Conceptual design and implementation of an external human-machine interface for an autonomously driving cargo bike

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Abstract

With the introduction of autonomous driving vehicles, road traffic is facing a great challenge. Especially if the vehicle is an autonomously driving cargo bike to be used in inner cities, this poses an unknown challenge for the people and the machine to get along and to create together conflict-free and safe road traffic. This thesis aims to design a human-machine interface for an autonomous cargo bike.

This interface consists, on the one hand, of the hardware interface itself but in particular of the designed interaction that is to be implemented with the interface. The focus is to design an interaction with the interface that allows the other road users to get the same information as if a cyclist would sit on the cargo bike with as little mental workload as possible.

In order to achieve this goal, the first step is to find adequate hardware to implement these interactions as seamlessly as possible in the cargo bike. For this purpose, a series of expert meetings and studies were scheduled to reduce the abundance of possible hardware and to decide on an interface in the final step, which will then be implemented in a prototype. Based on this interface, the interactions were designed and implemented. For this purpose, three main points were identified that should be implemented. First, the interactions of the cargo bike should be easily recognizable so that other road users can recognize the following type of interaction of the cargo bike without much thought. At the same time, the interactions should also adapt to the traffic situation and demand the necessary attention to defuse potentially dangerous situations. The last focus was to give people feedback so they feel recognized by the autonomous cargo bike, thus creating a sense of trust.

An online study with 120 subjects evaluated these interactions in the end. For this purpose, the prototype was filmed in different traffic situations where the interface performs different interactions. The study results show positive results but without significant differences between the different color and animation schemes that are part of the interaction.

Kurzfassung

Mit der Einführung autonom fahrender Fahrzeuge steht dem Straßenverkehr eine große Herausforderung voraus. Im Besonderen, wenn es sich bei dem Fahrzeug um eine autonom fahrendes Lastenrad handelt, welches in Innenstädte zum Einsatz kommen soll. Dies stellt eine unbekannte Herausforderung für die Menschen und Maschinen dar, die zusammen auszukommen und gemeinsam ein möglichst konfliktfreien und sicheren Straßenverkehr gestalten wollen.

Das Ziel dieser Arbeit ist eine Mensch-Maschine Schnittstelle für ein autonomes Lastenrad zu gestalten. Dieses Schnittstelle besteht zum einen aus der technischen Konstruktion, dem Signalgeber, selbst und zum anderen aus der ausgestalteten Interaktion, die damit umgesetzt werden soll. Am Ende soll dabei eine Schnittstelle entstehen, welches den anderen Verkehrsteilnehmern erlaubt mit möglichst wenig mentaler Belastung die gleichen Informationen zu erhalten, wie als wenn eine Fahrradfahrer auf dem Lastenrad sitzen würde.

Um dieses Ziel zu erreichen, muss zu Beginn als erstes ein Signalgeber gefunden werden der die vielseitigen Anfoderungen, bezüglich benötigte Kommunikation und der technischen Umsetzbarkeit, erfüllt. Hierfür wurden eine Reihe von Expertenrunden und Studien angesetzt, um die Fülle an möglicher Hardware zu reduzieren und im finalen Schritt einen Signalgeber zu finden, welcher dann in einem Prototyp umgesetzt wird. Auf Basis dieses Signalgebers wurde daraufhin mit der Gestaltung und Umsetzung der Interaktionen begonnen. Hierfür wurden drei Schwerpunkte identifiziert die umgesetzt werden sollen. Zum einen sollten die Interaktionen des Lastenrades leicht wieder zu erkennen sein, sodass andere Verkehrsteilnehmer ohne viele Gedanken die nächste Art der Aktion des Lastenrades erkennen zu können. Gleichzeitig sollten die Interaktionen aber auch auf die jeweilige Verkehrssituation anpassen und die nötige Aufmerksamkeit einfordern, wenn diese nötig ist um mögliche gefährliche Situationen zu entschärfen. Der letzte Schwerpunkt bestand darin die Menschen eine Art von Feedback zu geben, sodass sie sich von dem autonomen Lastenrad gesehen fühlen und damit ein Gefühl von Vertrauen entsteht.

Diese Interaktionen wurden am Ende durch eine Onlinestudie mit 120 Probanden evaluiert. Dafür wurde der Prototyp in verschiedenen Verkehrssituationen gefilmt in denen das Interface jeweils andere Interaktionen ausführt. Die Ergebnisse der Studie zeigen positive Ergebnisse, jedoch ohne signifikanten Unterschied zwischen den verschiedenen Farb- und Animationsschemas die Teil der Interaktion sind.

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List of Acronyms

ADB autonomous driving bicicyle

ADC autonomous driving car

ADV autonomous driving vehicle

UDL Urban Development Lab

ROS Robot Operating System

HCI human-computer interaction

HMI human-machine interaction

eHMI external human-machine interaction

iHMI internal human-machine interaction

SA situation awareness

HRU human road user

VRU vulnerable road user

P2V pedestrian to vehicle

AV2P Autonomous Vehicle to Pedestrian

V2P Vehicle to Pedestrian

PBQ Pedestrian Behavior Questionnaire

SSQ Simulation Sickness Questionnaire

IPQ Igroup Presence Questionnaire

ARBQ Absolescent Road-User Behavior Questionnaire

PRQF pedestrian receptivity questionnaire for FAVs

SA Situation Awareness

VR Virtual Reality

EDFT extended decision field theory

DARPA Defense Advanced Research Projects Agency

ICS Intent Communication System

LED light emitting diode

ORU other road user

EV electrical vehicle

AMT Amazon Mechanical Turk

HMD head mounted display

ADA autonomous driving automobile

UNECE United Nations Economic Commission for Europe

CIE International Commission on Illumination

IFF Fraunhofer Institute for Factory Operation and Automation

ITWM Fraunhofer Institute for Industrial Mathematics

MaXLab Magdeburg Experimental Laboratory of Economic Research

FMS Fast Motion Sichness Scale Questionnaire

POV point of view

SSE smart signaling emitter

AuRa Autonomes Rad

LPP local path planner

NOC need for communication

ROC risk of collision

HA human awareness

HD human density

DDS data distribution service

CW computing with words

COG center of gravity

COA center of area

TTC time to collision

IEC International Electrotechnical Commision

StVO Straßenverkehrsordnung

HRC human-robot collaboration

SART situation awareness rating technique

HAN human aware navigation

DL deep learning

RODOS Robot based Driving and Operation Simulator

MIT Massachusetts Institute of Technology

HAI Human-Automation Interaction

PID proportional-integral-derivative

UDP User Datagram Protocol

CVM Constant velocity model

SSE2ROS SSE to ROS

IMU Inertial measurement unit

GPS Global Positioning System

GUI Graphical user interface

ODD Operational design domain

DDT Dynamic driving task

OEDR Object and event detection and response

ADS Automated driving system

RCP rapid-control-prototyping

UX User Experience

PC personal computer

1 Introduction

Mobility in cities changes towards more climate-friendly alternatives, which means a needed change towards fewer private cars and more public transport and bicycles. Many countries and cities are investing in bicycle-friendly road traffic. An essential aspect of encouraging people to use a bicycle instead of a car is to make bicycles more suitable for everyday use. This includes being able to do everyday errands such as grocery shopping by bicycle. For this purpose, there is a wide range of different cargo bikes. These offer the possibility of transporting the groceries inside the city. A big help is the electric drive that many cargo bikes already have to make it easier for people to do heavy shopping or travel longer distances by bike. Cargo bikes also share some disadvantages with the cars they are trying to replace, although not as strong. First, cargo bikes, with or without electric drive, are pretty expensive. Furthermore, since they usually do not manage to replace either the bicycle or the car completely, it is instead to be considered an expensive additional alternative. And since it is then considered an alternative as a purely additional purchase, it is again less environmentally friendly than if it had replaced a car altogether. Secondly, cargo bikes need a suitable parking space. This problem is particularly prevalent in cities, where there are hardly any parking spaces, even for cars. So there are hardly any parking spaces for cargo bikes. Especially since, like the car, the cargo bike would not be in permanent use but would only be needed every few days for shopping. A solution that addresses both of these problems would be the establishment of a cargo bike rental system. Many cities have a rental system like the one already in use for bicycles and scooters. On the one hand, such a rental system for cargo bikes would mitigate the cost point since the customers only pay when they need the cargo bike, and at the same time, the customers do not need a parking space for it where it stands around unused. Through a rental system, individual bikes have a higher utilization rate than private ones. But such rental systems also have significant challenges that need to be addressed. A scooter rental system serves as a concrete example as it can be found in more and more large cities. A significant challenge here is the provision of scooters throughout the city, so customers never have a long way to go to the nearest scooter. As a solution, the scooters are usually collected in the evening, on the city's outskirts, and transported back to the city center. This is called balancing. This system also has to keep an enormous number of scooters available so that as many people as possible can still find a scooter in the city center in the evening, despite the one-sided distribution. This creates the problem of scooter littering. This would stand in the way of an identical implementation with cargo bikes. The idea of the AuRa (engl. autonomous bicycle) project is to create a solution to this problem by transferring the technology of autonomous driving, which is already being used successfully in cars and trucks, to the cargo bike[193]. The vision, as the figure 1.1 shows, is to equip a fleet of rental bikes with this technology, which would address several problems simultaneously.

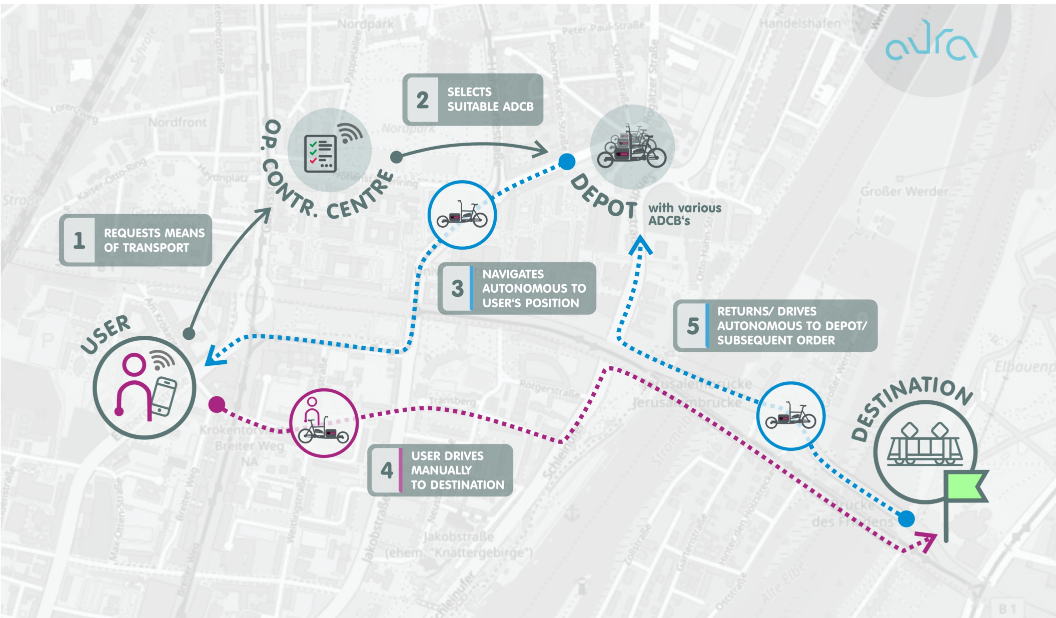


Figure 1.1: The lending process in the AuRa project using autonomous driving cargo bike

On the one hand, this would solve the problem of balancing, as the bicycles would be able to return autonomously and independently to the place they are needed after use. On the other hand, it would eliminate the need to keep a vast number of bicycles on hand, further increasing congestion in the city center. For this, however, some hurdles have to be overcome. The biggest and most obvious hurdle is the technical realization, as this still needs to be solved for the implementation of autonomous driving for cars and trucks. Various companies celebrate new successes yearly, but widespread deployment without human safety drivers is still a long way off. The same problem applied to a cargo bike poses new problems. Unlike cars, there is still a limited energy supply, leading to other issues. An example would be the cooling of the computers during midsummer, while every modern car has an air conditioner, for the bike an own solution had to be found. However, apart from that, introducing autonomous vehicles in the german traffic area is a legal challenge. As always, when new technology enters society, legal frameworks have to be created to make it safe for people even though it can be assumed that ADV will result in far fewer traffic accidents[179] and even Vision Zero has been pronounced as a goal by the European Commison[77]. Nevertheless, in addition to the aspect of safety, it is also a matter of not suddenly confronting people with autonomous dangers. Therefore, a slow introduction into society is a must. A central aspect of this is the human-machine interaction (HMI). To avoid making people uncomfortable with the contact of ADVs, it must be ensured that the machine supports the human. This is achieved on the one hand by the autonomous driving bicicyle (ADB) behaving as one would expect from other cyclists. On the other hand, it is a matter of replacing the lack of human interaction with signaling. On the one hand, this is a much more significant challenge with bicycles than with autonomous driving cars (ADCs). Cars already have certain signals like blinkers and warning lights. On the other hand, cars operate primarily on well-separated car lanes and have contact with vulnerable road user (VRU) only in particular, highly regulated situations, like crossing and zebra lanes. On the other hand, the bicycle operates either on the bicycle lane, which does not have to be separated by a curb, or even in shared traffic space, where unregulated contact with VRU is the usual case. To accomplish all this, it is necessary to realize a good HMI for the cargo bike in the AuRa project. However, it is helpful in the next section to look at autonomous driving in general and its development.

1.1 Autonomous driving

The AuRa(engl. autonomous bike) project has the implementation of an autonomous cargo bike as its goal. Autonomous driving technology has become the focus of development, especially in recent years, and almost all car manufacturers have their own development or have joined forces for the development. However, the foundation of autonomous driving was laid decades ago, starting with the construction of the first self-driving car in 1977 by Tsukuba mechanical engineering lab. This vehicle could detect lane markings up to 50 meters ahead and reach up to 20 miles per hour[96]. A decade later, the PAN-European PROMETHEUS Project by EUREKA[9] was born, which was the most significant autonomous vehicle project ever, with 749.000.000€ funding from the EUREKA member states[20]. From this, the VaMP was born in the early 90s under the leadership of Ernst Dickmann, one of the pioneers of driverless cars [10][29]. Building on these pioneering projects, many smaller projects followed that further investigated the feasibility of autonomous driving. For example, the CARSENSE project focused on more complex situations that were still a big problem and required more effort than highway driving. Furthermore, the vision was advanced to fundamentally change traffic through the cooperation of many autonomous driving vehicles, as in the demos of AHS and AHSRA. After that, the DARPA challenges competitions from Defense Advanced Research Projects Agency (DARPA) in order to 'sponsor revolutionary, high-payoff research that bridges the gap between fundamental discoveries and military use' [6]. Starting with the *Grand Challange* for autonomous ground vehicles in the Mojave Desert. These regular challenges ensured that the topic became more frequently present to the broader public. Over the years, other challenges with other terrains for autonomous ground vehicles in the urban challenge, but also subterranean and launch challenges for the harsh conditions in underwater and airspace and robotic challenges. This provided a platform for universities and companies worldwide to showcase their advances in autonomous driving.

In today's world, autonomous cars are poised to be unleashed on cities in a big way, with many large commercial companies already offering either Robo-taxis (with human safety driver) like waymo[31] and cruise[26]. Nowadays, most cars offer Automated driving system (ADS), which can be classified as level 2, and Tesla recurrently promises to reach level 5 next year[32]. These levels describe the features of ads in the area of autonomous driving. The norm that defines the classification of the Levels of Driving Automation comes from the *SEA International* in the standard SAE J3016 [189]. Here, a notable distinction is made between Dynamic driving task (DDT) and DDT fallback features. This means which tasks the car can take over and whether a human driver has to supervise them or not. In addition, car manufacturers have to specify in which Operational design domain (ODD) these features are allowed to work since their functionality can only be insured in these areas. The following table 1.1 gives an overview of the SEA 'Levels of Driving Automation'. Levels 0 to 2 mark the levels where the human driver takes over the tasks of many or all DDT. In levels 3-5, the ADS takes control of specific DDT. The Figure 1.2 shows an official illustration by SEA with examples for each level.

Level	Features	Information
	No Driving Automation	
0	No ADS present	Driver performs entire DDT
	Driver Assistance	
1	performing either the lateral or the longitudinal vehicle motion control	Driver supported by driving assistance e.g. automatic emergency braking
	Partial Driving Automation	
2	performing both,the lateral and the longitudinal vehicle motion control	Driver still in task of Object and event detection and response (OEDR)
	Conditional Driving Automation	
3	sustained and ODD-specific performance under normal conditions	Driver needed by failures or ADS leaving DDT
	High Driving Automation	
4	sustained and ODD-specific performance by an ADS of entire DDT and DDT fallback	Driver does not need to supervise ADS or be receptive to intervene during DDT
	Full Driving Automation	
5	sustained and unconditional performance by an ADS of entire DDT and DDT fallback	Driver does not need to supervise ADS or be receptive to intervene during DDT

Table 1.1: Overview off all levels of Driving Automation by SEA International[189]

Looking at the levels and the history of AD, it is striking that level 2, i.e., performing both the lateral and the longitudinal vehicle motion control, was reached early, but it progressed very slowly beyond that. One of the main reasons for this is the expansion of the conditions under which the ADS has to function reliably. This means, for example, that lane keeping has to perform just as reliably not only in daytime and sunshine but also at night, in rain and snow. This places new and higher demands on sensor technology and algorithms, which must be expanded. Nonetheless, autonomous driving technology is being extended to trucks or, as in the AuRa project, to cargo bikes.

The problems that arise there for the HMI will be described in the next section.

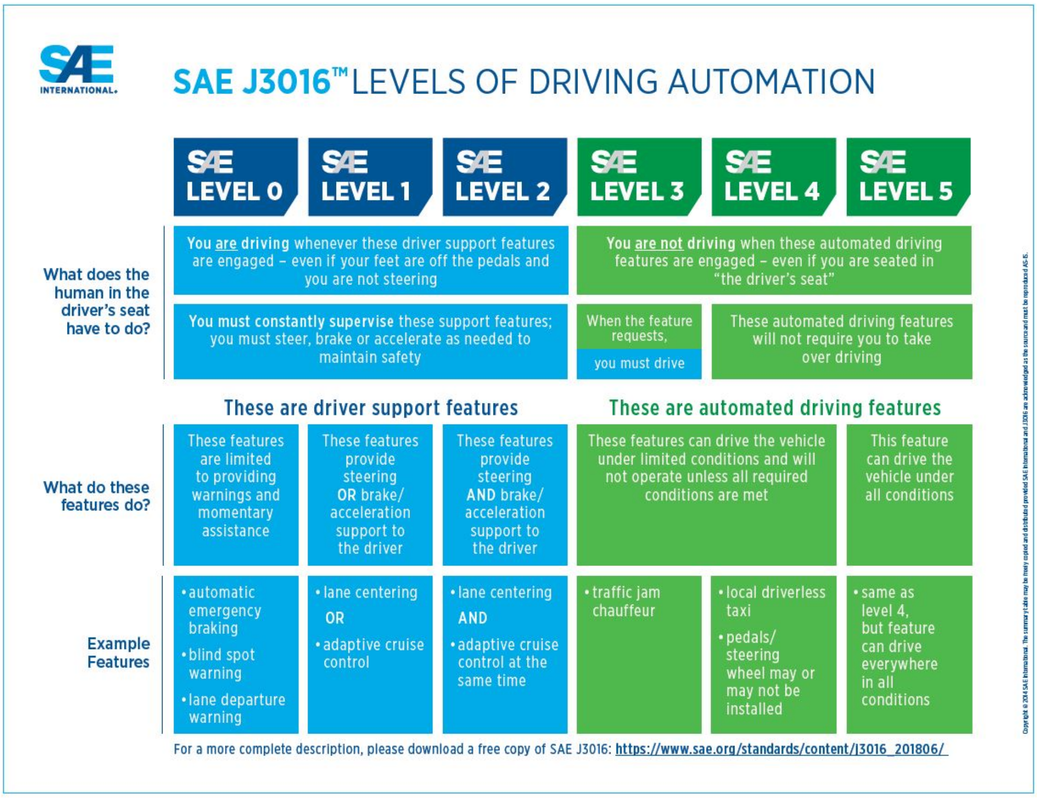


Figure 1.2: Classification of the Levels of Driving Automation from SEA[189]

1.2 Problem Statement

As discussed in the introduction, the AuRa project is about using a cargo bike to move autonomously in german road traffic. The focus is on bicycle lanes, parking lots, or shopping areas where bicycles are allowed. The task of the HMI is to take over the communication of the cargo bike with other road users. For this purpose, let us imagine a typical situation as it occurs in today's inner cities:

1. Pedestrian: [walks through a shopping street and approaches a bike lane]
2. Cyclist: [drives on the bike lane]
3. Pedestrian: [looks for arriving bicycles and catches sight of the approaching bicycle]
4. Cyclist: [sees the pedestrian approaching the lane]
5. Pedestrian: [makes eye contact]
6. Cyclist: [makes eye contact and nods toward the pedestrian]
7. Pedestrian: [nods back and crosses] *The pedestrian interprets the nod in this context that the cyclist will be giving way to the pedestrian*
8. Cyclist: [slows down, so the pedestrian has a comfortable gap to cross]

This a conventional situation as it often occurs in german city centers. The nod could also be replaced by a hand movement or even just by the bicycle or the arriving person slowing down, and the situation would be the same. Usually, all communication is nonverbal and stress-free for both, and it is also not a process for either to lose much thought over. Now imagine the same situation, but with no person sitting on the bike:

1. Pedestrian: [walks through a shopping street and approaches a bike lane]
2. ADB: [autonomously driving on the bike lane]
3. Pedestrian: [looks for arriving bicycles and catches sight of the approaching bicycle]
4. ADB: [sees pedestrian approaching the lane]
5. Pedestrian: [seeks eye contact but sees that no human is sitting on the bike]
6. ADB: [slows down and starts flashing in an orange light]

7. Pedestrian: [hesitates but notices the reduction in speed and the signals and crosses] *The pedestrian interprets the slowing down and orange flashing that the ADB will be giving way to the pedestrian*

8. ADB: [changes signals away from orange and accelerates again]

This exemplary encounter shows that with the omission of the human driver, the situation has a different dynamic. The pedestrian's expectation was thwarted, and he was suddenly placed in a situation that was new to him. This unpredictability of the situation is perceived as stress for the human[136, 165]. In addition, it can lead to uncertainty, which means that the person in an everyday situation behaves differently or hesitantly. A behavior that is not predictable by other road users and can therefore lead to more dangerous situations.

Therefore it is vital to provide a substitute for humans in the form of a human-machine interface. This interface has the task of making it as easy as possible for other road users to stay away from humans. But what does that mean? Humans should receive the same information from the interface as from a human. However, the communication itself looks completely different. There is no more eye contact, no more sustained pedaling of the cyclist or the like. The logical next question is, what does this human-machine interface have to look like to achieve this? This question can be divided into three sub-questions, each enclosing a challenge and can be viewed as a problem statement. In the following, I will discuss these questions and what requirements their solutions must have in order to solve them.

1. What kind of device is needed for communicating with other road users?

At first glance, this question seems exclusively technical, but this is not the case. Which device is used determines, for example, whether speech, images, or light signals can be used for communication. It determines the communication modality and can be described as a human-machine interface. Nevertheless, this question also has technical aspects. The cargo bike must be able to keep the communication of the interface as faithful as possible. This means that communication is not limited even in challenging traffic situations. For example, the bike's vibration or transverse position makes it difficult to read a text. Another aspect is the usability of the bike. The interface should not hinder the use of the cargo bike by limiting the usability of the cargo box or manual driving of the bike itself. However, also, very practically, the energy consumption of such an interface can affect the range of the cargo bike in autonomous mode. For all these aspects, a focused list of requirements can be compiled. These are colloquial requirements, and it is the task of the thesis to concretize them, prioritize them and answer them:

Requirements

- recognizability: the signals should be perceivable by all people who are potential communication partners.
- scalability: the interface should support the property of gradual activation to ensure that the communication allows as much as necessary and as little as possible.
- feasibility: the interface should be able to be implemented in the technical system of the cargo bike without limiting it too much in its function.
- reliability: the interface should be robust against all planned traffic situations and environmental conditions so that every communication process is executed as planned.

2. How does the communication look like via the chosen device?

The second question builds directly on the answer to the first question. The interface alone does not determine the interaction with other road users. On the one hand, the degree of freedom offered by the presentation of the interface must be discussed on the basis of the interface. For example, depending on the resolution, a screen can display complex content or only pictograms or text. Based on these degrees of freedom, it has to be determined how the interaction of the cargo bike has to look and what the communication with the other road users looks like. For this purpose, the communication from human to human has to be analyzed first in order to show the gaps based on these findings, which result from the omission of the human on one side. Here you can already derive some requirements the solution must have in place:

Requirements

- unambiguous: the interaction should be unambiguous and leave as little room for interpretation as possible.

- appropriate: the behavior should be designed to ensure that all road users to be communicated with have been adequately addressed, while at the same time not addressing all people in a blanket manner. This should prevent trivialization of the communication.
- feedback: the interaction should also provide feedback, so the other communication partner feels addressed.

3. How should the realization of such a concept be designed?

The third question focuses on the implementation of the communication concept between humans and the bicycle presented in question 2, into a system. The main aspect is to implement the communication concept so that its nature and effectiveness are faithfully maintained. Solutions have to be found to realize the technical realization feasibly and safely, but also to give the freedom to change the concept in order to support studies of different characteristics of the concept. Here, too, requirements can be derived that the solution must contain:

Requirements

- traffic: the different traffic situations in which the cargo bike operates must be taken into account.
- safety: the implementation should take into account the safety of the VRU.
- configurability: the system responsible for generating the communication should be highly configurable so that different interactions can be studied and compared with each other.
- response: the system should allow responding quickly to its environment since timing plays a central role in communication.
- reliability: the interface should be robust against all planned traffic situations and environmental conditions so that every communication process is executed as planned.

Answering these three questions is the task of this thesis. However, in addition to the limitations resulting from the requirements, there is also a significant other limitation. The HMI system focuses on visual and acoustic interaction with other participants via specially designed interfaces. However, communication with others also includes body language or, in this case, the movement behavior of the cargo bike. This behavior is not part of the work and is not subject to the influence of the HMI system. Instead, it is the task of the HMI system also to include such behavior.

1.3 Structure of the thesis

The general task of the thesis is to find a communication solution for the AuRa project. The task specification, requirements, and constraints have emerged from this application that guides this thesis. Therefore, in the next chapter, state of the art, we will look at the existing approaches to eHMI and their concepts and evaluation possibilities. For this purpose, publications that categorize and evaluate these interfaces have been consulted and compared. However, to understand the impact and intentions of the respective eHMI, we first go into the basics and state-of-the-art of human-machine interaction in general and in the traffic realm. Based on this knowledge, the studies presented in this paper were developed. Not only to provide insights into the context of AuRa but also into human-machine interaction in general. The third chapter introduces the AuRa cargo bike itself since many of the requirements are derived from it. Then the studies done at the beginning and conducted as a team are presented and used to investigate modality for the HMI. At the end of the chapter, the hardware realization of the interface is presented, which was developed in collaboration. The fourth chapter presents the HMI system as a concept. First, the concept of interaction is introduced, which is the central point of the concept. In addition, all parts that are necessary to process the data from the environment and the bicycle itself in order to generate these interactions are introduced. Finally, the concept of fuzzy logic is presented together with that of the fuzzy controller, as these are used at central points. The fifth chapter deals with implementing the concept presented in the fourth chapter. The focus is on the implementation of software modules in Robot Operating System (ROS). Nevertheless, the free configuration of the interaction generation and the interface with the hardware is described. In the second chapter, the implementation of the concept is evaluated. For this purpose, an online study was conducted with 120 subjects, and the data were evaluated in R. In the last chapter, a summary of the work is drawn, and everything that was achieved during the work is shown again. Finally, an outlook is given about possible further work based on the system.

2 State of the art

The goal of this chapter is to give an insight into the field of HMI(or human-computer interaction). This interdisciplinary field includes aspects of computer science, psychology, human factors, design, and cognitive sciences, which represents a major challenge[212]. HMI is about the communication between humans and machines. Most people today experience HMI with digital devices through buttons and slides shown on display or as the voice assistant on the smartphone. However, it also includes the movement and expressions of machines and robots or the experience one has within a virtual reality. The goal is to improve this interaction by analyzing and understanding it by adapting the machine to make it as productive and stress-free as possible for a human.

Interaction with autonomous systems is a subcategory of HMI. The field of autonomous systems ranges from industrial robotics over social robots to ADV, which are more and more focused on research. The term autonomous system does not specify which part of the system has been automated, but only that it contains elements of automation. In most cases, however, these are work steps that were previously carried out by humans, and that still require human assistance in the process. This is precisely where the interface between humans and machines is defined and describes the context in which communication occurs.

Parasuraman et al.[176] presented a classification of automated systems into four types. Here, autonomous systems are evaluated in 4 different categories, and these categories themselves were adopted from human information processing. These categories include Sensory Processing, Perception/Working Memory, Decision Making, and Response Selection, see figure 2.1.

The novelty coming with autonomous vehicles falls into the latter two categories, decision-making and response selection. For example, they now decide on their own whether to turn or to continue driving to reach their destination. This is just looking at the new functionality added to cars that already have advanced driver assistance systems. The first two categories have been elementary parts of

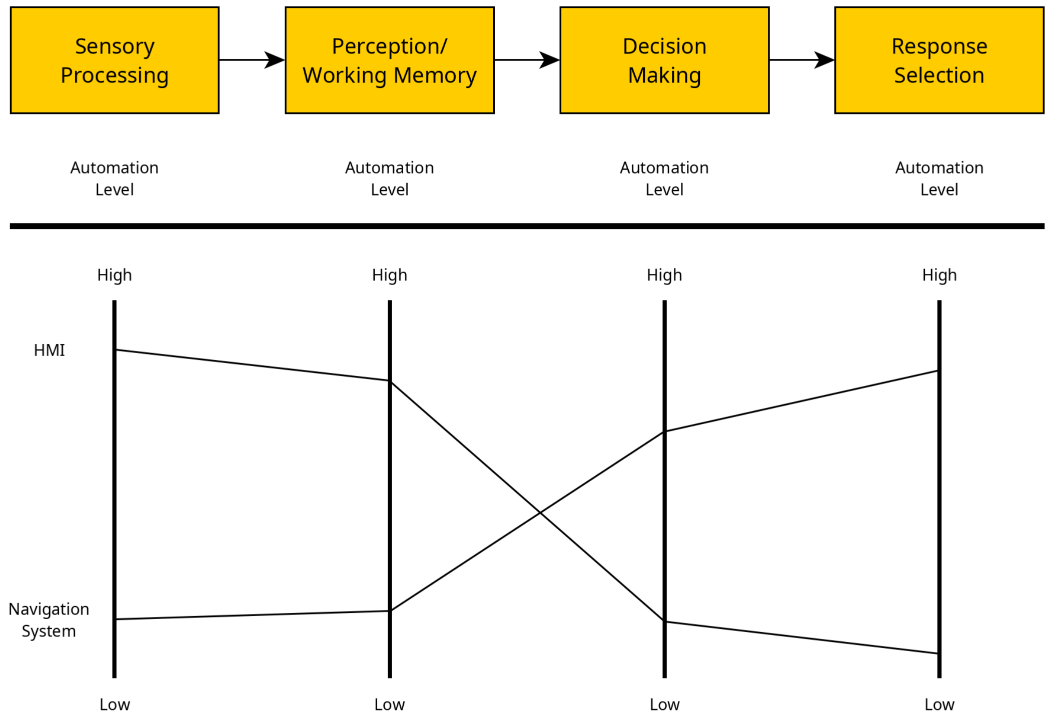


Figure 2.1: Proposed classification of Parasuraman et al.[176] with example systems

HMI for a long time. For example, when displaying relevant search results, they are prioritized according to their weighting and displayed more prominently to us. But the cockpit display in the car also counts. Nowadays, on-screen projections are also used to make it easier for people to take in information. The HMI of an autonomous bicycle also falls into these categories. Its task is to relieve the human being of the task of understanding what behavior the machine is currently exhibiting and what it intends to do next. For example, when a bicycle signals that it wants to start, a human must first collect the information that its tires are beginning to move and then draw the conclusion that it is about to start. Based on these types, one can now understand the system's effect on humans in terms of mental workload and situation awareness. Both concepts are discussed in more detail in section 2.2.1.

HMI can be divided into two categories: **external** and **internal**. This distinction is based on the system's point of view and on the fact that people can be divided into operators and non-operator from the system's point of view. The internal human-machine interaction (iHMI) is about communication with the operator. For example, in an autonomous passenger car, this would be the people sitting in the vehicle and operating the ADV from the inside. The iHMI would then be the assistance functions or the information displays available to help the operator use the machine successfully. In external human-machine interaction (eHMI), the focus is on people who are not identified as operators. Returning to the example of the autonomous passenger car, non-operators are all people outside the vehicle, e.g., all other road users with whom communication must take place via an external interface. Therefore the focus of this chapter is on eHMI. The chapter is structured as follows. In the first section, we look at communication, in general, to understand what it means when one of the two partners in human-to-human communication falls away. After that, we will examine the traffic scenarios in which the AuRa bike has to prove itself and how these scenarios can be viewed and classified in the literature. Consequently, we look at what models and concepts exist in human decision-making in the context of autonomous systems. Finally, we look at the concepts and implementation of eHMI in the field of ADV, showing the different goals, purposes, and realization of interfaces and how they are evaluated.

