performs the entire DDT, including environmental monitoring. The driver acts as a fallback-ready user who, in the event of a system limit, is requested to intervene and to take over vehicle motion control. In addition to the functionalities of Level 3, the ADS acts as a fallback level in the event of system limits in Level 4. The ADS, therefore, does not expect the user to take over vehicle control after a request to intervene. Level 5 has the same functionalities as Level 4, but these are available everywhere and at all times. (SAE International, 2018)

In the bottleneck scenario, the oncoming human driver performs the entire DDT driving in a vehicle with SAE Level 0 without any support from a driving automation system. The AV must be able to detect the environment in the bottleneck scenario in acquisition automation, predict the course of the situation in analysis automation, select the best option in decision automation, and communicate the right-of-way in action automation. Thus, it is not important what specific automation level the AV is at, but that the underlying driving automation technology can handle the vehicle motion control and the interaction in the bottleneck scenario. Consequently, the AV may have a driving automation system from Level 2 upwards, where the driver or user does not intervene in vehicle motion control during the interaction.

2.2.2 Driving Automation Technology

The driving automation system can be subdivided into its hardware and software components (Figure 6) (Pendleton et al., 2017). The hardware consists of sensors that receive information from the environment and actuators that execute the AV movements in the environment. In addition, vehicle-to-vehicle (V2V) communication is considered as part of the hardware, as it collects information from other AVs to render safer and smoother navigation. However, this thesis does not discuss V2V communication in more detail due to its lack of relevance when interacting with the oncoming human driver in a conventional vehicle with SAE Level 0 in the bottleneck scenario. The software side of the driving automation system itself is structured into three parts: Perception, Planning, and Control (Marti et al., 2019; Pendleton et al., 2017).

Perception: ***"Where am I and what is happening around me?"*** (Zucker & Ghose, 2019)

This question involves two different aspects. On the one hand, the AV localizes its position in the environment (Pendleton et al., 2017). On the other hand, the AV acquires information from the environment and derives relevant features in environmental perception. In addition to locating obstacles and road markings, it recognizes and classifies objects and determines their speed and movement direction (Marti et al., 2019; Pendleton et al., 2017).

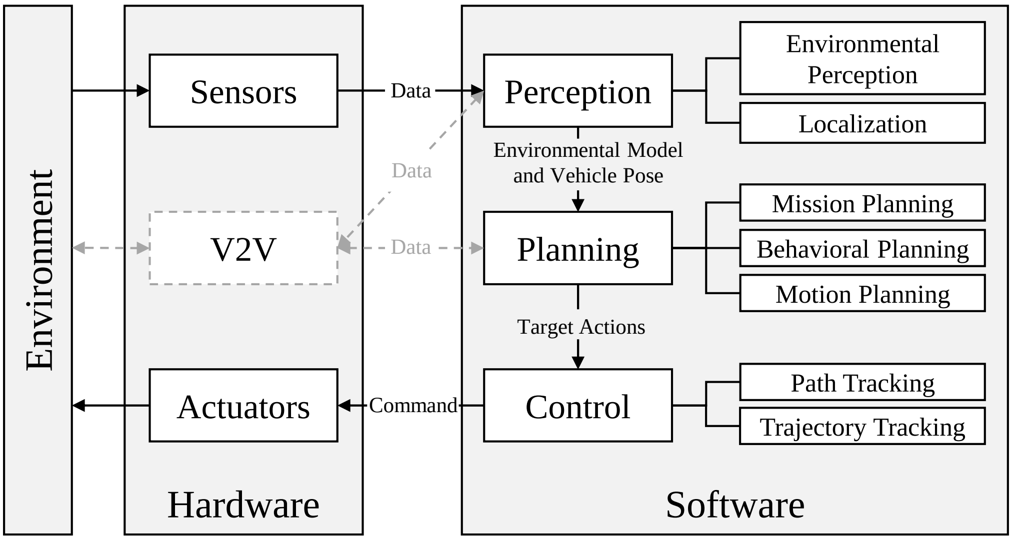

Figure 6: Structure of the driving automation system subdivided into hardware and software components (Pendleton et al., 2017). Vehicle-to-Vehicle (V2V) communication is not considered in this thesis.

Planning: ***"Given what's around me, what should I do next?"*** (Zucker & Ghose, 2019)

Planning receives information about the environment and the AV's position and orientation and it determines how to get to a defined destination. For this purpose, the AV considers other detected road users and obstacles. In order to improve the prediction of other road users' future trajectories, the time has to be included as an additional dimension within the calculation. (Pendleton et al., 2017)

Control: ***"How should I go about doing what I planned?"*** (Zucker & Ghose, 2019)

The AV performs the planned maneuver and forwards the signals to the actuators to generate the desired driving behavior. (Pendleton et al., 2017)

In the bottleneck scenario, the sensory range of the AV has to be sufficient to detect the bottleneck itself and the oncoming human driver, including the relative speed and acceleration, in order to communicate the right-of-way. In this complex and highly dynamic environment, single sensor solutions are not suitable (Marti et al., 2019) and it is necessary to combine the strengths of individual sensors in a typical configuration (Figure 7). As a result, a sufficiently detailed representation of the environment and all relevant road users can be achieved (Kernhof, Leuckfeld, & Tavano, 2018).

Ultrasound sensors are characterized by low weather dependency. Due to their short measuring range of 80 cm to 150 cm, ultrasound sensors are typically used in parking and side-view assistants. (Noll & Rapps, 2015)

Stereo cameras have a range of up to 100 m (Kirschbaum, 2015) and are used for object detection and object classification. The camera detects road lanes, moving objects such as other vehicles or pedestrians and can identify empty space. If several cameras are used simultaneously, depth information could be generated (Punke, Menzel, Werthessen, Stache, & Höpfl, 2015).

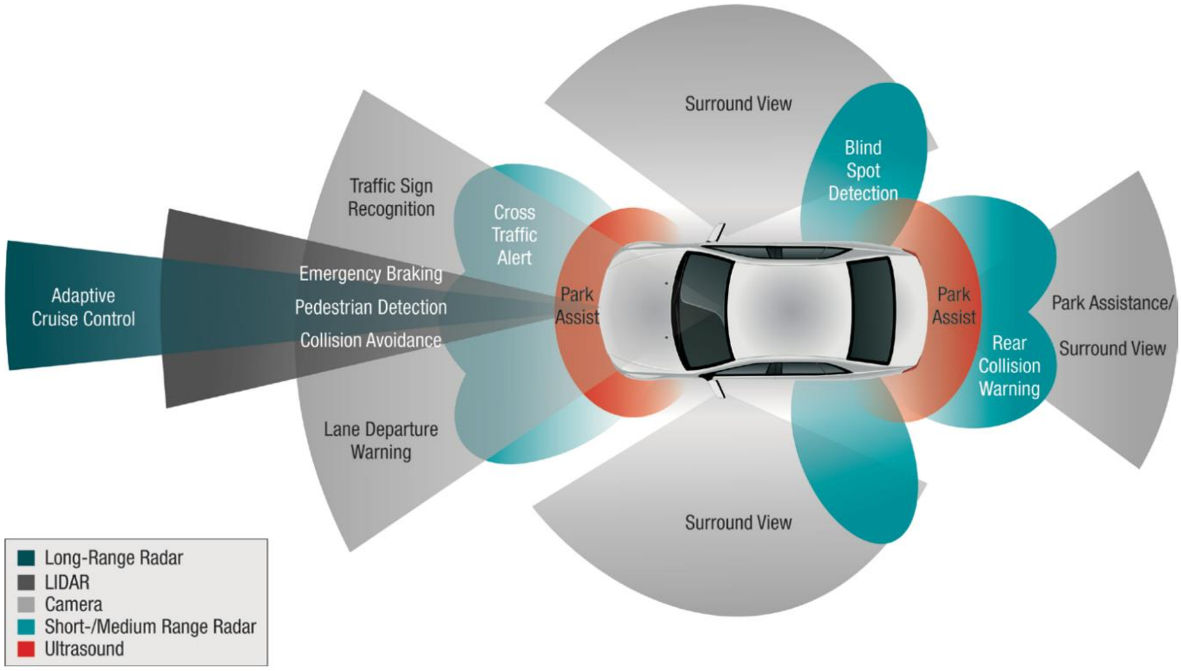

Figure 7: Typical sensor configuration of an automated vehicle. (Costlow, 2019)

Lidar sensors emit light pulses that are reflected by objects and received again by the sensor. Based on this elapsed time, lidars create three-dimensional digital maps of the environment. Lidars detect and classify objects in distances up to 200 m (Gotzig & Geduld, 2015; Marti et al., 2019) and measure objects' velocities and movement directions (Kernhof et al., 2018). Dark colors, a low vertical resolution, and weather conditions like rain and fog may pose problems for object detection using lidars (Marti et al., 2019).

Radar sensors are well suited to measure precise distances to individual objects, their velocities, and their direction along the straight line from the sensor to the target object. However, due to a lower angular resolution, there may be difficulties in separating individual objects. (Marti et al., 2019)

Long-range radars have a range of up to 250 m, which is beyond the capability of other sensors (Marti et al., 2019; Winner, 2015). Moreover, radars are largely independent of light and weather influences like rain, snow, darkness, and fog (Reina, Johnson, & Underwood, 2015).

Once the AV has detected the bottleneck and the oncoming conventional vehicle and once it has predicted the possible future encounter, it can communicate to yield the right-of-way or to insist on it. This raises the question of how the AV could communicate to interact safely and efficiently.

2.2.3 Implicit and Explicit Communication

Road traffic communication can be designed by specifying different dimensions (Colley & Rukzio, 2020). Clark (2020) stated that in order to achieve joint action, there must be a shared understanding of at least five different design dimensions. During interactions, all *participants* and their *roles* must be familiar to everyone and participants must have a shared understanding of the communication *content*, its *timing*, and the *location* (Clark, 2020). Building further on these five elements, Joisten, Freund, and Abendroth (2020) formulated six design dimensions (*Who*, *Why*, *In what situation*, *What*, *When*, *How*) also following the transmitter-receiver communication model of Shannon (1948) and specifying the external communication of AVs. In this thesis, the AV (*Who*) communicates the right-of-way (*What*) to the oncoming human driver in the bottleneck scenario (*What situation*) to interact safely and efficiently (*Why*). These four dimensions have already been sufficiently covered in the preceding chapters. This section mainly focuses on the *how*, the manner of communication, and in this context considers exclusively the visual communication channel.

AVs need to communicate right-of-way in a way that surrounding human road users can safely trust (Kitazaki & Myhre, 2015). Following this finding, the question arises whether AVs should mimic today's established road communication (Juhlin, 1999; Kauffmann, Raeth, Winkler, & Vollrath, 2017; Zwicker et al., 2019) without requiring explicit means (Schwarting, Pierson, Alonso-Mora, Karaman, & Rus, 2019) to be accepted (Hecker, Dai, & van Gool, 2019), or whether new technical devices will lead to safer, clearer, and more understandable interactions (Bazilinskyy, Sakuma, & Winter, 2020; Meyer, Miller, Hancock, Visser, & Dorneich, 2016). The resulting communication strategies include means attributed to *social signals*, which are developed for communication due to their effect on the message receiver, and to *cues*, which are object properties not specifically developed for communication based on which others can predict the AV’s future behavior (Mehu & Scherer, 2012). In road traffic, the indicator is a social signal because it is specifically designed to indicate the travel direction. A vehicle's deceleration is a cue because other road users can predict the right-of-way, while not being specifically designed to communicate it. In the field of AVs’ external communication, researchers make a similar distinction, differentiating *implicit* and *explicit* communication strategies (Fuest, Sorokin, Bellem, & Bengler, 2018).

Implicit communication

Implicit communication means that the AV’s message is contained in its driving behavior (Domeyer, Lee, & Toyoda, 2020; Fuest, Sorokin, et al., 2018; Moore, Currano, Strack, & Sirkin, 2019), which can consist of the conventional driving dynamics and additional vehicle movements specifically designed for external communication (Bengler et al., 2020; Brown & Laurier, 2017). Thus, the AV uses its movement to communicate by conveying its intentions or requesting actions from other road users (Markkula et al., 2020). In this context, the AV opens or closes gaps (Bengler, 2019) and provides space to interaction partners, for example, at road bottlenecks to yield the right-of-way. The interaction partners may in turn draw conclusions about the AV’s state and its intention based on the AV’s driving behavior (Dey & Terken, 2016). According to findings from human-robot cooperation, for successful communication, AV movements must satisfy the principles of predictability, the quality of reflecting the intentions of the driving automation system expected by the observer, and legibility, the quality of conveying the AV’s intention to the observer (Dragan, Lee, & Srinivasa, 2013).

An advantage of implicit communication in contrast to explicit communication is that surrounding road users are already familiar with communication about vehicle movements from conventional road traffic (Ackermann, Beggiato, Bluhm, & Krems, 2018; Risto, Emmenegger, Vinkhuyzen, Cefkin, & Hollan, 2017). Thus, human interaction partners might draw on accumulated experience when interacting with AVs and do not have to learn new communication strategies. Furthermore, implicit communication is visible from all sides of the AV (Ackermann et al., 2018; Risto et al., 2017) and is not, as a large part of explicit concepts, only visible from certain perspectives.

The design of implicit communication must satisfy a wide variety of requirements in terms of comfort, safety, and time or resource efficiency, where the optimization of one dimension can negatively or positively influence other areas (Schockenhoff, Nehse, & Lienkamp, 2020). Since defensive driving styles might be preferred by AV users (Yusof et al., 2016), there might be a trade-off between the comfort requirements of the passenger in the AV and, for example, the aim of increased traffic efficiency (Le Vine, Zolfaghari, & Polak, 2015) or other dimensions. Furthermore, for efficient interaction, the AV movement should be designed so that the implicit communication is easily perceivable by the interaction partner. This means that the AV movements in the bottleneck scenario must at least exceed the perception thresholds of the oncoming human driver to successfully communicate the right-of-way, and cannot be arbitrarily reduced to enhance driving comfort.

Regarding the comfort of drivers and passengers, jerk (Kilinc & Baybura, 2012), longitudinal, and lateral accelerations (Bellem, Schönenberg, Krems, & Schrauf, 2016) are of particular importance. These accelerations potentially cause carsickness, which further intensifies with increasing acceleration levels (Turner & Griffin, 1999). In automated driving, this issue may be exacerbated since, in contrast to drivers of conventional vehicles, passengers of the AVs cannot or can only inadequately predict the vehicle's future trajectory (Golding & Gresty, 2013). Researchers still disagree on whether in order to be comfortable, AV users require lower acceleration levels than today's human drivers (Le Vine et al., 2015), or whether AVs do not need to act less dynamically (Lange, Maas, Albert, Siedersberger, & Bengler, 2014). These findings require defining the areas of driving dynamics in which implicit communication maneuvers satisfy the comfort requirements of the AVs' passengers since a comfortable driving style is also a basic condition for their acceptance (Scherer et al., 2016).

This thesis bases the design of implicit communication on longitudinal deceleration and lateral acceleration levels driven by human drivers. In low-speed ranges, which is also the case in the bottleneck scenario, longitudinal decelerations are about -1.5 m/s^2 (Maurya & Bokare, 2012), between -0.5 m/s^2 and -2 m/s^2 (Bosetti, Da Lio, & Saroldi, 2014), or smaller than -2 m/s^2 (Moon & Yi, 2008), resulting in a desired comfortable deceleration of -2 m/s^2 in comfortable driving mode (Moon & Yi, 2008). At 30 km/h, drivers experience normal lateral acceleration levels up to 1 m/s^2 and dynamic levels up to 2.2 m/s^2 (Schimmelpfennig & Nackenhorst, 1985). Although, in 99.9% of the driving time, lateral accelerations are smaller than 0.5 m/s^2 (Bosetti et al., 2014) maximum lateral accelerations of up to 3.5 m/s^2 occur on urban and rural roads (Festner, 2019).

Considering comfort limits, implicit communication via the longitudinal deceleration of the AV influences the detection times and reaction times of pedestrians (Ackermann et al., 2018; Petzoldt, Schleinitz, & Banse, 2018) as stronger decelerations lead to shorter reaction times (Ackermann, Beggiato, Bluhm, Löw, & Krems, 2019; Kauffmann, Naujoks, Winkler, & Kunde, 2018). In terms of subjective measures, early well-perceivable decelerations reduce the perceived criticality of the encountering AV (Fuest, Michalowski, et al., 2018) and the driving behavior of the AV is a major determinant of other road users' trust (Jayaraman et al., 2018). Furthermore, performing a lateral offset can be successfully used to communicate with pedestrians (Fuest, Michalowski, et al., 2018; Sripada, Bazilinskyy, & Winter, 2021), to announce lane changes (Potzy et al., 2019), and to communicate the right-of-way in bottleneck scenarios (Rettenmaier, Dinkel, & Bengler, 2021).

Explicit communication

In addition to implicit communication via vehicle movements, AVs can also explicitly communicate their intention directly to surrounding road users via eHMIs (Bengler et al., 2020; Dey & Terken, 2016; Fuest, Sorokin, et al., 2018; Gasser et al., 2015). This approach of explicit communication, in contrast to implicit communication, does not affect the own movement but signals the AV's message to others or demands actions from others (Markkula et al., 2020).

Explicit communication is predominantly used in ambiguous interaction scenarios at low travel speeds (Schieben, Wilbrink, Kettwich, Dodiya, et al., 2019), where the possibilities of implicit communication are depleted (Bengler et al., 2020). Predominantly, eHMIs are used to interact with pedestrians in street crossing scenarios, where the AV communicates whether it yields or insists on right-of-way (Clercq et al., 2019; Dietrich, Willrodt, Wagner, & Bengler, 2018). Furthermore, AVs use eHMIs to communicate with cyclists (Bazilinskyy, Dodou, Eisma, Vlakveld, & Winter, 2020; Vlakveld, van der Kint, & Hagenzieker, 2020) in intersection situations, or to inform surrounding road users about the AVs behavior during minimal risk maneuvers (Schindler, Herbig, Lau, & Oehl, 2020). Besides the contributions in this thesis (Feierle, Rettenmaier, Zeitlmeir, & Bengler, 2020; Rettenmaier, Albers, & Bengler, 2020; Rettenmaier, Pietsch, Schmidtler, & Bengler, 2019) explicit communication in the bottleneck scenario is rarely studied, although it fulfills the requirements of an ambiguous interaction scenario due to the unregulated traffic situation in the bottleneck scenario and the participants' low travel speeds.

External HMIs can be grouped according to the human interaction partners' sensory channel which receives the message of the AV. Explicit communication can be transmitted visually via light signals or auditorily via sound signals (Fuest, Sorokin, et al., 2018) with tactile eHMIs being a possible addition (Colley, Walch, Gugenheimer, & Rukzio, 2019). The subgroup of visual eHMIs, which is an essential part of the contributions included in this thesis, could be subdivided into the categories light strip, display, and projection (Figure 8), according to the medium that encodes the AV's message (Ackermann, Beggiato, Schubert, & Krems, 2019).

Light Strip | Display | Projection

Figure 8: Different visual eHMI types categorized in the subgroups light-strip (Daimler AG, 2019), display (Daimler AG, 2017), and projection (Donath, 2019).

Currently, researchers do not agree on which visual medium is best suited for communicating with surrounding road users. While the largest group of researchers follows the approach of explicit communication via light strips (Chen, 2019; Dey et al., 2020; Dietrich, Tondera, & Bengler, 2019; Faas, Kao, & Baumann, 2020; Faas, Mathis, & Baumann, 2020; Habibovic, Lundgren, et al., 2018; Lagström & Lundgren, 2015; Lee et al., 2019; Petzoldt et al., 2018; Schieben et al., 2020; Schieben, Wilbrink, Kettwich, Dodiya, et al., 2019; Schindler et al., 2020), the display (Clamann, Aubert, & Cummings, 2017; Stadler, Cornet, Novaes Theoto, & Frenkler, 2019) and projection onto the road surface (Löcken, Golling, & Riener, 2019; Mitsubishi, 2015; Powelleit, Winkler, & Vollrath, 2019; Sadeghian, Hassenzahl, & Eckoldt, 2020) are also used in research studies.

This disagreement is based on the fact that none of the media combines only advantages as shown in the tabular overview published by Schieben, Wilbrink, Kettwich, Madigan, et al. (2019). Light strips transmit messages via light patterns, requiring no language skills of the receivers, and can thus be understood by people of different ages and nationalities (Schieben, Wilbrink, Kettwich, Madigan, et al., 2019). However, light patterns are usually evaluated as incomprehensible and unintuitive by human interaction partners (Ackermann, Beggiato, Schubert, & Krems, 2019; Bazilinskyy, Dodou, & Winter, 2019; Hensch, Neumann, Beggiato, Halama, & Krems, 2020), limiting their usability in road traffic. Displays show text or symbols, sending a more specific message. However, the area of the display needs to be large, especially at a greater distance, to deliver the AV's message legibly (Schieben, Wilbrink, Kettwich, Madigan, et al., 2019). At least this concern can be rebutted since the necessary area at the front of currently commercially available passenger cars is sufficient to display the required message size and to transmit messages over long distances, as is the case in the bottleneck scenario (Rettenmaier, Schulze, & Bengler, 2020). Projections onto the road are preferred by pedestrians when interacting with AVs for better recognizability, unambiguousness, and interaction comfort (Ackermann, Beggiato, Schubert, & Krems, 2019). However, projections are difficult to perceive due to their orientation especially at long distances (Eisma et al., 2020) such as in bottleneck scenarios (Rettenmaier, Pietsch, et al., 2019).

In addition to the medium, there is the question of what content should be conveyed to the human interaction partner. Researchers classify the information content into different groups (Bazilinskyy, Dodou, Eisma, et al., 2020; Faas, Mathis, & Baumann, 2020; Schieben, Wilbrink, Kettwich, Madigan, et al., 2019; Zandi, Singer, Kobbert, & Quoc Khanh, 2020). The category with the lowest information density is basic or status information that labels the automation mode or marks the driverless status of the AV (Fuest, Feierle, Schmidt, & Bengler, 2020) which would render potentially deviating driving behavior explainable or expectable to surrounding road users (Färber, 2015) and provide trust in and understanding of AVs (Kitazaki & Myhre, 2015). The second category contains information about the intention of the AV and transfers the message in an allocentric manner from the perspective of the human interaction partner. Messages in this category extend the informal communication channel and provide information about the AV’s next maneuver (Zandi et al., 2020). The third category contains messages that instruct or advise others to perform certain actions and are therefore transmitted egocentrically from the perspective of the interaction partner. Participants prefer this advice information (Ackermann, Beggiato, Schubert, & Krems, 2019) due to an enhancement in the user experience, perceived intelligence, and transparency (Faas, Mathis, & Baumann, 2020).

The message of the AV should be color-coded to support the human interaction partner in understanding the AV’s intention (Bazilinskyy, Dodou, & Winter, 2020). In this context, there are two different argumentations in current research. The first group proposes to use neutral colors such as cyan as the color of AV communication, which is not used in traffic context and therefore easily distinguishable from other information sources (Faas & Baumann, 2019; Werner, 2018). The other group argues that the colors red and green are already known in the context of regulating right-of-way, and therefore the AV should use the same colors. Green is preferred by pedestrians over cyan when the AV yields right-of-way (Dietrich, Willrodt, et al., 2018), is evaluated most intuitively (Bazilinskyy, Dodou, & Winter, 2020), and increases perceived safety in this context (Bazilinskyy, Kooijman Lars, Dodou, & Winter, 2020b). In the case that the AV insists on the right-of-way, it is not clear which color should be chosen from the perspective of the human interaction partner, since the so-called "red-green paradox" occurs (Bazilinskyy, Dodou, & Winter, 2020; Lavender & Ekstrom, 1968). Here, confusion arises regarding the allocentric and egocentric perspective, since red or green can refer to the AV (allocentric) itself or the human interaction partner (egocentric) (Bazilinskyy, Dodou, & Winter, 2020). For the aforementioned reasons, the AV could yield the right-of-way in green and insist on the right-of-way in a neutral color such as cyan to avoid the "red-green paradox" (Bazilinskyy, Dodou, & Winter, 2020).

Assuming that in a specific scenario the medium, the message content, and its color design are chosen to be suitable for communication, eHMIs have the potential to increase traffic efficiency (Burns, Oliveira, Thomas, Iyer, & Birrell, 2019) by significantly reducing pedestrians' decision or reaction time to cross the street (Ackermans, Dey, Ruijten, Cuijpers, & Pfleging, 2020; Chang, Toda, Sakamoto, & Igarashi, 2017; Holländer et al., 2019; Othersen, Conti-Kufner, Dietrich, Maruhn, & Bengler, 2018; Rouchitsas & Alm, 2019; Stadler et al., 2019) or by reducing the passing times of cyclists (Kaß et al., 2020a) and oncoming human drivers (Feierle et al., 2020; Rettenmaier, Albers, & Bengler, 2020; Rettenmaier, Pietsch, et al., 2019) in bottleneck scenarios. Furthermore, eHMIs increase road safety by decreasing the erroneous behavior of pedestrians when crossing the road (Ackermans et al., 2020) and by decreasing the crash rate of human drivers at road bottlenecks (Rettenmaier, Albers, & Bengler, 2020; Rettenmaier, Pietsch, et al., 2019). These findings lead to an improvement of the subjective feelings of the human interaction partners. Communication via eHMIs increases the perceived safety (Ackermans et al., 2020; Böckle, Brenden, Klingegård, Habibovic, & Bout, 2017; Chang et al., 2017; Clercq et al., 2019; Faas, Mathis, & Baumann, 2020; Habibovic, Lundgren, et al., 2018) and trust in the AVs (Holländer et al., 2019; Kaleefathullah et al., 2020; Matthews, Chowdhary, & Kieson, 2017; Sadeghian et al., 2020) which could have a positive impact on surrounding road users' acceptance (Böckle et al., 2017; Habibovic, Lundgren, et al., 2018).

In road traffic and especially in the bottleneck scenario, the AV should communicate the right-of-way both implicitly and explicitly together (Imbsweiler et al., 2017), since the eHMI supports the meaning of implicit communication (Imbsweiler et al., 2018). In this context, it is essential to coordinate both communication approaches, as there are dependencies between them (Bengler et al., 2020). First, the meaning of the explicit and implicit messages should be consistent (Bengler et al., 2020), which can enhance the user experience (Dey et al., 2020). Second, the two communication approaches should also be chronologically coordinated (Bengler et al., 2020). Currently, there is little research on whether human interaction partners blindly trust messages displayed by the eHMI regardless of the AV's driving behavior (Kaleefathullah et al., 2020) or whether they are more likely to pay attention to vehicle behavior despite divergent communication of the eHMI (Dey et al., 2020).

2.3 Human Driver: Acting within the Limits of Human Capabilities

2.3.1 Principles of Human Driving

In early 2020, approximately 19 million passenger car driver's licenses have been issued in Germany so far (Kraftfahrt-Bundesamt, 2021). This fact suggests that driving a vehicle is a simple task for humans. However, the driving task is very complex due to more than 1,000 behavior-relevant system characteristics (McKnight & Adams, 1970), more than 1,600 subtasks (Walker, Stanton, & Glendon, 2015), a high number of diverse objects, and the multitude of interactions with other road users (Litman, 2019).