2.1 Communication in Traffic

In order to understand what communication between humans and machines in traffic looks like or can look like, it makes sense to first look at the communication between humans in traffic. For this endeavor, the use of the implicit interaction theory of Ju[129] as also used in Rothenbucher et al. [186] helps, which suggests that the first step to considering the pattern of such an interaction is to make a step-by-step hypothesis about the expected pedestrian interaction without the machine. For such an interaction, the scenario where a pedestrian wants to cross the road for a non-automated passenger car was chosen:

1. Pedestrian: [walks and approaches an intersection]
2. Driver: [drives and approaches an intersection]
3. Pedestrian: [makes eye contact]
4. Driver: [makes eye contact]
5. Possibility 1:

6. Driver: [Driver nods] *The pedestrian interprets the nod in this context that the driver will be given ways to the pedestrian*
7. Driver: [stops or slows significantly down] *The speed of the car signals the pedestrian how fast the driver expects the pedestrian to cross*
8. Pedestrian: [nods to the driver and crosses]
9. Driver: [crosses]
10. Possibility 2:
11. Driver: [does not slow down] *Not slowing down represents the pedestrian that the driver will not be giving ways*
12. Pedestrian: [stops at curb]
13. Driver: [crosses]
14. Pedestrian: [crosses]

Looking at these individual steps and imagining that it is an automated car where no person is sitting, it quickly becomes apparent that some actions do not work in this way. The pedestrian does not have the opportunity to make eye contact to recognize whether he has been seen by the arriving car. It turned out that people also looked for confirmation behind the steering wheel in automated cars. This gap is neither limited to this one scenario nor to using a passenger car, and the type of communication would have been the same in an interaction with a cyclist. The example also clearly shows that traffic communication happens intentionally and varies only slightly between situations. Therefore, every traffic situation must also be evaluated as a social interaction[98].

However, communication generally can have a physical component, e.g., gestic, mimic, body movement, especially by communication in the traffic realm. Here we differ between driver cues, e.g., eye contact and hand movement, and vehicle cues, e.g., speed and stopping distance[155]. Communication is divided into explicit and implicit[81, 98]. According to this, **explicit communication** is where the transmitter sends his intention in direct signals to the receiver. Whereas **implicit communication** is information that is not directly said but is contained in the message. This form of communication is dominant because it is permanent, or in the words of Watzlawick et al.[214] 'one can not communicate'. This also applies to the traffic realm[81]. However, when talking about the different levels of communication, one does not get past Schulz von Thun's 4-level model[194].

According to this, I am effective in four ways when I say something as a human being. Each of my utterances contains, whether I like it or not, four messages at the same time: Factual information (what I am informing about); a self-disclosure (what I am revealing about myself); a relationship hint (what I think of you and how I relate to you); an appeal (what I want to achieve with you). The point is that the speaker has four beaks with which he announces a message, and the listener has four ears with which he receives a message. Unambiguous communication is the ideal case and not the rule. For example, let us take a social robot that says to a person close to it: *you are too close!*. The factual content of this message says that the distance between the robot and the human is too short. The appeal is that the robot wants the human to distance himself more between himself and the robot. The robot guesses the relationship between him and the human by assuming that the human would listen to him and follow his request. As self-expression, one could interpret that the robot wants to keep a mid-nest distance from humans in order to be able to move safely in their presence.

The difference with human-to-human communication is that communication in its four levels is not spontaneous and the will of a single human being but pre-planned and programmed interactions. Thus, different levels have emerged from the design of the interaction. Another question concerning human-machine communication is to what extent it can be seen as bidirectional communication. The human, as the machine's communication partner, will, intentionally or not, respond to the machine's communication, e.g., by stopping or continuing its movement, following the machine's response. AVs or robots already have their movement as a communicator even without eHMI. Early navigation and movement planning had the task of arriving at the given destination and not bumping into anything. For example, people's trajectory is predicted to avoid them with an adequate safety distance. In this case, speed and steering movements are communicators for humans without being considered as such and developed with the idea that they are. However, this is changing more and more, and work is being done to make robots understand the intentions and movements of humans without verbal communication[61, 175].

In the AuRa scenario, our communication partners are pedestrians, cyclists, and car drivers, which are grouped under the term human road user. This term refers to all road users a person controls to distinguish them from autonomous systems. A subset of human road user (HRU) is vulnerable road users (VRUs). This is the term used to describe road users who are not sitting in a vehicle. This is in contrast to humans sitting in passenger cars or buses, which are, therefore, potentially better protected from collisions. These passenger cars or buses make up to 80% of the studies regarding eHMI by a survey by Dey et al.[77]. For the interactions between communication partners, a lot of terms have also emerged, such as pedestrian to vehicle, Autonomous Vehicle to Pedestrian, and Vehicle to Pedestrian, to name a few. It is important to note what differences there are between the communication between pedestrian to car and pedestrian to bike. One such aspect is the scenarios in which the interaction takes place, and the context in which communication takes place is of great importance. Therefore the next section will focus on these traffic scenarios.

Traffic Scenarios

Scenarios are traffic places where interactions happen with conflict potential, e.g., there is no conflict in a separate bike line per se, but the pedestrian who wants to cross the line has the potential to create one. When looking at studies in the field of pedestrian decision-making etc., it is crucial to consider the scenarios they were carried out to evaluate them. Furthermore, it is also essential to determine what kind of ADV was in use. It is also the case that certain types of errors and accidents are highly dependent on the scenario in which they occur[215]. The most used scenarios in eHMI are where the interaction is about yielding; this is because they mostly take place in the focus of car-to-pedestrian interaction, and this situation is most dominant there. The survey of Dey et al.[77] shows that out of 70 studies, 45 were about yielding and 15 about not yielding/cruising. This scenario is very different from the interactions of a pedestrian with cars or bikes. In scenarios involving an autonomous car, the crosswalk often has either lane markings or even traffic signals.

In bicycle scenarios, this usually only applies if the bike lane is on the road or the bicycle has to ride on the road. However, some scenarios occur in a shared traffic area, where pedestrians and bicycles move freely. With the Aura project, we are in a German urban space with many shared traffic areas; one example would be shopping streets where bicycles and sometimes car traffic are allowed. Another example of a foregather of all kinds of traffic participants is the parking lot, which is available at almost every grocery shop. German traffic law(Straßenverkehrsordnung (StVO)) applies to the German traffic area, and everyone must comply with it. Nevertheless, many informal rules also ensure mutual safety and consideration. A study by Li et al. showed that communication is most important in traffic scenarios where both parties are unwilling to come to a full stop. This is especially the case in uncontrolled traffic situations, where there is no crosswalk, and is therefore of increased importance. There are some attempts to categorize the traffic scenarios and to create a taxonomy for them, with which the scenarios can be evaluated and compared according to factors.

Those taxonomies often focus on certain aspects or are created with specific use cases in mind. One early example is the taxonomy of Fastenmeier et al.[94], where the aim is to assess situations concerning the degree of complexity of the task for the car driver in terms of the need for information processing and the demand for vehicle operation. For this purpose, data were collected during the drives, such as dynamic vehicle parameters (speed, steering angle), the driver's gaze movement, and employing the 'Wiener Fahrprobe' or 'Vienna driving test', which collects the driving behavior utilizing trained observers.

Another approach is shown by Markkula et al.[159], which does not classify the situations themselves but the actions of people in interaction with automated road traffic. The classification is not sharp but is represented by overlapping sets, as a Venn diagram, to be seen in image 2.2. The categories are based on the intention of the human while executing the intention. For example, movement-signaling is an action that tells other road users which movement is planned. Another example is perception-achieving, which is an action that aims to get information, like moving the head or the car to get a better view of the traffic situation. Based on this diagram, all actions can be classified. In addition, Markkula et al. analyzed if the category is part of explicit or implicit communication to make further classification possible. With this taxonomy, it is not possible to classify traffic situations in general, but people's behavior in these situations. This can be deployed on our example of implicit interaction theory at the beginning of the chapter to classify each subject's activity.

The taxonomy by Fuest et al.[98] focuses on the interaction between ADV and other road users and is, therefore, particularly suitable. It includes, for example, physical attributes like distance, speed, and direction of travel but also things like intention and attention level of ADV and HRU. The point HRU character, in particular, is intended to show how strong the need for safety and information depends on whether the person is a car driver, a cyclist, or a pedestrian. A pedestrian potentially needs more security in the form of a formal nod of the head than a car driver who feels safer in his car. When planning or controlling the eHMI, this increased need can be considered. A complete list of all attributes and possible values can be found in table 8.19. One quickly notices a few inconsistencies

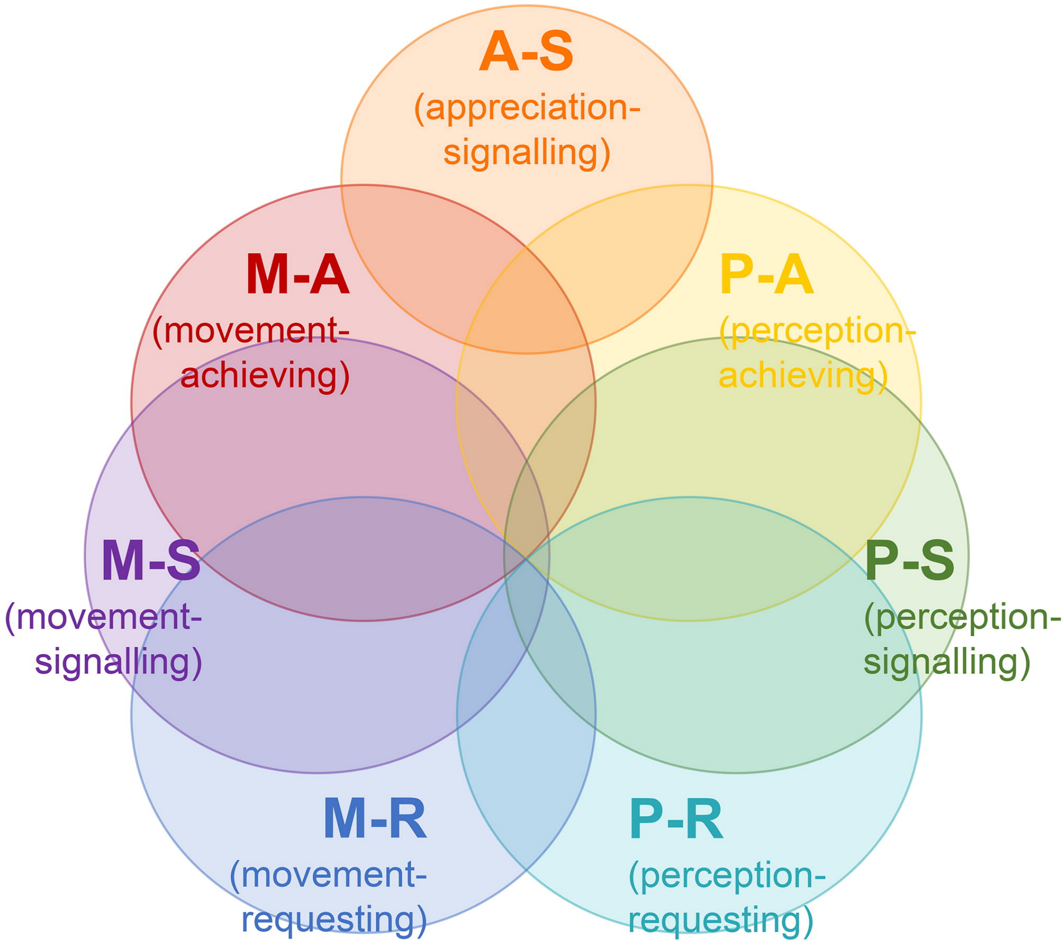


Figure 2.2: Illustration of the proposed taxonomy of behaviours in road traffic interactions, and some of the ways in which the different types of behaviours can overlap. From Markkula et al.[159]

when comparing the AuRa scenarios to the taxonomy. Firstly, the discretization of the speed of the ADV is apparently only designed for cars and not for ADB or micro mobile. For this category, speeds describing cyclists or pedestrians would make sense, similar to HRU speed facets. In addition, it is still being determined how a change in speed is to be assessed since speed does not indicate a range but a discrete value. Even if the information is, maybe, only intended as a guideline, it makes a big difference whether an ADV only travels 0 km/h or starts during an interaction. The same applies to braking.

A complete classification of all possible traffic scenarios is not feasible; therefore, a summary of the five actions of the ADB, whereby the location and status of the interaction partner would change the classification according to the taxonomy of Fuest et al.[98]:

- **starting**, at a parking spot or distribution station or where the bicycle has been released.
- **braking**, in front of a parking spot or distribution station or where the bicycle has been called to.
- **giving right-of-way**, on various situations towards various other road participants.
- **taking right-of-way**, on various situations towards various other road participants.
- **lane/direction change**, on bike lane or on shared traffic area.
- **active waiting**, at traffic intersections or places where the bike was called to go.

2.2 Pedestrian behavior and decision-making

Our goal with eHMI is not only to replace the human being and thus cooperate with the people in the environment but, in essence, to make the absence of the other human being as easy as possible for the human being. For this, it is vital to know the decision process of humans to support them in the situation facing ADB. According to Brehmer et al.[51] 'dynamic decision making relates to conditions that require a series of decisions, where the decisions are not independent, where the state of the world changes, both autonomously and as a consequence of the decision maker's actions, and where the decisions have to be made in real-time". Many models have been developed in science to describe the decision-making process of humans in different situations, a typical application being in the military, where the goal is to ensure that decision-makers are prepared to make serious decisions quickly that can put lives at stake. In addition, many studies deal with the general movement of groups of pedestrians, where crowd dynamics or trajectory predictions are involved[36, 112].

However, since it would be too much to show all decision models, we limit ourselves to those that have been applied to describe pedestrian behavior. For this, we look at studies from the field of pedestrian behavior also without the context of autonomous driving, such as with the explicit interaction of ADV. Many studies show that humans respond socially to technology, and reactions to computers can be similar to responses to human collaborators[184]. Research from Nass et al.[99] showed that people apply socially learned rules, such as politeness, to interactions with machines[115]. Automation has the potential to change the behavior of people[176] and is the focus of current research. Trust is seen as the foundation of many decision-making models, and Interest in trust has grown dramatically in the last five years, as many have come to recognize its importance in promoting efficient transactions and cooperation[146]. Moreover, public traffic is a place of collaboration between humans based on formal and informal rules, also called social norms, which play a significant role in how traffic participants behave and also how they evaluate the intentions of others[220]. They also rely on the fact that others follow these rules, where trust plays an important role. Considerable research has shown the attitude of trust to be important in mediating how people rely on each other[76, 75, 187, 199]. The following sections will introduce some of these models or essential concepts and their backgrounds.

2.2.1 Terms and concepts

Human decision-making has been studied from many perspectives, including psychology, social psychology, behavioral economics, and, more recently, cognitive neuroscience[92]. The consensus is that human decision-making is not exclusively rational; subconscious biases come into play, triggered by context or modulated by emotion[92]. For this purpose, different models and factors have been designed over the years to give an insight into the process of human decision-making with a focus on the interaction with automated systems. The next sections will overview the most essential concepts in this area and provide insight.

Pedestrian Behavior Factors

Rasouli et al.[183] did an extensive survey and clustered the different factors that influence the behavior of pedestrians. He distinguished between pedestrian and environmental factors. Pedestrian factors describe characteristics that go out of the person itself, like age, culture, and walking speed. These factors are summarized in table 2.1.

sub-factors	Pedestrian Factors
Social factors	group size: crossing behavior[111],
	pay less attention[108, 213, 191], do not look[203]
	social norms: psychological/natural right-of-way[221]
	acceptable actions[91]
	imitation: law-adhering/violating[224], influence of
	social status[147], social status vs. group size [83]
Demographics	gender: woman more cautios[111],[224, 116], woman more
	law compliance[122, 209], crossing behavior[224],
	attention patterns[209], crossing speed [121]
	age: eldery walk slower[121], eldery varied walking pattern[104],
	gap acceptance[205, 109], eldery pay more attenion[180]
State	speed: walking ped. are less conservative[173], speed change
	on crossings[207], speed change based on free space[167],
	speed change based on time of day[222], slower in groups
	[222, 82, 174], change in attention to objects[103]
	trajectory: improved speed estimation on cars[192]
Characteristics	culture and social norms[151], different traffic culture[47],
	culture differences on traffic problems[151],
	culture differences on gap acceptance[192]
Abilites	judging vehicle speed and distance[206]

Table 2.1: Tabulary summary of pedestrian factors on pedestrian behavior from Rasouli et al.[183]

Environmental factors are external factors that affect the person, such as the structure of the road, weather, and the type of passenger car. These factors are summarized in table 2.2. The studies also introduce essential concepts such as gap acceptance, which defines how much or long a gap should be in order to cross a road safely. Here the term refers to a temporal gap. Not only the gap itself but also the gap acceptance is dependent on two factors, vehicle speed and distance. This means that the same large gap, but resulting from different speed and distance values, also has a different effect on gap acceptance[181, 85, 65].

sub-factors	Environmental Factors
Physical	street delineations: traffic signs and marks on
context	behavior[167], traffic signs and marks on
	law compliance[168]
	signals: level of cautousness[180], (un)signalized
	crossings alter attention to vehicles and trajectory[209]
	walk faster on signalized crosswalks[168, 142]
	road structure: street width on attention[180]
	accept smaller gaps in narrows streets[192, 180]
	street width on law compliance[60, 56]
	lighting conditions: more conservative on bad weather[206]
	more cautious on warm weather[108]
	riskier decisions when it is darker[107]
	movement on slippery roads[167, 150]
Dynamic	time to collision (TTC) on cross chance[82, 192]
factors	vehicle speed on ped. ability to estimate distance
	and speed[63, 206], ped. accept rather higher speed than
	small distances[192], waiting time on gap acceptance[205, 213]
	communication: ped. feel uncomfortable with missing
	communication[185], ped. establish eye contatact f
	or savety[182],eye contact increase law compliance[105]
traffic	volume: higher density lower chance to cross[121]
characteristics	car types: more cautious on larger vehicles[65], vehicle size on
	speed estimations[55], vehicle type on crossing behavior[106]

Table 2.2: Tabulary summary of environmental factors on pedestrian behavior from Rasouli et al.[183]

No Communication or Attention

Some predictions are that the autonomous driving vehicle will ensure that there will be pedestrian-oriented cities or neighborhoods. In that, humans and autonomous vehicles will coexist closely every day. By having ADV as the highest command not to provoke collisions with a human and the humans being aware or having learned over time or having built up trust in this fact, it is predicted that humans will no longer pay any attention to the ADVs. Thus, the human will simply cross in traffic situations where the ADV has the right-of-way. Such a model was set up by Millard-Ball[164]. This work investigates the interaction between autonomous cars and pedestrians using game theory. In their presented scenario, it is assumed that there are no penalties for taking the right of way from the machines in the traffic space, for example. Furthermore, the existence of bike lanes would also be omitted. Bicyclists would ride together with the ADVs on the road and assume that the AVs would keep enough distance from them. This is also linked to the field study from Rothenbücher et al. [186] where he used a wizard-of-oz approach to study the interactions with pedestrians in a yield scenario and argued that even without any communication in the form of classic human communication like eye contact or autonomous interaction like eHMI, most pedestrians still crossed the road. However, as noted, there is a substantial limitation that the field study took place on the campus in silicon valley, where primarily young and technology-positive people are.

The problem with the theory is that ADVs slowly being introduced step by step into our traffic realm, and it is not evident at first glance whether, for example, a car is autonomous or not. Mueller et al. argue that people recognize an ADV as a conventional passenger car and expect particular behavior from it, whatever this behavior would look like. Research on the perceived risk in road crossing by pedestrians has shown that just eye contact helps pedestrians to make their decision to cross the road[55, 140].

Human-Aware Navigation

Human Aware Navigation is about movement and navigation around humans that, in addition to finding the shortest or fastest route, also incorporates human factors, e.g., social norms. These are primarily autonomous systems in the field of social or industrial robotics. Not all studies title human aware navigation (HAN) so clearly, and many studies focus on increasing the acceptance of the robot by reducing annoyance and stress for humans or achieving a more human-like movement. The definition by Kruse et al.[139] encompasses all of this:

- *Comfort:* Is the absence of annoyance and stress for humans in interaction with robots
- *Naturalness:* Is the similarity between robots and humans in low-level behavior
- *Socialbility:* Is the adherence to explicit high-level cultural conventions

According to Kruse et al.[139], the most common starting point is the identification of the behavior of the robot that triggers an uncomfortable feeling in the human to reduce or even eliminate this behavior in the next step. However, it takes work to improve the robot's behavior in general in a positive way with this approach. Therefore, it is then focused on imitating human behavior to increase the 'naturalness' of the robot as described in the definition. In addition, it is attempted to change the movements in terms of speed, dynamics, and direction of movement. The aspect of 'sociability' is about motion under social constraints. One tries to consider the social background of the deployment of the robot by, for example, having the robot drive on the right instead of the left side of the path or letting certain persons go ahead in yielding situations[139]. As already explained in the introduction of this chapter, movement is also a form of interaction, and in HAN, it is the only interaction. The emergence of HAN can be seen as the discipline in the field of electrical engineering/computer science moving closer to human factors. This vital step forwards could only happen after the fundamental problem of navigation was sufficiently solved and now with new methods like deep learning (DL)([160]) tries to include humans as social beings rather than seeing them only as physical obstacles.

Human Performance

In studies in the field of Human-Automation Interaction (HAI), the focus of the studies is on three concepts: mental/cognitive workload,Situation Awareness, and trust[131, 117, 177]. They are also called cognitive engineering constructs in this context[177], which aptly describes their intended use. the role of trust is discussed in a separate section 2.2.2. There are many parallels between workload and Situation Awareness (SA). As described by Wickens et al.[217] are both constructs distinct from behavior and performance, as well as constructs that are measured by triangulation from physiology, performance, and subjective assessments coupled with task analysis and computational modeling.

- **Situation Awareness** is defined as follows by Endsley "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" [89]. It is considered critical for effective decision-making and operator performance in a variety of dynamic control tasks[202].
- **Mental Workload** was described by Parasuraman et al.[177] as "the relation between the function relating the mental resources demanded by a task and those resources available to be supplied by the human operator".

Both terms are often used to evaluate automated or robotic systems, e.g., human-robot collaboration. For example, in a field study by Hopko et al.[117] where the influence of different fatigue states and varying levels of robotic assistance on mental workload and SA was investigated in a human-robot collaboration (HRC) task. Here the mental workload was measured with the NASA TLX[110] and SA with situation awareness rating technique (SART). This showed, among other things, that the SA decreased with increasing assistance. As described in the example, these cognitive engineering constructs are used because ways have been found to measure them and thus evaluate and compare systems. Trust has been the focus of research on ADV and is, among other things, a factor that describes how comfortable people are around ADV[161]. Since trust plays a significant role in the context of ADV, we will go into more detail in the next section.

2.2.2 Trust

Trust is used in many scientific fields, such as Sociology, Philosophy, Economics, Psychology, Organization Management, International Relations, Automation, Computing, and Networking. The work of Cho et al.[59] gives a detailed overview of the different definitions of trust in the various disciplines and is also becoming increasingly popular, as [146] already stated in 2004. Therefore, and because of the ongoing research in this world, the model of trust has continued to evolve. From the early definitions of Rotter[187] to one of the most influential contributions in the field of trust by Mayer et al.[162], who presented their model of trust, see figure 2.3.

However, this development has naturally led to conflicting definitions[146]. Nevertheless, the three essential components have always remained the same:

trustee, trustor, and something at stake, something with uncertainty or risk. Alternatively, formally from[162]: "the willingness of a party to be vulnerable to the actions of another party based on the expectation that the other will perform a particular action important to the trustor, irrespective of the ability to monitor or control that other party." which serves as the most widely used and accepted definition[146]. Nevertheless, with the advent of interactive computing, such as in automation and robotics, the term is becoming more critical in areas of engineering and computer science. Thereby trust in people interpersonal differs from trust in automation. Baier[39] argues that machines cannot have a relationship like trust with each other because a relationship of trust always has the possibility of *betray*. Further, she describes that people can rely on machines, and these then either fail or not[73]. Therefore, the transferability or applicability of the trust models to HMI was investigated and could be successfully substantiated. See Lee et al.[146] for a detailed breakdown.

To illustrate the principle of trust, the model of Hoff et al.[115] is used. Their model is the result of further developments of the models of Mayer et al.[162] and Lee et al.[146], which have looked at and analyzed many other studies in this area. Hoff et al.[115] draw on the definition of[146]: "the attitude that an agent will help achieve an individual's goals in a situation characterized by uncertainty and vulnerability." In their model, see figure 2.4, trust breaks down into three interdependent components: dispositional trust, situational trust, and learned trust.

- *Dispositional* trust describes person-related tendencies traced back to culture, age, gender, and personal characteristics (e.g., big five). These characteristics can change but are considered stable over a short period, e.g., the time of a study.

- *Situational* trust is again divided into external and internal factors. Internal factors are about a personal connection with the concrete situation. For example, self-confidence can be about the task, topic, or mood, all factors that relate to the current situation and the task to be done in the context. Emotions and moods are fundamental aspects of the experience of trust[127] Emotions are intense affective states that interrupt ongoing cognitive processes and behaviors and are tied to particular events or circumstances[200] external factors refer to the situation independent of the person. The focus is on the system. For example, what kind of system

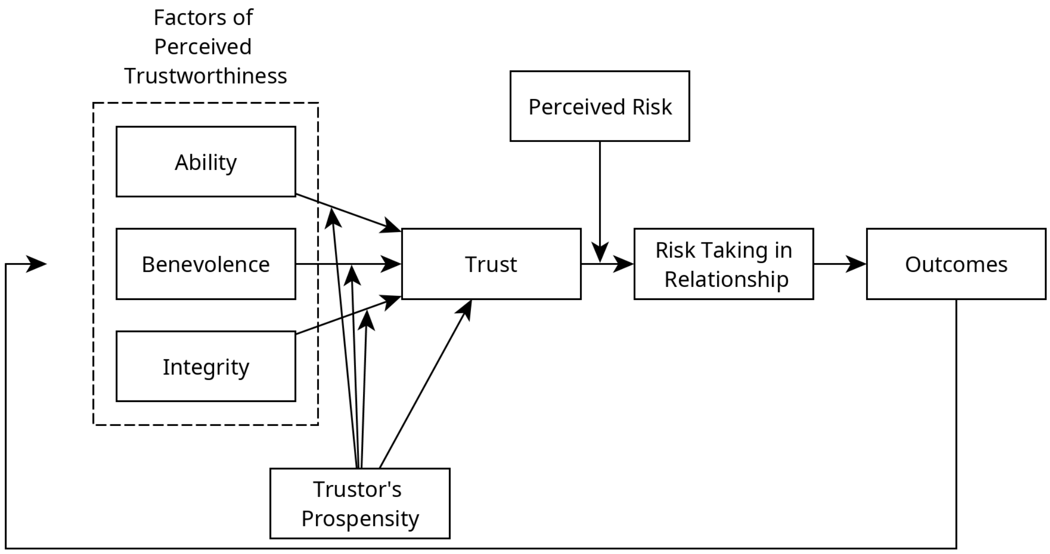


Figure 2.3: Proposed model of Trust by Mayer et al.[162]

is it, how complex is it, and how difficult is the task? What are the risks and benefits of using it?

- *Learned* trust is about the experiences a person uses when encountering a system. It does not have to be the same system but is drawn from experiences in a wide range. Experiments show that people with knowledge about the system and HMI have more trust than those without this prior knowledge.

A distinction is also made in terms of time. The initially learned trust relates to the experience that is called up directly when dealing with a new system for the first time and stems from past experiences. In addition, there is dynamically learned trust, which changes during the interaction with the system. This can happen positively or negatively, depending on the impression the system leaves through performance or design. Especially this temporal distinction stands out and is missing, for example, in earlier models like Mayer et al.[162]. Calibrating trust is the process of aligning the trust with the capabilities of the automated system[170, 145]. *Overtrust* is when the human trusts the machine beyond what the machine is actually capable of and thus results in *misuse* of the automated system. Whereas *distrust* is when the human trusts the machine less than what the machine is capable of, and thus *disuse* arises. The model of Lee et al.[146] in figure 2.5 describes the interaction of these three concepts.

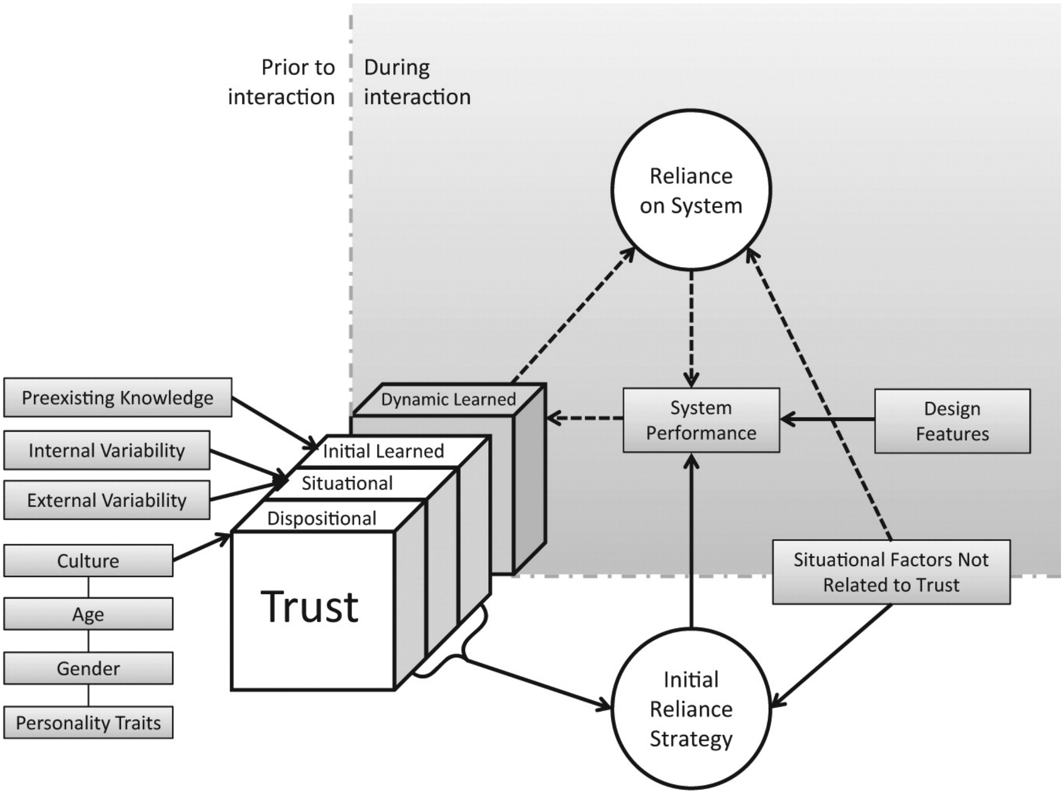


Figure 2.4: Full model of factors that influence trust in automation. The dotted arrows represent factors that can change within the course of a single interaction[115]

Relationship of Trust and Reliance

Due to the proximity of the two concepts of reliance and trust, differentiation is often challenging but all the more important. In Gao et al.[100], reliance is described as 'Reliance on automation in a supervisory control situation represents decision making under risk and uncertainty.' and trust as a 'Trust represents an affective response to the capability of the automation.' and as 'emotional factor influencing decision making as it relates to the decision to rely on automation'. What coincides with the definition of Lee et al.[146] to reliance 'Reliability refers to the consistency of an automated system's functions". The role of trust in automation reliance decisions has been confirmed in many studies[86, 202]. One model that relates trust and reliance to human decision-making in automation is shown in the model of Lee et al.[146]. See figure 2.6.