While driving a car, the system of driver and vehicle can be described as a closed loop consisting of the human model as the controller and the vehicle as the controlled system (Johannsen, 1993). This driver-vehicle control loop (Figure 9) describes the interaction between driver and vehicle under the premise of a non-distracted driver who has focused all attention on the driving task. On the one hand, the driver-vehicle control loop is affected by environmental factors (Abendroth & Bruder, 2015), such as the behavior of other road users (e.g. the external communication strategy), the traffic infrastructure (e.g. the bottleneck type), and the characteristics of the driver's vehicle (Fuller, 2000), which influence the driver's strain, thus the performance, and error occurrence (Johannsen, 1993). When passing through

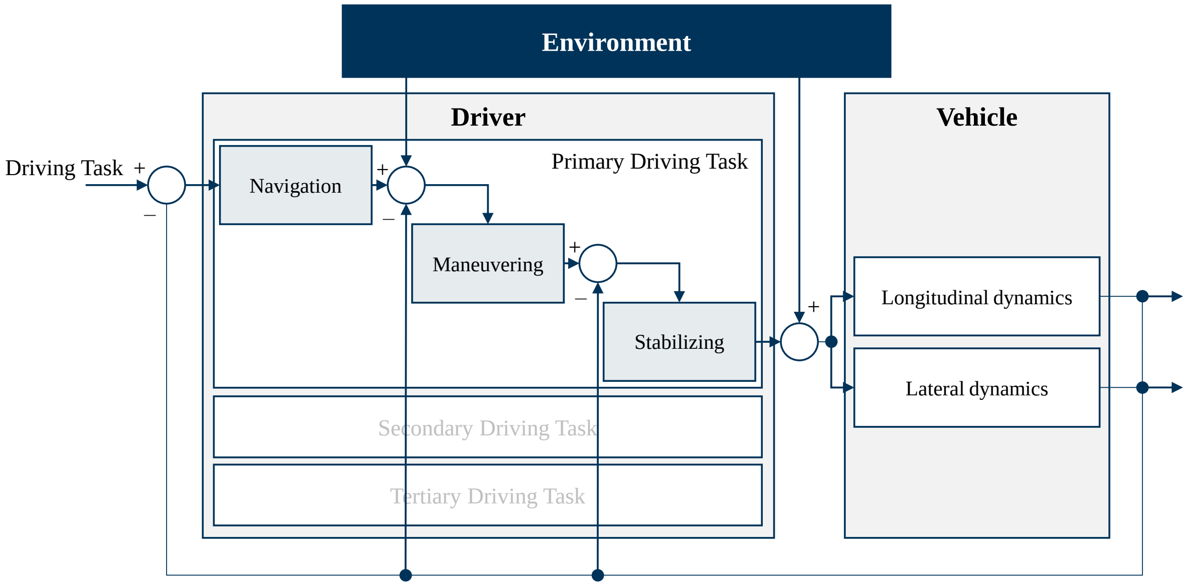

Figure 9: Classification of the driver's driving tasks in the driver-vehicle control loop (Körber, 2018) based on Bubb et al. (2015)

the bottleneck scenario, human drivers adjust speed to assure that their driving capabilities exceed task demand and consequently maintain a safety margin that ensures safe driving (Fuller, 2000). On the other hand, subjective motivations affect the driver's behavior. Aggression or the demand for competition lead to offensive driving behavior, whereas defensive driving behavior is often based on the need for risk avoidance (Irmscher & Ehmann, 2004).

In the driver-vehicle control loop, the human driver is a multimode, adaptive learning controller (McRuer & Jex, 1967) whose driving task can be subdivided into primary, secondary, and tertiary tasks (Bubb, Bengler, Grünen, & Vollrath, 2015). This thesis focuses on the primary driving task since it analyzes components that aim at keeping the vehicle on the desired course through the bottleneck scenario. The primary driving task, in turn, includes the three hierarchical levels of navigation, maneuvering, and stabilizing (Bernotat, 1970; McRuer, Allen, Weir, & Klein, 1977; Theeuwes, 2001). Navigation involves route selection tasks, to reach the destination in a given time, and involves a temporal horizon of several hours before the considered action occurs (Donges, 2015). Maneuvering contains the tasks of setting the intended trajectory and speed choice considering the current traffic conditions in a time horizon of a few seconds to one minute (Donges, 2015). In the driver-vehicle control loop, the task of maneuvering can be seen as anticipatory open-loop control, as the driver has to plan his actions based on the environmental factors (distance to the bottleneck, external communication of the AV, etc.) without receiving immediate feedback on the outcome (Schweigert, 2003). Stabilizing encompasses a temporal extent of approximately one second (Donges, 2015) and includes the adjustment of longitudinal and lateral manipulated variables to maintain the desired trajectory and speed. It consists of compensatory control since the driver perceives the difference between the desired and the actual lane position and an immediate matching of manipulated variables (e.g. human steering input) and controlled variables (e.g. lane deviation) is possible (Bubb, 1993).

The classification of the driving task into three levels corresponds to the model according to Michon (1985), which divides the driving task into strategic (planning), tactical (maneuvering), and operational (control) levels. The strategic level with its wide time horizon corresponds to the navigation level since both contain tasks of general trip planning. According to Michon (1985), maneuvering comprises controlled action patterns and includes activities with a time horizon of a few seconds, whereas the control level includes automatic action patterns due to its temporal expansion of milliseconds (Michon, 1985).

The conventional vehicle, representing the controlled system in the driver-vehicle control loop, consists of longitudinal and lateral vehicle dynamics. Accelerator and brake pedal interventions and the steering behavior from the stabilizing level serve as manipulated variables or inputs, imposing a certain driving behavior on the vehicle. This driving behavior is fed back to the driver by comparing it with the intended behavior at the navigation, maneuvering, and stabilizing levels, taking into account environmental influences and adjusting the steering, accelerator, or brake inputs as necessary.

The analysis of the human driving behavior in the bottleneck scenario focuses predominantly on the hierarchical level of maneuvering and stabilizing and is thus located in the area of the primary driving task. Controlled human steering and pedal inputs and the resulting trajectory and speed during the interaction with the AV are analyzed in a temporal range of a few seconds, considering the external communication of the driving automation system.

In addition to the dimension of the primary driving task, the description of the human driver contains two further dimensions with the parts of human information processing and the performance levels of skill-based, rule-based, and knowledge-based behavior (Rasmussen, 1983; Theeuwes, 2001), which are presented in more detail in the following section. Here, the thesis primarily focuses on information processing and, in this context, discusses the effects of performance levels.

2.3.2 Human Information Processing

This section covers research from the field of information processing over several decades beginning with the mid-20th century to the present day and provides an understanding of the interrelationships among the various theories and traditions. Human information processing regards the human operator as a system that receives environmental stimuli as input, processes them, and performs a reaction as system output (Card, Moran, & Newell, 1983; Proctor & van Zandt, 2018). This process is illustrated by the Information Processing Model (Figure 10), which visualizes and describes the flow of information through the human operator in detail (Wickens, Hollands, Banbury, & Parasuraman, 2016). In this context, information passes through sequential sub-processes (Bubb, 1993), during which they are subject to various transformations resulting in human system delays within the individual parts (Gerlough & Huber, 1975; Macadam, 2003).

A central component participating in the different parts of information processing is memory, which can be subdivided into the sensory register, working memory, and long-term memory (Atkinson &

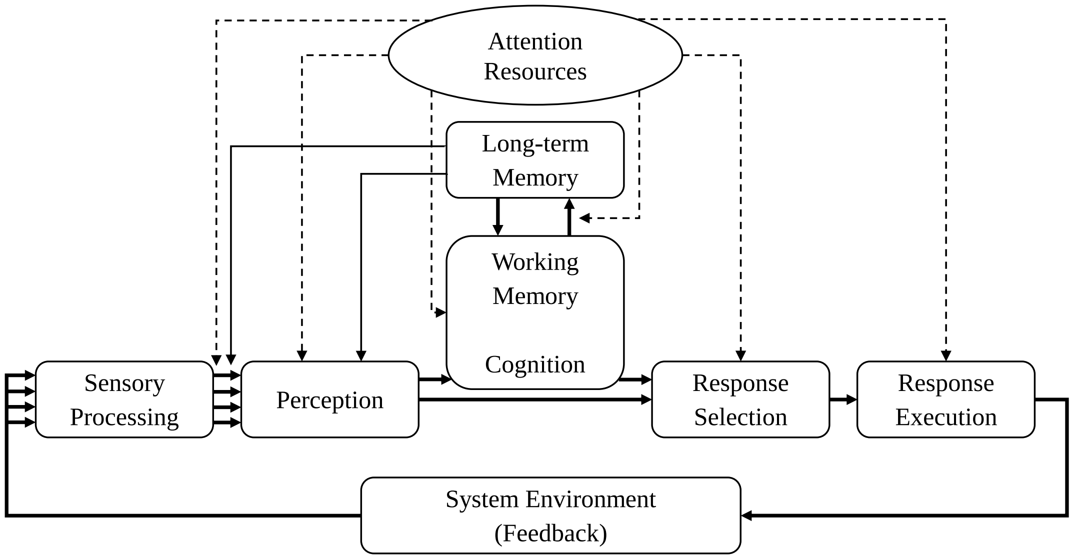

Figure 10: The Information Processing Model (Wickens et al., 2016)

Shiffrin, 1968). Memory consists of processes that involve retaining, retrieving, and using information from stimuli or images after the original information is no longer present (Goldstein, 2008).

Another central unit of human information processing is attention resources, which act as a filter of information overload (Damos, 1991; Kahneman, 1973; Pashler, 1998; Wickens & Carswell, 2012) and as the fuel for the sub-processes of information processing (Wickens & McCarley, 2008). The design of human-machine interfaces supports information processing the better, the faster, and more accurate if the sub-processes of information processing proceed with simultaneous minimal use of attentional resources (Wickens et al., 2016) which could be allocated to perception, response selection, response execution as well as working memory (Johannsen, 1993). On the one hand, a proper attention allocation enables humans to perform the task efficiently; on the other hand, insufficient attention allocation may lead to errors (Johannsen, 1993). Attention is divided into the three parts of divided, focused, and selective attention (Wickens & Carswell, 2012) which is addressed when designing the external communication of the AV. In the context of selective attention, the driver selects which environmental information to perceive by selectively directing their attentional resources to driving-relevant information, such as the AV's external communication, based on their memory of visual context (Chun, 2000, 2003; Chun & Jiang, 1998; Groeger, 2013), thus making it a part of driving situation awareness (Baumann & Krems, 2007).

In driving, the visual sensory channel dominates in information acquisition and thus in the performance of the driving task, since up to 90% of the relevant information in sensory processing is acquired through the visual system (Olson, 1996; Rockwell, 1972). The visual stimuli reach the receptor cells in the eyes, which convert the physical energy of the light into neural signals (Proctor & van Zandt, 2018). Sensory processing is influenced by selective attention in the form of the bottom-up factors salience and effort, whereby a stimulus is more likely to be processed when the salience of an object is higher (Theeuwes, 1992; Wolfe, 1994) and the perceptual effort is lower (Wickens & Carswell, 2012).

Moreover, the top-down factors of expectancy, that a particular stimulus will occur at a particular time in a particular place, and the value attributed to a piece of information influence sensory processing (Wickens & McCarley, 2008). Good HMI design should address bottom-up and top-down factors simultaneously by presenting valuable information in a salient way, minimizing effort, and increasing user expectancy through consistent use (Wickens & Carswell, 2012).

After being processed, the stimuli enter the short-term sensory store for a very brief period, are held there for perceptual processes, and are subsequently deleted (Atkinson & Shiffrin, 1968; Johannsen, 1993; Proctor & van Zandt, 2018; Wickens et al., 2016).

In perception, only a fraction of the sensory information is attributed meaning after filtering by attention resources (Wickens et al., 2016). The decision regarding which stimuli are processed further is made based on bottom-up and top-down processes. Bottom-up processes occur when perception is triggered data-driven with stimulation of receptors based on the properties of the stimulus such as coloration and brightness (Goldstein, 2008; Proctor & van Zandt, 2018; R. J. Sternberg, Sternberg, & Mio, 2012). In top-down processes, specific stimuli are perceived based on the knowledge and experience of the individual (R. J. Sternberg et al., 2012). In terms of efficient perception, the AV should take into account the limitations of the sensory system and the receptors of the receiver to communicate efficiently.

After perception, either a response is selected directly from the number of available possibilities, or the working memory is used in the process of cognition (Wickens et al., 2016). Cognition identifies, classifies, and interprets the sensed material by using information from the working memory and generating possible responses based on this information (Proctor & van Zandt, 2018).

In working memory, information is usually stored for about 30 seconds, although a limited amount of information can be stored for longer periods with repetition (Atkinson & Shiffrin, 1968). Working memory also serves as an interface between the sensory register and long-term memory, as it matches filtered information from the sensory register with information stored in long-term memory and additionally transfers information to long-term memory for permanent storage (Johannsen, 1993). In long-term memory, information is stored permanently and adapted over time as needed by new experiences (Atkinson & Shiffrin, 1968).

In response selection, the driver decides on a particular reaction from all possible responses. Among other factors, the decision time is influenced by the number of possible responses (Green, 2000; Hick, 1952; Hyman, 1953), human uncertainty (Berger & Calabrese, 1975; FeldmanHall & Shenhav, 2019; Proctor & van Zandt, 2018; Redmond, 2015), and risk assessment (Wilde, 1982). In this context, decision time increases with an increasing number of alternative response possibilities, with increasing uncertainty, and with a perceived risk exceeding the limit risk.

After response selection, the information must be transformed into neuromuscular signals so that the response can be executed (Proctor & van Zandt, 2018). The human driver then applies the brake or accelerator pedal and performs steering movements to keep the vehicle on the target trajectory.

The action can be executed in a skill-based, rule-based, or knowledge-based manner (Rasmussen, 1983). Skill-based performance occurs without conscious control of the human being, with sensory information triggering the human action and thus inducing automated behavior. In contrast, rule-based performance runs subroutines in a familiar work environment by performing actions based on rules acquired in previous experiences and encounters. In rule-based performance, the goal is often not explicitly stated, but it is inherent in the situation. A performance is knowledge-based when unfamiliar situations exist in which rules for task accomplishment are not yet known. Based on an analysis of the environment, the goal is explicitly formulated, plans for achieving the goal are designed, and possible effects of the action are predicted and weighted. (Rasmussen, 1983)

The executed response, in turn, leads to a change in human driving behavior and thus to changes in the environment, resulting in new information that is perceived by sensory processing (Wickens et al., 2016). This closes the loop in the Information Processing Model in a way that the cause, the perceived stimulus, and the response, the driver's intervention, are so dynamically linked that it is not obvious what is the cause and what is the effect (Jagacinski & Flach, 2003).

3 Research Questions

This thesis aims to design the communication of the AV and thus the interaction between AV and human driver in the best possible way in order to maintain traffic safety and to increase traffic efficiency. To achieve this goal, an in-depth analysis of the interaction and its sub-processes is essential to evaluate the effects of external communication strategies. In this respect, the first research question (RQ) focuses on the development of a suitable method for interaction description in the bottleneck scenario.

RQ1: How can the sequence of the interaction between the human driver and the automated vehicle in the bottleneck scenario be described from the human perspective?

After the description of the interaction has been elaborated in a required level of detail, the question arises, how to render the communication strategy of the AV best possible. In this context, the external communication design requires considering the possibilities and limitations of the human interaction partner from sensory processing of stimuli to response execution. This is addressed by the second research question focusing on human information processing.

RQ2: How should the external communication of the automated vehicle be designed to match the characteristics and processes of human information processing?

Finally, the question remains to what extent the human-centered design of external communication helps to improve the two areas of interest of the thesis, traffic efficiency and traffic safety. Accompanying this, it is necessary to use appropriate metrics to quantify and evaluate the overall AV-HD interaction. RQ 3 is dedicated to these issues.

RQ3: To what extent can the interaction strategy of the automated vehicle increase traffic efficiency and traffic safety in the bottleneck scenario?

The body of this thesis contains 4 articles that address the stated research questions. While Article 1 examines the design and potential of explicit communication via eHMIs, Article 2 deals with implicit communication via AV movements. Both articles thus address RQ2 and RQ3. Article 3 deals with the timing of external communication, models the AV-HD interaction in more detail, and thus addresses RQ1. Article 4 combines the findings from the three previous articles, examines explicit and implicit communication strategies separately and together, validates the temporal modeling from Article 3, and thus further specifies RQs 1-3.

4 Article 1: “After You?! – Use of External Human-Machine Interfaces in Road Bottleneck Scenarios”

Rettenmaier, M., Albers, D., & Bengler, K. (2020). After you?! – Use of external human-machine interfaces in road bottleneck scenarios. *Transportation Research Part F: Traffic Psychology and Behaviour*, *70*, 175–190. https://doi.org/10.1016/j.trf.2020.03.004

This work analyzed the potential of an eHMI in terms of enhancing traffic efficiency and maintaining traffic safety and it additionally evaluated the influence of the prevailing traffic regulation by investigating the interaction in regulated bottleneck scenarios narrowed only on one side and in unregulated bottleneck scenarios narrowed on both sides of the road.

The first part of the contribution deals with the development of the eHMI design. Based on the fundamentals of human visual perception, color design, and animation, 14 concept pairs were designed and evaluated in a preliminary study with 29 participants. A subsequent expert interview was conducted to determine the final eHMI concept.

The second part includes the evaluation of the final eHMI in a driving simulator study consisting of a 2 (interface) x 2 (message) x 2 (scenario) mixed design. The experimental group (n = 21) encountered an AV that communicated via the eHMI and the baseline group (n = 22) experienced an AV that did not have an eHMI for communication. In a first experimental drive, all participants experienced four different use cases four times each, resulting from a combination of the AV’s message (*AV yields the right-of-way* and *AV insists on the right-of-way*) and the scenario (*Narrowed on one side* and *Narrowed on both sides*). The second experimental drive included an automation failure where the AV first communicated to yield right-of-way, then changed its maneuver, and passed through the bottleneck despite the oncoming participant.

In terms of traffic efficiency, communication via the eHMI increased the participants’ average speed and it significantly reduced their passing times in case the AV yielded the right-of-way. In addition, participants who experienced the eHMI yielding the right-of-way steered earlier towards the road center to pass through the bottleneck indicating good comprehensibility of the AV’s message. Regarding traffic safety, communication via the eHMI reduced the number of crashes in scenarios in which the AV insisted on the right-of-way. However, the associated traffic regulation was decisive since the aforementioned effects were only present at unregulated bottlenecks narrowed on both sides. The automation failure was not controllable by the participants since it resulted in high crash rates regardless of the presence of the eHMI.

In conclusion, eHMIs are suitable to communicate the intention of the AV and thus to increase traffic efficiency and maintain traffic safety in unregulated bottleneck scenarios.

5 Article 2: "Communication via Motion – Suitability of Automated Vehicle Movements to Negotiate the Right of Way in Road Bottleneck Scenarios"

Rettenmaier, M., Dinkel, S., & Bengler, K. (2021). Communication via motion – Suitability of automated vehicle movements to negotiate the right of way in road bottleneck scenarios. *Applied Ergonomics*, *95*. https://doi.org/10.1016/j.apergo.2021.103438

This work aims to develop comprehensible AV movements to communicate the right-of-way externally in order to maintain traffic safety and increase traffic efficiency during AV-HD interaction in the bottleneck scenario. Based on findings on AV-pedestrian interaction, comfort limits of driving dynamics, and traffic observations, nine AV movements were designed to yield or insist on the right-of-way.

The evaluation of AV movements involved 34 participants attending a driving simulator study consisting of a repeated measures design with the three factors message, speed, and offset. Message contained the factor levels "AV yields right-of-way " and "AV insists on right-of-way ". Speed described the longitudinal part of the AV movement with a one-step deceleration just in front of the bottleneck or a two-step deceleration starting when entering the Interaction Phase to yield the right-of-way and with maintaining speed to insist on it. Laterally, the AV performed a distant offset or close offset each to the road center to insist on the right-of-way and to the road edge to yield right-of-way or it abstained from performing a lateral offset. Furthermore, the aftereffects of an automation failure were investigated in which the AV first communicated to yield right-of-way, then changed its intention and insisted on the right-of-way.

The results show significantly shorter passing times of human drivers and fewer crashes with the AV when its movement included a lateral offset. In this regard, the lateral offset should be executed at a greater distance from the human driver since this strategy entailed the most efficient passages and was rated significantly better than the close offset. In addition, the intention and future behavior of the AV is subjectively rated to be more comprehensible and distinguishable due to the offset than communication via only adjusting the longitudinal driving behavior. The automation failure was not controllable and resulted in a crash in nearly all encounters, thus significantly decreasing participants' trust in AVs.

In conclusion, implicit external communication has the potential to communicate the right-of-way in the bottleneck scenario and thereby increase traffic efficiency and maintain traffic safety. In the future, the AV should maintain speed and perform a distant offset to the road center to insist on the right-of-way, and it should perform a distant offset to the road edge additionally to a two-step deceleration to insist on it.

6 Article 3: “Modeling the Interaction with Automated Vehicles in Road Bottleneck Scenarios”

Rettenmaier, M., & Bengler, K. (2020). Modeling the Interaction with Automated Vehicles in Road Bottleneck Scenarios. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *64*(1), 1615–1619. https://doi.org/10.1177/1071181320641391

Article 1 and Article 2 of this thesis defined the start of external communication at a distance of 100 m between the AV and the human driver. In reality, however, on the one hand, technical capabilities of the driving automation system, e.g. the sensor range, may limit the earliest possible communication start. On the other hand, the communication of the AV may not start arbitrarily late, because the human driver's information processing needs time. This fact could argue for the time-based triggering of external communication since a distance-based communication start provides the human drivers with different amounts of choice reaction time (CRT) depending on their approaching speeds.

Based on these estimations, Article 3 deals with the questions of how to describe the AV-HD interaction in the bottleneck scenario and when the latest possible communication start is to render the interaction comfortable and safe. To answer these questions, the passage through the bottleneck scenario was divided into four phases (Approaching Phase, Interaction Phase, Passing Phase, and Departure Phase) and we conducted a task analysis of the human driver during the Interaction Phase. The resulting interaction model contains the human task durations in time to make it applicable for all speed ranges. The interaction model consists of the four parts (Detection, Identification, Decision, and Response) of the CRT (Alexander & Lunenfeld, 1975 as cited in Henderson, 1987), the braking distance, and stopping distance. Within the interaction model, the decision time was the only parameter that cannot be determined theoretically, since it strongly depends on the specific human task (Card et al., 1983) and therefore was determined from data of a previously conducted study (Rettenmaier, Pietsch, et al., 2019). By adding up the individual components of the interaction model and assuming a speed of the human driver and the AV of 30 km/h, the latest possible start of communication is reached at a distance of 72.02 m between both interaction partners. If the AV starts to communicate below this distance, the interaction may theoretically no longer be comfortable and safe for the human driver.

Further analysis showed that the decision time is the only parameter of the interaction model that can be shortened by an optimal external communication design. The durations of all other components are determined by transferable human information processing processes obtained in studies and physical driving parameters. The more comprehensible and attracting the communication of the AV the less time is needed by the human driver to run through the entire interaction model. Meeting these aspects may decline human uncertainty (Berger & Calabrese, 1975) and fasten human processing of the AV’s communication resulting in a later last possible communication start and a smaller necessary sensor range of the AV. In addition, the AV should not change its communication during the passage through the bottleneck, since otherwise, the sequentially structured interaction model must be completely or at least partially rerun resulting in a prolonged interaction.

7 Article 4: “The Matter of How and When: Comparing Explicit and Implicit Communication Strategies of Automated Vehicles in Bottleneck Scenarios”

Rettenmaier, M., & Bengler, K. (2021). The Matter of How and When: Comparing Explicit and Implicit Communication Strategies of Automated Vehicles in Bottleneck Scenarios. *IEEE Open Journal of Intelligent Transportation Systems*, *2*, 282–293. https://doi.org/10.1109/OJITS.2021.3107678

This article combines the findings of Articles 1-3 and investigates the best possible communication strategy for AV-HD interaction. A driving simulator study varied the four factors contact (*1st*, *2nd*, *3rd*), intention (*AV yields right-of-way*, *AV insists on right-of-way*), eHMI (*eHMI on*, *eHMI off*), and offset (*offset*, *no offset*) in a repeated measures design. All 31 participants experienced the resulting eight communication strategies three times each in a first experimental drive, where the human driver encountered an AV communicating right-of-way via the eHMI simultaneously and separately to the lateral offset. The communication start was triggered in a time-based manner based on the interaction model from Article 3. As soon as the human driver's time to arrival (TTA) to the speed-dependent last possible comfortable braking onset was equal to the required time for human information processing the AV started to communicate. Furthermore, at the end of a second experimental drive, participants experienced the automation failure from Article 1 and Article 2, in this study communicating the maneuver change saliently via a change in eHMI and lateral offset.

The results show the shortest passing times due to the most efficient human decision times when the AV simultaneously communicated via eHMI and offset to the road edge. Additionally, this work plotted the times of individual sub-processes of AV-HD interaction including their probability distributions. This allowed validating the interaction model from Article 3 and recommending an earlier communication start for additional efficiency gains. Furthermore, there were no crashes when communicating via eHMI and offset. Subjectively, this communication strategy was rated most comprehensible explaining the efficiency and safety benefits. During the automation failure, approximately half of the sample collided with the AV, corresponding to a substantially lower crash rate than in Article 1 and Article 2, but is still not controllable for the human driver.

In conclusion, the AV should communicate right-of-way to the human driver simultaneously explicitly via an eHMI and implicitly via a lateral offset without changing intention in any case. Furthermore, the communication start should be triggered in a time-based manner based on the required CRT to give the human interaction partner sufficient time to process the information and to react appropriately. Following these suggestions, external communication will increase traffic efficiency while ensuring traffic safety.

8 Discussion

"Discussion and argument are essential parts of science; the greatest talent is the ability to strip a theory until the simple basic idea emerges with clarity."

~ Albert Einstein

Following the results of the thesis body (Sections 4-7), this chapter discusses the new findings on the AV-HD interaction with regard to the presented theoretical background (Section 2) and thereby answers the underlying RQs (Section 3). Section 8.1.1 reviews the sequential interaction description developed throughout Articles 1-4 and explains why the most advanced approach for interaction description from Article 4 needs further development. Thereupon, methods for interaction description used in research are discussed and their suitability regarding the necessary level of detail and reciprocity of interaction in the bottleneck scenario is evaluated (Section 8.1.2). Subsequently, Section 8.2 applies the closed AV-HD control loop (RQ 1), which emerged as the most suitable method for interaction description in the bottleneck scenario, and derives five principles (Sections 8.2.1-8.2.5) for optimal external communication design (RQ 2). Section 8.3 discusses to what extent the implementation of the aforementioned five design principles increases traffic efficiency while maintaining traffic safety in the bottleneck scenario (RQ 3). From there, the discussion detaches from the bottleneck scenario and addresses potential other application areas (Section 8.4) to which the principles of AV-HD interaction might apply, and which could benefit in terms of safety and efficiency. In the end, the thesis discusses the limitations underlying the presented results (Section 8.5) and provides an outlook on future research directions based on the interaction in the bottleneck scenario (Section 8.6).

8.1 Interaction Description: Developing the Appropriate Method

In heterogeneous road traffic, the interaction is characterized by mutual communication (VandenBos, 2015) between the interaction partners. This also applies to the bottleneck scenario of this thesis, which is considered to be relevant for investigating road traffic interaction. However, to analyze this dynamic process between the AV and the oncoming human driver at road bottlenecks, the development of a suitable method is essential.