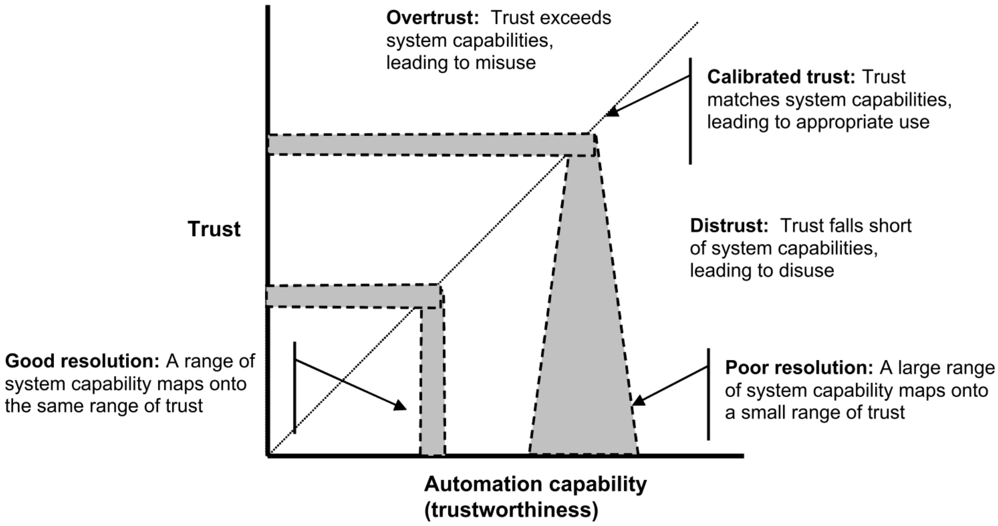


Figure 2.5: The relationship among calibration, resolution, and automation capability in defining appropriate trust in automation. Overtrust may lead to misuse and distrust may lead to disuse[146]

Here a closed-loop process is shown in the dynamic interaction of automation. Since trust is primarily built from observations, trust cannot increase if the system is not used. Nevertheless, relying on automation gives the possibility for humans to observe automation and thus also understand the functioning of the machine. From this understanding, trust in the machine grows again[40]. Another model which describes the relationship between trust and reliance is the work of Gao et al. [100]. In this model, one again sees a closed loop embedded in a structure of a extended decision field theory (EDFT) and adds a second closed loop showing the manual intervention process instead of trusting the automation. In each loop, the beliefs are updated based on the experience of the previous loops. Belief represents the information that determines attitudes(e.g., trust and self-confidence), which determines intentions, which manifest them in behavior, here reliance[100].

Hoff et al. examined the strength of this interplay between trust and reliance and which external factors are decisive and compiled a model, see figure 2.7. These factors are the complexity of automation, the novelty of the situation, the operator's ability to compare automated performance to the manual, and the operator's degree of decisional freedom. According to Hoff et al., these factors are more

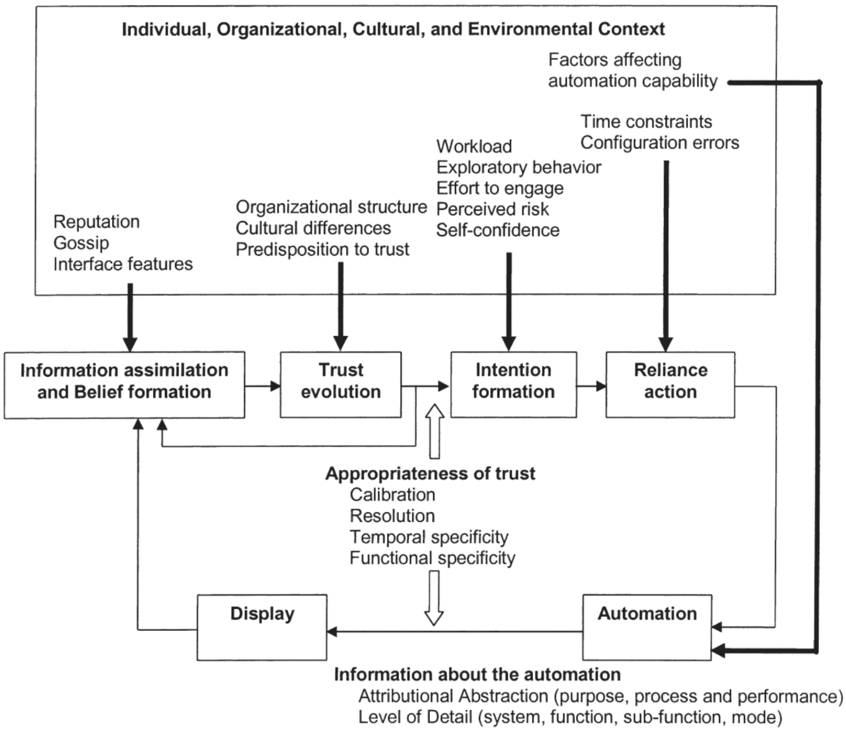


Figure 2.6: A conceptual model of the dynamic process that governs trust and its effect on reliance[146].

or less pronounced for people with automated systems. Moreover, the weaker these factors interact, the weaker the relationship between trust and reliance.

2.2.3 Influencing Trust

Many studies have focused on determining individual factors that directly influence trust and how they influence trust. In order to gain an overview of the different factors, Lee et al. developed a categorization into three categories.

- **Performance** describes *what* the autonomous system does, i.e., from the operator's point of view, whether the system has the ability to achieve the operator's goal. Central aspects in this respect are predictability, i.e., is the system always able to achieve its goals? In order to find this out, the system must be repeated use by the human, i.e., a trial and error phase, which, if it is successfully passed, is finally rewarded with reliability by the human.

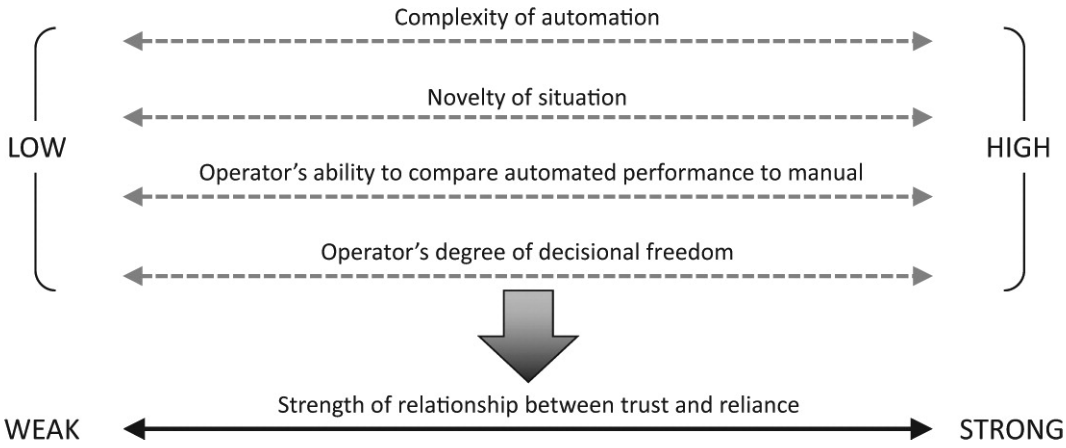


Figure 2.7: Environmental conditions that are likely to promote stronger relationships between trust and reliance[115]

- The **process** addresses the algorithms and actions that determine the behavior of the autonomous system. Thus *how* the system operates. This refers to the aspect of dependability and whether the system can achieve the operator's goals without effort or whether it needs several attempts to do so. It also includes how well it can be understood why the autonomous system behaves the way it does.

- The **purpose** here is the focus on the reason for setting up the automation, i.e., *why* it is there and whether it is used for that purpose. This can refer to a general value, automation, and technology in general. Or whether the trustee has received the exact intention of the automation and is evaluating it.

In the context of the autonomous cargo bike, one has to differentiate between the operator of the autonomous system and the road user who shares the traffic space with the bike. For an operator, performance would describe the successful and timely arrival of the loaded bike after an ordering process. Suppose a human has successfully gone through this process a few times. In that case, reliability is projected to the autonomous system, and one trusts that the bike will successfully make it to the destination at a particular time in the future. This is more difficult to describe for a road user because he needs to project a clear goal onto the system. Here one can interpret the successful autonomous maneuvering through the traffic space as performance because also, for road users, it becomes clear that this is the goal of the autonomous system. Process describes, on the one hand, the impression the ADB has on the bystanders during maneuvering, i.e., whether it has visible difficulties in reaching its goal. On the other hand, it refers to the comprehensibility of the behavior of the bicycle. Here, an eHMI is of central importance in communicating the bicycle's intention.

In the case of purpose, the question arises whether people know about the autonomous bicycle and what task it is on the road and if they do not know what they think. This can mean that enthusiasts of autonomous systems or advocates of the cargo bike have more confidence in the bicycle. In contrast, people who are critical of technology likewise have no confidence in the autonomous cargo bike. A unique role is played by the factors of **errors and failures** and the lack of trust in the operator about these. This is because trust has to be built up in part by repeated successful and error-free use. If errors happen at the very beginning of the operation, this can further affect the human's belief about the automated system, and the trust has to be built up again[170, 145].

Dzindolet et al.[86] have done some research on this. In their first study, they showed that people assigned above-average trustworthiness to the machines at the beginning of the interaction. Their second study, however, showed that when a machine made half as many errors as the human, the human rated the machine as below average trustworthiness. However, the trust could be significantly increased after explaining to the human why the machine was making human errors, even in cases where the machine subsequently made twice as many errors as before. A study by Johnson et al.[126] focused on the indicators of errors in automated systems. They classify these errors in the system into two types.

- **misses:** false-negative; system malfunctions and does not indicate this malfunction; thus resulting in an omission error of an operator, where he fails to respond to a system malfunction
- **false alarm:** false-positive; system indicates a malfunction, but there is no one; thus resulting in a Commission error of an operator, when he inappropriately complies with false automation directions

The result was that trust does not vary with the type of error. A phenomenon that is the target of much research is the 'first failure effect' or 'first automation failure effect.' It describes the effect of the first failure of a previously unproblematic interaction with a system on human performance. It is assumed that after a long experience with a perfect system, the human does not react adequately to the error and adjusts his trust. In contrast, a further occurrence of errors would cause a recalibration of trust to happen[188].

The results showed that the strength of the first failure effect could be strongly influenced depending on whether the subjects in the studies have been informed beforehand whether the automated system is a non-perfect system[113, 219, 218]. However, this effect still needs to be adequately investigated or with conflicting restults[190]. Another aspect of errors is their timing. A study on the distribution of errors during a more extended interaction with automated systems has been done by Sanchez et al.[190]. It was shown that people change their behavior with the machine's handling to maximize overall performance. This kind of self-adjustment shows that an appropriate level of trust has been tried to be found.

2.3 External Human-Machine Interfaces

This chapter is intended to give an overview of how eHMI can be developed, what different tasks they can fulfill, and how they can be evaluated. All within the area of ADV, whether it is cars, trucks, or micro mobiles. To clarify once again, it is about external HMI, not about the counterpart of internal HMI, which always describes the communication with the operator of a system. In the autonomous vehicle example, the iHMI is the cockpit design available to the operator, and it presents all kinds of information and control options. In contrast, the external HMI is responsible for communication with all non-operators. To stay with the example, virtually all other road users also interact with the ADV during operation in traffic. In the literature, however, one sometimes comes across different terms that describe the eHMI. For example, Matthews et al.[161] talk about an Intent Communication System (ICS). The term already describes the part of the information that the system wants to communicate: intention. The purpose is to get an overview of the signals themselves and which categories they can be divided into. For example, an eHMI can have a task in the sense that it is supposed to communicate a specific type of information. For this task, design measures were taken to shape the signal in such a way that it fulfills this purpose. There are no limits to the design in the first place. It is also sometimes very vehicle-specific in the sense that the vehicle exploits specific characteristics for its purpose. The last part of the chapter is about the evaluation of these systems. Studies are carried out, for example, by checking whether the intention to be communicated is ultimately received by the subjects or which color best signals which ADV status. The evaluation can be carried out and measured in a wide variety of environments, whose advantages and disadvantages will be shown.

2.3.1 Indented Purpose of Signals

This section is intended to give an overview of the tasks of signals and how they can differ. In other words, a distinction of what kind of information the signals are supposed to communicate. The tasks of signals can be roughly divided into three categories: attention, intention, and awareness. These can be further subcategorized, as seen in the work of Dey et al.[77], where a total of 11 categories were used to subdivide the different tasks. The tasks are thus subdivided according to what information the signals are supposed to communicate. Attention is about generating attention from other road users. The information to be communicated is the pure existence in the immediate space, but not the vehicle's state. The other road users are supposed to perceive the vehicle. An example of this is probably familiar to everyone: the police, fire brigade, and ambulance lights. These are supposed to indicate their existence by visual means, and the people in the vicinity then know from learned behavior and the context of what behavior is expected of them, e.g., moving aside or forming an emergency lane. The emergency services also use acoustic support if the situation requires it. For example, if the light from the system does not penetrate behind a corner of a house at an intersection due to the walls of houses. Then the differently functioning propagation path of sound waves helps to fulfill the task. The goal, which is tried to achieve with ADV, is similar. Here, of course, with the difference that there is no learned behavior or none yet, that comes to mind at the sight of an ADV. Here, attention is to be used to anticipate prudent behavior, e.g., not jumping in front of the ADV, or attention is used to communicate a specific intention afterward.

Next, we come to the task of communicating intention. This is considered to be a more complex task than that generating attention. Mainly because an ADV can have many different intentions, all of these have to be communicated as information and have to be well distinguishable so that the pedestrian quickly and easily understands them. A classic example from the traffic area is the turn signal. The simple flashing up and down in orange light on one of the sides of a vehicle signals the intention of a turn or lane change. Yielding is a particular intention that should be emphasized. This is mainly due to the fact that direct contact with the person at the steering wheel is often sought here. The pedestrian seeks eye contact before crossing the road. The potential for danger is exceptionally high at crossings. This visual contact is completely eliminated by the use of ADV. For this reason, this task is also the focus of many studies[97, 148, 171, 79]. The task of intention can be further subdivided: into informative, advisory, and commanding. These can be well explained based on the crossing situation. Here, an external HMI using informative information would indicate that the vehicle is reducing its speed by showing its speed or the word 'BRAKING.' The pedestrian can decide based on this information. Advisory information gives the pedestrian an assessment of the situation, for example, 'SAVE TO CROSS' or 'DANGEROUS TO CROSS.' The recipient is thus relieved of a thought step in the decision-making process. A commanding type of information goes one step further. Here, an instruction is given in a commanding tone, such as the words 'WALK' or 'CROSS.' In the work of She et al.[198], it is investigated which of these three types of communication increases the trust of the participant in the ADV with the result that advisory and commanding significant are better than only advisory information. However, there are concerns about giving commands to people[58]. Baz et al.[43] summarise and say that it is currently unclear whether ADV should communicate its status or the action required by the pedestrian. Another point of view that comes into play here is the system's transparency to the pedestrian. One definition of transparency in this context is given in the work of Soeng et al.[195] by 'Transparency refers to the degree to which "the inner workings or logic [used by] the automated systems are known to human operators to assist their understanding about the system".' Many studies show the beneficial effects on the operator's or participant's insights into the system, e.g., the work of Jamieson et al.[123] examined the influence of participant's information on the reliability of the system and showed how these could generate a more appropriate trust into the system. The study of Gao et al.[101] showed that sharing performance and reliance on information increase cooperation by themselves and in an additive manner. In general, the current approach is implementing fewer tasks or states to be communicated in an eHMI. Dey et al.[77], for example, shows that in the 70 studies they examined, 47 examined up to 3 states. Of the remaining 23, the rest did not have more than three but did not specify it in the study or could not apply the concept of states to the study. Coming to the last of the three categories the communication of awareness. More specifically, the information that the ADV has perceived one or more people and communicating this information. This is done for humans in the traffic realm through non-verbal human-to-human communication, such as eye contact. Therefore, this task is challenging to replicate for eHMI, as it has to completely replace the human part of a human to human communication. The work of Liu et al.[152] also shows the desire of pedestrians to be perceived by an ADV. There are also approaches to incorporate transparency into developing eHMI to obtain better interpretability of the automated system through understanding[114].

The three pieces of information(awareness, intention, and attention) presented in the following example are illustrated in a scenario. This is about two cars (not autonomous) reaching an intersection. In this case, driver 2. has the right of way, and driver 1. must stop.

1. Driver1: [drives and approaches the intersection]
2. Driver2: [drives and sees the car from the left]
3. Driver1: [fails to recognize that driver2 has the right of way and keeps its velocity] *shows no* ***awareness*** *due to not looking at driver2 and shows the* ***intention*** *not to yield by keeping its velocity*
4. Driver2: [recognises that driver1 does not slow down and honks] **attention**
5. Driver1: [stops immediately and looks to driver2]
6. Driver2: [Makes a gesture that he has the right of way] **intention**
7. Driver1: [recognizes the right of way and makes a gesture to apologize] **awareness**
8. Driver2: [drives through the intersection]
9. Driver1: [waits for driver2 to leave the intersection and then also drives through]

However, this example shows that some tasks in the interactions are very intertwined. The information to be communicated is not limited to one task but is usually a combination of intention and awareness. Therefore, the eHMI must be designed to provide the information simultaneously. This means whether the expression is chosen in such a way that it is communicated from the point of view of the ADV or the pedestrian. The distinction is called **egocentric** or **allocentric**. For example, the statement *yield* can be interpreted that the ADV will yield, and the pedestrian has the right of way, so the reference is egocentric to the ADV. An alternative interpretation would be that the pedestrian has to stop, and the ADV has the right of way, which is then called allocentric from the ADV. If not further specified, egocentric usually means egocentric from the pedestrian's point of view. A study by Bazilinskyy et al.[43] showed that pedestrians respond better to an egocentric eHMI. So if the ADV displays 'WALK' or 'DON'T

WALK', instead of 'WILL STOP' or 'WON'T STOP', seen in picture a2.8. This was also confirmed in studies by Eisma et al.[87]. Here, subjects were shown different eHMI's, once with an allocentric and once with an egocentric point of view for the pedestrian, and measured response time and eye movement. Here, most people walked when 'GO' was shown and stopped when they were shown 'STOP'. Furthermore, longer messages like 'DON'T GO' did not increase response time. Eisma et al. argue that people adopt an egocentric point of view when presented with ambiguous signals. Another advantage of egocentric signals is that they are more unambiguous due to the lack of a direct communication partner. So everyone reading communication knows what is up with the vehicle but does not think the signals are meant for them in particular. Burns et al.[53] raise an additional concept regarding the ambiguity of signals. They distinguish between absolute and relative eHMI. For example, in the case of signals that indicate an intention to turn, the classic turn signals count as relative signals. They do not explicitly indicate where the vehicle is going to turn, but it is inferred from the respective context. Usually, everyone thinks of the next exit, but it could also be a house driveway or the beginning of a parking maneuver. So the signaling is not precise and therefore has the potential for misinterpretation. According to Burns et al.[53], absolute turn signals would be signals that clearly indicate which exit or where to turn. Projector-based signals best illustrate this. These allow the precise indication of which exit is meant and therefore offer potential advantages as other road users can adjust to this and carry out their actions better and more safely.

Figure 2.8: Example of allocentric and egocentric textual eHMI from Bazilinskyy et al.[43]

A similar problem deals with the tractability of communication signals. More specifically, the problem is that acoustic and visual signals can only be used to indicate a direction, if at all, and not towards a single person or group of people. However, this is often the case, especially if one wants to communicate the intention of a ADV, such as yield at pedestrian crossings. Figure 2.9 shows an example scenario where this can lead to misinterpretation of eHMI. It is currently unclear to what extent this dispersion effect of eHMI 's leading to a problem, especially concerning the spread of ADV and, therefore, the introduction of different eHMIs into society. This is a common aspect that is ignored in studies. Almost all studies examine their eHMI only in relation to a single person. A problem that scientists are in part aware of[148]. Since the feasibility of the field studies is already difficult, no faithful representation of the situation can be made, significantly often for safety reasons alone when it comes to using prototypical ADC.

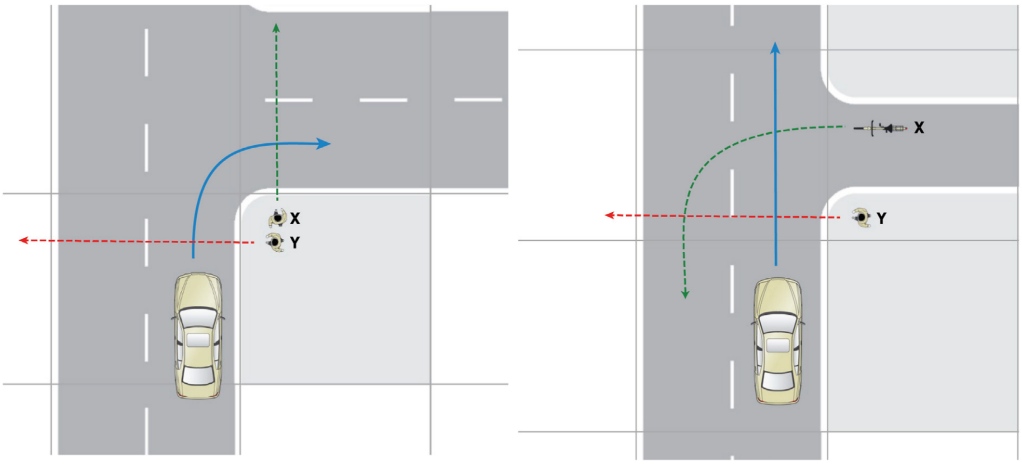


Figure 2.9: An example from Dey et al.[77] shows the problem of "communication resolution." The two scenarios show an ADC and two VRU, respectively, but only one has the right-of-way, and the other does not

2.3.2 Message Coding

In this section, we want to look into the modalities and ways of expressions, also known as message coding, as seen in table 2.3. In general, we differentiate between 3 modalities: visual, acoustic, and haptic, which represent their physical way of communication. The biggest and most important category is visual eHMI. This fact originates from the human value of their vision as the most important sense[90]. Therefore, there are a lot of different ways of visual communication. Most of these concepts are based on light-emitting hardware like LED, but some concepts do without it. For example, a study by Mahadevan et al. showed a concept where a construct that looks like a hand was mounted on the roof of a car and could then communicate the direction with a pointing gesture. However, in general, light emitters are used as they are already used in non-autonomous vehicles, such as a single bulb of the indicator at that time or a more complex LED strip as found on cars today. These have the advantage that they do not require passive light but emanate light themselves and are, therefore, easily visible even in the dark. The number of LEDs describes the resolution, and as the resolution increases, there are more possibilities for expression and, thus, more possibilities for communication. Nevertheless, a single LED can already communicate a lot, for example, the distance of a person to the object, either by changing the content, e.g., changing the color from green to orange to red in the example, or by changing the intensity, e.g., increasing the blink frequency the closer the person gets to the object. A vehicle that has been fitted with many individual distributed diodes can be seen in the work of Metayar et al.[163]. Here the color changed based on the vehicle's status, e.g., driving and braking. This is extended the more complex the emitter becomes. In the case of a LED strip, it is already possible to describe a position by selectively switching on a few LEDs, such as the position of the nearest pedestrian to the vehicle. This was translated into a digital concept art by Dey et al.[80], who presented a variety of LED-based concepts, signaling states, or positions of near VRUs. Another concept is shown by Benderius et al.[45]. Here, however, the concept was transferred to a semi-trailer truck and implemented in reality. It was presented at the 2016 Grand Cooperative Driving Challenge, where it was judged the best human-machine interface. A similar realization was carried out in the work of Zhang et al.[230]. Here, however, the concept was implemented on a typical ADV, and the LEDs were also placed on the car's sides. There, five different colors communicated the five different states. The PEV project, which is a cooperation of the National Taiwan University of Science and Technology and Massachusetts Institute of Technology (MIT), is close to the AuRa project[149, 54, 33]. Likewise, deploying an autonomous driving bicycle and the development of a matching eHMI. They use a LED strip around the front of the cab and short strips on the side and rear. They use mainly three colors: blue to signal the autonomous driving state, green to show pedestrians when crossing that it is safe to pass, and red when it has detected an obstacle on the road. At a certain vertical resolution, a LED strip becomes a LED matrix, and text can be displayed, as in a classic 7-segment display. This text can directly express information such as intention and awareness. In general, results show that this eHMI captures results well with participants, as shown in the work of Bazilinskyy et al.[43] and further extended by pictograms in Fridman2017 et al.[97]. This originates from the fact that they have fewer problems regarding interpretability, which can be complicated by point of view (POV), as explained in section 2.3.1. A limiting factor of text-based communication is that someone must read the whole message to be sure about the intended communication, which can be obstructed by rainy weather or vegetation encroaching on the road. This makes textual-based communication less practical for omnidirectional communication. The main disadvantage, however, is that it excludes people who cannot read the script because, for example, they cannot yet read like children, do not speak the language, or have inadequate eye performance. Examples of text-based eHMI are, as already mentioned, the work of Bazilinskyy et al.[43] with 'WALK', 'DON'T WALK', 'WILL STOP', and 'WON'T STOP' seen in image 2.8, where the perspectives of pedestrian and ADC were compared. Alternatively, in Deb et al.[72], where from the car's perspective, the car describes its own action with 'BRAKING'. Moreover, in Fridman et al.[97] only as an instruction to the pedestrian with 'STOP' and 'DON'T WALK'. However, it is also possible to illuminate the entire surface of the matrix in different colors in order to describe the danger of a situation and emphasize it through the larger surface, as in the work of Li et al.[148], where visibility in the dark and at different high speeds was also examined. In the work of She et al.[198], an attempt was made to investigate the influence of additional information communicated on interpretability. There, in addition to the text 'CROSS', the vehicle's current speed was also displayed. Going one step further in the resolution, we are coming to devices that can be described as low-resolution monitors that enable the display of pictograms or signs. Symbolism from the traffic realm is often used to communicate an intention. Often the human silhouette of traffic lights is used[97, 72] or the stop sign[97]. Another step further is to use projectors instead of monitors to project the symbol onto the ground, which was used as a comparison in a concept study by Fridman et al.[97]. However, there are also implementations such as in Burns et al.[53] where the turn intention was projected onto the ground, whereby the advantage of projectors was exploited here so that one can directly illuminate the point of departure in order to avoid misunderstandings. Or the goal is to create a **anthropomorphism** in the design of the visual eHMI, e.g., a humanization of the machine in this case. There are already numerous findings in the field of human-robot interaction and automated systems that show that the same mirror neuron is activated in the human brain when a robotic hand performs a series of actions as if it were a human hand[102]. Or that automated systems that are observed are trusted more when they exhibit human-like features[130]. In the field of ADC, anthropomorphism is used, for example, by using shiners that look like eyes. These 'eyes' can then be used to show the VRU that it has been seen by opening its eyes or even to follow the human to give it some feedback during the interaction as well. Studies have shown that driving agents with anthropomorphic features were regarded as more trustworthy than non-communicating/non-anthropomorphic ones[43]. The preliminary study by Mahadevan et al.[155] investigated how an animated face on a display mounted on top of the car can be used for yield interactions. The focus was on the crosswalk scenario, where the pedestrian sought reassurance that he could safely cross the zebra crossing. The concept was further deployed to a car and segway, and results showed that participants preferred this explicit communication over motion as a cue. However, in addition to visual, there are also auditory and haptic HMI. These are far less often implemented as the sole medium in a concept. This is also shown in a study by Tran et al.[210], who looked at the different modalities of eHMI in studies using VR between 2010 and 2020 and showed that 74%(23) were visual, 29%(9) were auditory, 3%(1) were haptic. The auditory signals already exist in non-autonomous traffic, like car honks and bikes bell or even the person talking directly to another road user. From this, one can describe the two types of sound in eHMI, abstract and speech. A typical example of an abstract sound is the ring of a bell, which can be used as a signal at the beginning of a movement from to a complete stop, as shown in Brockle et al.[48]. The majority of ADV's are electrical vehicle (EV) or Hybrid, which can be seen by the two frontiers of self-driving cars Tesla with Model S,X,3,Y [1] as EV and Waymo's Model One Toyota Prius[11] as Hybrid and as EV in Waymo Jaguar I-PACE[30]. The effect of artificial motor sound is researched as part of human-machine interaction. For example, in the study by Moore et al.[166], subjects showed increased interaction quality and clarity of intent compared to interaction without additional driving noise. On the other hand, speech can also be seen as a kind of anthropomorphism. Here, the intention of the ADV can be communicated very clearly and directly. According to a study by Dey et al.[77] speech is used in 6 out of 20 cases. In robotics, on the other hand, it is used more frequently and was shown by Hoff et al.[115] to provoke the trust of the human in the robot. The last kind of communication is on the vehicle itself or remotely

		message coding	
		behavior	content
modality	visual (simple)	activation frequency, intensity	color
	visual (complex)	activation frequency, location, intensity	color, text
	auditory	amlitude	sound, speech
	physical	vibration, velocity	none

Table 2.3: Simple classification of signals in their modular expression and expression discussed in the chapter

on the physical layer. One example is the behavior or body language of the ADC itself, which is already used in today's traffic, e.g., by slowing down to show the intention to yield. However, few eHMI concepts use this kind of communication. Only 4%(3) of eHMI by a survey by Dey et al.[77], where they also point out that this kind of communication needs further investigation. One main reason for the separation could be the modular structure of the software within ADC, where the safety-relevant parts that are responsible for the movement of the cars, for example, are physically separated from the components that have no safety relevance, where the control of eHMI also falls down. Mahadevan et al.[155] show one example of remote physical communication. Here they used an app installed on the participant's smartphone to generate vibration. The vibration should signal the awareness and intent of the ADC towards the pedestrian. Due to the different benefits of different modalities, it is evident that multimodal concepts are an essential part of eHMI research. This is also shown in the survey by Dey et al.[77], where 97% of all studies were at least visual, and only 29% were visual with another modality, such as auditory or haptic. The use of multimodal eHMI is of particular importance, especially with respect to the support of people with special needs, e.g., vision or hearing impairments.

2.3.3 Utilization of Colours and Transitions

The first internationally agreed definition of a color space is from International Commission on Illumination (CIE) 1931 and was named after it, CIE 1931. This color space is based on additive primaries, known as tristimulus values, which are derived from the human perception of colour[134]. Humans have three different types of eye cones responsible for receiving light for a specific color spectrum. The three cones have their sensitivity in the short ("S", 420 nm - 440 nm),

Figure 2.10: Example of projector-based and absolute eHMI, from Burns et al.[53]

middle ("M", 530 nm - 540 nm), and long ("L", 560 nm - 580 nm) wavelengths, which we perceive as blue, green, red and briefly refer to as LMS[120]. These three primaries span a coordinate system with which each color can be represented, called the CIE 1931 RGB color space.

Because of the poor mathematical manageability, the CIE XYZ color space was derived from this, which is based on not "real" primaries[134]. The CIE XY chromatic diagram, where the x,y coordinates of the CIE XYZ are used[120], see figure 2.12. The CIE color spaces are still frequently used today[201]. For example, it was used in the definition of the 11 basic colors terms[46][67], which are still used today for the study of eHMI[125]. These colors are composed of the landmark chromatic colors: red, green, yellow, and blue; the as achromatic colors: white, grey, and black; and basic surface color: orange, pink, purple, and brown[49]. Colour and animation are essential for eHMI because everyone has an association with certain colors. For example, various studies show that people interpret the colors green and red as go and stop even if they are processed within an eHMI concept and do not appear as classic round lights in a traffic light[78]. Whether this can be helpful when using these colors in the eHMI is debatable. Li et al.[148] suggest that these signals are easier to understand and interpret due to their role in the traffic realm. Li herself used red, yellow, and green alongside white and

Figure 2.11: Example of an LED strip attaching to the front of a truck from Benderius et al., best-rated human-machine interface that was presented during the 2016 Grand Cooperative Driving Challenge[45]

black in her study and argued that their use would reduce the cognitive workload. She refers to the work of Winkielman et al. who concluded that information that is displayed in a familiar manner is easier to process and comprehend[223]. A recent study by Dey et al.[78] focused on color and animation on light bands as eHMI on ADV and conducted an online survey with 400 participants. The results show that people recognized the usage of green as a signal for their communication to 'go', whereas red signals 'stop'. However, the usage of these colors on an ADV showed ambivalent results. Most participants had an egocentric view of the signals of the ADV and concluded that they were free to go or had to stop,

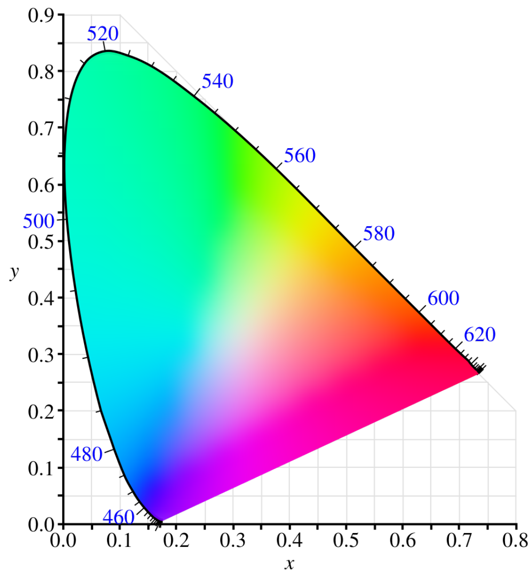


Figure 2.12: The CIE 1931 color space chromaticity diagram[5]

respectively. Some people had an egocentric view of the ADV and concluded the other way around, which is highly problematic. Dey et al. resumed that cyan is the best suited as a yield color because participants did not have any recognition together with the color and were able to learn that cyan would mean 'free to go. Animation patterns were less important than color, and the side-mounted animations caused confusion, e.g., sweeping. Only uniform animation may be suited for communicating yield intention. In the work of Carmona et al.[57] it is recommended to use traffic-related colors only in combination with pictograms or text. Another aspect highlighted by Carmona et al. is that color is not invariant in appearance and is dependent on external factors such as time and place, which change the perception of colors through the color of light from the sun or the casting of shadows. Therefore they advise that eHMI constantly calibrate itself to adapt to external influences. A good overview of the most commonly used colors is shown in a recent study by Dey et al.[77] reviewed 70 eHMI concepts and listed all used colors, see figure 2.13. This diagram shows the dominance of the color used in the traffic realm: red, yellow, and green, with white, cyan, and blue, which represent 56 colors out of the 59 specified colors in the studies.