8.1.1 Articles 1-4: From Phase Model to Interaction Sequence

In the progress of this thesis (Articles 1-4), the interaction description steadily evolved (Figure 11). The distance-based phase model (Rettenmaier et al., 2021; Rettenmaier, Albers, & Bengler, 2020), which has been established in research (Dozza, Schindler, Bianchi-Piccinini, & Karlsson, 2016; Gstalter & Fastenmeier; Habibovic, Lundgren, et al., 2018; Köhler, 2018; Várhelyi, 1998), especially in the context of behavioral and communication description, formed the starting point. The phase model divides the

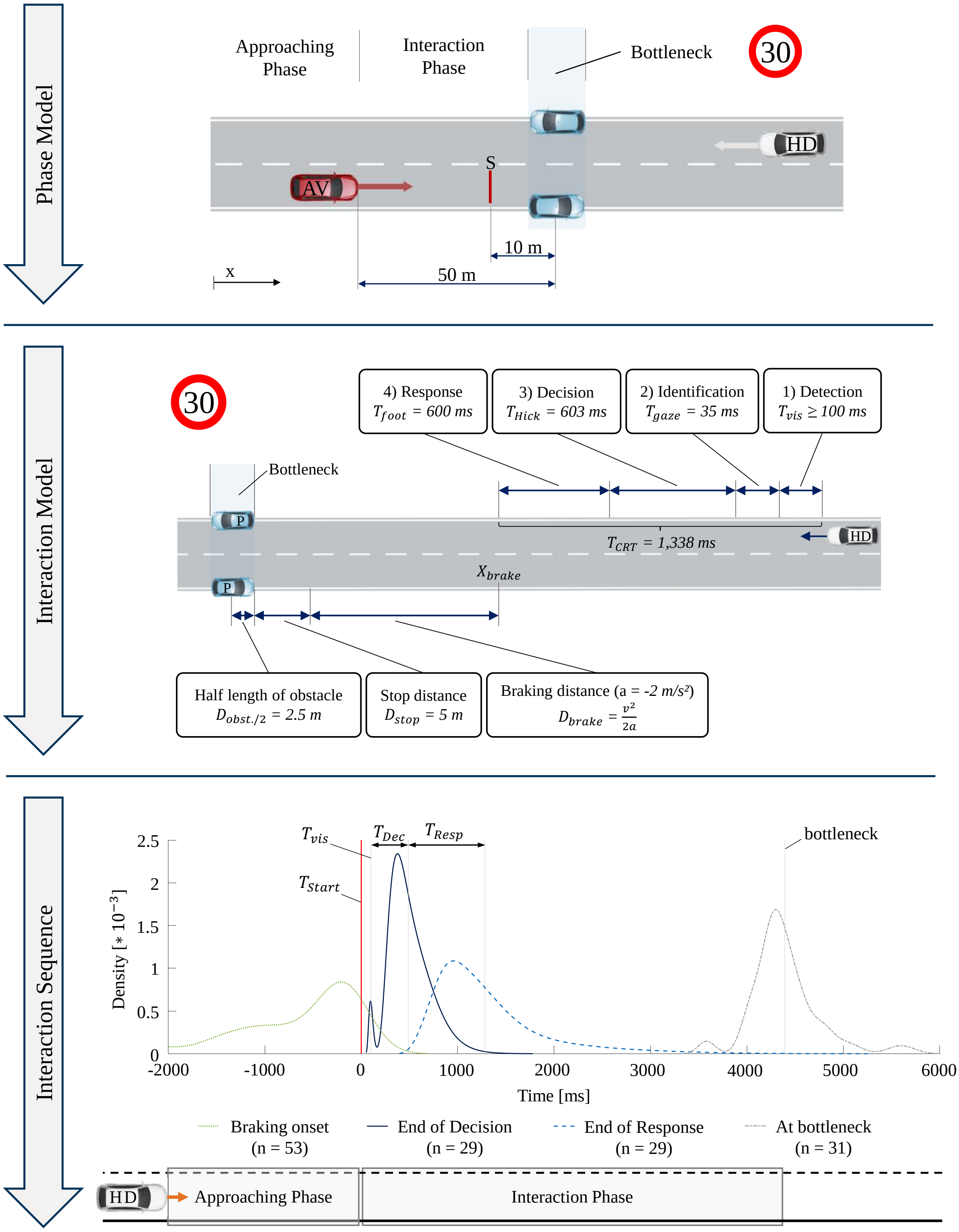

Figure 11: Evolution of interaction description methods from Phase Model (Rettenmaier et al., 2021), to Interaction Model (Rettenmaier & Bengler, 2021), to Interaction Sequence (Rettenmaier & Bengler, 2021). This figure mainly focuses on the Interaction Phase. A detailed description of all four phases can be found in the Interaction Model in Article 3 (Rettenmaier & Bengler, 2020).

passage through the bottleneck into four spatially defined phases (Approaching Phase, Interaction Phase, Passing Phase, and Departure Phase), with Article 1 (Rettenmaier, Albers, & Bengler, 2020) and Article 2 (Rettenmaier et al., 2021) defining the first two phases and focusing on the design of external communication and human driver response within the Interaction Phase. However, this subdivision was too simplistic for detailed interaction analysis and the extension of the phases in the distance-based approach only applies at certain speeds, since the information flow within the AV and the information processing of the human driver exhibit temporal delays resulting in different speed-dependent distances. For these reasons, Article 3 (Rettenmaier & Bengler, 2020) subdivided the Interaction Phase based on the sub-processes of human information processing (detection, identification, decision, and response) and quantified them in a time-based manner rendering the resulting interaction model applicable to all speed ranges. This allowed the definition of the latest possible external communication start, after which the interaction can no longer proceed efficiently for the human driver. However, this timing was determined under the best conditions of a non-distracted driver in a clear scenario with only one interaction partner and should be verified and adjusted under more complex settings. In Article 4 (Rettenmaier & Bengler, 2021) the interaction model could be validated and the mean durations of the parts of information processing could be extended and visualized as an interaction sequence by probability distributions within the sample. With Article 4, the method for interaction description had been developed to the point where the individual sub-processes of AV and human driver during the interaction and also their sequence could be described in sufficient detail. However, the sequential structure of the interaction model and the interaction sequence does not reflect the dynamic reciprocity between the AV and the human driver that is underlying an interaction by definition (VandenBos, 2015). Thus, the necessary level of detail introduced in the interaction model and the aforementioned reciprocity between both interaction partners are two main requirements for a suitable interaction description method. To address both needs, methods applied in research for the detailed description of mutual communication are discussed and evaluated for their suitability in the bottleneck scenario.

8.1.2 Level of Detail and Reciprocity: How to Meet Both Requirements

When describing the interaction between humans and AVs, research uses the following methods, among others, to describe the actions of the interaction partners and meet the requirement for a sufficient level of detail.

The system ergonomic task analysis, which was used in a similar way to create the interaction model in Article 3 (Rettenmaier & Bengler, 2020), is suitable for a detailed description of the tasks during a take-over-request (Damböck, 2013) and results in a flow diagram with a defined beginning and a defined end. Although this method provides the level of detail needed in this thesis to describe the human tasks, the crucial disadvantage is that the reciprocity between the interaction partners cannot be depicted.

Unified Modeling Language (UML) diagrams have already been used to describe the interaction between a driver and his AV (Flemisch et al., 2008) or between two drivers and their respective vehicles during cooperative lane change maneuvers (Zimmermann & Bengler, 2013). Again, the disadvantage is that the dynamic reciprocity during the interaction is difficult to represent and the UML diagram quickly becomes confusing in complex interactions.

Sequence diagrams are suitable to describe the interaction in road traffic between a vehicle and a crossing pedestrian (Dietrich, Bengler, et al., 2018; Rasouli, Kotseruba, & Tsotsos, 2017; Stuckert, Shi, Singer, Lin, & Khanh, 2019). Here, the interaction is represented as an action sequence of the involved interaction partners and sometimes plotted in a time-based manner (Rasouli et al., 2017). However, the dynamics and interplay between the interaction partners cannot be represented without an extension of the x-axis and further sequencing of the actions.

Sankey diagrams provide a representation of pedestrian actions before and after roadway crossings (Rasouli et al., 2017) and contain the quantitative share of the applied means of communication. This method was not used in this thesis since it does not describe the actions in a time-based manner and cannot represent the interplay between the AV and the human driver.

Variable-drift diffusion models, including sensory cues based on eHMI, TTA change, distance, and TTA, are used to quantify human decision time (Pekkanen et al., 2021). They are an interesting approach to mathematically describe the human decision-making process. However, without further modifications, variable-drift diffusion models refer exclusively to the human interaction partner and are therefore not pursued further.

So far, the methods mentioned fulfill the requirement of a sufficient level of detail. However, the approaches also share the fact that they do not address the second requirement of reciprocity between the interaction partners. For this reason, this thesis decided to analyze and extend the method of the closed driver-vehicle control loop, which was already used in Figure 9 to represent the dynamic interplay between the agents, for interaction description in the bottleneck scenario. This approach allows the description of the interaction between the driver, who acts as a controller regulating the deviation from the target trajectory, and the vehicle representing the controlled system in a dynamic time-unbounded way (Bubb et al., 2015).

Finally, this thesis combines the closed-loop approach to describe reciprocity between the interaction partners (Naumann & Stiller, 2017) with the system ergonomic task analysis method to achieve the desired level of detail and incorporates the advantages of both methods in the AV-HD control loop.

8.2 The Automated Vehicle – Human Driver Control Loop

This section resumes the most relevant findings from the state-of-the-art and the highlights from Articles 1-4, puts them into context, and visualizes the interaction between AV and the oncoming human driver in the bottleneck scenario. Furthermore, five principles of AV-HD interaction are formulated and integrated as independent sections which can be used to set requirements for the technical implementation of the driving automation system.

The encounter at the bottleneck is structured as a closed control loop (Figure 12) reflecting the mutual communication between both interaction partners and thus meeting the definition of an interaction (VandenBos, 2015). For this purpose, the AV and its components (Figure 6) are integrated into the control loop and the human driver is represented by the Information Processing Model (Wickens et al.,

2016) including the durations of the respective tasks (Rettenmaier & Bengler, 2021). However, the resulting AV-HD control loop (Figure 12) is a time-based approach within distance-based boundaries. The control loop starts as soon as the AV and its message are within the human detection range and the human driver is within the AV's sensory range. In this case, the communication of the interaction partner is perceivable and there may be an awareness of the negotiation situation. The control loop reflects the behavior of both negotiation partners in the Interaction Phase and fulfills all requirements concerning a suitable method. The AV-HD control loop is valid in all speed ranges and the mutual dynamics can be represented in detail within the distance-based boundaries mentioned above. Furthermore, the method could be adapted to other scenarios such as the AV-pedestrian interaction at road crossings by adjusting the human task durations within the Information Processing Model.

While both interaction partners approach the bottleneck, the sensor system of the AV perceives the oncoming human driver and plans based on traffic dynamics and static environment whether to yield the right-of-way or to insist on it. In this case, the processing latency of T_{AV} = 100 ms determines the period between scene recognition and operational decisions (S.-C. Lin et al., 2018; Shalev-Shwartz, Shammah, & Shashua, 2016). To decide on the right-of-way, the driving automation system considers the time the human driver needs for information processing (T_{CRT} = 1,298 ms) and the time required by the conventional vehicle to transform driver inputs into vehicle dynamic outputs. This time span consists of the periods that elapse from applying the brake until the braking force is fully built up ($T_{long.}$ = 220 ms) and the peak-response time defining the time span from steering angle input to maximum yaw angle of the conventional vehicle ($T_{lat.}$ = 500 ms) (Mitschke & Wallentowitz, 2014).

Taken together, the mentioned periods add up to T_{Total} describing the earliest time after which a human response to external communication is measurable by the sensors of the driving automation system. In case the AV insists on the right-of-way T_{Total} = T_{AV} + T_{CRT} + $T_{long.}$ = 1,618 ms and for yielding the right-of-way T_{Total} = T_{AV} + T_{CRT} + $T_{lat.}$ = 1,898 ms. By comparing T_{Total} and the human driver's TTA (TTA_{HD}) to the last possible comfortable braking start (Principle 1, Section 8.2.1), the AV is able to choose its message. If TTA_{HD} is greater than T_{Total}, the AV can either yield right-of-way or insist on it. If TTA_{HD} is smaller than T_{Total}, the AV has to yield right-of-way.

The AV externally communicates its intention to the human driver implicitly via the AV movement and explicitly using the eHMI (Principle 2, Section 8.2.2). The human driver perceives the AV's message, processes it, and reacts accordingly by adjusting the longitudinal and lateral driving behavior (Principle 3, Section 8.2.3). The AV closes the control loop by perceiving the changes in human driving behavior and, based on this, assessing whether the human driver has understood external communication and will behave accordingly. Based on this assessment and the meanwhile changed ratio of T_{Total} and TTA_{HD}, the AV can continue to communicate to insist on right-of-way or it must yield right-of-way in case of uncertainty about the human driver's future behavior (Principle 4, Section 8.2.4).

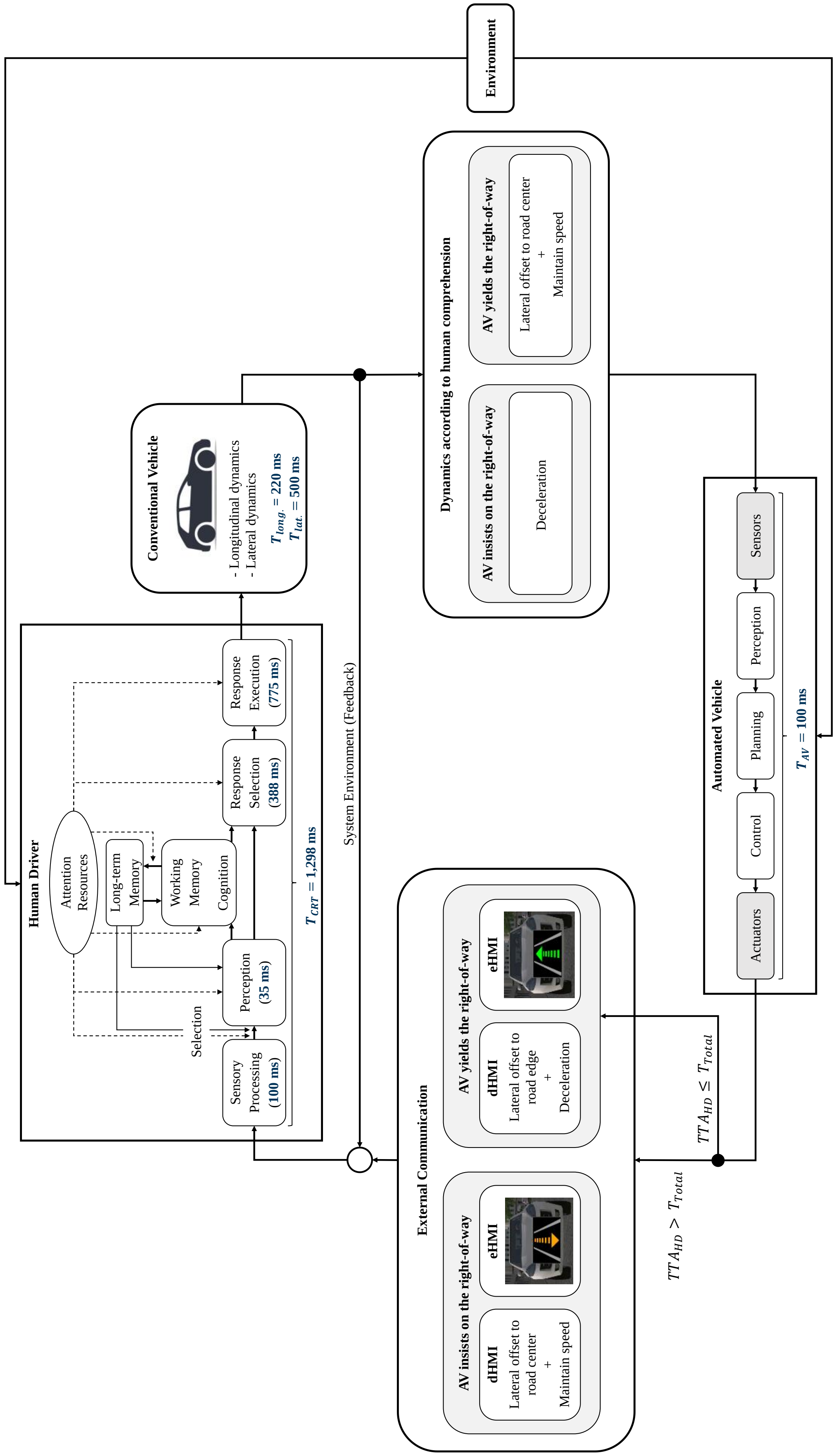

Figure 12: Automated Vehicle – Human Driver Control Loop: A detailed time-based description of the interaction between the automated vehicle and the human driver in the bottleneck scenario. The images of the eHMI are taken from Article 1 (Rettenmaier, Albers, & Bengler, 2020).