There are also government and private specifications and standards with United Nations Economic Commission for Europe (UNECE) Regulation R-65[2] and SAE International J578[17], respectively. These suggest that colors already in use or

Figure 2.13: Frequency of individual colors and the number of colors used, according to the survey of Dey et al.[77]

reserved should not be used within eHMI. According to Werner[216] these are Red, Yellow (Amber), Selective Yellow, Green, Restricted Blue, Signal Blue, and White (Achromatic), and colors like Turquoise, Selective Yellow, Mint-Green, and Purple/Magenta should be used. Werner examined these in terms of central and peripheral visibility, uniqueness, and attractiveness, with the following results ranking: Turquoise, Mint-Green, Purple/Magenta, and Selective Yellow as fourth. Based on this, Faas et al.[93] did a study comparing turquoise with white. They used the wizard of oz approach with a car, where a person disguised as a car seat controls the car, but it looks to the passerby as if the car is driving autonomously. They mounted two rotating beacons that illuminated either white or turquoise. The outcome is that turquoise was rated better in terms of: more visible, more salient, and higher awareness but also more informative than white due to white having already been used on cars.

An additional aspect of the colors themselves is the color change. This transition influences how the colors are perceived. Many early studies on such effects have been done in the context of animation studios[144]. Nowadays, colors and animations are elementary parts of HCI, for example, considered in infotainment in cars or smartphones[135, 118]. However, such transitions are often brought together with the shapes and thus have more possibilities for transitions. There are fewer options with a one-dimensional object, like the change between colors.

The obvious one is the fading in and out. Here there are several possibilities of expression based on the duration of the fade in or out parts, as seen in the picture 2.14. But also, the omission of fading can be instrumentalized to get the opposite effect of fading, which is used to make the transition more natural and smoother. A field study by Pavlovic et al.[178] showed that in ambient User Experience (UX), a fading of the ambient light made the room perceived as more comfortable and inviting.

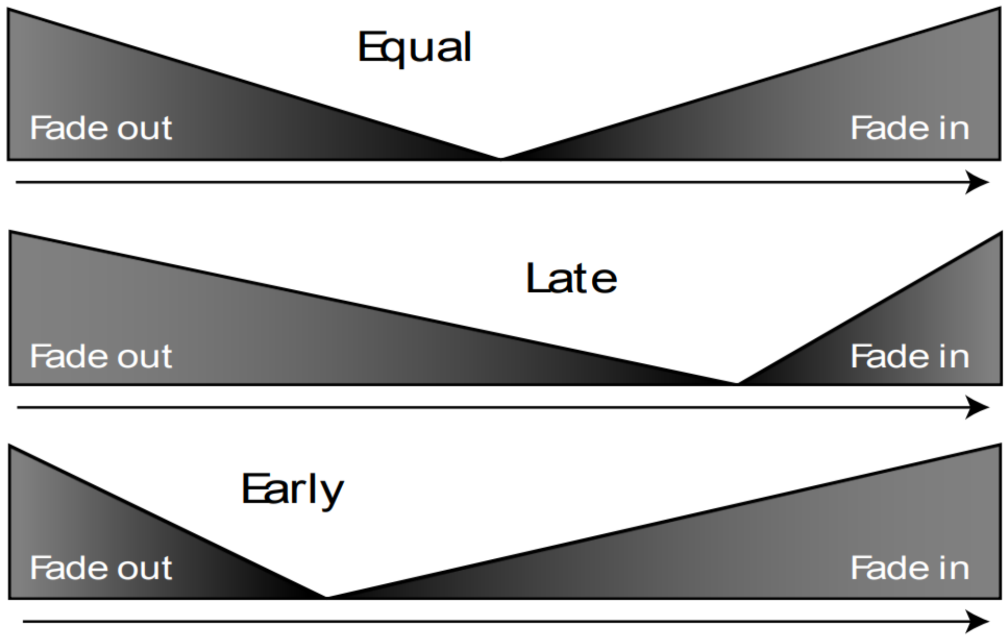


Figure 2.14: In equal timing, the fade in and fade out had the same length. Late timing changed the image when 75 percent of the time was elapsed, and early timing at 25 percent. By Huhtala et al.[118]

2.3.4 Evaluation of eHMI's

In order to find out if an eHMI is better than the previous version or if a specific color or animation scheme is better for humans to interpret the status of the ADV, these eHMIs need to be evaluated. Furthermore, researchers and engineers evaluate how their eHMI concepts are perceived by participants and if the information which is tried to communicate is, in fact, communicated to the designated user group. This information can differ from the state, intention to awareness as presented in section 2.3.1. Those studies evaluating interfaces can be distinguished according to the medium with which they are carried out. These mediums can be divided into three categories: video and image, real environments, and virtual reality and will be presented in more detail in the next section. The effect is that the possibility of different types of evaluation also has an impact on eHMI itself. The survey by Dey et al.[77] argues that while most concepts were designed for existing cars (54 concepts, 77%), only a few were realized as physical implementations. Therefore, it is unclear whether all eHMI concepts are feasible at all. Another survey done by Carmona et al.[57] showed a similar distribution, with 21 out of 28 of the surveys not done in a real environment. The second section deals with the subjects' data collected in the studies. That is, whether the subject's behavior is measured or whether the subject is asked about his or her condition using a variety of questionnaires.

Stimulus

This section provides an overview of how a study can be conducted. Common categorization of real environments, virtual reality, and image/video, as presented in Dey et al.[77] and Carmona et al.[57].

Video or Image based stimuli can be a good approach, especially in the prototype phase where only images or videos of the maybe even virtual HMI are shown. Hence, the researcher receives early opinions from participants on prototypes and how they would react under specific circumstances, e.g., zebra crossing. This kind of evaluation can be made accessible to many participants via web services like Amazon Mechanical Turk (AMT), where everyone can acquire a workforce for a small task to be done for payment. This allows access to a vast and diverse amount of potential subjects. The drawback lies in the limited presentation of the eHMI and thus the limited experience of the participants with it. However, this disadvantage is often pointed out in the conclusion, e.g., by Bazilinskyy et al.[43]. An example of a study using image-based stimulus in their methodology is Troel-Madec et al. In particular; they investigated how eHMI can still be seen and interpreted when the ADC is obscured by vehicles in front. For this purpose, they generated images from a virtual environment to obtain a realistic perspective of the pedestrian on the vehicles. Their results suggest that eHMI placement should also include the sides and not only the front of vehicles due to the potential complete superposition.[211].

Real environments, on the other hand, can be further differentiated into controlled and natural areas. Controlled areas give more certainty about the study parameters as a trade-off for a less realistic experience for the subjects. An example would not be a marked-out area such as a parking lot or company premises, e.g., Burns el at.[53]. Here, the Urban Development Lab (UDL) was used, which has the appearance of an indoor parking lot but is equipped with obstacles, mannequins, and movable walls, as shown in image 2.11. This allows the environment to be very well aligned with the study's goal while maintaining excellent control over the risks and course of events. Naturalistic environments are the other way around. An attempt is made here to carry out a study in an actual traffic area. However, Both have an increased risk of subjects being exposed to prototypical ADC, which is always a potential hazard. Alvarez et al.[37] conducted an exciting study in a real traffic environment. They developed a autonomous driving automobile (ADA) with one front-facing monitor and two LED signals showing either a red human silhouette or a green walking one. This ADA drove two days around the campus and collected information about pedestrians at crossings situations with the automobile. A naturalistic environment but with, to a certain degree, controlled aspects, due to campus traffic policy being generally more restricted as open roads and their homogenous traffic user.

Virtual Reality is the newest coming technology, valued for its cost-effectiveness, flexibility in developing various traffic scenarios, safe conduct of user studies, and acceptable ecological validity[210]. It allows a compromise between video/image-based and real environments by digitally overlaying the ADC; one has the freedom to create various prototypes, even those that may not be technically feasible if the study so desires. In addition, VR provides a more authentic experience of the environment, task, and ADC for the subject during the study. This happens through the more vital involvement of the senses and the body. An important factor is the possibility of free movement through the digital environment and more freedom in processing tasks. One example is On-Foot from Mahadevan et al.[154] a VR-based simulator, which allows different configurations of traffic and street characteristics, the behavior of virtual pedestrians, and enables an examination of participant's behavior, see image 2.16. A similar approach has been taken by Dalipi et al.[64] to create a benchmark for the simulation of ADV to pedestrian interaction and awareness. It currently includes one traffic scenario and weather conditions and allows measurement of eye and body movement and physiological signals, e.g., electrodermal activity. Ferenchak et al.[95] present a VR study with high fidelity graphics with egocentric messages for pedestrians using two textual and two non-textual eHMI. They measured participants' understanding, trust, comfort, and acceptance of each of their different eHMIs. Their results show that the usage of their eHMI improved the participant's understanding and identification of Right-of-Way, whereas comfort correlated with the participant's stated interests in ADV. For an up-to-date and detailed overview of VR in ADV to pedestrian interaction, see Tran et al.[210].

Assessment

Assessments can be categorized into two groups: self-reported and direct measures to gain insight into the pedestrian decision-making process.

Direct measures means that measurements were taken to describe a participant's behavior. This can be, for example, the time until a pedestrian decides to cross the street, as shown by the study by Locken et al.[153] by which the crossing time as follows defined: started when the ADV start braking and ends the moment the pedestrian reached the other side of the street. However, this can only be used as a variable for comparison with other studies to a minimal extent, as this definition of crossing time can differ, as Tran et al.[210] also point out with the counterexample of Deb et al.[68]. Here the starting point of the crossing time was defined as the time when the proband initiated the crossing. However, the way the study was conducted can also be advantageous. VR also offers the possibility to use the head mounted display (HMD) in use to obtain additional movement information and head movement from the subjects[172].

Self-reported includes the different types of questionnaires. Questionnaires are the most common and easiest-to-use method of data collection[69]. In the field of ADV to pedestrian interaction, some standard questionnaires have emerged, which are available in different versions, e.g., long and short versions of the Absolescent Road-User Behavior Questionnaire (ARBQ) with 21 or 43 items, respectively. This one is not exclusively designed for pedestrians but focuses on the whole group of young age VRU[88]. Another example is one of Diaz's first Pedestrian Behavior Questionnaire (PBQ) to study the relationship between traffic regulation violations and age or sex. As a result that on the one hand, young people are more inclined to violate as pedestrians than adults, and men report more frequent violations[169]. A recently developed and validated PBQ was presented by Det et al.[71]. They were able to categorize and differentiate pedestrian behavior into five categories: violations, errors, lapses, aggressive behaviors, and positive behaviors, and concluded that the PBQ can be used for pedestrian safety research in the U.S. under specific circumstances, e.g., the introduction of advanced vehicles on the road. Alternatively, one can use the pedestrian receptivity questionnaire for FAVs (PRQF) also developed by Deb et al., which was designed explicitly for the use of FAVs[70]. Furthermore, several additional questionnaires are used to determine additional factors within the study, e.g., Self-Assessment Manikin for emotions[50]; NASA-TLX for workload[110], Simulation Sickness Questionnaire in VR (SSQ)[143][133], System Usability Scale (SUS)[52]. For example, the SSQ is used to identify subjects who suffer from simulation sickness, which has similar symptoms to motion sickness but is usually milder[133], and then to exclude them from the study. For example, in the Deb et al.[72] study, if subjects score above five on the Simulation Sickness Questionnaire (SSQ). Deb et al.[69], and Carmona et al.[57] provide a more detailed and up-to-date overview. However, creating a questionnaire from scratch that is fully adapted to the constructs to be investigated in the respective study may also be helpful. Like the study by Li et al.[148] where the questions were asked in order to gain insight into the urgency of pedestrian crossing behavior with questions like if they would cross the road before or after the incoming car and if tho if they would walk faster or slower in order to achieve their goal. The answers were given via a 7-point Likert scale. In a few studies, psychophysiological signals are also used, which has the advantage over self-reported measurements in that the measurements take place during the interaction and not afterward. For example, Ajenaghughrure et al.[34][35] measured the varying levels of risk perception and their effect on trust and reliance using an ADV driving game. For this, the electroencephalogram (EEG), electrodermal activity (EDA), and facial electromyography (EMG) of the subjects were generated and evaluated.

2.3.5 Discussion of eHMI's

In summary, no single eHMI concept meets all the requirements of the various AVs, as has been concluded in multiple studies[152]. This is illustrated by a large number of different types of eHMI's. To make matters worse, many of these concepts have only been evaluated digitally. It needs to be clarified to what extent they are feasible and what problems and requirements such an implementation would entail. In addition, many concepts have only been tested in a few scenarios, and many signals have only been designed for a few states and intentions. However, this is a great challenge, especially in the context of an autonomously driving bicycle that operates in an informal traffic environment. In particular,

Figure 2.15: Example crossing situation where the vehicle displaying the opened eyes image to the pedestrians, from[37]

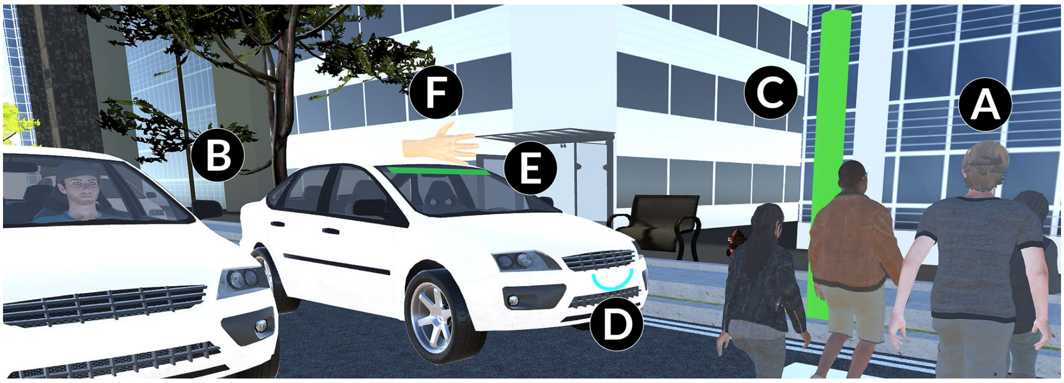


Figure 2.16: OnFoot: A VR pedestrian simulator designed to study ADV-pedestrian interaction in mixed traffic. OnFoot simulates (A) other pedestrians, (B) ADV and non-ADVs, (C) street signals, and (D, E, F) interface cues communicating ADVs awareness and intent, from by Mahadevan et al.[154]

in the AuRa project, an eHMI is needed to provide a solution in all traffic situations requiring communication. In addition, requirements such as robustness, energy efficiency, and visibility are easier to solve in autonomous cars. Furthermore, there is no consensus on whether the communicated message should be informative, advisory, intent, or awareness. However, results show that familiarity is increased more by intent than by awareness[197, 155], which leads to the conclusion that awareness can be communicated optionally or additionally. This is appropriate because awareness can be communicated more straightforwardly and unambiguously, as shown, for example, in the study by Benderius et al.[45]. In contrast, the beginning of a consensus on the use of color for autonomous vehicles is becoming apparent. The turquoise color is best suited for autonomous vehicles, along with mint green, purple/magenta, and selective yellow. The first studies show positive results[216, 93].

3 Human-Machine Interface

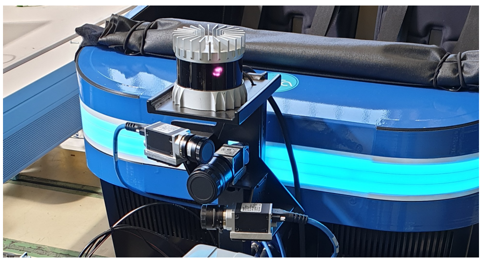
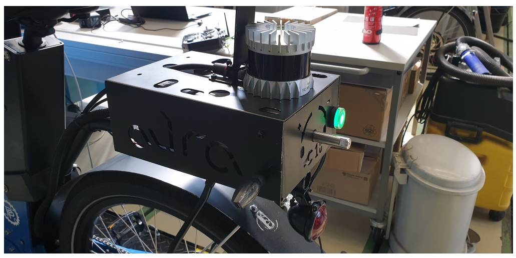
This chapter aims to give an insight into the AuRa project and its developments, which have significantly influenced the work of the overall external human-machine interface system. First, the chapter will briefly introduce the autonomous cargo bike and its key features. This overview also allows an insight into the hurdles and possibilities for installing possible interfaces. Afterward, the studies carried out within the project's framework are presented. These studies were conducted in collaboration between the research group on autonomous vehicles and the department of Environmental Psychology within the AuRa project. In these early studies, among other things, the modalities and, thus, the type of hardware were put under the microscope in a series of studies and focus groups. The chapter will conclude with the hardware implementation examined in the previous studies.

3.1 The Autonomous Driving Cargo Bike

This paragraph is intended to give a brief insight into the hardware structure of the autonomous bicycle. This is important for the eHMI development because the autonomous bicycle must be seen as an overall concept where all the different components influence each other. In this way, the bicycle's construction also impacts the development of the eHMI. They were designed and built as a 3-wheeled cargo bike for transporting children and goods. The bike has two wheels at the front and one in the back. In order to always have a stable stand while not moving, unlike 2-wheeled bikes. The cargo box is located between the front axle and the steering wheel. In addition to a power-assisted pedal function, as most cargo bikes have, it also has a separate drive to enable movement in autonomous mode. In addition, there are electrified brakes and an emergency stop system. The power supply consists of a battery management system that can use up to two lithium-ion batteries separately. Each of the two batteries has a power of 1456 watt-hours and can provide a current of 25 ampere[13]. In order to enable autonomous driving, there are four industrial computers, an rapid-control-prototyping (RCP) system, and several small embedded devices in the bike. An overview of the software system running on the computers is given in the introduction of the next chapter 5. All computers have been combined in the compute box. Because of the high load on the PCs, much heat is produced simultaneously. A specially designed cooling system was developed for this box to ensure full autonomous operation during high summer temperatures. This fan-based system was introduced to suck cooler air from the front through the box and then draw it out at the rear. For this purpose, the personal computers (PCs) inside the box were arranged in such a way that they allowed an ideal air supply.

The imaging sensors have the most significant impact on people's first impression of the autonomous bike and make it apparent that it is not a conventional bike, as seen in the images of table 3.1. These sensors are located at the front and back of the bike. In the place of a luggage rack, the AuRa bike has a rear sensor mount. There is room for a lidar, an emergency brake, and a Global Positioning System (GPS) antenna on this mount. On the front side, near the front axle, a sensor mount has been designed to carry three cameras and one lidar. One of the goals in designing the mount was to make it as unobtrusive as possible. Since it is in front of the bike, it is often the first point of view for pedestrians.

Table 3.1: Environmental Perception Sensors

Sensor front	Sensors back and Emergency Brake
	

In addition to the manual operation of the bicycle and the autonomous riding mode, there is also the possibility of remotely controlling the bicycle. The remote control covers all bicycle functions and offers many opportunities for testing during its development. In particular, during the execution of field studies carried out in the context of the evaluation of the eHMI system presented in chapter 6. In addition to the remote control, there is an emergency braking system consisting of an emergency brake and a remote emergency stop. These three components together enable safe handling during potentially safety-critical operations.

Another essential point for consideration is the technical restrictions coming from the bike itself. These mechanical and electrical limitations are derived from the technical properties of the bicycle—for example, the freedom of possible mounting points on the bike. Another aspect was to keep the bike's weight as low as possible, or at least not unnecessarily heavy. Because of the limited power of the motors, the weight has an impact on the riding behavior. The same applies to the capacity of the batteries, which can only supply a limited number of electrical devices with a prescribed voltage. All these limitations were taken into account during the studies in section 3.2 in the early conception of eHMI.

In the project, a fleet of five autonomous bicycles was built. These bicycles were given different tasks in the project, and to distinguish them better, they were also given the names of famous scientists. The first bicycle with a complete set of sensors was named Guericke. Guericke's task was to be ridden through the streets and record data with the attached sensors, mainly used to train the neural networks used in the project. The name Guericke comes from a german scientist who became famous for his pioneering work in developing experiments and methods to study the vacuum and is the namesake of the university that hosted the project[137]. The bike with the most significance for the eHMI is Immerwahr. This bike is the only one that has been equipped with a fully functional cargo box. This box combines the functionality of a conventional cargo box that can be used to transport children and goods but also has enough storage space for sensors and a processing computer. Further details are discussed in section 3.3. Immerwahr was named after the German chemist of the same name who became famous for being the first woman to receive a doctorate in chemistry in Germany[4].

In the section 2.1, we discussed the traffic situations in which the bike will find itself, such as approaching and maneuvering in a shared traffic space. In comparison, in ADC where the situation of yielding in front of other road user (ORU) is dominant. From this variety of complex scenarios, it is clear that the proposed solution must be designed for flexible use. One crucial aspect is the visibility of the signals in different situations. People do not always encounter the bicycle head-on and need to be able to see the interaction quickly from the side. Therefore, at the beginning of the project, the needs of other road users were taken into account for communication with the bicycle and will be presented in the following chapter 3.2.

3.2 First eHMI Studies in AuRa

The technical prerequisites of the AuRa bike showed that we needed to design an interface that is tightly adapted to the cargo bike. Consequently, studies are needed to examine the interaction between the AuRa bicycle and other road users. Our goal in these studies was to create a concept of eHMI which is matching as feasible for the AuRa bike and with it all coming use cases, limitations, and necessities it includes. Furthermore, these studies allow the inclusion of local people and thus include local social norms, which are an essential aspect of such studies and differ worldwide. Factors such as dispositional trust, discussed in chapter 2.2.2, also vary from culture to culture, as do age and gender. The table 3.2 shows the road we followed along our process of surveying an appropriate eHMI. At first, we started with carrying our focus groups in Berlin and Magdeburg. In this focus group, our goal was to collect impressions and options from the autonomous cargo bike in general without any eHMI equipped. Afterward, we conducted an expert panel where we gathered information about technical and legal restrictions, ergonomic requirements, and information about eHMI in autonomous vehicles and human robotics in literature research. The goal was to develop a first concept draft for the AuRa bike, including different aspects of use cases and hardware modalities. This first concept was used as a discussion draft in the following pre-test, where probands had to evaluate the eHMI presented with images and sound clips. With the gathered results and findings, we developed a more precise model in 3D as CAD-Model with different colors, animation, and pictograms. This model was used in the following simulation-based studies. One is pedestrian-centric, and the other one is driver-centric simulation. To gain valuable insights from these perspectives. The results of the early studies have been published in a joint publication[158] and an unpublished version[157]. In the focus groups, the pre-test, and the mixed-reality simulation studies, other data were also included, such as the potential or likelihood of using the AuRa transport system or the acceptability of an autonomous cargo bike. However, as these do not influence the conceptual design of the eHMI, they were not considered and are not listed here.

Date	Method	Description	Goal
Early 2019	Focus group	Impressions and opinions on the bicycle without eHMI	Need for communication and visibility, 5 key traffic scenarios
Late 2019	Expert panel	technical and legal restrictions, technical possibilities, ergonomics requirements	visual description; need of sound; Design-Model
Early 2020	Pre-Test	Evaluation of the digital, prototypical communication tools using images and sound clips	technical description; driving sound and classic bicycle bell; CAD-Model
Late 2020	Ped.-Centric Study	Evaluation of the communication tools in an 360 degree mixed reality simulator; focus on the need of pedestrians	First prototype based on the evaluated communication tools
Late 2020	Driver-Centric Study	Evaluation of the communication tools in an driving simulator; focus on the need of car driver	Second prototype based on the evaluated communication tools of this results weighed against the results from the first simulation

Table 3.2: Roadmap, based from Menoeva et al. [158]

3.2.1 Early Studies

Early studies include the focus groups, the expert panel, which includes ideation state and prototyping, and the pre-test, a usability study as a questionnaire. These were conducted at the beginning of the project before the bike had the shape described in3.1. Therefore, the studies had to anticipate the bike's visual appearance and possible cargo box. Together, the studies aimed to create a concept from which a model for simulation-based usability studies can be generated.

Focus Groups

Three focus groups were carried out in Berlin and Magdeburg. The goal was to collect impressions and opinions on the autonomous cargo bike-sharing system from pedestrians, cyclists, and car drivers. The discussions showed that people were concerned about the visibility of the autonomous bike to all other road participants, including cars. In particular, the clear indication of the autonomous state of the bike was an important point. One idea regarding visibility, especially towards car drivers, was the addition of a safety flag to the bike. So that if no one is sitting on the cargo bike, it has comparable visibility as a recumbent bike or child's bike. However, these types typically have a flag attached to the back in Germany that protrudes far above the maximum height of the bike or child. The banner gives visibility to some degree, even if close to cars, e.g., while passing on the street or in a parking lot. Furthermore, language independence was discussed, and it was pointed out that the signals should be clear to everyone. Some participants mentioned the desire for a clear sound in this context.

Expert Panel

The goal was to create a concept for the eHMI of the AuRa bike. The findings from the focus groups served as a basis for this. Based on this, literature research was carried out with regard to eHMI in ADC, but also in other areas, such as human robotics. We decided to start by focusing on fundamental states and designing an eHMI for them. As a result, the following states were identified: autonomous state, attention-seeking state, change in driving direction state, stopping and starting state. An overview of these states can be found in the table 3.3. Based on this, we discussed modality and message coding. We decided to include visual and auditory signals in our concepts. Because this is most similar to how non-autonomous bicycles communicate, and they use visual signals or cues to show the intent of action and acoustic sound to grab attention. Despite concerns, a concept with writing was also included in the concept list. Concerns because writing can especially easily exclude people who, for example, do not speak German or English, as well as people who cannot read properly, would be excluded. Thus concerns were also pointed out in other studies, as seen in chapter 2.3.2. For example, the word 'Achtung!!!' (eng. attention) was used for the attention/-danger scenario, and the word 'autonom' for the autonomous mode. Based on the idea of a safety flag from the focus groups. We devised a 'tower' equipped with communication signals that would be mounted on the bike's rear axle. In addition to the flag, the tower would indicate pure existence and communicate the bike's intention. The tower would always supplement the device on the cargo box and never serve as the sole interface. Furthermore, the information would be at the height where the cyclist's head would otherwise sit and thus match the pedestrian and driver mental model, which is preferable[141]. Table 3.3 shows the first draft with respect to the scenario where we consider modality, medium, and message coding.

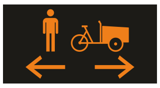
One point of discussion was the use of a rotating beacon. A signal type that has a high potential to generate enough visibility and attention. It is already widely used by police forces, fire brigades, or road maintenance depot vehicles. However, this also leads to a significant disadvantage in the potential use of rotating beacons. Because of the multiple-use, the chance is increased that road participants can trigger strong associations. On the other hand, a one-by-one implementation of a rotating beacon as they already exist would be prohibited by law, so any alteration would be necessary. Nevertheless, we have considered investigating this concept in the context of a prototype concept.

Due to several points of technical restrictions, a realization of a projector-based communication signal was considered not feasible. A projector's size and power consumption would make it very difficult to install on the bike and possibly reduce the bike's range, as all electrical devices, such as the motor, are powered by one battery system. There were also concerns about the suitability for everyday use. On the one hand, strong sunshine would nullify the visibility of the projection. On the other hand, the vibrations that such a vehicle has to endure on a daily basis would not be compatible with sensitive projection technology. There were also concerns about the possible realization of the tower, which would negatively affect the bike's weight and center of gravity. However, these concerns were not strong enough to prevent the tower from being included in the concept.

Table 3.3: Communication concepts overview

Scenario	Modality	Medium	Message Coding
1. Status	(a), (v)	Loudspeaker, Rotating beacon, LED, Display	sound: classical, futuristic image: symbols, letters, signs light: blue, green
2. Attention	(a), (v)	Rotating beacon, LED, Display	sound: classical, futuristic image: symbols, letters, signs light: yellow, red
3. Direction	(v)	Rotating beacon, LED, Display	image: symbols, letters, signs light: yellow, green
4. Stop	(a), (v)	Rotating beacon, LED, Display	sound: classical, futuristic image: symbols, letters, signs light: red
5. Start	(a), (v)	Rotating beacon, LED, Display	sound: classical, futuristic image: symbols, letters, signs light: green, blue

Table 3.4: Pictograms displayed on monitor and tower

State	Autonomous	Danger	Direction	Stopping
Front				
Site				
Tower				

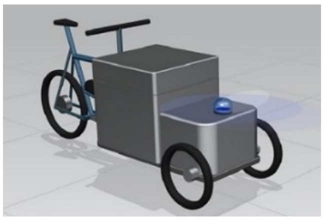
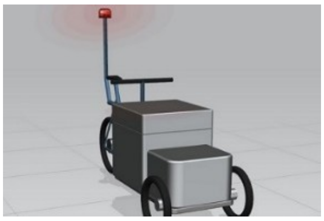
The positioning of the tower was also adapted to ergonomic aspects so that people sitting on the bike would not be disturbed by the tower.

The choice of pictograms was based on established symbols. For the autonomous mode, a radio or wifi connection symbol was chosen, as it was assumed that this would best signal to humans that the bike was being controlled or autonomous at that moment. We also discussed ways to reduce the problem of point of view, which was presented in chapter 2.3.1. The problem describes the phenomenon that people correctly interpret the status of the signal but are wrong about whether it is intended for the ADV itself or them. To address this problem, we have added a pictogram of the bicycle and people to the turn symbol and the symbol of the bicycle to the pictogram for the autonomous mode to show that the bicycle is connected and not possibly confused with a wifi hotspot. The table 3.4 shows the complete selection of pictograms.

Pre-Test

We want to run a usability research session to validate the concepts and collect usability data. For this reason, a questionnaire in the German language was created using SocSciSurvey [27]. A total of three sessions in mid-February 2020 were carried out in Magdeburg Experimental Laboratory of Economic Research (MaXLab). When selecting the scenarios, we focused on the typical bicycle-pedestrian interactions: separated bicycle and pedestrian lane, roadside bicycle lane, and mixed area for pedestrians and bicycles. We excluded scenarios where the bike drives on the road because this is not part of the AuRa Vision. For each scenario, a pair of auditory signals were played: one sound of a conventional bell

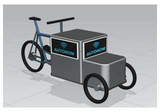
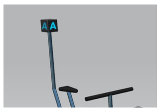
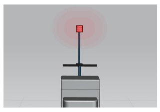
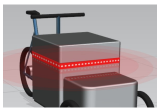
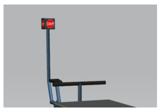
Table 3.5: Design and technical Models

Design LED on Cargo Box	Design with Monitor and Tower	Design with Beacon and Tower
		
		

of a bicycle and one futuristic, artificial sound. The visuals had, in conclusion, three different device types: LED, monitor, and rotating beacon. Each with varying colors or pictograms for the different scenarios. Two mounting points on the bike were designated for all devices: the cargo box and the tower. Table 3.7 shows an example of the different setups.

A total of 66 participants were divided into two groups. One group would only see concepts with the tower, this group had 32 members, and the other group with 34 members would only see concepts without the tower. The gender distribution among the participants was as follows 43.9% male, 54.5%, and 1.5% did not give any information. The average age was 24.32. The respondents were more likely to be educated, with 56.1% high school graduates, 37.9% university graduates, and 4% a vocational diploma or different degree. The two groups did not differ in the aspects of education ($\chi^2(3) = 2.95, p = 4$), gender($\chi^2(2) = 1.91, p = .38$), experience with virtual reality($M_{sop}(no\_tower) = 4.07, M_{sop}(tower) = 3.95; t(64) = 0.8, p = 0.43$) and automated devices ($M_{exp}(no\_tower) = 2.15, M_{exp}(tower) = 2.093.95; t(64) = 0.43, p = 0.67$) [157]. The scenarios were described to the subjects with a description of the events and a schematic representation, see 8.4. The subjects were then shown a representation of the AuRa bike, depending on which scenario and group were present. In addition to the recordings, the audio recordings were also played back. The data recording was done with a 5-Point Likert scale regarding intention recognition and signal unambiguousness. In the

Table 3.6: Best-rated visual interaction of early studies

Szenario	Cargo Box	Percantage of people		Tower
1. Autonomous		79.4%	28.1%	
2. Attention		33.3%	31.3%	
3. Direction change		64.7%	68.8%	
4. Stopping		31.3%	54.8%	
5. Starting		36.4%	54.8%	

last question, the participants could choose one visual signal that they thought was best suited for the AuRa bike.

First, let's look at the visual signals evaluated in a total of five scenarios. The goal was to select the concepts with which we went into the next phase. We weighted the respondents' answers as to which they considered the most suitable and particularly valuable. This was primarily because this question was asked after the respondents had been told what the intention was to be communicated. Therefore, we ranked each scenario and looked more closely at the best-rated concepts. In the following, the groups of probands who were exposed to the concept with and without a tower are referred to as the t-group and the nt-group.

In the first scenario, where the bike was supposed to signal its autonomous status, the display with the "A" scored best for the t-group with 28.1%. For the nt-group, the concept with the wifi symbol together with the "Autonomous" scored best with 79.4%. In the second scenario, the attention scenario, the t-group rated the red illuminated LED as the best with 31.3%, and the nt-group rated the lettering with "Attention" with 33.3%. In the third scenario, which was about signaling the change of direction, both groups rated the pictogram showing an orange bicycle with an arrow and a green person with an arrow best, with 64.7% for the nt-group and 68.8%. In the fourth scenario, which involved signaling the stopping of the cargo bike, the stop sign together with the red LED was rated best by the nt-group with 31.3%. The stop signal was also rated best by the t-group, with 54.8%. In the last scenario, about starting the bike, the wifi symbol was rated best in the t-group with 51.6%, and in the nt-group the pictogram with the green arrow and speed indicator was rated best with 36.4%. An overview of these results can be seen in table 3.6.

A detailed list of all concepts used as visualization can be found for the concept with rotating beacon under 8.1. for the concept with pictograms under 8.2 and for the concept with LED stripes under 8.3. The results regarding auditory signals show that generally, the conventional sound was preferred over the futuristic one in three out of 4 scenarios. in the first scenario, autonomous driving, a driving noise was used: $(M_{conf} = 2.69, M_{fut} = 2.66; t(64) = 0.17, n.s)$. In the second or attention scenario, an alarming signal was used: $(M_{conf} = 4.71, M_{fut} = 2.76; t(65) = 13.47, p < .01)$. In the third sound, or fourth overall scenario, which involved signaling to brake, a corresponding braking signal was also used: $(M_{conf} = 2.86, M_{fut} = 1.95; t(64) = 4.7, p < .01)$. In the last scenario, that of starting, the following results were obtained: $(M_{conf} = 3.59, M_{fut} = 2.36; t(65) = 5.71, p < 0.1)$[157]. with these results, the concepts and models for the mixed-reality studies were developed.

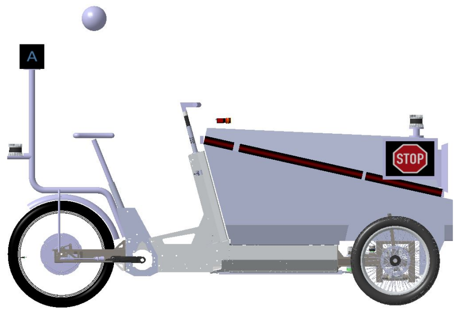
3.2.2 Simulation-Based Studies

In summary, two types of simulations were planned to meet other road users' different eHMI needs. The first study took part in the Elbedome in Magdeburg and focused on pedestrian's interaction with eHMI[132]. The Elbedome is a 360-degree mixed reality laboratory from the Fraunhofer Institute for Factory Operation and Automation[7]. The study was conducted in collaboration with the Fraunhofer Institute for Factory Operation and Automation (IFF). Picture 3.1 shows a person inside the Elbedome. The person is wearing special glasses which allow the tracking of head position and orientation, which is used to transform the 2-d projection on the walls around. This transformation, together with the glasses themselves, results in a three-dimensional vision of the surroundings with the person in the center. The room is shaped like a hemisphere but with a larger flat surface in the center so that the test person can still move around freely before approaching the curved wall. The second study was conducted together with the Fraunhofer Institute for Industrial Mathematics, which is focused on the car driver's perspective towards eHMI[14]. They have developed an interactive driving simulation called Robot based Driving and Operation Simulator, which was constructed for testing and simulation of driver-vehicle-environment under reproducible conditions [15]. For this purpose, they use a 6-axis serial robot kinematics arm with a 1000kg payload with a car cabin mounted on the end of it. This allows the dynamic from the simulation to be transferred faithfully to the driver's cab and thus to the test person[22]. Picture 3.2 shows an exemplary section of how a subject perceived the simulation during the study. The results from the previous studies were analyzed and compared for the simulations. In doing so, we removed the concepts containing writing due to concerns regarding the exclusion of groups of people as described in 3.2.1. That aside from some good results in the pre-test, where this concept was rated best in two scenarios, autonomous state signaling, and attention scenario, notably with a small margin, especially in the autonomous state signaling scenario in the no tower group. The exclusion allowed the creation of two more homogeneous concepts, one using pictograms and the other using only LED strips. These two concepts were then implemented together with a 3d model of the bicycle to be used in the simulation-based studies. The study's goal was to determine which of the two concepts better supports car drivers' perception of the ADB in different scenarios. Resulting in the following research questions[157]:

- Which designs work well for the users in the described scenarios?
- Do they meet the usability goals?
- How does one design compare against the other?
- Which prototype is most likely to be seen in the future?

The table 3.7 shows the 3d models created for the simulation. Here, the design of the cargo box was also adapted to the developments of the current project—for instance, the inclusion of imaging sensors on the top of the cargo box. Furthermore, the final substructure of the cargo box was incorporated into the model. At that time, the final cargo bike, as seen in section 3.3, was not even in the planning phase. However, this made it possible to test concepts that heavily impact the structure of the box, later influencing the design of the cargo box itself. On the other hand, one was also responsible for integrating a cargo box into the concept that had not yet been worked out, which included various technical aspects, such as space requirements and the cooling system designed in-house. Together

Table 3.7: Design and technical Models

CAD Model from front/top	CAD Model from right side
	

with the digital model of the bike, a more monolithic-looking cargo box was designed to fit together. The scenarios in the two studies differed because they were adapted to the respective situation from the perspective of pedestrians or car drivers, respectively. However, care was taken to ensure that all intentions to be signaled were included in each case.

Elbedome

The trial in the Elbedome was held at the end of 2020 in 10 days within two consecutive weeks. As the Elbedome is located in Magdeburg, the probands also came from Magdeburg and the nearby region. The study procedure was conducted in that every proband will go through all traffic scenarios(within-subject) but experience different eHMI concepts(between-subject). The two concepts were LED stripes with different colors and activation patterns and monitors with different pictograms. Additionally, both concepts had a version with and without the tower. In the beginning, each participant first experiences a scenario without ADB in the virtual world to familiarize themself with and move inside the simulation. The virtual places inside the study were all well-known places in Magdeburg, and the familiarization scenario was in the same place as the first scenario with the ADV. In total, the probands experienced eight scenarios. For the first scenario, the probands did not receive any instructions, only a short description of where they were. Otherwise, the probands received a short description

Figure 3.1: Picture from inside the Elbedome. The person wears VR glasses which enables the 3-dimensional viewing of the projection coming from the roof-mounted projectors[3].

of the environment and a small instruction for each scenario. These instructions were essential because, all scenarios had a start point, an end point, and a trigger point. The starting point was where the proband would start in each scenario. Then, for the interaction to have a repeatable behavior, a trigger point would initiate these interactions. This trigger point would be in between the starting and the endpoint. The moment the proband reached the endpoint, the scenario was successfully done. The instructions at the beginning of each scenario had the goal of leading every participant through the scenario, so the interaction between the participant and ADB is always the same. With these tools, it was possible to control how and when the ADB with the eHMI was seen. For Instance, the participant receives the instruction to cross a bike lane, and the view of possible incoming bikes is blocked right before stepping onto the bike lane. As a result, a fast interpretation of the bike's state and intention had to be made by the participant. Another example would be the participant moving beside a bike lane in the same direction so all bikes reach from behind. The instruction than would request a bike lane crossing, forcing the participant to watch over his shoulder

Figure 3.2: Segment from a recording during a scene in the driving simulator. On the right side drives the AuRa bike.

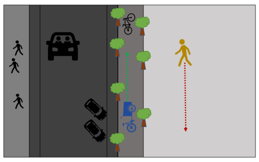
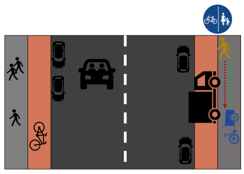
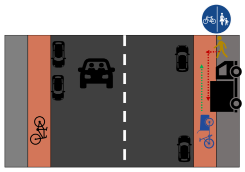
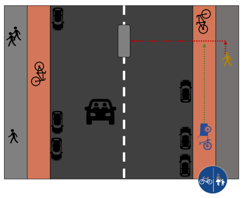
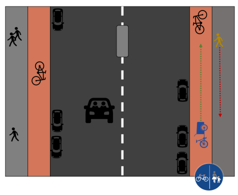
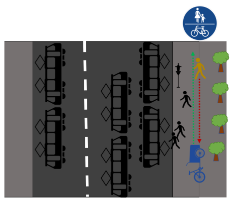
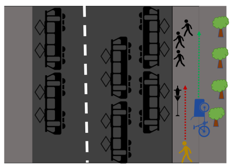
for oncoming bicycles and again for a quick assertion of the bike's state and intention to decide whether it is safe to cross the road. Both examples genuinely re-enacted real traffic situations and were study scenarios.

The instructions also protected the probands from accidentally running into the wall as they slowly walked up like a half pipe. In the first scenario with AB, the bike passed the probands at some distance on a bike path, while the probands had the task to move only a short distance closer to the bike path. The bike signaled its autonomous status. In the second scenario, the bicycle had to move into the participant's path because a van blocked the bicycle path. Here, the bicycle had to indicate that it was deviating from its intended path by signaling the state of attention. The participant had the task of walking past the stationary delivery truck, which forced him to walk toward the oncoming bicycle, resulting in a confrontation. The third and fourth scenarios were similar because the subject had the task of crossing the bike lane on which the autonomous bike was approaching. The difference was that in the third scenario, a truck significantly reduced the visibility of the bike lane, and thus the bike appeared unexpectedly. In the fourth scenario, the participant walks closely beside the bike line with the approaching ADB in front. As the bike comes close (approx. 5m) to the participant, it switches from state-signaling autonomous mode to attention. The fifth scenario is the speed scenario. Here, the bike passes the pedestrians at three different velocities 5 km/h, 13 km/h, and 20 km/h. These velocities come from the use cases of the AuRa cargo bike, where 5 m/h is the lowest speed to be assumed, 20 km/h is the highest planned speed, and 13 km/h is a possibly pleasant speed. The proband was maneuvered close to the bike lane in the scenario to achieve realistic proximity or proximity perception, and the bike only signaled its autonomous status. In the sixth scenario, the participants were instructed to walk a short distance, and the bicycle would start riding towards them and then go around them at an average distance. In the seventh and last scenario, the bicycle was already present, standing still and facing away from the participant. The moment the person starts walking, the bike starts moving as usual. In addition, to increase the immersion of all scenarios, the bike was given additional sounds that sound different depending on the bike's speed. The table 3.8 gives an overview and an order of the applied scenarios. The assertion was done using a questionnaire with a 5-Point Likert scale. The questions related to whether the subjects felt safe in the vicinity of the autonomous bike, whether the bike behaved as the subjects expected, whether they found the signals helpful and whether they trusted the bike. In addition, there were questions from IFF in the form of SSQ and Igroup Presence Questionnaire (IPQ).

RODOS

The study in the Robot based Driving and Operation Simulator (RODOS) was also carried out at the end of 2020, but in contrast to the Elbedome, it was carried out at the Fraunhofer Institute for Industrial Mathematics (ITWM) site in Kaiserslautern. Here, the same concepts of the eHMI were tested in an in-between subject design but with different traffic scenarios. The execution of the scenarios was easier to control in the driving simulator, as the test person did not move but sat at the actual steering wheel of a virtual vehicle. The driver's cockpit was a familiar environment, and the simultaneity could be controlled and changed without the test person's intervention. Here there were a total of 6 scenarios. The first scenario took place on a straight road with a bicycle lane on the right-hand side. The ADB drove along this bicycle lane, and the participant in his car drove past it. Here the bicycle signaled its autonomous status. Similar to the first Ebedome scenario, this scenario also served as familiarisation. In the second scenario, the participant approached a traffic intersection where the bike shared the street with the car but had its dedicated bike lane. In this case, the participant was

Table 3.8: Elbedome scenarios

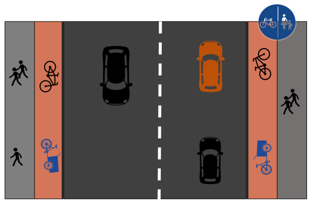
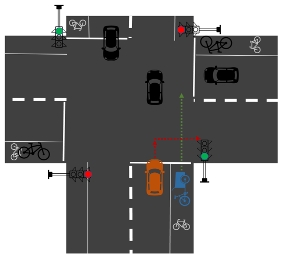
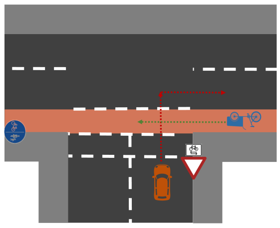
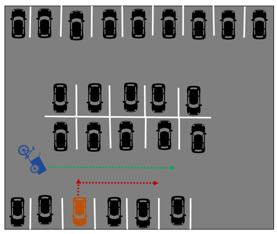
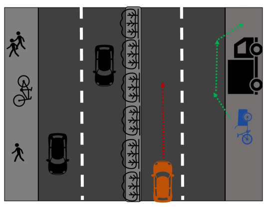
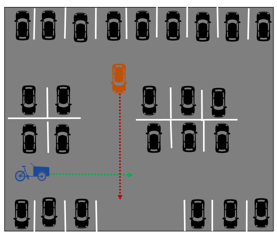
Scenarion	Description	Image
1. Drive by	both are coming from opposite directions(facing each other), no crossing, juridically: separate lanes	
2. Confrontation	both coming from opposite directions, bicycle lane is blocked, ADV dodges into the pedestrian lane, juridically: separate lanes	
3. Crossing	pedestrian crosses the bicycle lane with an arriving ADV, side is blocked, ADV stays on the lane, juridically: separate lanes	
4. Crossing	both starting from the same direction, busy area with other pedestrians and tram, juridically: separate lanes	
5. Drive by	both coming from opposite directions, ADV drives in three different velocities, juridically: separate lanes	
6. Bypass	both coming from the opposite direction, ADV starts moving, busy area with other pedestrians and tram, juridically: one area for both	
7. Start up	both coming from opposite directions, ADV start with three different velocities, juridically: one area for both	

supposed to turn right while the bicycle was supposed to go straight ahead. The bicycle, therefore, had the right-of-way, and the participant had to wait until the bicycle finished crossing and left the turning area so that he could also turn. During the scenario, the bike signaled its autonomous status before and during the approach. In the third scenario, the car is approaching a t-intersection. The bicycle is coming from the right onto the bicycle lane, which is accessible from both sides. The car must give the right-of-way to the bicycle, and the bicycle again indicates its autonomous status. The fourth scenario involves a parking space. Here, the participant has to reverse the parked car out of its parking space. In the process, the bicycle drives along behind him. The driver must therefore be able to recognize it through the rear-view mirror and the back seat. The bicycle was signaling the attention status. The fifth scenario takes place on a 4-lane road with a bicycle path on the side. The car and bicycle are driving in the same direction. However, the bicycle has to swerve onto the road, but different car lane, because of a blockage on the bicycle path. In doing so, the bicycle signals its change of direction. The sixth and last scenario takes place in a car space. It involves a right-before-left situation, where the bicycle comes from the right and has the right-of-way. The bicycle signals its attention state. The car space is full of cars, and the bicycle is therefore not immediately visible. The table 3.9 gives an overview of the scenarios and the sequence. The ITWM has also conducted an Fast Motion Sichness Scale Questionnaire (FMS).

3.2.3 Results

We now come to the results of the two studies, which are summarised and compared here. In the Elbedome, there were 115 participants, of which 55.7% were female, 43.5% male, and one person did not specify. There was a wide range of ages represented, from 18-81. The average age was 42.35. the participants were more educated, with most having either a high school diploma or a university degree. In the RODOS, there were 127 participants, with 25.4% female, 73.8% male, and one without specification. The age range was 19-63, with an average of 32.15 years. The educational status was even higher than in Elbedome, with most having a university degree. In both studies, the probands had a driving license (Elbedome 95%, RODOS 99%) and at least one car. The Results in Elbedome showed hardly any significant results between the concepts and the respective scenarios. However, it should be emphasized that all concepts performed well to very well. The significant results were drawn in the seventh scenario for the

Table 3.9: RODOS scenarios

Scenarion	Description	Image
1. Drive by	both starting from same direction, seperate lanes, car has to drive straight on	
2. Start up	both starting from same direction, seperate lanes, car has tu turn right, ADV starts driving straightforward and has right-of-way	
3. Turning	both starting from different directions, seperate lanes, Car crosses bike lane and has to turn right, ADV drives straight on and has right-of-way	
4. Parking	parking space, car has to reverse out of parking space, ADV drives behind the cat and has right-of-way	
5. Bypass	both starting from same direction, car has to drive straightforward, ADV dodges into right car lane	
6. Crossing	parking space, both start from different directions, ADV partly hidden behind parking cars, ADV has right-of-way	

difference between tower and non-tower to the disadvantage of the tower. There were also no significant differences in the speeds, but all with good results. Very similar results were obtained in the driving simulator. Likewise, there were hardly any significant results between tower and non-tower and display or LED. Then again, the concepts were generally rated well. In conclusion, both concepts rated well without a significant difference between tower and no tower setup.

3.2.4 Discussion of Simulation-Based Studies

Regarding the first research question, ‘How does one design compare against the other?’ no unanimous result could be found. For this reason, it was decided which concept had a higher chance of being successfully implemented in reality since we are still dealing with digital models. Therefore, the choice fell on implementing the LED stripes. There were several concerns about the concept of the monitors. Firstly, the visibility of the content on the monitors, as they have a limited opening angle and a low light output, can mean that nothing can be seen on the screen in direct sunlight. Additionally, there were concerns about the weight, as the monitors have a high momentum at the mounting point and should be attached to the cargo box outside. The last point would be the power consumption and connection possibilities, and these requirements would again only be implemented with considerable effort or with a reduction in the range of the bike itself. On the other hand, the LED strips do not have weight problems and poor handling. Nevertheless, they also have visibility and power consumption issues, but far less than the displays. Moreover, because the LED strips can be used more flexibly and the cargo box design was still pending at the time, the planning could be approached more flexibly. Concerning the second research question, ‘Does the tower significantly impact the human perception of the ADB?’. This result was against the expectation that the tower would be perceived as a helpful visibility aid by car drivers. Since it has no benefit, it was decided not to implement the tower. It became apparent during the expert panel that the tower’s implementation could significantly negatively impact the bike’s behavior. In addition, there were concerns about the weight and the possibility that pedestrians or AuRa bike riders could bump into it.

3.3 eHMI Hardware Implementation

The next step was implementing the eHMI based on the study's results. The bicycle presented in section 3.1 serves as the basic framework. The conception and implementation of the eHMI were done together with that of the cargo box because, in the best case, they are designed to support each other. On the one hand, the eHMI does not reduce the functionality of the cargo box, e.g., opening the cargo box; on the other hand, the cargo box gives the eHMI the necessary visibility it needs for communication. The digital designs from the studies (see table 3.7) were taken as a model. There were many adaptations regarding material and fitting for the underbody of the cargo bike.

The first type of cargo box one was planned as a regular cargo box, and it should be able to transport goods and children with it, e.g., seats, belts, and cushions were incorporated. Only a minimal amount of computing hardware and battery are installed under and behind the seat, a space that would otherwise be used for additional storage and therefore did not influence the interior design of the cargo box. This box is intended to show how the AuRa bike can look if the computing hardware can be scaled down. This is why the box is called a demonstration box.

The other type of cargo box is very different. From the outside, both boxes look identical, and at the same time, the interior is missing entirely. This allows the cargo box to be put over the preexisting box containing all computing hardware. This trick allows us to create an autonomous cargo bike that looks like a regular cargo bike on the outside but can drive autonomously. In order not to obstruct the cooling system, which is based on airflow, air inlet and outlet holes have been provided. However, these are not visible at first glance and therefore do not change the appearance. Due to its purpose, this type of cargo box is called a dummy box. In summary, a total of four cargo boxes were manufactured, one of which was a demonstration box, and the other were dummy boxes. These boxes were mounted on the AuRa fleet's bicycles.

The acoustic output is a detail that was not considered in the eHMI studies and, thus, in the digital model. Here, with the acoustic eHMI, a system was chosen to ensure that it could be heard even in loud traffic. In addition, it also had to be robust. Therefore, a pressure chamber speaker was chosen. One of the essential requirements for the visual eHMI is to ensure visibility, e.g., the bike's signals can be seen even in direct sunlight. Therefore it was decided to use LED strips that potentially have the highest radiance. Furthermore, it was essential to stay as

Table 3.10: On the left are two images of the inside and outside of the cargo box, and on the right is the front with the speaker underneath the sensors

Demonstration Type Cargo Box	Speaker in front of the Cargo Box
 	

faithful as possible to the concept, even though there have been changes to the bike since the digital prototypes. However, it should be ensured to a certain degree that the concept is still the same as in the studies. Therefore, the LED stripes were placed as high up in the cargo box as possible, and three rows of stripes were used to increase visibility and achieve a similar appearance as in the study design. The LED strips are mounted under a plexiglass cover. Firstly, this protects the LED stripes, which only have IP40, from dirt and water splashes. Secondly, the cover would blur away the light of single LEDs into one homogenous light. Two custom circuit boards were designed and implemented for power supply, and activation of the LED stripes with the help of a colleague. The first board serves only to distribute the current to the LED stripes; therefore, all six ends of the LED strips are connected to it. The second board can be considered the main board, as it has an integrated microcontroller and memory. Therefore, its purpose is to convert the digital control signals from the software so that the LED strips faithfully convert it. Both boards are summarised under the term smart signaling emitter (SSE). The second board is connected to a PC in the bike via a serial port. Section 5.9 is more about the interface between SSE and the software.

4 System design

This chapter gives an overview of the eHMI system. It begins with the requirements placed on the eHMI and thus also on the concept of the eHMI. These have already been shown in part in the chapter 1. By the findings from chapter 2 and eHMI these requirements can now be specified. Afterward, the various concepts that are contained within the eHMI system are shown and described. Among them are also the interactions that lie in the center of the concept and are subdivided into different kinds of interactions. In the end, the concept of the need for communication. This concept aims to package the required context-based need for communication into a value. As a result, situations can be evaluated and compared in terms of urgency. In order to implement this, a fuzzy controller is used, and its concept is presented together with the fuzzy logic based on it.

4.1 Requirements

Requirements came from the outside and were introduced in the 1 and illuminated by the chapter 2 in the context of the current studies.

- **Consistency** is about the bicycle showing the same interaction in the same situation; thus, a habituation effect occurs in humans, and the behavior of the bicycle is classified as more predictable; when this occurs, then humans have a positive emotion; so that people can become accustomed to it and, over time, trust it[225].
- **Appropriate:** the behavior of the bicycle should be appropriate to the current situation; that is, it should allow for dynamic interaction so that in more difficult situations, it communicates in a manner appropriate to the situation; this should reduce the danger by communicating more forcefully in more dangerous situations
- **Feedback:** the bicycle should also interact directly (not indirectly as in dynamic) with the human; it should give the human the feeling that the au-

tonomous agent is aware of the human; this feedback increases the human's trust in the autonomous agent

As seen by looking at the requirements, it becomes clear that they do not behave entirely orthogonally but are partially mutually exclusive. For this reason, an interaction model or strategy had to be found that fulfills these requirements as well as possible without diminishing the effect of the individual solutions.

4.2 Concepts of the eHMI system

The interactions do not stand for themselves but need a concept in which they are embedded since they arise from a particular context and have their objective. It describes the entire system required to generate the appropriate interactions in the current situation that arises from the environment of the bicycle. Figure 4.1 visualizes the core of the HMI concept.

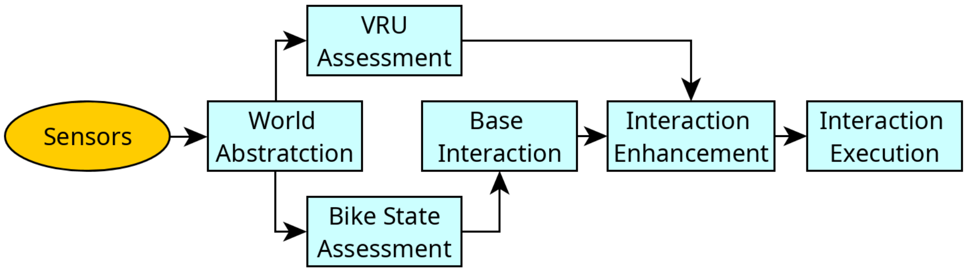


Figure 4.1: HMI Basic Conzept

At first, we need a representation of the world surrounding the bike. Therefore, this must contain all the necessary information we need for the interactions. This includes information about the vehicle itself, such as position and speed. Furthermore, other entities in the traffic domain, like pedestrians and cyclists, and their position and speed must be available. However, the information is also crucial when other entities saw the bike and when they saw it. All this data has to be taken from the other software system. Furthermore, these data have to be filtered and structured in a processible way for the eHMI system. A complete and detailed description of this process can be found in 4.2.2. The bike's current states are then interpreted from this environmental information. Examples for states are the process of parking or simply driving on a bike lane. These states, together with the other information, are put together in situations and form the basis of communication. The concept of states is further explained in section 4.2.4. In addition, it is determined how critical this situation is, based on the surrounding traffic participants and their movement and perception of the ADB. This is then used to generate a parameter called NOC, which describes how important the communication of our current state is. The situation and the NOC are then used to determine the appropriate communication and, from this, generate the necessary interaction. A more detailed explanation of NOC can be found in section 4.2.5. These interactions describe the configuration of the LED strip and the output of the speaker. However, these interactions also have further gradations in addition to their visual and acoustic parts. These always serve to have an appropriate response ready and are explained in detail in the following section 4.2.1

4.2.1 Interaction Concept

Interactions are the digital representation of bicycle communication, describing which information will be communicated via the signals. The interactions cover up to two modalities: visual and acoustic; The visual part of an interaction describes the signals coming from the LED strip. In addition, color can be expressed in its actual color value but also its intensity. A cyclic change of intensity without a fading effect is perceived as blinking. On the other hand, a cyclic change of intensity with fading is perceived as a kind of pulsation. This fading, i.e., the smooth intensity transition, can also be applied to the color change. i.e., there can either be a 'hard' color transition where a completely different color is displayed in the next moment, or there can be a slow transition between colors. Both have different effects on humans, as presented in section 2.3.3. Additionally, an interaction can use the acoustical modality. This is especially useful when there is no eye contact between humans and autonomous bikes; thus, two-way communication has not yet started.

In order to meet the requirements: to make the interaction always recognizable, but on the other hand also appropriate to the situation and to give feedback to the pedestrian. The interaction concept was divided into three parts. Each part is responsible for one of these tasks and has different prerequisites, depending on how the environment presents itself. Figure 4.2 shows the relations of these three parts, which are presented in the following:

The **Base** interaction is the part of the interaction that is always executed or upon which the other interaction parts are built. This base communication should

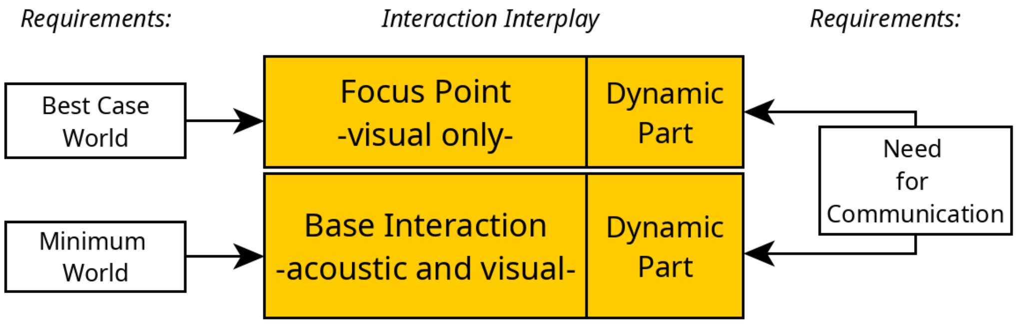


Figure 4.2: Interaction interplay and requirements

ensure that the interaction of the bicycle is, to a necessary extent, **consistent**, which was one of the requirements leading into the chapter. The people can thus learn which interaction results in what behavior of the bicycle. Furthermore, the bicycle offers certain predictability for other road users. The color used for this purpose is always referred to as the base color in the following. This designation serves to differentiate from the color changes described in the following. The base interaction communicates the intention of the bicycle.

The **Focus** interaction uses a base interaction and adds a focus part to it based on world information. It has the task of giving direct human **feedback** on his interaction with the bike. This is done by changing a short part of the LED strip to a different color, which we call the focus point. This focus point is at the position of the LED strip where the person to be communicated with is standing and moves with the person while walking along the front of the autonomous bike. This is to communicate to the pedestrian awareness that the bicycle has recognized the existence and position of the person. As shown in section 2.3.2, people's trust in the ADV can increase[197, 155]. The expression of the focus point is as versatile as the rest of the led strip. It can change color and flash. Fading, non-fading and the focus point's size can be changed. Since the focus point and the rest of the LED strip have different colors, resulting in an area of color change between them, called slope. This slope can be disabled or used to fade the color between the focus point and the background. Consequently, expanding the possibilities of expression of the focus interaction.

The **Dynamic** interaction, which uses the base interaction or focus interaction and adds a dynamic part to it based on NOC. It is there to help the base interaction communicate the intention. This means that it is responsible for generating the **appropriate** level of attention in situations where it is necessary to ensure that the interaction communicated by the base interaction also reaches the targeted communication partner. This enables communication that is adapted to the context of the situation. For example, if the situation causes an increase in NOC, which can occur when it is identified that a person is walking directly towards the bicycle and is not far away, then a little more emphasis can be placed on communicating and drawing the attention of the environment to the bicycle. Not all types of interactions have to offer all possibilities of expression. The individual components are only used in specific situations where they increase the value of the communication. Besides, it would also be detrimental to the task if an acoustic signal were added to every interaction or if the communication were to become too complex if every interaction were to indicate a focus point permanently. For example, in the turn-taking interaction, no focus interaction is present. It is a short interaction that simultaneously changes the bike's direction, making the focus point challenging to follow.

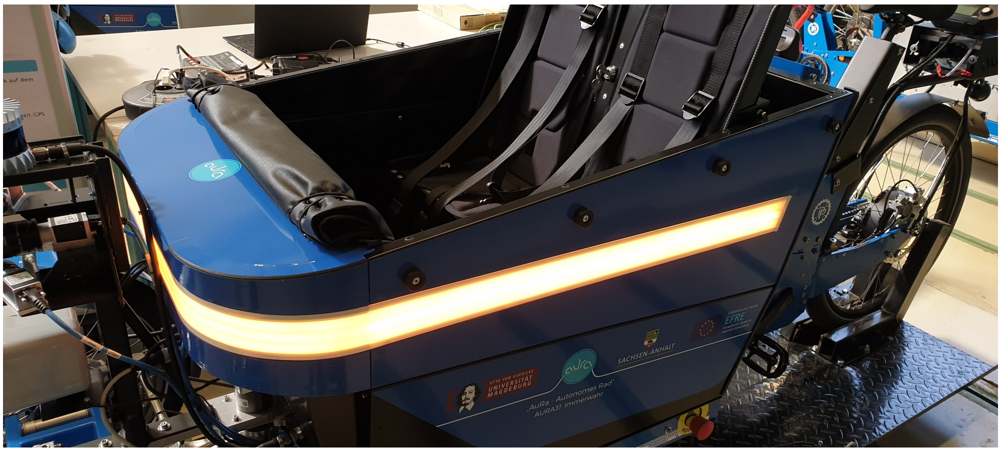
4.2.2 World Abstraction

The world consists of all the data the HMI needs to implement its goal, and it maps the entire context from which the interaction arises.

The figure4.2 shows a visualization of the concept. On the left side, you see all the world's data put in context. On the right side, you see the same concept but additionally with parameters that classify the situation that the world represents, which will be explained in section 4.2.5. The focus is on the autonomous bicycle itself and all the information we need about the bicycle. This includes the current position, speed, and rotation rate, but above all, the trajectory to be ridden. This is necessary to assess how dangerous a current and future situation is and, therefore, how urgent we consider communication. In addition, all people in our environment are part of the world. Information such as position relative to the bike and speed are calculated for the people. We also distinguish between pedestrians and bicyclists. In addition, we try to determine the pose of the person. The pose includes the position of the arm, legs, and head rotation and is used to determine whether the human saw the bicycle or not. Furthermore, it is planned to predict humans' trajectory in the world. This information is complicated to extract; therefore, it is unreliable if it is always available or available for all humans in the vicinity. The most important information is the position and the identification that it is a human being. Without this information, the interaction cannot

Table 4.1: Overview of visual interactions

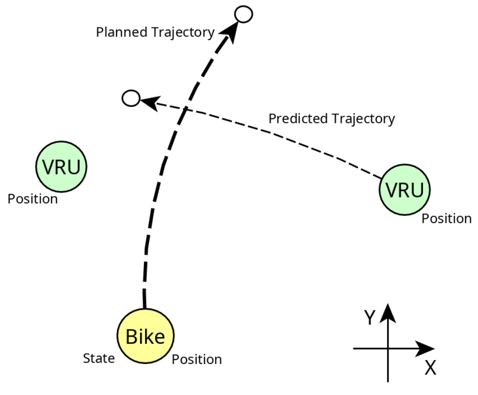
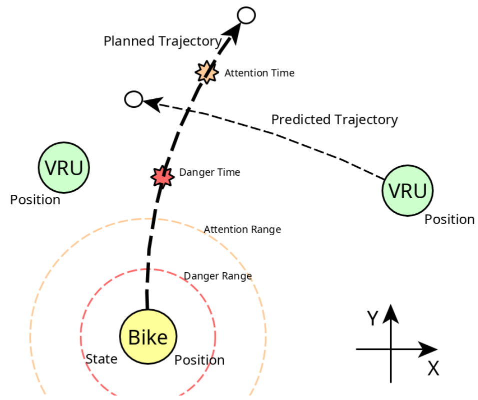
cyan base color with orange focus point



orange color to get more attention

red color to show danger

Table 4.2: HMI World Concept

World Representation	World with Situation Parameters
	

consider a person. Nevertheless, only the combination of all information, i.e., all people, the information about the bicycle, and the situation, ensures a suitable interaction can be generated. As already mentioned, the completeness of the world depends on the other bike software. That means if the world has many objects with missing attributes, it shows that the other software has difficulties. However, these missing data should be absorbed by the interaction concept. This will be discussed in more detail in section 4.2.5.