8.2.1 Principle 1: Communicate in a Time-Based Manner

In Article 1 (Rettenmaier, Albers, & Bengler, 2020) and Article 2 (Rettenmaier et al., 2021), the AV started to communicate the right-of-way distance-based as soon as it reached a defined distance to the bottleneck and the oncoming human driver. Since the participants in the studies only rarely adhered exactly to the 30 km/h speed limit, human drivers had different amounts of time, depending on their own speed, to perceive, process, and react to the external communication. Furthermore, human drivers evaluate encounters with oncoming vehicles and plan their own driving behavior rather time-based using the TTA than distance-based (McLeod & Ross, 1983; Schiff & Detwiler, 1979; Todd, 1981). For these reasons, this thesis formulates Principle 1 stating that the AV should convey its message in a time-based manner and proposes to trigger external communication based on TTA_{HD} within the distance-based boundaries of the AV-HD control loop. The principle thus spans the time period, during which the AV could communicate externally, starting as soon as both interaction partners are able to perceive the communication of the other. This communication period ends when TTA_{HD}, the time until the human driver reaches the last possible comfortable deceleration start, and T_{Total}, the time span composed of all delays (T_{CRT}, $T_{long.}$ or $T_{lat.}$, and T_{AV}), reach the same value. If TTA_{HD} is longer than T_{Total}, the human driver has more time available to process the information than the minimum time needed to do so. In this case, considering the driving behavior of the human driver, the AV can decide whether to insist on or yield right-of-way in order to increase traffic efficiency. Moreover, the AV could continue to uphold its initial message even without a corresponding reaction of the human driver and wait for the adjustment of the human driving behavior until the threshold where TTA_{HD} equals T_{Total}. However, if TTA_{HD} is smaller than T_{Total}, the human driver does not have enough time to process the AV's information and react appropriately until braking might be necessary. Therefore, the AV has to yield the right-of-way in these situations to avoid critical encounters.

This comparison of available and required time ensures that the AV-HD interaction in the bottleneck scenario proceeds safely. The AV only considers the offensive driving behavior of insisting on right-of-way if the human driver has sufficient time to adopt the defensive role. Furthermore, yielding the right-of-way too late, without providing the human driver with the necessary information processing time, leads to an increase in passing times, thus a decrease in traffic efficiency (Rettenmaier, Pietsch, et al., 2019) and worse subjective ratings (Rettenmaier et al., 2021).

Moreover, triggering the external communication based on time allows applying the principles of this thesis not only in the bottleneck scenario with a speed limit of 30 km/h. The findings could also be applied in all speed ranges and other scenarios with two interaction partners, such as during AV-pedestrian interaction at road crossings (Faas, Stange, & Baumann, 2021) or AV-cyclists interaction at intersections (Vlakveld et al., 2020). However, in these scenarios, the duration of the different parts of information processing should be adapted to the respective human task, since, for example, the response execution of a pedestrian crossing the road substantially exceeds the duration of the foot movement from accelerator to brake pedal in the bottleneck scenario.

Based on the time-based triggering, this thesis derives clear requirements for the AV's minimum sensory range, the distance $D_{sensory}$. Depending on the AV's speed and the permitted or expected speed of the oncoming human driver, the minimum required sensory range can be determined using formula 1. It is composed of the distance of the AV ($D_{AV-bottleneck}$) and of the human driver ($D_{HD-bottleneck}$) to the bottleneck respectively. Thereby, $D_{HD-bottleneck}$ consists of the distance to the last possible comfortable deceleration start ($T_{Total} * v_{HD}$), the braking distance ($D_{brake} = \frac{{v_{HD}}^2}{2*a}$), the stopping distance to the bottleneck (D_{stop}), and the bottleneck length ($D_{bottleneck}$).

$$D_{sensory} = D_{AV-bottleneck} + T_{Total} * v_{HD} + D_{brake} + D_{stop} + D_{bottleneck} \quad (1)$$

8.2.2 Principle 2: Communicate Explicitly and Implicitly Together

Within the existing temporal range (Principle 1), the AV should simultaneously communicate explicitly via the eHMI and implicitly via its driving behavior, whereby a consistent meaning and temporal coordination of both communication approaches is necessary (Bengler et al., 2020) to ensure traffic safety and increase traffic efficiency (Rettenmaier & Bengler, 2021).

Regarding implicit communication, the AV should perform a lateral offset to the road center and maintain speed to insist on the right-of-way and it should perform the offset to the road edge with a simultaneous deceleration to yield right-of-way (Rettenmaier et al., 2021). A specific amount of deceleration is not important to increase traffic efficiency (Rettenmaier et al., 2021), however, it should be below the limit of -2 m/s² regarding passenger comfort (Moon & Yi, 2008). For this reason, this thesis suggests that the AV decelerates with the constant amount being necessary to stop in front of the bottleneck. In contrast to deceleration, the lateral offset is essential to render the AV's message legibly since human TTA estimation is insufficiently accurate at temporal distances greater than 2-3 seconds (McLeod & Ross, 1983; Schiff & Detwiler, 1979) and head-on approaches further complicate this fact (Schiff & Oldak, 1990). The lateral offset results in a larger visual angle change for the oncoming human driver (Hills, 1980) and thus conveys the intention of the AV more saliently. For these reasons, the AV should not decelerate before communicating via lateral offset and eHMI since this would result in a decrease in traffic efficiency (Rettenmaier et al., 2021).

In terms of explicit communication, it is not decisive which interface concept is used provided that the AV's message is easily perceivable, considering among others luminance, contrast (Andrén, Brunnström, & Wang, 2014), and symbol or letter size (Rettenmaier, Schulze, & Bengler, 2020), and its meaning was understood by human drivers. In this case, the results concerning traffic safety and traffic efficiency of the thesis could be transferred to other eHMI concepts. Instead of using a simple light, which might be enough for indicating the right-of-way, the AV communicated via a slightly more complex design. This eHMI was developed iteratively in a preliminary study and an expert interview resulting in an interface being highly comprehensible (Rettenmaier, Albers, & Bengler, 2020). Therefore, participants understood the AV's explicit message within a few encounters (Rettenmaier, Albers, & Bengler, 2020; Rettenmaier & Bengler, 2021) quickly reducing the learning effect and enabling the measurement of the future increase in traffic efficiency.

The concurrent communication via eHMI and AV movement conveys the greatest stimulus resulting in faster human reaction times (Werneke & Vollrath, 2011). In the bottleneck scenario, the top-down factors of human information processing, expectancy and value (Wickens & McCarley, 2008), are present by the human driver expecting the AV to communicate the right-of-way and the resulting value in terms of an increase in traffic efficiency. In addition, the eHMI and the AV movement address the bottom-up factor of saliency supporting the perception of the communication signal. In this context, a consistent meaning of the explicit and implicit signals is essential since a comprehensible external communication strategy reduces the uncertainty of the human interaction partner. This fact eliminates additional information seeking (Berger & Calabrese, 1975), enables predictions about the behavior of the interaction partner (Berger & Calabrese, 1975; Redmond, 2015), and thus reduces human reaction time (Proctor & van Zandt, 2018). Reducing uncertainty, in turn, lowers the perceived level of risk and increases the gap to the target risk level (Wilde, 1982). The human driver tries to minimize this gap by driving offensively through the bottleneck in case of the AV yields right-of-way. As a result, the low levels of uncertainty and perceived risk increase human processing speed significantly reducing human decision time (Card et al., 1983).

8.2.3 Principle 3: Do not Expect an Immediate Human Reaction

People need time to process information. This becomes evident by applying the Model Human Processor (Card et al., 1983), the Information Processing Model (Wickens et al., 2016), or the Interaction Model of this thesis (Rettenmaier & Bengler, 2020). Article 3 and Article 4 subdivided human information processing into the different parts of the CRT (detection, identification, decision, response) (Alexander & Lunenfeld, 1975 as cited in Henderson, 1987) which also correspond to the four stages of the Information Processing Model (Sensory Processing, Perception, Response Selection, Response Execution). In this sequential process, sensory processing (100 ms) is determined by human neural conduction speed (Lamme, 2000; Schmidtke, 1989), perception (35 ms) consists of the gaze transition to the AV (Rettenmaier & Bengler, 2020), and response execution (775 ms) describes the foot movement between the accelerator and the brake pedal (Rettenmaier & Bengler, 2021). The duration of response selection (388 ms) is quantified by human decision time and represents the only parameter of the sequential flow of information that could be minimized by the optimal design of the AV's communication strategy described in Principle 2. Furthermore, comprehensible communication strategies enable the human driver to process the information rule-based rather than knowledge-based leading to a more efficient performance (Rasmussen, 1983).

In terms of control engineering, the duration of human information processing (T_{CRT} = 1,298 ms) represents delay 1 in the AV-HD control loop, since the perceived information remains in the controller "human" for this period until it is processed and a reaction can be measured at its output. In addition, the AV-HD control loop contains two further delays. Delay 2 describes the time lag in the controlled system "conventional vehicle" and contains the time from the driver input via pedals and steering wheel to the output in the longitudinal ($T_{long.}$) and lateral ($T_{lat.}$) vehicle control that can be measured by the sensory system in terms of deviating driving dynamics. This sensory detection entails delay 3 which is quantified by the processing latency of the vehicle automation (T_{AV}), that specifies how fast the system should respond to the sensor data (S.-C. Lin et al., 2018). Consequently, the adaptation of human driving behavior due to the AV's external communication can be detected by the sensory system at the earliest after $T_{Total} = T_{AV} + T_{CRT} + T_{long.}$ = 1,618 ms if the AV insists on the right-of-way or after $T_{Total} = T_{AV} + T_{CRT} + T_{lat.}$ = 1,898 ms if it yields the right-of-way.

In conclusion, the information flow in the AV-HD control loop passes three delay times, which must be taken into account when implementing the external communication strategy and especially the communication timing. After these delays have elapsed, the sensors of the driving automation system could detect a change in the longitudinal and lateral driving behavior of the conventional vehicle due to the external communication at the earliest. This finding could be confirmed by analyzing participants' lateral driving behavior in Article 1 (Rettenmaier, Albers, & Bengler, 2020) and Article 2 (Rettenmaier et al., 2021), which showed the human drivers reaction being delayed by approximately the time of information processing. Minimizing these three delays would make the interaction more time-efficient and would reduce the sensory range requirements of the driving automation system.

8.2.4 Principle 4: Yield the Right-of-Way in Case of Uncertainty

Based on the driving behavior of the conventional vehicle the driving automation system can predict whether the oncoming human driver has understood the external communication and will act accordingly in the future. If the AV communicates to insist on the right-of-way, it should measure a deceleration of the conventional vehicle after T_{Total} has elapsed. If the AV communicates to yield the right-of-way, the sensor system should detect that the human driver is maintaining speed or even accelerating and performing a lateral offset to the road center after T_{Total} has elapsed. In encounters where the conventional vehicle does not show the expected driving behavior during the interaction but the AV still insists on the right-of-way, crashes may occur decreasing traffic safety (Rettenmaier et al., 2021; Rettenmaier, Albers, & Bengler, 2020; Rettenmaier & Bengler, 2021; Rettenmaier, Pietsch, et al., 2019).

Consequently, if there is uncertainty about the future course of the interaction at the bottleneck, the AV should yield the right-of-way in any case. With this regard, uncertainty could be divided into three different areas. The first area concerns the uncertainty about the longitudinal and lateral driving behavior of the human driver. If the human driver behaves as predicted, the AV should maintain its communication and its maneuver. If the human driving behavior does not indicate whether the driver will behave according to the AV's message or if the driver misunderstood the external communication, the second area of temporal uncertainty becomes relevant. Here, the AV has to assess whether there is the certainty that the human interaction partner has sufficient time to process and react appropriately. For this purpose, the comparison of TTA_{HD} and T_{Total} of Principle 1 should be used and the right-of-way must be yielded in case of uncertainty. The third area involves the processes of perception, planning, and control within the driving automation system operating under uncertainty conditions. Since vehicle automation algorithms detect or predict surrounding road users and their behavior based on probability estimations (Sprenger, 2020), a sufficient probability level has to be entailed throughout the interaction. Otherwise, the AV has to yield the right-of-way until it regains sufficient control of the situation.

8.2.5 Principle 5: Do not Change the Communicated Maneuver

In contrast to Principle 1 and Principle 4 dealing with the initial communication strategy regarding timing and uncertainty, Principle 5 covers possible changes in the intention and maneuver of the AV and the associated changes in external communication during the interaction. Here, this thesis mainly considers the case that the AV communicates to yield the right-of-way and, due to sensory uncertainties, changes its maneuver and communicates to insist on right-of-way instead. This scenario represents a high-risk situation that cannot be controlled by the human driver including a high crash probability (Rettenmaier et al., 2021; Rettenmaier, Albers, & Bengler, 2020; Rettenmaier & Bengler, 2021).

Once the AV communicated to yield right-of-way, it has to uphold this strategy in any case. If the oncoming human driver does not understand the intention of the AV and a deadlock situation arises, in which the human driver shows no indication to drive through the bottleneck, the AV could slowly approach and pass the bottleneck area. A maneuver change at high relative speeds between the interaction partners cannot be safely communicated and implemented explicitly (Rettenmaier, Albers, & Bengler, 2020), implicitly (Rettenmaier et al., 2021), or by a combined approach (Rettenmaier & Bengler, 2021).

The sequential course of the Interaction Model (Rettenmaier & Bengler, 2020), the Information Processing Model (Wickens et al., 2016), and the entire AV-HD control loop explain this finding. Once the AV communicates the maneuver change, the entire control loop including the three delay times (Principle 3) has to be run through again resulting in the minimum amount of time that must be available before the braking onset of the conventional vehicle to prevent an accident. Furthermore, participants reported that they shifted their attention away from the AV after the right-of-way was initially yielded. This could be explained by the fact that the process of information seeking was completed due to low perceived uncertainty (Berger & Calabrese, 1975) and attention resources were distributed to the other processes of information processing (Johannsen, 1993). Furthermore, the human driver's performance when interacting with the AV is rule-based precluding feedback correction during human reaction since the action is taken exclusively according to the learned rule (Rasmussen, 1983).

It can be criticized that the automation failure including the maneuver change, occurred at a bottleneck narrowed only on the AV’s side of the road where the human driver has the right-of-way anyway and no external communication is needed (Rettenmaier, Albers, & Bengler, 2020). This fact may have favored the high crash rates during the automation failures. However, this thesis originally aimed to analyze if a maneuver change could be communicated and thus controlled even in the worst-case scenario at the regulated bottleneck. Furthermore, due to the high crash rates of almost 100% (Rettenmaier et al., 2021; Rettenmaier, Albers, & Bengler, 2020) or approximately 50% (Rettenmaier & Bengler, 2021), it is assumed that a maneuver change at unregulated bottlenecks narrowed on both sides of the road could not be reliably communicated without a considerable amount of crashes.

8.3 Traffic Safety and Traffic Efficiency: Benefits of Effective Communication

By following design principles 1–5, the driving automation system can ensure the high level of traffic safety in the bottleneck scenario common in today's traffic (Gerlach et al., 2011). On the one hand, time-based triggering prevents accidents or critical incidents caused by delayed communication or a short-term change in the AV’s intention and its driving maneuver. On the other hand, comprehensible external communication leads to appropriate human responses and thus to safe encounters. The increase in traffic safety becomes evident by comparing the AV-HD interactions with explicit (Rettenmaier, Albers, & Bengler, 2020) and implicit (Rettenmaier et al., 2021) communication with the respective baseline without these communicational means. During the baseline, where the AV communicated only by maintaining speed to insist on the right-of-way, the crash rate was significantly higher (10.23% (Rettenmaier, Albers, & Bengler, 2020); 17.65% (Rettenmaier et al., 2021)) compared to communication with eHMI (0%) or lateral offset (distant offset = 2.94%, close offset = 4.41%). This can be explained by the fact that the AV’s comprehensible communication reduces human driver’s uncertainty about the future course of the interaction, enabling time-consuming information seeking (Berger & Calabrese, 1975) to be completed expeditiously and selecting the appropriate response. In addition, the salient eHMI and lateral offset to road center increase human driver's perceived level of risk above the respective target risk level (Wilde, 1982) inducing a more defensive driving style.

Ensuring traffic safety in the bottleneck scenario provides the basis for using external communication to increase traffic efficiency that is evident from the significantly higher human speed trajectories and the associated decrease in human passing times (Rettenmaier et al., 2021; Rettenmaier, Albers, & Bengler, 2020; Rettenmaier & Bengler, 2021). With compliance to Principle 1 and Principle 2, the passage through the bottleneck is most efficient for the human driver reducing the passing time by up to 27.57% compared to the baseline condition. Critics might note that an efficiency gain of almost one third seems a lot at first glance, but in absolute terms, it only amounts to a temporal benefit of about three seconds per interaction and therefore is negligible for urban journeys. However, this can be countered by the high number of bottlenecks (Gao & Ozbay, 2016; Kladeftiras & Antoniou, 2013; Lu et al., 2007) due to delivery traffic, other double-parked vehicles, or construction sites, whereby the small time gains add up over all interactions during the trip, or the potential impact on the traffic system efficiency at a macroscopic level.

The studies of this thesis focus almost exclusively on the efficiency of the human driver since the driving behavior of the AV is hard-coded. Due to the finding that the AV's deceleration characteristics do not influence human passing time (Rettenmaier et al., 2021), the AV's passage through the bottleneck might be optimized. By calculating the point in time when the human driver is expected to have passed the bottleneck, the AV could adapt its deceleration rate to reach the bottleneck area once it is cleared and passable. This approach would maximize overall traffic efficiency in the bottleneck scenario in case the AV yields the right-of-way by leading not only to a more efficient journey for the two interaction partners but also to positive effects on other surrounding road users in the second or third row, potentially enhancing the entire traffic flow on a larger road section.

Subjectively, the benefits in terms of traffic safety and traffic efficiency due to external communication may lead to an increase in perceived safety (Böckle et al., 2017; Habibovic, Lundgren, et al., 2018), higher trust in AVs (Kaleefathullah et al., 2020; Rettenmaier et al., 2021), and higher acceptance by surrounding road users (Habibovic, Lundgren, et al., 2018). Thus, external communication contributes to a positive attitude of human drivers towards AVs, providing one of the basic requirements for the introduction of automated traffic in urban environments.

Moreover, since external communication leads to smoother human speed profiles and the AV could adjust to optimal deceleration values, heavy braking of the interaction partners may be avoided, thus expectedly saving energy and increasing resource efficiency. The extent to which external communication has the potential to reduce emissions or contributes to energy efficiency should be evaluated in future work, as this thesis does not consider this topic.

8.4 External Communication Strategy: Extending the Scope of Application

The communication strategy developed in this thesis via eHMI and offset and the method of interaction description using the AV-HD control loop could be transferred to other road traffic scenarios and further areas of application. Depending on the scenario, the times of human information processing, especially during response execution, need to be adapted to the human interaction partners and their tasks and the conventional vehicle might be removed from the control loop. However, the following considerations are limited to interactions between a driving automation system and another interaction partner, since the interaction description of several agents using the control loop cannot be adopted without further effort.

The AV could adapt the external communication strategy to interact with a pedestrian, since eHMIs (Burns et al., 2019; Stadler et al., 2019) promise benefits in traffic efficiency, lateral offsets increase the intuitiveness of the AV's message (Sripada et al., 2021), and the combination of eHMI and AV movement is considered to have further potentials (Dey et al., 2020). For this use case, the latest possible communication start could be determined by replacing the period of response execution within the T_{CRT}

with the necessary time to cross the lane, taking into account the average walking speed of pedestrians (Goldhammer et al., 2014) and adding a buffer time that reduces the pedestrian's perceived risk level. However, the transferability of the communication design and its timing is not limited to individual traffic, as automated driving shuttles (Hagenzieker et al., 2020) or automated delivery vehicles (Neubauer & Schauer, 2018) could also share their intention via eHMI and lateral offset with surrounding road users and could derive the communication start using the control loop.

Finally, this thesis addresses human-machine interaction apart of road traffic and discusses the rapidly growing (International Federation of Robotics, 2020) field of mobile robotics. In this context, the focus is on scenarios involving automated mobile systems and human interaction partners, where the findings regarding the developed external communication strategy and the interaction description in the control loop could be transferred to increase safety and efficiency. A possible field of application for externally communicating robots is in the area of service robots that perform cleaning tasks in supermarkets (Pacchierotti, Christensen, & Jensfelt, 2006), on sidewalks, or snow removal (Neubauer & Schauer, 2018). Mobile automated systems are used in the transport of goods and logistics of medical supplies (Bacik et al., 2017; Mutlu & Forlizzi, 2008) or luggage (Takahashi, Suzuki, Cinquegrani, Sorbello, & Pagello, 2009) in hospitals. Automated transport systems perform in-house transports on-site at company premises, ports, or airports (Neubauer & Schauer, 2018). In this context, automated guided logistics robots carry pallets, raw materials, or finished products to warehouses (R. Lin, Huang, & Li, 2021) and automated forklifts contribute to more efficient goods delivery (Li, Liu, Fang, Zheng, & Tang, 2015).

In all these scenarios, automated systems interact with surrounding human operators, such as hospital staff (Bacik et al., 2017), factory workers, or forklift drivers (Sabattini et al., 2018) in the same space, and obstacles could even create kind of bottlenecks. In this context, the human interaction partners must accept the mobile robots enabling safe and efficient human-robot collaboration (Klumpp, Hesenius, Meyer, Ruiner, & Gruhn, 2019). For this purpose, the robots could communicate their intention externally by adjusting the robot motion and performing a back-off (Reinhardt, Prasch, & Bengler, 2020) or by using the communication strategy of this thesis including eHMI and lateral offset. The communication start could be achieved in all the mentioned use cases via an adapted human-robot control loop.

8.5 Limitations

8.5.1 Driving Simulation: A Sufficient Tool to Study Interaction?

Driving simulators make it possible to represent the environment and thus stimulate participants' natural driving behavior. Consequently, the results found in the simulation can be transferred to reality to a certain extent (Schmieder, Nagel, & Schöner, 2018). The advantages of driving simulation, in addition to the ability to collect data quickly and inexpensively, are the controllability and reproducibility of driving scenarios (Breuer, Hugo, Mücke, & Tattersall, 2015; Winter, van Leeuwen, & Happee, 2012). These advantages were also utilized in the studies of this thesis. The interaction in the bottleneck scenario was performed in a controlled and standardized manner in which participants, as human drivers, arrived at the bottleneck exactly synchronously with the AV during each encounter. Moreover, external communication always started exactly when the distance- or time-based trigger point was reached. Furthermore, driving simulation allows exploration of traffic conflicts and hazardous driving conditions without exposing the participant to real-world risk (Breuer et al., 2015; Winter et al., 2012). This was especially beneficial in cases where external communication was misunderstood or a crash occurred due to the maneuver change of the AV during the automation failure.

However, the use of driving simulation has some disadvantages, which must be noted as one of the limitations of this thesis. The main criticism of using driving simulation is that a driving simulator can only represent physical, perceptual, and behavioral fidelity to a limited extent (Winter et al., 2012). Regarding perceptual fidelity, the main deviations of the driving simulation from reality in the bottleneck scenario concern distance perception (Schmieder et al., 2018; Ziemer, Plumert, Cremer, & Kearney, 2009), speed perception (Hurwitz, Knodler, & Dulaski, 2005), and risk perception (Schneider & Bengler, 2020). Since all objects are displayed on the same level on the simulator screens, regardless of their virtual distance, depth perception is impeded compared to real-world driving (Negele, 2007; Schöner, 2018) and changes in participants' distance and consequently in speed perception arise (Winner & Zöller, 2019). Furthermore, the estimation of distance and speed of an oncoming vehicle is related to the characteristics of the visualization in the driving simulator such as pixel resolution, background texture (Blakemore & Snowden, 2000), luminance (Takeuchi & Valois, 2000), and contrast (Blakemore & Snowden, 1999; Schmieder et al., 2018). The altered distance and speed perception are particularly relevant in negotiating right-of-way (Schöner, 2018), as present during interactions in the bottleneck scenario, since the AV communicates right-of-way by adjusting speed and the time-based communication start (Rettenmaier & Bengler, 2021) based on a realistic human distance and speed perception. To mitigate these limitations, the driving simulator, in which all studies of this thesis were conducted, contains a large horizontal field of view of 120° with a resolution of 4k (3840 x 2160 pixels) and a motion system that simulates the vestibular cues necessary for speed control and thus supports correct speed perception (Kemeny & Panerai, 2003). Furthermore, the high-resolution monitors of the driving simulator ensured that the eHMI was easily legible despite the lower resolution compared to reality.

If studies are conducted in the driving simulator, it is necessary to be aware of the limitations and the different types of validity. The goal in researching the interaction in the bottleneck scenario was to analyze the behavior of human drivers raising the issue of behavioral validity, which refers to the similarity of human perception, cognition, and observable actions compared to real-world observations (Blana, 1996; Zöller, Mautes, Ren, & Abendroth, 2015). Behavioral validity can be assessed in terms of relative or absolute agreement (Blana, 1996; Schneider & Bengler, 2020). While the absolute agreement of quantifiable numbers is indispensable especially for safety-related measures relative agreement of effect size and direction is sufficient when comparing different interfaces or behavioral patterns (Schneider & Bengler, 2020). This relative agreement is sufficient to study internal validity, which refers to the degree to which observations can be attributed to the factor under investigation (Jiménez-Buedo & Miller, 2010). External validity, denoting the generalizability of results beyond the particular study to other populations (Andrade, 2018) or ecological validity, which refers to the generalizability of results to real-life settings (Lewkowicz, 2001), is only attainable to a limited extent in driving simulation (Breuer et al., 2015).