4.2.3 Interaction Planner

For each situation, a specially designed interaction must be generated. The interaction planner is responsible for this task. In order to create these interactions, we need, on the one hand, information about the situation we are in and, on the other hand, information about how critical the context of this situation is. Consequently, a module called' state assertion' is used to determine the current traffic situation from the presented concept of the world, 4.2.2. The concept of NOC, introduced in 4.2.5, is used to estimate how critical the situation is. In short, a single value is used to describe how urgently we need to express our interaction in order to communicate our status to the other traffic participants with the required attention. Suppose the information needed to generate the NOC is not available or is of poor quality. In that case, it is up to the interaction planner to decide whether only a base interaction can be generated. One goal of the concept was also to give the freedom to add more states and interactions. Therefore, there is no 1-to-1 mapping between states and interactions since an interaction can be appropriate for many more states. Therefore, the interaction planner also decides in which state which interaction type should be triggered.

4.2.4 States and Interactions

States describe all situations in which the bike can find itself and, thus, also all contexts and information that the HMI has to communicate. A single state can express the situation of parking or that of starting. All states can be summarized in a state graph, which visualizes the interrelationships between the states. In particular, it visualizes the interrelationships between the states. i.e., under which conditions one state can change into another or from which state one cannot change into another under any circumstances. These states themselves do not describe the state of the HMI but of the bicycle itself or the state of movement. In an autonomous system, the local path planner is responsible for this. Based on the environment and the task at hand, it plans which movement is necessary to fulfill the task. Therefore, the local path planner's work is of great importance for the HMI because the interaction of movement and interaction determines the perception of the human of the bicycle. Furthermore, the interaction between these components of the autonomous bicycle is of central importance for the external effect of the bicycle. Moreover, the interface between these components is the states that emanate from the local path planner (LPP). This module helps fill the information gap created by covering the states of the LPP and the required states of the interaction planner. Therefore a large part of the state set is determined by this module, and for this, the world is used.

The interplay between states and interactions is not flat 1to1, i.e., each state must always have a different interaction. Since the states are an internal representation of the bike's state, the interactions are only meant to communicate specific information or states with the environment. Therefore, there are potentially fewer interactions than states, and state transitions serve as activation for the interactions.

An additional aspect is the interplay of individual interactions. Although these are defined and described individually, they affect each other. For example, changing a status light from green to yellow can be interpreted as worsening the state. In contrast, changing a red status light to yellow would be interpreted as improving the state. The interaction types of the bicycle also have an interplay, or

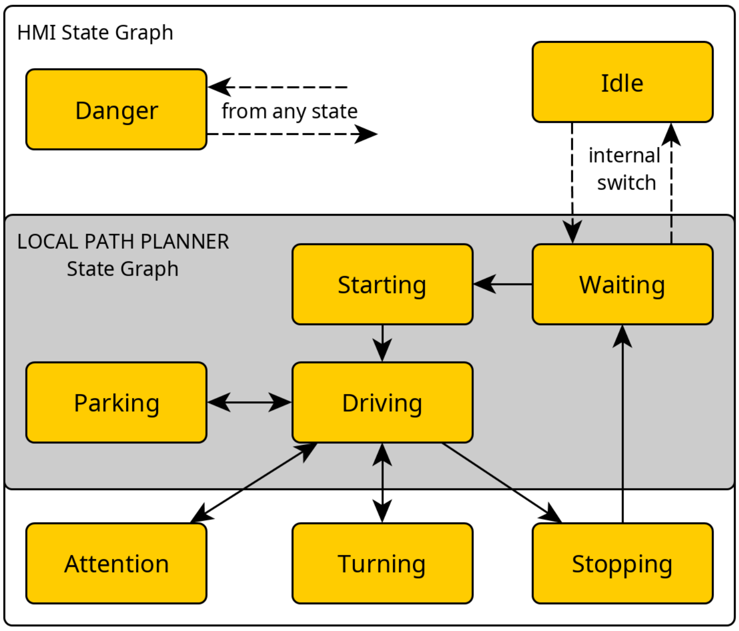


Figure 4.3: State Transition Graph

an implicit order, defined by a state machine. In addition, individual interactions define the transition from the previous to the current one and can thus influence the interaction.

The individual interactions and how they are shaped in detail are presented below:

Initialising

The initializing state is used to interact with the developer or maintenance technician. The interaction only indicates that the bike is on but not yet in autonomous mode, where all other interactions come into play. Therefore, the interaction is virtually only a readiness check of the hardware. Therefore, the whole LED stripe is permanently activated and changed between the colors to check if the LEDs is working fine or if there is any damage. Additionally, a sound is played at the beginning to show the maintainer if it is in an error-free state. Since this state is not in autonomous mode and therefore intended for communication with pedestrians, it does not have a dynamic or focus interaction part. The visual part of the interaction is shown in table 8.7

Waiting

This interaction is intended to show that the bike is in autonomous mode and is actively waiting. This state is necessary, for example, when the bike has to stop at a traffic intersection due to traffic. It replaces the human being that would be seen sitting on it in a non-autonomous bike and implicitly indicates with its presence that he could drive off with the bike. The base color signals that it is in a base state. The base color cyan is used in this interaction, which glows with a low frequency up and down. The focus point is in orange, and the blinking frequency of the focus point is the attribute of the dynamic. The visual part of the interaction can be seen in table 8.7.

Start und Stop

Both states are to show that the bike is about to start or to come to a standstill from the drive. These states are unique because they are assumed only for a relatively short moment and can be assumed as a transition state between drive and wait and vice versa. Nevertheless, these are potentially dangerous states because they involve speed changes, leading to other road users having to swerve or slow down to avoid colliding with the bicycle. This is especially true for rear traffic. This critical state change is made clear by changing from the base color cyan to yellow and ringing once. The blinking has a frequency of 1Hz. The focus point is in orange, and the blink frequency of the focus point is dynamic. The visual part of the interaction is shown in table 8.7.

Drive

This interaction type is used when the bike is in its normal autonomous driving state. This state is potentially maintained over a more extended period of time and is, therefore, more of a normal state. This should also find expression in the design of the interaction. This is done by choosing the bass color cyan, which should show that we are in autonomous driving mode. In addition, the color lights up at 2 Hz to show the difference in the state of active waiting, where we express the same interaction but with a lower frequency for the blinking. The faster blinking should express the increased activity compared to active waiting. The focus is in orange, and the blinking frequency of the focus point is the attribute of the dynamic. The visual part of the interaction can be seen in table 8.7.

Turn taking

This interaction is intended to indicate that a change in the direction of the bicycle is imminent. Very similar to the usual flashing of a car or holding out the hand of the bicycle. Because this is a typical interaction, the base color cyan is used. In addition, the color flashes, but unlike most other interactions, the fading is not present here, so there is a 'sharp' change in intensity. This is similar to the signals used in cars, which also have a sharp flashing up and down. No focus point is provided for the interaction. This is because it is a short state, but mainly because the focus point is difficult to follow while the bike is turning, which eliminates the effect of the focus point.

Attention

This attention state is unique because it is not defined for a single situation. This interaction is intended to draw attention to the bicycle without communicating the exact action of the bicycle itself. An excellent example of this is the situation of parking. Here the bike will probably change its direction of movement several times and turn around to position itself as best as possible in the parking spot. Since these are very diffuse movements, it makes little sense to announce individual movements since they can be different a moment later. As a result, the interaction should indicate that increased attention from other road users in the vicinity is intended. This increased danger potential should also be expressed in the interaction by choosing orange as the base color. In addition, there is blinking with 1Hz with fading, which should underline the dynamic of the interaction. As this is again a state that is not accepted for a long time, it is appropriate to use such a penetrating and conspicuous interaction. The visual part of the interaction is shown in table 8.7.

Danger

This interaction is similar to the attention state; again, there is no clear situation where this interaction is used. This interaction is used when the bike is in an emergency state. For this reason, the state is not part of the accessible state graph; see 4.3. Such an emergency is reached, for example, when a part of the software or hardware of the bike has failed, and a safe continuation of the ride is, therefore, not possible. For this reason, the state can also occur at any other state or time. Therefore, the interaction must express that the continuation of the journey is not guaranteed and that the bicycle should be parked. Therefore, the base color is selected as the signal color, red with a fast blinking without fading. No focus point is displayed. The visual part of the interaction is shown in table 8.7.

4.2.5 Need for Communication

The communication of the AuRa bicycle is about communicating two things. On the one hand, the intention of the bicycle. That is the action the bicycle is about to perform or is currently performing. On the other hand, it is about generating attention to make people perceive the communicated intention. Because it does not help if you know how to communicate the intention perfectly, but nobody looks at the right time to perceive it. The effect of intention and attention was shown in 2.3.1. In communicating intention, the goal is to make it so that people can interpret it as quickly and unambiguously as possible and then act on it when necessary. The task of attracting attention is easy to describe but difficult to implement. It is a matter of making people aware of it for whom our communication of intention can be helpful, but at the same time, more than just making everyone aware of it. Otherwise, one could communicate with maximum signal strength, which would quickly lead to people feeling annoyed and coerced. One goal is to prevent this in any case. That is why regulating the attention part of our communication is so important. Precisely for this task, the concept of the need for communication was formed. This value is supposed to represent how important and, therefore, how much attention has to be generated so that the bicycle can perform its action. As described before, this value depends on the environment of the bicycle. On the one hand, on its own actions, and on the other hand, on the people it influences. This value depends on our own status in the sense that if we move faster, we should communicate our intention more urgently. At the same time, the planned path of the bicycle influences which people in front of us are more relevant than others who do not potentially cross our path. On the other hand, people far away or behind us are less relevant to our communication. An exception is a bicycle driver behind us. This driver is, of course, very interested in knowing our braking and turning intentions. Therefore, three variables were designed to summarize the necessary information needed for the NOC. The 3 variables are risk of collision (ROC), human awareness (HA), human density (HD).

- The **Risk of Collision** indicates how high the risk of a collision is. A low value indicates the probability is low, and a high value indicates the probability is high. It should be noted that the value itself does not indicate a probability but rather a key indicator. The risk of collision is used to identify critical situations and, if necessary, express them with a high value. The calculation of this value also changes the information available to the HMI system.
- **Human Awareness** indicates how much attention people around us pay to our bikes. i.e., a high value indicates that people have seen our bike recently, and a low value indicates that they have never seen the bike or have not seen it for a long time. This value is calculated from all relevant people and their perceptions. As a result, there is one value for a situation, not for every person. Considering HA helps not to generate unnecessary attention by considering people who know about the bike's status.
- **Human Density** indicates how many people are around us. This value is interesting for several reasons. On the one hand, communication between the bike and the environment is more difficult when there are many people around because they usually bring a certain level of noise and partially obscure the bike for other road users. Therefore a high value of human density always comes with the need to generate more attention to generate the same perception than if it is a small value of human density. An additional reason why this value is significant is that many people have a negative influence on the predictability of ROC and HA. as explained before, the overlap is a fundamental problem for the sensory system of the autonomous bicycle and therefore also on the possibility of generating these values.

As mentioned earlier, the NOC value is based on the people around us. However, the data we have about people is not always complete, which means that we have the position of the people but not their planned trajectory.

The figure4.4 shows the world concept in the context of a typical traffic scenario. it becomes clear that people who seem to come straight toward us can be less decisive than people who are more distant but who will cross our path. The prediction is based on a trained neural network, which is always provided with a probability for the prediction, which expresses the security with which the network is in the prediction. Therefore, a threshold may decide that some predictions are not safe enough and are therefore not included in our world. However, we must ensure that the NOC can always be calculated since our interaction concept is

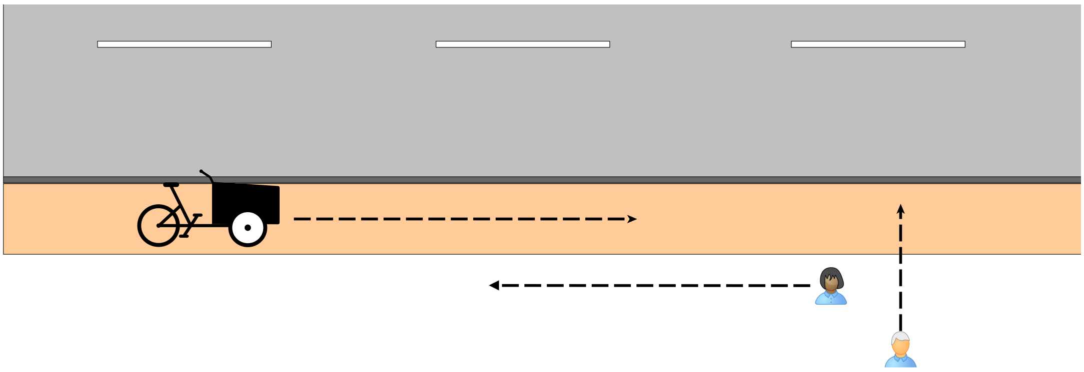


Figure 4.4: Traffic situation with visualized pedestrian predicted trajectory

based on it. For this reason, a fallback strategy comes into play when there is no prediction data for one or more people. Then the position data of the people are evaluated, and a constant velocity model is applied. As a result, it is possible to assemble a simple form of prediction that assumes that people continue to move in the same direction at the same speed. The data required for this comes from the multimodal sensor system, consisting of multiple cameras and lidars, a high level of accuracy, and is always available and thus a reliable fallback level.

If you go back and look at the concept figure at the beginning of the chapter and go one step further. It becomes apparent that the interaction that originates from the bicycle goes back into the environment. People perceive the interaction and may change their behavior in response. However, the interactions were based on the people's behavior in the first place. Therefore, one can speak of a control loop. Figure 4.5 shows how the concept is thereby expanded.

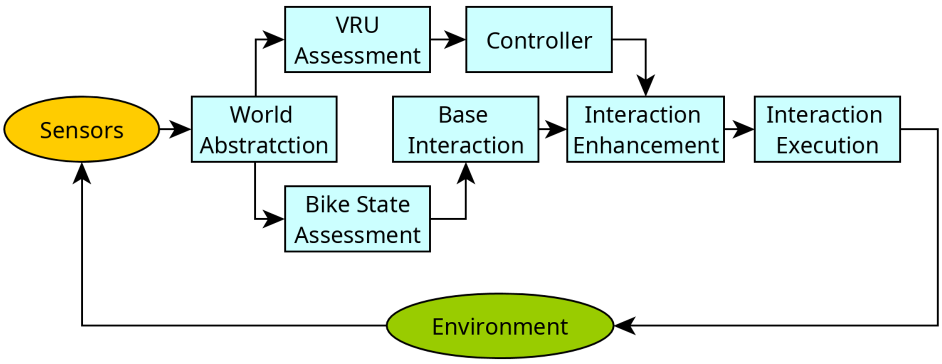


Figure 4.5: HMI Concept with a control loop

However, this regulation differs from the classic regulation, whereby it is a question of constantly measuring a physical variable around an actual and intended value, generating a control difference with which the regulation is fed. In this case, we want to regulate the necessary communication, and this communication can differ from situation to situation, as already described previously. People's attention to the bike is what we want to regulate, but measuring it takes work. This type of measurement is generally a challenge even without the context of the autonomous bicycle.

Due to the limited possibilities, the focus was on the eye contact between the person and the bike. However, the reliable tracking of the eyes is impossible due to the great distance and limited computing power. Therefore, tracking of the person's line of sight and not tracking of the eyes is done. Besides, it is also the case that people perceive other objects' movements without direct eye contact. Some people do not even turn around completely when they hear a bicycle bell from behind and assume that they may be meant if they happen to be walking around on their bicycle.

We are returning to the discovery that we are dealing with a control system. As already described, our system has three input parameters and one output parameter, which are directly and complexly related to each other, as figure 4.6 illustrates. Therefore, the deployment of the controller is an obvious choice. The first thing that comes to mind is a PID controller. The more than 110 years old controller, again popularized in 1942 by Ziegler-Nichols'[231] tuning methods, is still used in 90% of all industrial controls and is characterized by applicability, simplicity, and clear functionality[38, 42].

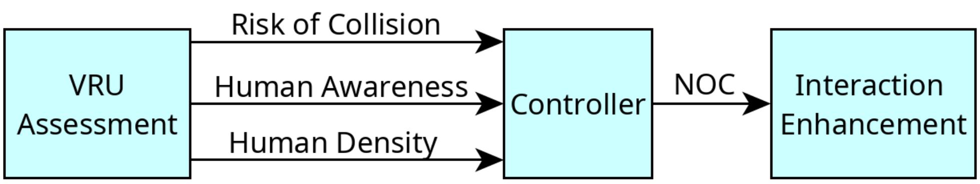


Figure 4.6: Generation of NOC from the 3 environmental parameters

However, one quickly encounters problems when trying to apply the controller to our task. One is the nature of our input variables. For example, the risk of collision is discontinuous. This is because a person drops out of our calculation from one time step to the next, for example, because he goes outside the relevant distance, or the eHMI-system suddenly uses another person as a basis for our calculation. As a result, the variable is discontinuous with large jumps, which poses a challenge for a proportional-integral-derivative (PID) controller. In addition, the design of such a PID controller would be challenging since the poor feedback of the output variable(the attention) makes it difficult to determine the individual PID components accurately. For this reason, a better alternative was sought and found with the use of a fuzzy controller. This does not have the problem of discontinuous input variables and, at the same time, has other advantages, such as the uncomplicated and human-readable interpretation of the rules based on the controller works. Especially the transparency and derivation of the rules are well suited for this application, as seen in section 8.1.

4.2.6 Fuzzy Controler into the eHMI system

Now we have to design a fuzzy controller for our presented problem from 4.2.5 with the help of the presented tools. An introduction to fuzzy and fuzzy controllers can be found in the appendix 8.1. For the design of controllers in general, according to Shaw et al.[196], there are three different methods, all with their advantages and disadvantages, which I will present in the following. In order to get a complete overview, they will be presented in the following, even though we have already seen in chapter 4.2.5 that a fuzzy controller is best suited for our application. On the one hand, there is the **experimental method** where test runs with different parameter sets are made, the input-output behavior can be displayed graphically, and thus the desired behavior can be checked directly. This method has the disadvantage that the system always has to perform a control run which can be expensive and time-consuming for specific systems and thus not practicable. The second method is **mathematical modeling**, which tries to build an idealized mathematical model using differential or difference equations. For this, some assumptions about the process have to be made, like linearity, that output is proportional to the input or that the system is time-invariant despite wear and changes of environmental influences. These conditions are disadvantages, which make the development of a realistic mathematical model[84]. The third method is **heuristic method** where modeling is based on previous experience, rules-of-thumb, and often-used strategies[84]. A heuristic rule is a logical implication in the form: **IF** <condition> **Then** <consequence> or in the context of control situation **IF** <condition> **Then** <action>—rules associate conclusions with conditions. The heuristic method is similar to the experimental method in constructing a table of input and output variables[196]. This method has the advantage that it does not need to assume the linearity of the model and consists of simple and understandable rules for humans. Moreover, these advantages are also used in developing the construction n of the controller for the eHMI. We have expert knowledge about the context and thus can set up informed rules based on linguistic terms. For a different approach to the interpretation of the fuzzy controller, the literature offers a variety of hints and best practices. First, we introduce and prepare the input parameters that our controller should process.

An important method that can be used for the processing of input parameters is the scaling method. Here, the data available as a real number in its metric is calculated with a scaling factor. On the one hand, this can be used to hide unimportant ranges of values by calculating them with a scalar of 0.0. But one can also use the method to increase the distance between the values by using a scaling factor greater than 1. For example, unimportant ranges like < 15 or > 27 can be removed when controlling the temperature since the control has a maximum impact here. Furthermore, one can increase the value range from $19-23$, where the control will mainly operate[138].

After the input values risk of collision (ROC), human awareness (HA) and human density (HD) are calculated, they are normalized, i.e. mapped to the unit interval $[0,1]$. ROC is usually based on the shortest time of a possible collision of all people in the environment called TTC. This TTC is then normalized to the bounds found to be significant. If no time can be calculated, the distance to objects is used as a fallback strategy. The lower limit is called $treshold_{danger}$ because falling below this lower limit causes the bike to enter the danger state. A good value is a limit above which the sensor system works, which is about 3m from the bike's center. If the value is close to the lower limit, 1 is output; if the value is at the upper limit, called $threshold_{attention}$, then 0 is output.

$$ROC = f(ttc) = \begin{cases} 1 & TTC < threshold_{danger} \\ 0 & TTC > threshold_{attention} \\ \dfrac{TTC - threshold_{danger}}{threshold_{attention} - threshold_{danger}} & else \end{cases} \tag{4.1}$$

HA increases non-continuously linear between $[0,1]$. A low value indicates that people around us have not seen the autonomous bike yet or have not seen it for a long time and a high value indicates that people around us are currently seeing the truck or have just seen it. For the calculation of HA first, the arithmetic mean is calculated of the time when the people around us have seen the bike the last time, denoted as *HumanTime*.

The value $threshold_{HumanTime}$ is an externally added parameter that specifies what time limit can be assumed that the human can accept the bike or the status of the bike as *no longer seen*.

$$HA = f(HumanTime) = \begin{cases} 0 & HumanTime > threshold_{HumanTime} \\ 1 - \dfrac{\frac{1}{n}\sum_{i=1}^{n} HumanTime_i}{threshold_{HumanTime}} & else \end{cases} \tag{4.2}$$

The HD increases non-continuous linear between $[0,1]$. A low value says that few people are in the vicinity of the autonomous cargo bike, and a high value says that many people are in the vicinity of the autonomous cargo bike. The value $threshold_{AmountHumans}$ indicates the upper limit, but when the number of people does not allow the value to increase anymore. One can interpret the value so that one person $threshold_{AmountHumans} + 1$ cannot worsen the situation anymore.

$$HA = f(AmountHumans) = \begin{cases} 1 & AmountHumans > threshold_{AmountHumans} \\ \dfrac{AmountHumans}{threshold_{AmountHumans}} & else \end{cases} \tag{4.3}$$

The next step is to describe the fuzzy sets, i.e., to develop membership functions that describe our linguistic variables for our input and output parameters. This is called computing with words in the literature because its focus is to define linguistic variables [229]. To be able to determine the fuzzy quantities is simple since it can be titled from human knowledge concerning the situation. For example, one can divide the temperature into the fuzzy quantities cold and warm [128]. The challenges lie elsewhere. It is to be considered that for each possible input variable of the input variable always, at least one fuzzy quantity exists [138]. Otherwise, comes the fact that no output value can be calculated for this input value. Where one wants the controller to react very sensitively to the input value, it is advantageous to use very narrow fuzzy sets. However, this is different from our eHMI system. Therefore it is sufficient to limit oneself to a few fuzzy sets.

In the conception of the membership function, it was decided to use two simple function types, the ramp function and the triangle function. The ramp function is used for the boundary calculations of the value range, e.g., to describe the terms *low* and *high*. This ramp function has as a property that one can reach full membership quickly with the platform of the ramp and therefore allows an early output. This is useful, for example, when the limits of the value range can be reached only with difficulty or not at all. At the same time, the slope still offers the possibility of allowing a gradual decrease in membership. On the other hand, the triangle function almost exclusively allows only incomplete membership and grants full membership to only a few or one element.

As foreseen by Mamdani, rules were made in the form of control statements **IF** <condition> **Then** <action>. In the creation of these rules, expert knowledge was used in the form of statements about how the autonomous cargo bike has to behave in relation to the three input parameters. The behavior is represented by the output value need for communication. The value ensures that the interactions are equipped with the necessary contextual knowledge to react appropriately to the situation, as presented in 4.2.5.

- **Rule 1.**: high risk of collision between bike and pedestrian results in a higher need for communication
- **Rule 2.**: high awareness of pedestrians towards the bike results in a lower need for communication
- **Rule 3.**: high density of humans around the bike results in a higher need for communication

This creates the input parameters, while the reverse statements can be made analogously without restriction.

- **Rule 4.**: low risk of collision between bike and pedestrian results in a lower need for communication
- **Rule 5.**: low awareness of pedestrians towards the bike results in a higher need for communication
- **Rule 6.**: low density of humans around the bike results in a lower need for communication

We know that a high number of people standing around us can be a problem for the system in general. This is due to the nature of imaging sensors and their problem with occlusion, i.e., people can partially or completely occlude other people and thus not be included in the other calculations even though they fulfill other criteria for relevance. Therefore, a high HD has an influence that makes the other parameters worse. Therefore, it is logical to relate a high HD to the other input parameters ROC and HA.

- **cond. statements:** *IF* HD is high *AND* ROC is mid *THEN* NOC is high
- **cond. statements:** *IF* HD is high *AND* HA is mid *THEN* NOC is high

As a different use case, one can take if a human being approaches the bicycle and wants to look at it from close. This is per se no case where we have increased NOC because the human being approaches the bicycle consciously and with attention. On the one hand, a high value of HA is generated; on the other, by approaching the bicycle, a high ROC is generated. So it is conclusive that one combines these cases into one expression.

- **cond. statements:** *IF* HA is high *AND* ROC is high *THEN* NOC is low
- **cond. statements:** *IF* HA is mid *AND* ROC is mid *THEN* NOC is mid

In addition, conditional statements can be derived from the simple rules presented above.

- **cond. statements:** *IF* ROC is high *THEN* NOC is high
- **cond. statements:** *IF* ROC is low *THEN* NOC is low
- **cond. statements:** *IF* HA is high *THEN* NOC is high
- **cond. statements:** *IF* HA is low *THEN* NOC is low
- **cond. statements:** *IF* HD is high *THEN* NOC is high
- **cond. statements:** *IF* HD is low *THEN* NOC is low

When creating the set of rules, it is essential to note that at least one rule is activated for every possible input vector of the system. However, this does not mean there must be a rule for every possible combination of fuzzy sets. Furthermore, it is important that one does not create rules that come to different conclusions for the same premises.

Now that we have a set of conditional statements, which are expressed by the fuzzy sets *low*, *mid* and *high* and take all input parameters into account, we proceed to the last step, the defuzzification. This means we calculate a crisp value from the fuzzy sets of need for communication. As already described in the section 8.1, there are different mathematical functions.

Here, the *centroid method* was chosen. It represents the accumulated fuzzy sets very well and uses all fuzzy sets to calculate the crisp value. Thus, it has a significant advantage over the *max membership method* where we would only consider the fuzzy set with the highest membership. In addition, the centroid method gives us the free choice of fuzzy sets. In contrast, the *weighted average method* restricts this choice by allowing only symmetric fuzzy sets for calculation.

The last step was to check the fuzzy controller for correct operation. For this purpose, all possible inputs were fed into the controller, and the results were stored along with the inputs into a file. This data was used to check each statement used to generate the cond statements. This is done by picking out the data matching the statement and checking the result to see if it matches the expectations. Below is an example of 3 different inputs that generated three different NOC. First, a low NOC was calculated, which is logical since ROC and HD are low while HA is high. In the 2nd field, you see a medium NOC generated despite a high HA because the ROC is medium and the HD is high. In the 3rd field, you see a high NOC value that was generated by a high ROC and a medium HD, and the HA is too low to reduce the NOC. All these data correspond to our statements or expectations of how the controller should behave. This exemplary check was made for all statements and thus confirmed the correct working method of the controllers.

Listing 4.1: Small example of data generated for evaluation.

```
fuzzy_controler_data_example.txt
{
  riskOfCollision humanBikeAwareness humanDensity NOC
  0.160 0.740 0.160 0.100 <- low
  0.620 0.940 0.720 0.524 <- mid
  0.920 0.260 0.420 0.862 <- high
}
```

5 Implementation

This chapter presents the implementation of the concept presented in the previous chapter. The first section offers the core of this implementation, i.e., the software of the autonomous bike itself and the framework ROS used. Afterward, the requirements are extracted, which result from the necessary integration into the existing system. These are not entirely explicit requirements but also best practice requirements. The central part of the chapter describes the individual modules and their relations.

5.1 AuRa Software System

The image 5.1 shows a simplified overview of the software system in the AuRa bike. All components in blue boxes mark hardware components. All in green are software components not part of the ROS system, like the remaining yellow components. In the figure, the processing chain as it goes from the left, starting with the sensor data, to the right, with the control of the actuators. It begins with the sensors that have already been introduced in section 3.1 and can be seen in the figures of 3.1.

The sensor system includes three cameras, two lidars, GPS, and several Inertial measurement unit (IMU)'s. The respective drivers are then responsible for converting the partly proprietary interfaces of the hardware to the computers into data formats so that they can be made available to the rest of the system. As an exception, the internal human user interface is available as an app on the smartphone. With the app, it is possible to order the bike for oneself. These order processes are passed on as orders to mission control.

Afterward, the sensor information is received by the core perception modules. Here the information from the imaging sensors like lidar and camera are processed separately. So on the camera data, neural networks are applied to classify objects like humans and cars—furthermore, information about the ground, i.e., the different bicycle lanes and lane markings. At the same time, lidar data is used to determine the position and size of the objects and where there is free space to drive, regardless of whether there is a bicycle lane. In addition, the GPS is used to determine the position roughly. This unrefined position is enhanced by the localization performed with the lidar data to obtain a continuous and accurate bicycle position.

In the next step, the extended perception starts, where the processed data of the sensors are merged and fused. This means that the recognized objects from the respective data points are now merged, and objects recognized as one entity are now merged as a date. Furthermore, specific objects are processed, like people and traffic signs. Regarding detected humans, the face's pose and position are recognized.

As the name suggests, the autonomous driving function is about the modules responsible for realizing autonomous driving. This includes the model of the global planner and mission control that work closely together. Here, routing can be made based on the app's incoming orders, the bike's current position, and a city map. For that reason, a route is generated for the bike that describes which roads must be taken to arrive at the destination successfully. This information then goes into the local planner together with a variety of information from the extended perception layer. The local planner has the task of successfully using the routing and the information from the environment to reach the destination. In doing so, a variety of things have to be taken into accounts, such as the correct movement in the traffic area, such as stable driving on the road, and taking into account traffic signs and lights. In addition, it has to be guaranteed at all times that no human beings can come into danger during the movement. The last module in the layer is the eHMI which, in short, has the task of supporting the autonomous driving operation by communicating with the environment in the best possible way so that the risk of possible dangerous encounters is as low as possible, while seamlessly integrating it into the road traffic without attracting negative attention.

In order to implement the commands from the local planner and eHMI, it needs software modules that can interact with the hardware. For the local planner, the User Datagram Protocol (UDP) bridge helps, which receives the steering and driving movements, translates them and forwards them to the motors. For the eHMI, the SSE helps, which receives the interaction message and converts it into signals that the LED strips and the speaker can understand.

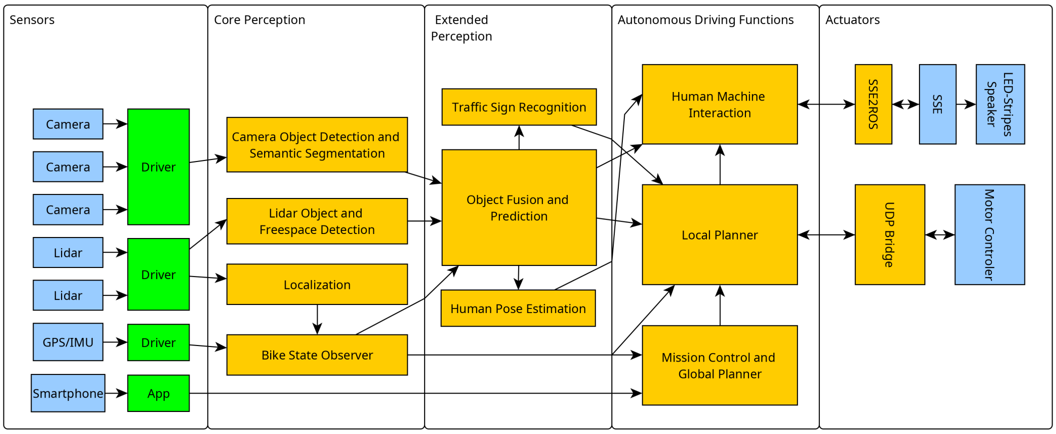


Figure 5.1: Overview of the AuRa system modules

5.2 Robot Operating System

ROS is a middleware that works on the PCs operating system and describes a publish/subscribe model. Data packets are sent over the network via TCP from ROS nodes to ROS nodes via topics. In order to find out which ROS client provides which data via which topic, the ROS master is requested to provide this information. The Nodes offer, for example, raw data from sensors or more complex data such as robot states or objects in the environment. ROS has predefined data types known to all ROS nodes for seamless data serialization. In addition, to the data transfer via topics, there are other constructs like services and actions. Both can be offered by nodes and are rather to be understood as on-demand information that nodes can request. i.e., data that are not meant to be processed by the nodes in a permanently running callback. For example, information that triggers the node's action and wants to communicate feedback about the success or results of this action. This exchange can happen in a network of PCs and within a PC as interprocess communication or intraprocess communication via nodelets[18]. The ROS framework offers a palette of helpful tools for visualizing, logging, or triggering service calls. One example is RVIZ, which serves as a central visualization platform. Here, classic data from imaging sensors such as cameras and lidars can be viewed, and visualizations of data can also be loaded, such as a planned path that shows the direction of the visualized robot model with arrows. The ROS framework lives from its open source policy and its modularity, which allows the creation of modules and visualizations and sharing them in the ROS community. Over 15 years, an extensive library of software has been created. Consequently, this development encouraged more and more companies to provide a driver for their sensors and actuators for ROS, such as intel depth camera [16] and Stereolab stereo camera [28]. This popularity caused an opening of platform and OS, since it is now not only on the x86-64 but also on ARM and also not only Ubuntu but also Windows, Debian, Arch [19, 24]. The accumulation of additional modules and opening to other systems resulted in the introduction of ROS2, which was a complete re-implementation and renewal of some basic concepts.