8.5.2 The Influence of Scenario Complexity

The bottleneck scenario was not varied and was kept simple across all studies in this thesis. During each encounter, the participant and the AV simultaneously arrived at the bottleneck which was located on a long straight road. Apart from the AV, no potentially distracting surrounding traffic was implemented, allowing the participants to fully devote their attentional resources to the external communication. This approach aimed to attribute the changes in human driving behavior and subjective evaluation solely to the variation of the external communication strategy as the dependent variable. Thus, the pure influence of the eHMI (Rettenmaier, Albers, & Bengler, 2020), the AV movement (Rettenmaier et al., 2021), as well as their combination (Rettenmaier & Bengler, 2021) on the participant's behavior and attention could be assessed. By standardizing the scenario and eliminating confounding variables, such as varying surrounding traffic or weather influences, this thesis ensured the internal validity (Jiménez-Buedo & Miller, 2010) of study results and determined the best communication strategy in this specific bottleneck scenario.

However, changes in the task characteristics, for example variations in the bottleneck scenario, most likely result in a change in human behavior and human reaction time (S. Sternberg, 1969). The scenario complexity, which is characterized by the infrastructure, surrounding road users, or environmental influences, determines the reaction time of human drivers (Rafał, 2019). An increase in the complexity of the driving context accompanies a higher human workload and consequently increases reaction time (Cantin, Lavallière, Simoneau, & Teasdale, 2009).

Based on these findings, there is a trade-off between achieving internal and external or ecological validity. On the one hand, the strong simplification of the scenario and the standardization of the encounters increases the internal validity and satisfies a relative agreement of the results in the simulation and reality. On the other hand, the strong simplification of the scenario and the standardization of the encounters limit the generalizability of the results to different simulated but also real bottleneck scenarios.

In summary, the simple design of the scenario and the resulting high internal validity have enabled the generation of initial insights into external communication strategies and the AV-HD interaction in the bottleneck scenario, thus forming the basis for future studies. This means that the AV should also communicate in reality via eHMI and lateral offset to best address human information processing and increase traffic efficiency. However, the generalizability of the human information processing times or the passing times to different scenarios and a direct transfer of the measured values to real-world interactions are only provided to a limited extent.

8.5.3 Sample Balance

Recruiting the sample at the Technical University of Munich led to the attendance of an above-average number of young, male, and technically skilled participants in the driving simulator studies of this thesis, which might have influenced their interaction with the driving simulator and their behavior in the driving simulation. Although this was not the research question of this thesis, I had the impression while conducting the studies that young male participants acted more offensively than other subject groups when interacting with the AV, which may have had a positive effect on average passing times. This impression is supported by literature, as males predominantly drive faster than females (Stephens, Nieuwesteeg, Page-Smith, & Fitzharris, 2017; Watson, Watson, Siskind, Fleiter, & Soole, 2015), and younger drivers drive faster than older drivers (Cantin et al., 2009; Maxwell, Weaver, Gagnon, Marshall, & Bédard, 2020). In this regard, the influence of subjects' age can be attributed to differences in their information processing. Due to deficits in contrast sensitivity, the useful field of view (Horswill et al., 2008), and degraded motion perception of angular movements (Staplin & Lyles, 1991), elderly drivers require more time to recognize that a road user is approaching. This fact might have influenced the reaction to the oncoming AV resulting in higher reaction times of elderly drivers (Cantin et al., 2009) and increased passing times. In response selection, the deficits in perception and cognition cause elderly drivers to reduce their attentional demand, especially under increased time pressure or high cognitive load, by performing steering movements and braking serially rather than simultaneously (Bélanger, Gagnon, & Stinchcombe, 2015). These facts might have led to the slightly altered driving behavior of elderly human drivers during the interaction in the bottleneck scenario and may necessitate an earlier triggering of the external communication due to an increase of the T_{CRT} within the AV-HD control loop.

However, these restrictions do not change the fact that the AV should communicate simultaneously via eHMI and lateral offset to maintain traffic safety and maximize traffic efficiency since the relative differences between the communication strategies (Rettenmaier & Bengler, 2021) and thus their ranking should remain unaffected.

8.6 Future Work

This thesis sets the foundation for the investigation of AV-HD interaction in the bottleneck scenario. Based on the findings obtained, there are still some research areas that should be addressed in the future and which are subdivided in this section into the topics of generalizability of results, system boundary selection within the bottleneck scenario, and transferability to other fields of application.

Generalizability of results

This thesis made temporal, infrastructural, and traffic dynamic simplifications to determine the influence of external communication on human driving behavior. In future studies, these parameters should be varied using an age- and gender-balanced sample to obtain generalizable statements about the AV-HD interaction at different bottlenecks.

Based on the respective TTA of both interaction partners to the bottleneck, there could be a range within which humans perceive the encounter as "simultaneous" and in which the communication strategy of this thesis should be applied. In the future, it will be necessary to determine the dimension of this range, integrate it into the AV-HD control loop, and enhance the external communication strategy.

Considering the infrastructure, influences of the road curvature within the bottleneck scenario including an analysis of the evolving sensory and human detection ranges should be investigated, because curved lanes could prevent the necessary unobstructed visual range ($D_{sensory}$) resulting from the AV-HD control loop. Furthermore, environmental influences, such as rain, fog, or darkness, on the perceptibility of external communication should be investigated in the future, since the aforementioned factors may especially affect implicit communication via vehicle movements.

Additionally, in more realistic urban scenarios, there is diverse surrounding traffic including other vehicles, pedestrians, and cyclists. These road users attract the attention of the human driver, which thus cannot be directed to the AV's message. This fact could increase T_{CRT} required for human information processing in the AV-HD control loop, requiring the AV to communicate earlier for safe and efficient interaction. However, this results in a trade-off for the driving automation system, as the increased scenario complexity and the required earlier communication start increases the difficulty to predict and plan the future course of the interaction, and thus to communicate reliably.

System boundary extension

Surrounding traffic necessarily leads to multiple human interaction partners, creating the need for an external cross-scenario communication strategy of the AV and an extension of the system boundary of the bottleneck scenario. The fact that human drivers, pedestrians, and bicyclists will perceive the external communication will also affect the behavior of all message receivers simultaneously. This circumstance might have the consequence that the results of this thesis possess restricted validity in scenarios with several road users. For this reason, the external communication strategy should be investigated in future scenarios with several road users at the same time to answer the question of how surrounding road users react to the AV-HD interaction. Is the lateral offset of the AV to the road edge understood by the following driver as a signal to park or as a request to overtake? Does a pedestrian standing at the roadway misinterpret the eHMI directed to the human driver and begin to cross the road? Does the human driver's deceleration after the AV insisted on right-of-way encourage a pedestrian to cross the roadway? All these questions could be answered using multi-agent simulations (Bazilinskyy, Kooijman Lars, Dodou, & Winter, 2020a; Feierle et al., 2020) before the communication strategy is applied in reality in urban traffic.

In addition to the impact of external communication on surrounding traffic in the first row around the AV, the system boundary could be extended and the positive influence or potential problems in the second and third row could be investigated. This issue is closely linked to a traffic system engineering perspective that derives results on the traffic system at the macro level from findings in the bottleneck scenario at the micro level. This approach could answer the question to what extent the increase in efficiency or the improvement of traffic flow directly at the bottleneck spreads further in the traffic system and influences other participants, possibly across intersections.

Further fields of application

Provided that sufficient knowledge is gained about the influences of the aforementioned parameters and the external validity of the driving simulation results and thus about the risk during the interaction, studies with vehicles in real-world traffic could be conducted in the future. In this context, studies with automated private transport, public transport in automated shuttles, or automated delivery traffic would be reasonable, which communicate with surrounding road users via eHMI and lateral vehicle movements. Furthermore, the transferability of the external communication strategy for interactions with mobile service robots or automated transport systems in logistics (Section 8.4) should be investigated to gain maximum benefit from the findings of this thesis.

However, it is still a long way to go before generalizable findings will be obtained in more complex bottleneck scenarios and potentially transferred to the aforementioned fields of application. Until that point, the articles of this thesis highlight the potentials of time-based joint explicit and implicit external communication, and the AV-HD control loop specifies five design principles that define how to implement safe and efficient AV-HD interaction at road bottlenecks. Consequently, this thesis not only forms the basis for human-centered external communication but also generates requirements for the technical capabilities of the driving automation system. Transferring these findings to more complex scenarios with multiple interaction partners or even to other fields of application such as logistics could provide the next stage for this thesis in the future.

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Appendix

A Complementary Work

A1: "Passing through the Bottleneck – The Potential of External Human-Machine Interfaces"

Rettenmaier, M., Pietsch, M., Schmidtler, J., & Bengler, K. (2019). Passing through the Bottleneck - The Potential of External Human-Machine Interfaces. *IEEE Intelligent Vehicles Symposium (IV)*, 1687–1692. https://doi.org/10.1109/IVS.2019.8814082

This work forms the foundation of this thesis since it was the first to investigate AV-HD interaction in bottleneck scenarios. The study investigated whether eHMIs have the potential to communicate the AV's intention and to enable an efficient and safe passage through road bottlenecks. We analyzed which eHMI medium is suitable for communication and whether the start of communication influences the human drivers' passages. For this reason, the study compared three different interfaces as a within-subject factor: a display at the front of the AV, a projection on the road, and the baseline group without any eHMI. Within each interface type, the AV communicated three times to yield the right-of-way and three times to insist on it. In addition, the between-subject factor varied the start of communication: early start of communication (50 m in front of the bottleneck, n = 23) and late start of communication (25 m in front of the bottleneck, n = 20).

In terms of traffic efficiency, the average speed curves were highest and the passing times of the participants were lowest when the AV started to communicate early via the display. Regarding the passing times, the interface type had a significant large effect and the start time had a significant medium effect. Learning effects were present, as the participants showed less efficient passages at the first contact with eHMIs compared to the third contact. Traffic safety was poorest in the baseline group, as it had the highest number of crashes regardless of the start of communication.

The results highlight that eHMIs have the potential to increase traffic efficiency and traffic safety. Moreover, the AV should communicate its intention early on via the display, as this medium provides the best visibility over long distances.

A2: "How Much Space is Required? – Effect of Distance, Content, and Color on External Human-Machine Interface Size"

Rettenmaier, M., Schulze, J., & Bengler, K. (2020). How Much Space Is Required? Effect of Distance, Content, and Color on External Human–Machine Interface Size. *Information*, *11*(7), 346. https://doi.org/10.3390/info11070346

In this study, we investigated the size requirements for an eHMI display. For this purpose, the work analyzed the potential available package space in current vehicle models and it examined ergonomic requirements for the interface design concerning the required display size and the layout of symbols and texts to transmit them legibly. Based on these findings, we developed an eHMI prototype and we conducted a study with 30 participants in a repeated measures design. Two experiments investigated whether there are differences in legibility from a constant distance between different content types (text or symbol) and differences in the human detection range due to the content coloration (white, green, red).

The study shows that symbols were more legible and were correctly identified at greater distances than text. The coloration of the eHMI had no content-overlapping influence on the human detection range.

Following the results, we state that the required display size is smaller than the potentially available package space at the front of current vehicle models and that eHMIs could theoretically be realized in this form under real conditions for legibility. Furthermore, AVs should use symbols instead of texts for communication, whereby the meaning of the symbols could be highlighted by color-coding without impairing their legibility.

A3: "Multi-Vehicle Simulation in Urban Automated Driving: Technical Implementation and Added Benefit"

Feierle, A., Rettenmaier, M., Zeitlmeir, F., & Bengler, K. (2020). Multi-Vehicle Simulation in Urban Automated Driving: Technical Implementation and Added Benefit. *Information*, *11*(5), 272. https://doi.org/10.3390/info11050272

This study investigated the simultaneous interaction between an AV and its passenger and between the same AV and an oncoming human driver in one simulation environment. For this purpose, we implemented a multi-vehicle simulation consisting of two driving simulators, where one participant acted as the AV's passenger and another participant as the human driver. The scenarios considered were bottlenecks narrowed on one side and bottlenecks narrowed on both sides of the road. The external communication of the AV consisted of the eHMI concept, which was developed and evaluated in Article 1 (Rettenmaier, Albers, & Bengler, 2020). In addition to the regular interactions between the AV and the human driver, we also implemented the automation failure defined in Article 1, Article 2, and Article 4, in which the AV first yielded the right-of-way, then changed its intention and maneuver and insisted on it.

The study confirmed the participants' passing times during regular interactions derived from the single-driver study in Article 1 (Rettenmaier, Albers, & Bengler, 2020). Therefore, we conclude that the results regarding traffic efficiency stated in Article 1 are correct. Moreover, the crash rate of Article 1 (95%) (Rettenmaier, Albers, & Bengler, 2020) and Article 2 (97%) (Rettenmaier et al., 2021) was considerably reduced in this study (40%) due to the intervening passenger in the AV. Despite this difference, the automation failure was still not controllable for the participants and we confirm the statements regarding traffic safety that the AV must not change its maneuver during the interaction in any case.

B Article 1: "After You?! – Use of External Human-Machine Interfaces in Road Bottleneck Scenarios"

Rettenmaier, M., Albers, D., & Bengler, K. (2020). After you?! – Use of external human-machine interfaces in road bottleneck scenarios. *Transportation Research Part F: Traffic Psychology and Behaviour*, *70*, 175–190. https://doi.org/10.1016/j.trf.2020.03.004

C Article 2: "Communication via Motion – Suitability of Automated Vehicle Movements to Negotiate the Right of Way in Road Bottleneck Scenarios"

Rettenmaier, M., Dinkel, S., & Bengler, K. (2021). Communication via motion – Suitability of automated vehicle movements to negotiate the right of way in road bottleneck scenarios. *Applied Ergonomics*, *95*. https://doi.org/10.1016/j.apergo.2021.103438

D Article 3: “Modeling the Interaction with Automated Vehicles in Road Bottleneck Scenarios”

Rettenmaier, M., & Bengler, K. (2020). Modeling the Interaction with Automated Vehicles in Road Bottleneck Scenarios. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *64*(1), 1615–1619. https://doi.org/10.1177/1071181320641391

E Article 4: “The Matter of How and When: Comparing Explicit and Implicit Communication Strategies of Automated Vehicles in Bottleneck Scenarios”

Rettenmaier, M., & Bengler, K. (2021). The Matter of How and When: Comparing Explicit and Implicit Communication Strategies of Automated Vehicles in Bottleneck Scenarios. *IEEE Open Journal of Intelligent Transportation Systems*, *2*, 282–293. https://doi.org/10.1109/OJITS.2021.3107678