This 2nd version aims even more than the first version at the possibility of offering ROS as a commercial solution. For this purpose, the data distribution service (DDS) was used, which is already widely used in commercial applications [23]. DDS is a network middleware similar to ROS1, which allows the discovery, transportation, and serialization of data in a network system. but different from ROS1, this discovery system has no need for a ROS master. A significant advantage to ROS1 makes ROS2 more flexible and fault tolerant.

5.3 Presettings

In the previous section, it became clear that the eHMI must be integrated into an extensive software system in order to function homogeneously within it. This system was developed with the help of ROS. In order to realize this, ROS relies on a variety of interfaces and standardized formats to ensure the functionality of the network. Since an integration for the eHMI module is a prerequisite for its functionality, the integration of ROS is a complex challenge.

It is a practice to divide the software into modules where the software is divided into functionalities. This can be seen well in the AuRa software in picture 5.1.

In addition, one request can be considered as best practice, which was the creation of the HMI module as a core ROS independent module despite a ROS interface. As a result, an interface was designed to exchange data with the eHMI, allowing ROS removal in deeper layers of the eHMI library. This led to the introduction of the ROS and world handler modules presented in the sections 5.5.1 and 5.5.3. This also further promoted the modularization of the eHMI system, a positive software feature. Not only between the individual components as in the system 5.1 but also within the individual components themselves. Modularization obliges to design of interfaces between these modules. This makes it easier to get an overview of the functions and parameters that a piece of software has. Therefore, the HMI software is also structured in modules; see 5.5.

In addition, there were aspects of the software that I placed particular emphasis on. These are, on the one hand, the robustness of the software solution. In the context of robotics, it ensures the software's functionality in the event of erroneous input data. This is a common problem with complex software solutions in robotics in general and with ROS in particular. The extreme load on the compute hardware in moving systems can quickly lead to sensors generating partially or fully erroneous data. The goal in implementing the HMI was to always generate an appropriate interaction under all circumstances, which needs to be strongly adapted to the situation due to missing data. For this case, fallback strategies are used and explained in section 5.5.5. Furthermore, the interactions needed to be configurable to a large extent. This allows testing other interactions without changing the code. This was, for example, used to realize the interactions in the study in the elbedome, which becomes essential again in section 6.1.

5.4 eHMI System Overview

The respective concepts described in the section 4.2 divide the system into functional modules. Therefore, these have been implemented individually in programming structures, which can be seen in the picture 5.2. The processing chain of the system starts with integrating the ROS interface. The *ROS handler* is responsible for this. The task of this module is to handle the whole ROS communication, which includes reading all configuration parameters from files and via Graphical user interface (GUI). Since the configurability of the eHMI system is highly important, there is a separate section 5.7 for it. Furthermore, the *ROS handler* module serves as an interface between the ROS-independent part of the eHMI and the rest of the ROS system of the AuRa bike. All subsequent modules of the eHMI system have no dependency on ROS. The *ROS handler* communicates with the eHMI system using the controller module. The controller serves as an interface between the *ROS handler*, the other eHMI modules, and the central unit of the eHMI system. the controller initializes the other main eHMI modules: the *world handler*, and the *interaction planner*, and offers the *ROS handler* some of the HMI functions. The *world handler* is used to handle and create worlds. These worlds are the implementation of the world presented in the concept part, 4.2.2. These worlds are a structured collection of data, including constructs like humans, the bike itself, or the remote control, which is used explicitly to control the interaction types and animations. The *interaction planner* supervises the interaction generation and execution. For this purpose, it receives from the *world handler* the current world for which a interaction is to be generated. This world is then interpreted based on the present configuration. The configuration describes, for example, which distances or reaction speeds are assumed for the processing. The module state assessor makes this interpretation; see section 5.5.5. The *interaction planner* then passes on the result to the module, which is responsible for the actual generation of the interactions. At the end, the interaction is passed back to the *ROS handler*. This takes over again the conversion to the ROS format and sends it to the SSE, which is responsible for the control of the hardware.

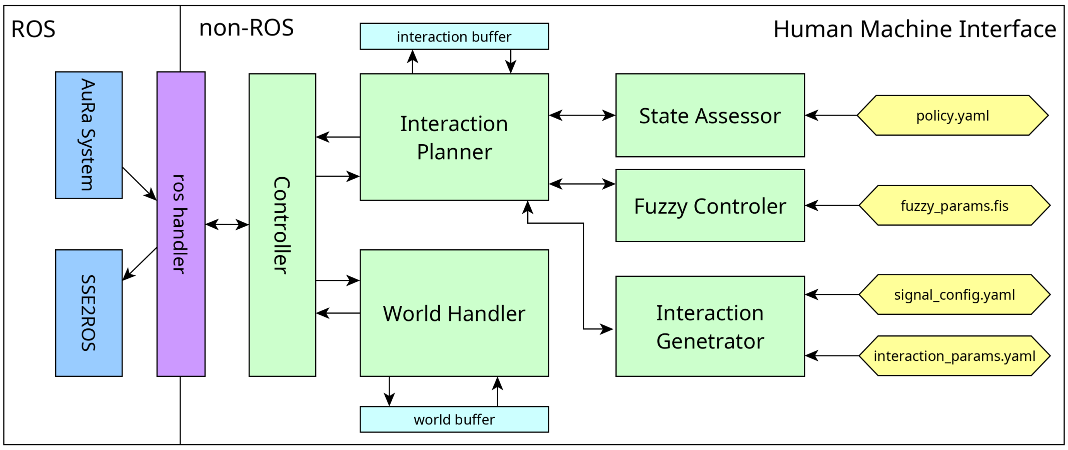


Figure 5.2: Overview of eHMI software modules

5.5 Modules

In the following sections, the individual modules of the framework are presented, and the implementation of the concepts presented in chapter 4 is shown. These descriptions serve to understand the functionalities, the mode of operation, and how the concepts' ideas were realized in concrete terms.

5.5.1 ROS Handler

This module serves as an interface between the system in the bike and the eHMI system. Here the data from ROS is received and converted into the ROS-independent format of the eHMI data types. This separation allows replacing the *ROS handler* with the framework of another middleware, e.g., mqtt[119]. The data is received in so-called callbacks, i.e., whenever a module in the system has new information about objects from the object recognition, then the *ROS handler* also receives the data and stores it briefly. As soon as a new message arrives, the old one is discarded so that the latest version is always available. This module also determines the frequency with which the eHMI works. The eHMI system does not have a fixed frequency but works on demand and can be set via parameters. This frequency determines whenever a new packet of data is passed to the eHMI, generating a world from it. However, interaction is not automatically calculated as soon as a new world is present, but only when the *ROS handler*r requests one through the interface. This procedure ensures that interactions are only generated if it is desired, and thus unnecessary computing power is not expended. Nevertheless, it should be considered that interactions can only be generated if a new world has been created; otherwise, the old interaction will be sent again. This is not the desired behavior and is, therefore, output together with a warning. The interactions are then passed to the *SSE2ROS* by service calls. More about this in section 5.9. Additionally, the *ROS handler* is responsible for reading the parameters and dynamically changing the parameters, more in section 5.7. These new configurations are then passed to the HMI controller.

5.5.2 Main Controler

The *controller* serves as an interface to the *ROS handler*, so that the *ROS handler* does not need to have any information about the underlying HMI modules. It also serves as a central controller for the eHMI. Here the modules *interaction planner* and *world handler* are created and managed. The controller is given the information about the environment and passes it to the world handler. The functions UpdateInteraction and getInteraction allow requesting a new interaction without using the old one. Furthermore, new configurations received by the controller from the *ROS handler* are passed to the *interaction planner*. This can be done during runtime without reinitializing the system.

5.5.3 World Handler

This module creates a world based on the data passed through the controller. The worlds created were implemented according to the concept shown in the figure 4.2 of the previous chapter 4.2.2. Therefore they fully comply with the requirements of the eHMI. The *world handler* has a small world stack that holds not only the current world but also the last used world and the latest world from which no interaction has been generated yet. The current one is deleted as soon as it receives the controller's command, and the next one takes its place. If the handler receives more worlds than are used, then the next world is always kept up to date. The people's information can only be processed if a position exists. So it does not matter that we can calculate a pose or make a prediction if we do not know the current position of the people. The people's information comes in different messages to the eHMI because different modules generate the information. Therefore a matching has to happen when generating the world that brings the people from the different messages together. For this purpose, the id field must be consistent over the messages and is also in the AuRa context. The position of the person serves as basic information. Basic information means that the other information is useless if no information about the position is present. Therefore the other information is optional. Every time the system receives a person's position, other messages are searched for additional pieces of information about the person, which is vital for further processing in the HMI system. All objects and the bicycle itself have a position in the ENU coordinate system. This is because the AuRa system is a multi-bike system, and all objects and bikes can be mapped in one coordinate system. Since only the relative positions to the bicycle are relevant for the eHMI, all object positions are transformed into the coordinate system of the bike the eHMI system is running on. An additional advantage is better readability and improved traceability for humans.

5.5.4 Interaction Planner

This module is responsible for generating all the information necessary for interaction creation. It does not calculate anything but decides what should be calculated and lets the state assessor calculate the missing information. Figure 5.3 shows the workflow for each interaction request. First, the module receives a world about the controller from the world handler. This world is then passed to the state assessor module. This module extracts all the necessary information from the world, such as the bike's state. Based on these states, which base interaction should be generated is decided. In addition, the input parameters for the *fuzzy controller* are obtained from the state assessor and passed to the *interaction planner*. These input parameters are then passed to the *fuzzy controller* 5.8, and it can calculate the NOC based on them. Afterward, the NOC is passed to the interaction generator together with other parameters responsible for the actual generation of the interactions. In addition to monitoring the described processing chain, the *interaction planner* also monitors the duration of interactions and the time between the interactions. This is necessary to make the horn sound only for a short time, although the actual interaction has not yet been completed, or to execute only a flashing down. As a result, the expected time between the interactions is also used to decide whether the time for the horn to stay with the example should better be switched off with the current or next interaction iteration. Such precautions are crucial since we have no guarantees for times and therefore cannot say with which frequency the interaction generation iteration will be made.

5.5.5 State Assessor

This module has the task of extracting all critical information needed from the world and embodies the part of 'Bike State Assessment' in figure 4.1. Furthermore, this module is commissioned exclusively by the interaction planner, as it does not process anything itself. For example, one of his tasks is calculating the bike's state. As described in the concept part 4.2.4 the states are partly received from the LPP and partly calculated from the world itself. The information about the autonomous bike itself is of enormous importance. The speed and acceleration data can decide whether the bike is driving, starting, or moving at a constant speed. All these estimations are reflected as states. Furthermore, the bike's trajectory can be used to determine whether it intends to turn or overtake soon, which is also part of the states graph 4.3. As a special use case, the remote control is to be emphasized; in this mode, no actual state assessment is performed, but the state given in the remote control is assumed. The remote control is, therefore, part of the world and serves the explicit triggering of interactions, mainly used in the evaluation. The second primary task of the module is calculating the input values for the later computation of the NOC by the fuzzy controller, which has already been introduced as a concept in 4.2.5. As already described in paragraph 4.2.5 this gives the three input values **risk of collision**, **human awareness**, and **human density**. In the calculation of the risk of collision, there are gradations to

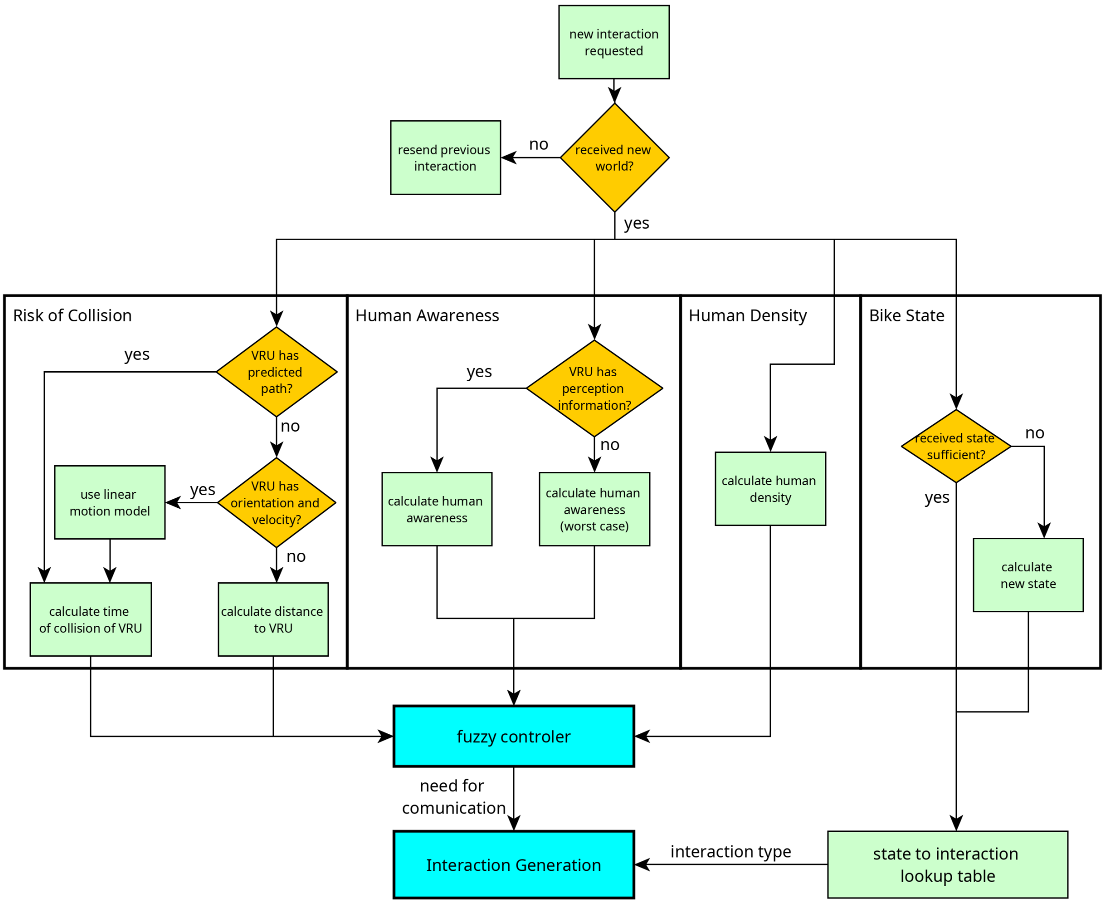


Figure 5.3: Flow chart of interaction planner internal working

be able to react robustly to the quality of the data. The "best case" plan is based on time and indicates when the bicycle and the human come critically close to each other, as it can potentially come to a collision. For this calculation, the bicycle's trajectory is used, as well as the people's prediction.

Since the prediction of the people's paths can be of different confidence, it is discarded if the confidence is too low. If the prediction is rejected, the Constant velocity model (CVM) is used in the first fallback case. The speed and position of the human are used to get an estimation of where this human will be in the next time step. The CVM is not intended to be an adequate substitute for prediction but still gives an evidence-based estimate for small time values in the future. If the person additionally has no velocity, we fall into the last fallback level. Here only the position of the person is used. We always have position information for a human since this is the basic information for objects. This fallback is applied to humans and the bike itself, resulting in many possible cases for the calculation of the NOC. Human awareness is calculated using the human pose. The pose contains information about whether the person's face is towards the bicycle. Whenever this happens, the information is stored together with the occurring time for all surrounding humans, and HA is calculated. Human density is an easy-to-calculate value. For this, the people's positions are used to calculate the absolute number of people standing directly around the autonomous bicycle and output as the value HD. Not all people are included in the calculation, and the people are filtered based on their distance to the bike. For this distance, a threshold as a parameter is used. A Similar threshold exists for other calculations. For example, there exists a danger threshold which describes at which range or time of collision we enter the danger state with the bicycle and thus communicate danger to all around. The danger state is not part of the regular state cycle in figure4.3, but can be activated at any time.

5.6 Interactions and Interaction Generation

This section is about the implementation of the concept of interaction shown in paragraph 4.2.1. Here the class of interaction itself is divided into three parts. The visual, acoustic, and focus points are seen in 5.4. The **visual** interaction is the standard control of the LED strips, which describes appearance like color, blink frequency, and different types of fading. Furthermore, settings like the one-sided left and right activation of the LED stripe are also described here. This option is only used for the turn signal. The **acoustic** interaction includes the description of the sound generation. It can be configured whether the standard ringing is played or a custom one. The standard ringing is the sound of a classic bicycle bell that is played back digitally. The custom sounds are exchangeable sound files stored on the SSE when the ss2ros is started. This option allows playing other sounds at a later time, for example, to perform different eHMI studies. Furthermore, the volume can be changed dynamically. The **focus** interaction describes the focus points displayed on the LED band. On the one hand, it is a list of descriptions for each focus point. All points can be described in color, size, position, and blinking frequency. If two points overlap, an internal ID decides which point will be overlapped. Further configuration is possible. For example, a parameter describes the interaction between focus points and background. Thereby it can be determined whether only the background, the focus points, or both flash together.

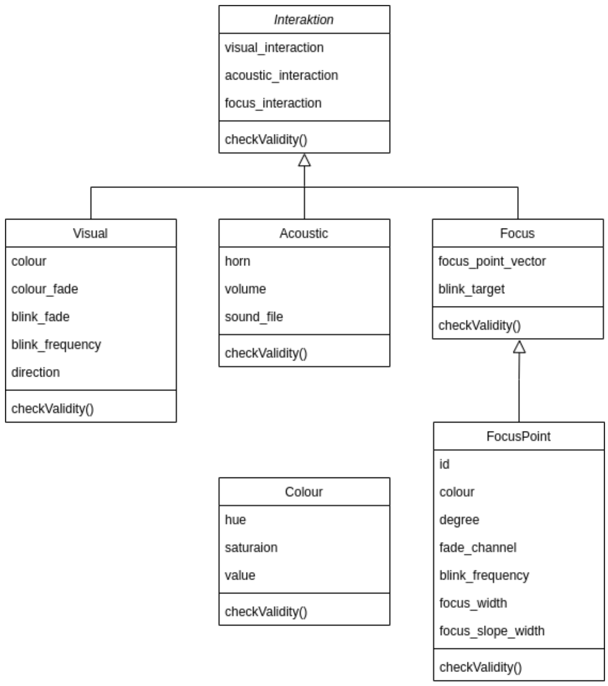


Figure 5.4: Schematic representation of the compositon of an Interaction Obejct

All three parts together form a complete interaction, which does not mean that a sound has to be played for every interaction or focus points are drawn on the LED band. Toggles exist for disabling individual functions—boolean values, which, if false, mean that the interaction part is not included. Additionally, the focus interaction builds on the visual one, as it still describes the background and its color, reducing the parameters. The concept of the base, dynamic, and focus interactions from section 4.2.1 can be found here again. in the case of the base and focus implementation explicitly as a single part of the interaction with visual and focus interaction. The dynamic part of the interaction is transferred to the parameters themselves. The dynamic part is the adjusted interaction based on the environment and represented by the NOC. An example of this is the use of the NOC in the sound interaction, where the volume of the sound depends on it. As a result, in situations where a high NOC is generated by a person coming directly towards us and not seeing us, the sound is played with more volume. As a result, more attention is generated because the situation demands it. This concept is not only applied to the loudness of the bell but also to the intensity of the light.

Another example of a dynamic not based on NOC is the focus interaction. Focus points have as one of their expressive possibilities the width of the focus point. If the dynamic part s disabled in the focus interaction, then this width is always the same width, whether the human is close to the bike or not. If the dynamic part is enabled, then the width of the focus point changes based on the distance of the human for whom the focus point was generated. In summary, if the human is close to the bike, the focus point is very wide, and if the human moves away from the bike, the focus point will be smaller. This aims to give the person the feedback that the autonomous bike has detected him. The module interaction generator is responsible for the presented interaction generation process. The necessary information comes from the configuration files and the *interaction planner*: This passes the necessary information, such as interaction type, NOC, and people position, to the module, from which the appropriate interactions are generated. The interactions are sent back to the *ROS handler* at the end, which passes them to the *SSE2ROS*.

5.7 Configurability of the System

This section is about showing the configurability of the eHMI system. The parameters that make up this configuration decide, on the one hand, how an interaction will look in detail but simultaneously make the limits for the dynamically generated values in the interaction generation process. These limits keep the interaction generation process on track and ensure that no interactions are generated; the SSE and its hardware limits cannot execute that. All this information is not hardcoded because it would have severely limited the usability of the eHMI. The eHMI was designed not only to realize a rigid and particular interaction case but also to explore and test limits regarding these interactions. Therefore the eHMI needs to support this in the best possible way. The parameters for the eHMI are kept in three semantically separated structures: Policy, Signal Config, and Interaction Parameters. The policy parameters describe how the system assesses its environment, i.e., the working behavior of the *interaction planner* and state assessment. It is controlled whether the prediction is to be used with humans or which values the fuzzy controller has and thus how fast and start the controller starts to regulate interaction. The signal config contains parameters that describe the interface with the SSE, see 5.9. It contains information about parameter limits for blink frequency, volume, and maximum color intensity. These limits are not only the limits within which the parameters go to the

SSE but also the limits within which specific parameters of the interactions may lie. As the term implies, the interaction parameters are parameters that specifically describe the interaction. These include all the parameters interaction can have, e.g., the base colors for the various interaction types. Base colors because the dynamic and focus interaction can change the color, whether it is the color itself or the intensity. However, it also includes the base blink frequency or the base size of the focus interaction.

Listing 5.1: Example and structure of Dynamic Reconfigure File.Comments has been removed for better readability.

```
#!/usr/bin/env python
PACKAGE = "human_machine_interaction"

from dynamic_reconfigure.parameter_generator_catkin import *

gen = ParameterGenerator()

...
## acoustic interaction
gen.add("acoustic_horn", bool_t, 16, "play back horn", True)
gen.add("acoustic_volume", int_t, 17, "Volume", 50, 0, 100)
...
```

All these three parameter types can only be integrated into the system differently. The policy and especially the signal config are configured statically, meaning they are only read once at system startup. In contrast, the interaction parameters can also be configured dynamically, i.e., during the system runtime, in addition to the static configuration. The static configuration is partly about parameters that influence the initialization of the system and can only be changed by a restart. On the other hand, it is also about parameters that depend on the properties of the SSE or SSE to ROS (SSE2ROS) and therefore do not need a dynamic change. On the other hand, a dynamic configuration is desirable with the interaction parameters. For example, it is possible to test how a color that is represented by an HSV value looks and acts in reality. The ROS module *dynamic reconfigure* is used for the system's dynamic configuration. This module allows changing parameters during runtime[8] using a GUI. This parameterization during runtime allows

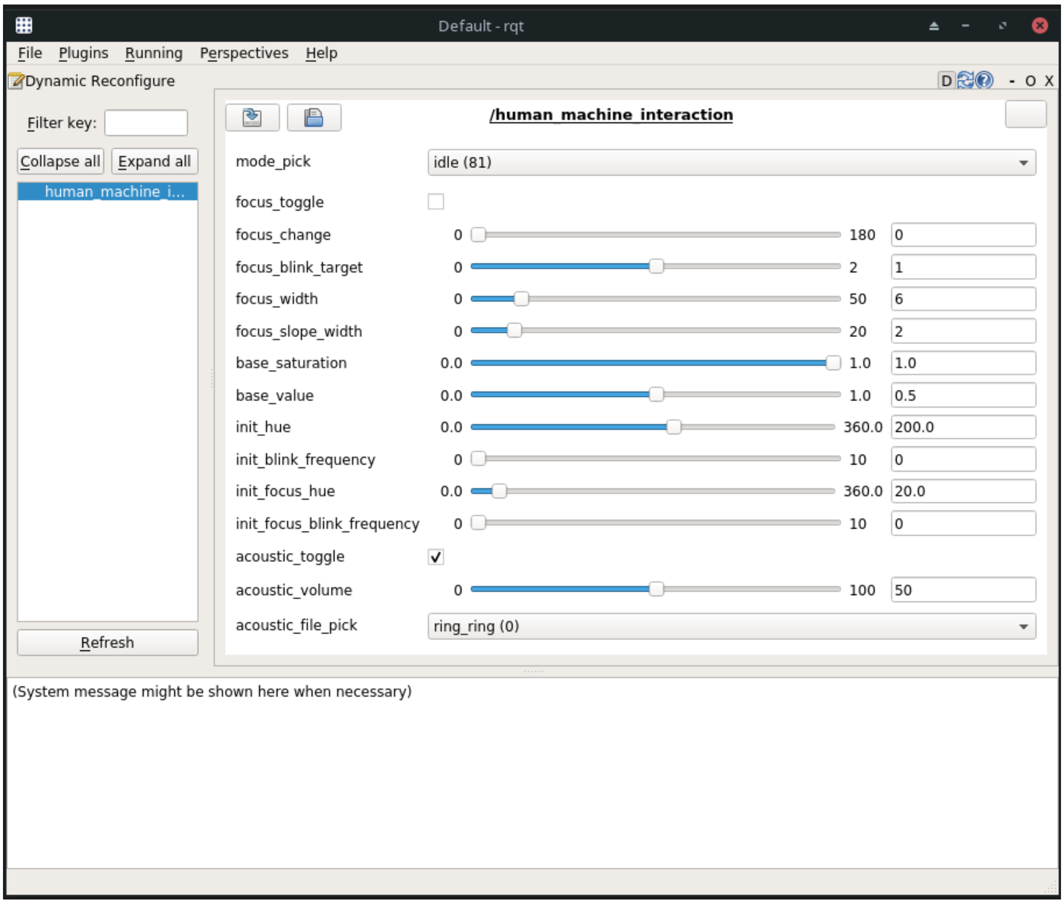


Figure 5.5: Image of the configuration window of ROS's dynamic reconfigure tool

manipulating the color of interaction to have the desired color or intensity. Nevertheless, also other parameters like volume and gaze frequency can be easily changed with it. In addition to integrating the module and providing the parameters, the modification must be intercepted in the *ROS handler* and propagated through the HMI controller to the other HMI modules.

5.8 Fuzzy Controller

This section is about the implementation of the fuzzy controller presented in chapter 8.1. for this, a library is needed to execute the fuzzy controller during the software's runtime. Since the previous software framework was written in c++, it makes sense that the library is also available in c++ to avoid incompatibility and another unnecessary integration layer. The same is true for open-source property. Furthermore, a necessary requirement is that the fuzzy controller library can be read from the usual fuzzy file formats. Among them, there is the .fis format which stands for fuzzy interference system and is introduced by Matlab, and on the other hand, there is .fcl, which stands for fuzzy control language and was introduced by International Electrotechnical Commision (IEC)[12][62]. As introduced, there are also several different types of controllers(e.g., mamdani[156], sugeno[204]), membership functions(e.g., triangle, ramp), and defuzzification methods. The most common methods must be implemented to support the implementation in its breadth. Such a library was found with *fuzzylite*[**?**], which fulfills all these criteria. In order to simplify the creation of the fuzzy controller and to make it possible to work with different sets of test data and visualize the interaction of the different rules, the use of a fuzzy tool with a graphical user interface is also recommended. This allows quick and easy testing of different methods and controller types. The fuzzy system created can be exported to .fis and imported directly into *fuzzylite*. For this purpose, the fuzzy system is read in from the file during the initialization phase of the eHMI system. The input parameters are processed as described in section 4.2.6. All necessary thresholds are read as parameters from the configuration files described in 5.7.

The rules presented in 8.1 were implemented in Matlab, and their plausibility was tested. Figure 5.8 shows an example of how they work. The effect of the input parameters on the output parameter NOC can be represented in a 3-dimensional coordinate system, where the individual axes are the input parameters, ROC, HA and HD respectively. As seen in figure 5.8 with the resulting surface then representing NOC and its expression.

The fuzzy control system created in Matlab is then exported as a .flc file and added to the configuration files of the eHMI.

5.9 Hardware Interface: SSE2ROS

This module is about the interface between the eHMI and the SSE. Figure 5.6 illustrates this principle. The SSE2ROS is a ROS module that is connected to the SSE via a serial port.

The interface between SSE2ROS and the eHMI is a set of ROS messages and services with which the two components communicate and exchange data. During

Listing 5.2: Example and structure of the .fis format.

```
fuzzy_system.fis
{
   [System]
  Name='HMI'
  Type='mamdani'
   ...
   [Input1]
  Name='roc'
  Range=[0  1]
  NumMFs=3
  MF1='low':'trapmf',[0  0  0.25  0.5]
   ...
   [Rules]
  1  0  0,  1  (1)  :  1
  2  3  0,  1  (1)  :  1
}
```

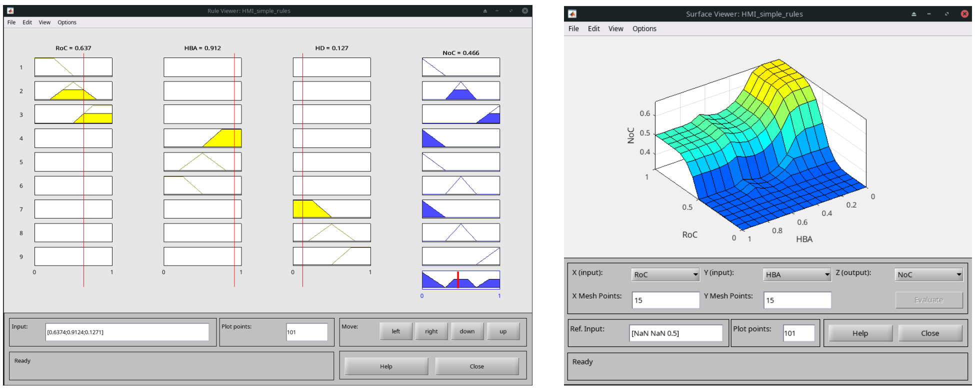


Table 5.1: On the left side, Matlab's Fuzzy Logic Designer shows the rule set activation with an example input. On the right side are the combined rule graphs shown as surface.

the development of the interface, it was taken into account that, on the one hand, an abstraction has to be given so that the eHMI does not have to access every single LED. But also not too specific to limit the conception of the HMI and all

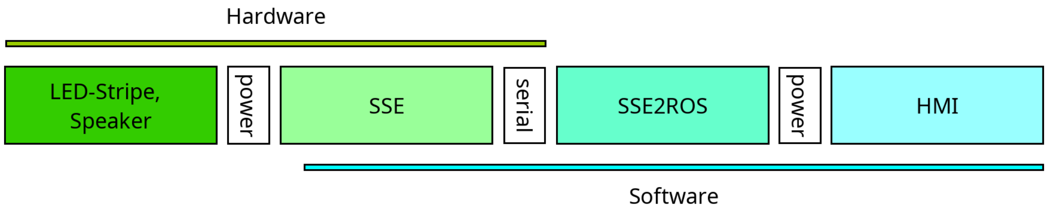


Figure 5.6: SSE as a bridge between the eHMI system and the interaction hardware

possible interactions. This is partly an iterative process where the SSE2ROS was adapted that way. The communication is based on service calls, meaning that the SSE2ROS initiates a service server to which the HMI connects as a client. The HMI uses these services by sending messages to the server. The SSE2ROS checks these messages and sends them to the SSE. Afterward, the SSE2ROS sends feedback to the HMI again. For these service calls, there are three essential messages:

- *Sound.srv* (appendix 8.1) is used to control the loudspeaker. there is a default sound called horn which plays a classic bicycle bell. However, there is also the possibility of specifying the name of a sound file that will be played. This sound file must have been played on the SSE before. This option allows using any other sound for further HMI studies. For example, instead of a bicycle bell, the bike could verbally communicate its intentions using an artificial voice generator. As a last option, it is possible to control the volume of all played sounds.

- *LEDStripe.srv* (appendix 8.4) this is one of the messages you can use to address the LED stripe. The service consists of 2 LEDBlock messages, which are used for the left and right sides of the LED stripe. This division is used for indicating a lane change. For all other interactions, the two blocks are identical and behave as if they were one block. The message contains all information about the interaction, as shown in bild5.4.

- *LEDFocus.srv* (appendix 8.2) is, as the name already shows, responsible for the control of the focus points. It, therefore, contains all information like the corresponding interaction, which can be seen in bild5.4.

Additionally, there are other services that the SSE2ROS provide to the HMI. The most important one is the *getLEDStripeUpdateFrequency.srv*, which is used to get the highest possible update rate from the SSE. The update frequency of the SSE mainly depends on the number of LED elements in the stripes; the more elements, the more LEDs have to be addressed in one cycle. Therefore the possible update frequency becomes smaller. As a result, the HMI asks the SSE2ROS for the update frequency at the beginning of the initialization.

6 Evaluation

This chapter is about the evaluation of the eHMI presented in previous chapters. The focus is on the virtual interaction patterns and the hardware implementation. For the investigation, an online survey was conducted that included different traffic scenarios. In these different scenarios, appropriate interactions of the autonomous cargo bike are seen for each situation. As a comparison, not only the interaction pattern from the chapter was used, but also the interaction patterns reproduced from the Elbedom study. Two response interaction types were added as a further point of the investigation. The interaction type used was, on the one hand, the lighting up of the whole LED strip and, on the other hand, the enlarging of the focus point. Both animations are executed when a person comes closer to the cargo bike. The final point of the investigation is to compare the two studies using the same scenarios and interaction patterns to determine if it is possible to achieve similar results. The difference is that we no longer deal with a digital prototype but a functioning actual cargo bike.

The chapter is structured as follows. First, the study design is presented together with the research questions. Then the traffic scenarios used in the studies are described in detail. Afterward, we come to the results of the statistical analysis. In the end, the results are interpreted, and possible causes and solutions are discussed.

6.1 Online Study Design

With the investigation, essential aspects of the eHMI are to be examined. On the one hand, it is about whether people can recognize the different intentions of the bicycle or whether they are surprised by the behavior of the bicycle. On the other hand, it is about the associated feeling of security, for example, whether the bicycle seems reliable. In addition, there is the emotional state that the bicycle triggers in the person, for example, whether the bicycle surprised them with its actions or calmed them down. On the one hand, the different interaction schemes from the concept and the first study, the Elbedome, which was already presented in chapter 3, will be compared. Furthermore, the results of the interaction scheme from the Elbedome and the online survey will be compared to investigate how the estimation differs between real scenarios in video and VR. Finally, the two different response options provided by the concept will be compared. The faster and faster flashing of the LED strip when approaching a person and the increasing focus point. These research questions lead to the following hypotheses, which are summarized in the table 6.1.

To answer these questions, an online study was provided. For this purpose, the *SoSci Survey* was used[27]. A tool with which one can create and publish online surveys. In order to present the interactions in the questionnaire, short videos were created in which the cargo bike was shown in a traffic situation. All these traffic situations had to be recorded on the campus of the University of Magdeburg. For participation in the online questionnaire, the participants could receive 10€ compensation. The online questionnaire was advertised for seven weeks on different social media channels and to the psychology students of the University of Otto von Gericke.

Subjects were asked questions after playing each video. On the one hand, the online survey questions referred to the subjects' feeling of safety towards the cargo bike, e.g., SI05 'The autonomous cargo bike behaved as I expected it to.' On the other hand, questions were asked about the subjects' emotional state after the confrontation, e.g., 'Emotional state between anxious and relaxed'. The questions were answered on a 5-point Likert scale and can be found in the table 6.2. The original German questions can be found in the appendix. Some questions are identical to the questions from the study in the Elbedome to allow a comparison, namely the questions SI01, SI03, SI05, and SI06. In summary, three independent variables exist the traffic scenario, the response type, and the color scheme as a within-subject design. On the other hand, the dependent variables can be seen as a sense of security, SA, and trust.

For the statistical analysis, the Mann-Whitney-U-test was used since the underlying data were collected as a Likert scale and are therefore available in an ordinal scale. The language R(version 4.2.1) was used for the calculation with the software r studio[21, 25].

Table 6.1: Hypothesis summary

RQ		Hypotheses
RQ1	H1	Individuals have a different perception of safety, emotional status, and intention recognition of ADB in all scenarios of the elbedome study and the online study using same interactions patterns.
	H1a	Separately for scenario ‘Start up’.
	H1b	Separately for scenario ‘Stop as confrontation’.
	H1c	Separately for scenario ‘Drive by’.
	H1d	Separately for scenario ‘Crossing’.
RQ2	H2a	Individuals have a different perception of safety, emotional status, and intention recognition of ADB within the interaction pattern ’Focus’ to interaction pattern ’None’.
	H2b	Individuals have a different perception of safety, emotional status, and intention recognition of ADB within the interaction pattern ’Blink’ to interaction pattern ’None’.
	H2c	Individuals have a different perception of safety, emotional status, and intention recognition of ADBwithin the interaction pattern ’Blink’ to interaction pattern ’Focus’.
RQ3	H3	Individuals have a different perception of safety, emotional status, and intention recognition of ADB in all scenarios with the Elbedome color scheme and the new color scheme.
	H3a	Separately for scenario ‘Start up’.
	H3b	Separately for scenario ‘Stop as confrontation’.
	H3c	Separately for scenario ‘Drive by’.
	H3d	Separately for scenario ‘Crossing’.

Table 6.2: List of questions the subjects received after each scenario(the german orginal questions are in the appendix)

Code	Statements	Answer posib.
SI01	I would feel safe around the autonomous cargo bike.	5 pt. Likert scale
SI02	The autonomous transport bike is reliable.	5 pt. Likert scale
SI03	I found the signal of the autonomous cargo bike helpful in the situation.	5 pt. Likert scale
SI04	The autonomous cargo bike provides safety.	5 pt. Likert scale
SI05	The autonomous cargo bike behaved as I expected it to.	5 pt. Likert scale
SI06	I can trust the autonomous transport bike.	5 pt. Likert scale
SI07	Using the autonomous transport bike will bring harm.	5 pt. Likert scale
EM01	Emotional state between anxious and relaxed.	5 pt. Likert scale
EM02	Emotional state between agitated and calm.	5 pt. Likert scale
EM03	Emotional state between aware and surprised.	5 pt. Likert scale

6.2 Scenarios

The video clips in the survey are supposed to represent specific traffic scenarios. These scenarios are a selection of the scenarios from the Elbedome study. The scenarios where the same or very similar interaction of the bicycle is intended or would have been difficult to implement practically were sorted out—for example, blocking the sidewalk so that the subject is forced to turn onto the bike path. In the end, the result was five scenarios with different interactions, which will be presented in the following. Here, the pedestrian should virtually take the POV from the camera; therefore, the pedestrian is always referenced in the scenes, not the camera.

The first scenario was about the pedestrian approaching the bike and the bike reacting. This scenario was different from the others because it was only about the type of response interaction. So there were three versions of the scenario, one with a flashing interaction where the flashing became faster and faster as the distance between the pedestrian and the bike was reduced. The flashing itself was briefly orange and then changed back to the previous cyan. The flashing was sharp and had no fading, so it did not have a smooth transition but instantly changed to the other color. In this case, the complete stripe was blinking. In the following type, the focus was used. This part of the stripe can have a different color and potential interaction than the rest of the stripe. In this scenario, the stripe has an orange color and gets wider as the pedestrian approaches. The rest of the stripe is cyan. The last type has no response as interaction from the bike. This serves as a control scenario to evaluate if there is any difference between the blink and focus response to no response.

The following four scenarios aimed to evaluate the interaction patterns from the Elbedome with the newly designed ones. Therefore all four scenarios were recorded two times, once with the interaction pattern from Elbedome and once with the new one.

The second scenario is called 'Start up' and is comparable to the seventh scenario from the Elbedome study, as seen in the table 3.8. In this situation, the cargo bike starts up from a standing position, and the pedestrian observes this. The interaction pattern should communicate this process so that the observer is not surprised. Avoiding surprises is an important goal in the communication of the bicycle, as this is not a desirable emotional state while in traffic, and it also means that the human did not anticipate the action of the bicycle, suggesting a poor SA. Two interaction patterns were used. The Elbedome interaction pattern provides for a single ring at startup and then flashes its base color green at a frequency of 1. the new interaction pattern also provides for a single ring at startup and then assumes its attention color yellow during the settling process before changing to its base color cyan.

The third scenario is called 'Stop as confrontation' and is comparable to the second scenario from the Elbedome study, as seen in the table 3.8. This scenario was about the bicycle being blocked on its way by the subject, and the bicycle had to communicate to the subject that the subject was in the way. In order to make the blocked path more apparent, a narrow path was used in the video on which the bicycle drives so that it becomes clear that the bicycle cannot avoid the human. In Elbedome, this was realized using a transporter that stood on the pedestrian path, so the subject had to sidestep to the bicycle path. In this case, the bicycle started with the interaction of autonomous driving and then had to change the interaction pattern. For the Elbedome interaction pattern, the bicycle changed from a constant glow of its base color, green, to flashing of its attention color, orange, with a frequency of one. In the new interaction pattern, the bicycle first flashed its base color, cyan, with a frequency of two and then changed to its attention color, orange, with a frequency of one.

The fourth scenario is called 'Drive by' and is similar to the fifth scenario from the Elbedome study, as seen in the table 3.8. It is about the bike passing the pedestrian and communicating its autonomous bike status. This is a simple scenario but, at the same time, probably the most dominant one in terms of mundanity since this is how the pedestrian experiences the bike most of the time. In the Elbedome interaction pattern, the strip is constantly lit in its base color of green. In the new interaction pattern, the LED strip flashes with a frequency of two in its base color, cyan.

The fifth and last scenario is called 'Crossing' and is similar to the fourth scenario from the Elbedome study, as seen in the table 3.8. The pedestrian wants to cross the bike lane, and the autonomous bike comes toward the human on this bike lane. The bike has priority over the pedestrian but is aware that the human is about to enter his bike lane. For this reason, the bike changes from the status of autonomous driving to the status of attention. This means in the Elbedome interaction pattern that, the bike changes from its base color of green to flashing in its attention color orange with a frequency of one. In the new-interaction pattern, however, the bike changes from flashing in frequency two in base color cyan to flashing in attention color orange with a frequency of one. The table 6.3 provides an overview of the scenarios used in the study.

6.3 Online Study Results

A total of 119 people participated in the online study, with an average age of 28 years, the youngest being 18 and the oldest 55. Of these, 64 were male, 53 were female, and two gave no information. Of these, 62 participants had a university degree, 33 had a high school diploma, and the remainder had a middle school diploma, or a technical college diploma, and high school students. In comparison, 115 persons participated in the Elbedome, of which 55.7% were female and 43.5% male. In Elbedome, the average age was much higher, at 42.35, but a similar distribution of educational qualifications, with most having either a high school diploma or a university degree. Since the complete analysis is neither clear nor informative in textual form, only the significant results are shown here. The complete statistical analysis is included in the appendix for each study. First, we look at the first research question—comparing the scenarios with the data in the Elbedome study.

Table 6.3: Szenario overview of online study

Scenarion	Description	Image
1. Approaching	Pedestrian comes closer and closer to the bicyle; bicyle reponses with different reponse interaction to the approaching pedestrian	
2. Start Up	Pedestrian watches from comfortable distance, that the bikes starts driving and passes next to the pedestrian, bike communicates the starting process	
3. Stop as Confrontation	Bike moves towards pedestrian stops in front of, bike communicates that movement is blocked	
4. Drive By	Bike is moving and passes next the pedastrian bypassing the pedestian, bike communicates normal driving process	
5. Crossing	Pedestrian wants to cross the bike lane, where the bike is coming from; bike communicates that it seeks attention from the pedestrian	

Regarding the first scenario, 'Start up' and the matching null hypothesis1.1, the Elbedome subjects were significantly different from online subjects concerning all safety questions and EM01. With the following results: for question SI01 with $U(N1 = 28, N2 = 119) = 2956.0; z = -7.74; p = 1.56 \times 10^{-11}; r = 0.56$, for question SI03 with $U(N1 = 28, N2 = 119) = 2133.5; z = -2.50; p = 1.0123; r = 0.21$, for question SI05 with $U(N1 = 28, N2 = 119) = 2303.5; z = -3.32; p = 9.15 \times 10^{-4}; r = 0.27$, for question SI06 with $U(N1 = 28, N2 = 119) = 2506.0; z = -4.37; p = 1.27 \times 10^{-5}; r = 0.36$, for question EM01 with $U(N1 = 28, N2 = 119) = 2197.0; z = -2.79; p = 0.0052; r = 0.23$. Of particular note is SI01 with an $r = 0.56$ and thus by a large effector. Apart from EM03, the responses in the Elbedome study are extremely positive, with mean responses ranging from 4.39 to 4.86. In contrast, the responses in the online study are mostly only between 3.61 and 4.11. In the case of EM03, the mean of the online study is slightly higher than that of the Elbedome. The plot 6.1 gives an overview of the average results.

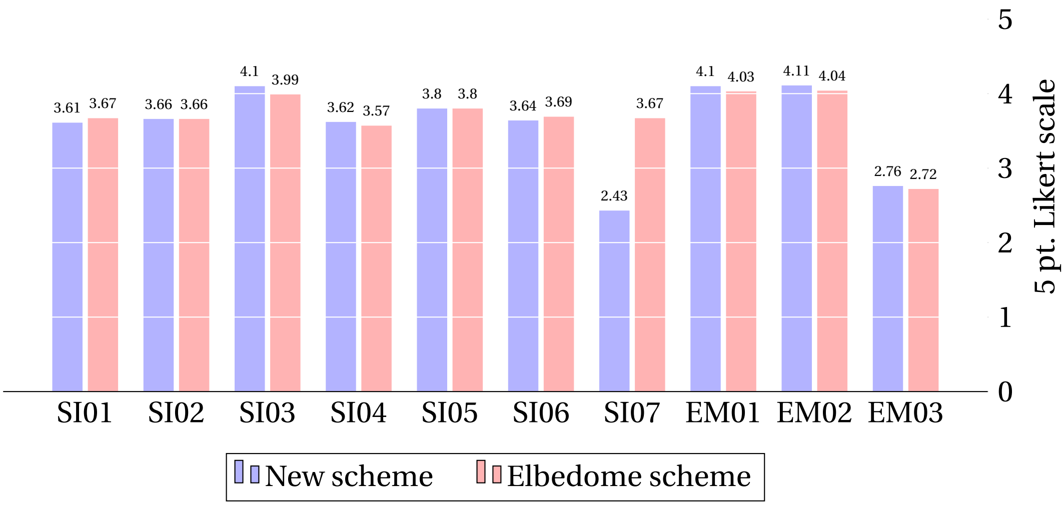


Figure 6.1: Average answers for scenario Start up

Regarding the second scenario, 'Stop as Confrontation' and the matching null hypothesis 1.2, the Elbedome subjects showed significant differences compared to online subjects regarding the safety questions SI06 and EM03. With the following results: for question SI06 with $U(N1 = 28, N2 = 119) = 2085.5; z = -2.17; p = 0.0298; r = 0.18$, for question EM03 with $U(N1 = 28, N2 = 119) = 2095.5; z = -2.19; p = 0.0285; r = 0.18$. Both results have only a weak effect with an r-value of around 0.2. Here the means are much closer in the comparison between the studies, with average values of 3.57 to 4.07 in the Elbedome and 3.05 to 4.08 in the online study. The plot 6.2 gives an overview of the average results.

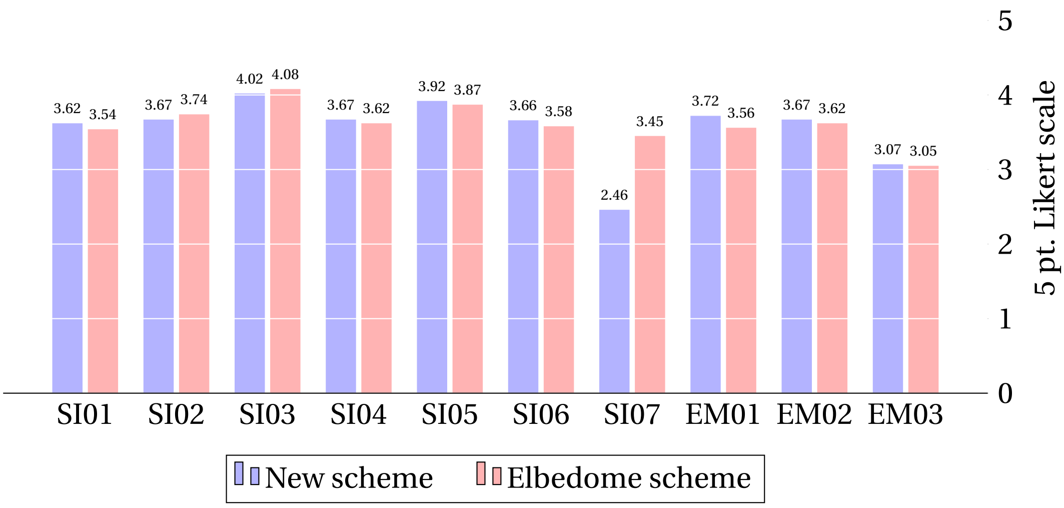


Figure 6.2: Average answers for scenario Stop as Confrontation

Regarding the third scenario, 'Drive by' and the matching null hypothesis 1.3, the Elbedome subjects were significantly different from online subjects concerning all safety questions and EM03. With the following results: for question SI01 with $U(N1 = 28, N2 = 119) = 2353.0; z = -4.36; p = 1.31 \times 10^{-5}; r = 0.36$, for question SI03 with $U(N1 = 28, N2 = 119) = 2725.5; z = -6.75; p = 1.43 \times 10^{-11}; r = 0.21$, for question SI05 with $U(N1 = 28, N2 = 119) = 2057.0; z = -3.23; p = 0.0123; r = 0.27$, for question SI06 with $U(N1 = 28, N2 = 119) = 2314.0; z = -4.17; p = 3.06 \times 10^{-5}; r = 0.34$, for question EM03 with $U(N1 = 28, N2 = 119) = 2122.0; z = -2.32; p = 0.02; r = 0.19$. Of particular note is SI03 with an $r = 0.56$ and thus by a large effector. Here the means in the Elbedome are again mostly very high, with 3.10 to 4.72, and in the online study, only between 2.57 to 3.96. The plot 6.3 gives an overview of the average results.

For the fourth and last scenario, 'Crossing' and the matching null hypothesis 1.4, the Elbedome subjects were significantly different from online subjects concerning the safety questions SI01 and SI06 and EM02 and EM03. With the following results: for question SI01 with $U(N1 = 28, N2 = 119) = 2964.0; z = -6.73; p = 1.67 \times 10^{-11}; r = 0.56$, for question SI06 with $U(N1 = 28, N2 = 119) = 2848.0; z = -6.10; p = 1.03 \times 10^{-9}; r = 0.50$, for question EM01 with $U(N1 = 28, N2 = 119) = 2652.0; z = -5.13; p = 0.89 \times 10^{-7}; r = 0.32$, for question EM02

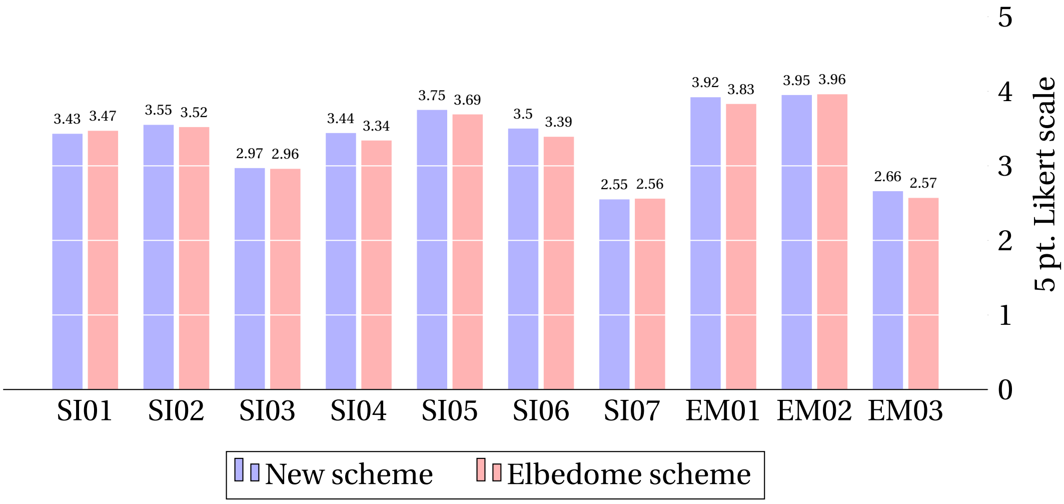


Figure 6.3: Average answers for scenario Drive by

with $U(N1 = 28, N2 = 119) = 2411.5; z = -3.86; p = 0.0001; r = 0.32$, Highlighting the results on SI01 and SI06 with a $r \geq 0.5$ and thus by a large effect. here the mean of the data from the Elbedome is again far higher than in the online study, with 4.06 to 4.86 and 2.92 to 3.77. as an exception, it can be seen that in EM03, the mean of the online study is 0.5 points higher than for the online study. The plot 6.4 gives an overview of the average results.

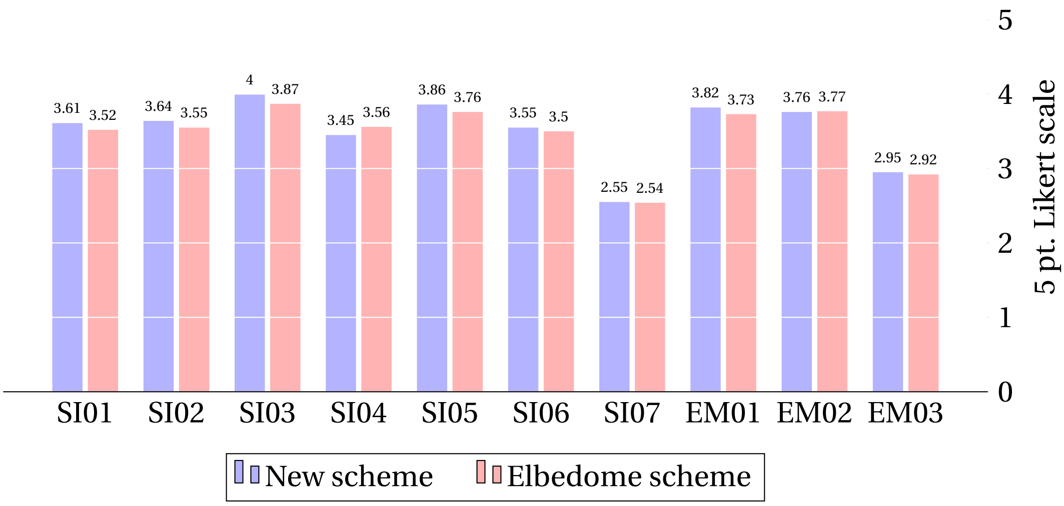


Figure 6.4: Average answers for scenario Crossing

Let us move on to the second investigation concerning the response interaction patterns of *focus* and *blinking*. Regarding the interaction pattern 'focus' and the matching null hypothesis 2.1, the subjects with the *focus* showed no significant difference in their assessment of safety or emotional status compared to the subjects without the interaction pattern. The means are pretty similar, with most scores between 3.0 and 4.2. with the exceptions of SI07 and EM03, which are both around 2.3.

Regarding the second interaction pattern, 'blinking' and the matching null hypothesis2.2, the subjects with the *blinking* showed no significant difference in their assessment of safety(SI01-SI07) with no p-value below 0.05 or emotional status(EM01-EM02) compared to the subjects without interaction pattern. However, for question EM03 with U (N1=119, N2=119) = 8365.0; z = -2.4988340; p = 0.0125; r = 0.16, indicating that people were surprised by the blinking. The means of the two studies are very similar, with most values between 3.0 and 4.3. with the exceptions of SI07 and EM03, which are both around 2.4. Regarding the interaction pattern 'blinking' and the interaction pattern 'focus' (hypothesis H2c), the subjects with the *focus* showed no significant difference in their assessment of safety or emotional status compared to the subjects without the interaction pattern. Here, the means of the two studies are between 3.0 and 4.3. with the exceptions of SI07 and EM03, which are both around 2.4. Figure 6.5 gives an overview of the average results.

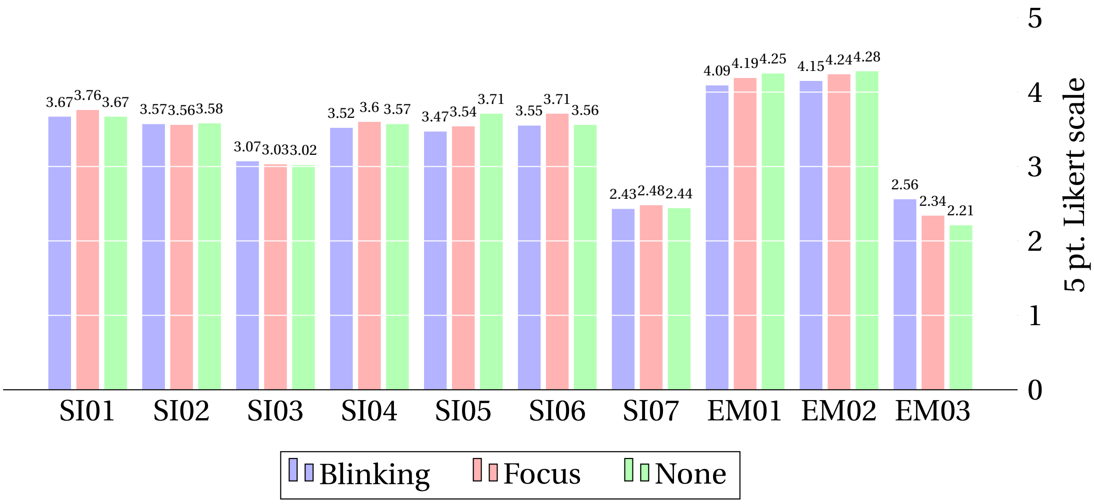


Figure 6.5: Average answers for scenario Approaching

Finally, the third investigation concerns the different interaction schemes from Elbedome and the new interaction scheme from the concept in the individual scenarios. The results of all hypotheses H3(a/b/c/d) were not significant. The means of all scenarios was approximately between 2.5 and 4.0.

6.4 Discussion of the Online Study Results

Aus den ergebnissen der studie lassen sich erkenntnisse für aura und für hmi entziehen. aber beginnen wir mit einem vergleich In comparing the studies in the Elbedome and the online study, significant results were found for most of the subject's statements. However, the number and strength of the effects differed enormously between the different scenarios. In this respect, a significant difference between the 'stop as confrontation' scenario and the other three scenarios can be seen. In the other three scenarios, substantially more significant results were found, especially in the safety questions compared to the statements regarding the emotional state. Here, the bicycle from the online study was usually rated more negatively. For example, this can be seen in the scenario 'drive by' results. Here, p-values well below the threshold of $alpha = 0.05$ were found for all safety questions, with in some cases strong effect sizes of $r = 0.56$, as in the case of question SI03 regarding 'how helpful the signal is in the scenario'. The fact that one scenario was rated less bad than the others suggests that it is not exclusively due to a systematic difference. One could add that both studies were carried out with different methods. An additional difference is that the traffic scenarios could not be clearly reproduced due to the different execution of the studies. In both studies' stop scenarios, an unpleasant situation was created for the test person. Next, we come to the investigation results of the different response interactions. Here, there were few to no significant results. The only time a significant result was found was concerning EM03 in comparing the blink response to the no response, but with a weak effect of $r = 0.16$. This could indicate that the blink was somewhat surprising for the subjects.

One possible explanation is that it was precisely in the response interactions that the light signals were the most difficult to see. This was also proclaimed by statements of the subjects after the survey. Another possible explanation is that the response interaction patterns have no influence on people's interaction with the bicycle. This assumption must be accepted first but seems unlikely. Therefore, it is probably best to repeat this investigation of the response pattern with a different methodology in order to find a suitable solution for AuRa. In the end, we come to the investigation of the different interaction schemes in the different scenarios. Here no significant results were shown. This may indicate that the two interaction schemas were judged to be equally helpful, which is reasonable since the two interaction schemas are not fundamentally different from each other. However, whether a difference can be found by using a different study method arises. It is pretty likely that by using a real prototype in a real traffic situation, the people's perception was more dominant, and therefore, the 'subtle' differences of the interaction schemas could no longer come to bear.

Based on past eHMI studies, more significant results were to be expected. Especially in the case of the response pattern, the feedback for the human should give additional information. On the one hand, the bicycle has seen the passer-by; on the other hand, the machine perceives continuous movement towards the bicycle. Particularly with the blinking response pattern, it would have been expected that the faster blinking at a reduced distance would have caused an interpretation by the subject, for example, increased activity or danger when the color red is used in combination, which was not part of the study parameters.

During the execution of the study, there were problems with the video recordings for the online survey. There were difficulties with the visibility of the LED strip lights. These were more difficult to see in the video recordings than in persona. For this reason, in some recordings, the focus was placed on the LED strips to make their interaction more visible. This action, in turn, worsened the clarity of the traffic scenario in which the interaction took place. Therefore, it was a balancing act between the visibility of the LED strip lights and the traffic situation.

From this, some conclusions can be drawn about the evaluability of eHMI. On the one hand, prototypical studies in virtual environments and their results cannot be projected so easily into the real world. This results mainly from the numerous influencing factors that a simulation, at least at this point, cannot yet depict. For example, lighting conditions can change the color interpretation or minor changes in the machine's movements, which can unsettle pedestrians but cannot be systematically prevented in a real environment.

The visibility problem could be solved in a couple of ways in the AuRa project. One obvious solution would be to increase the power consumption of the LED strips or to replace the LED strips with a more powerful model. However, this is not practical since these LED strips already have very high power consumption, and none could be researched that could absorb even more. Furthermore, the bike's power to the eHMI is already at its maximum. The question arises as to what extent there is hardware that can meet these requirements. In recent years, automobile vehicles were deployed using some LED stripe as turn indicators, where instead of simultaneous flashing, a light animation is used, which flashes every LED separately from left to right or vice versa. This technology comes from the in-house car manufacturers and is therefore not free evaluable.

Another way to address this problem would be to relocate the video recording site, and one possibility would be a hall with traffic infrastructure. They were similarly seen in Burns et al.[53], who evaluated their LED and projector-based eHMI in such an environment. Another solution would be to remove the video recordings by performing the study in person instead of changing the location of the video recordings. Here there were fewer problems with the visibility of the LED strip lights. However, with performing such a field study would come its disadvantages, such as difficult repeatability of the interactions, environmental influences, and increased effort and thus usually reducing the number of subjects.

7 Summary and Future work

This chapter represents the conclusion of the thesis and is intended to summarize the achievements and answers that the thesis gave to urgent questions. After this, a short excursion will be made into possible follow-up work, which will show improvements and extensions for the presented result.

7.1 Summary

The thesis task was to realize the human-machine interaction of the autonomously driving cargo bike in the project AuRa. This was a pioneer project in the field of autonomous driving. At the same time, this meant that there are only some similar prototypes for such a human-machine interface and standards that make specifications in this field. Nevertheless, it was possible to specify the problems and requirements for such an interface. These were driven from the point of view of substitution since it is necessary to replace the missing human on the bicycle. For this purpose, the emerging problems were analyzed and formulated into two problems or questions:

1. What kind of device is needed for communicating with other road user?

The first step was to research in a round of experts which devices could be considered in order to discuss whether and how these could be implemented. After a preliminary study, two candidates of a monitor and LED stripe emerged and were then implemented in a digital model and evaluated in two VR studies. For this, basic communication patterns had to be introduced. i.e., to what extent the LED strip and the monitor can be used for communication? This resulted in a list of animated colors and pictograms that were implemented on the respective device. These studies focused on the needs of pedestrians on the one hand and on the needs of car drivers on the other hand. With no clear favorites from the studies, the decision was made in favor of LED strips based on different factors. Influential advocates were the simple but sufficient possibility of expression through color and animation, simultaneously offering excellent visibility and perspective security. But also, the safe and openly designable technical implementation was an important factor, which ultimately found an actual and functioning implementation.

The requirements were approached and solved as follows:

- recognizability: With the LED strips, only color and animations can be displayed. These are similar to those of conventional cars and, therefore, reasonable to use in road traffic.
- scalable: LED stripes to allow you to specify the strength of the colors and the speed with which animations are shown or switched between them.
- feasibility: can be integrated very well into a cargo box without any restrictions for the usability of the cargo box nor the autonomous bicycle.
- reliability: LED strips are robust and, since they are located behind a diffuser, also protected from external influences. In addition, they have a low intrinsic weight, which prevents disturbing impacts on vehicle dynamics.

2. How does the communication look like via the choosen device?

It was decided that the bicycle should communicate its current or future actions in the form of interactions based on the internal status of the bike. These interactions should reflect the status of the bicycle. These statuses either come from the existing software modules or are extracted from all available information. This should enable other road users to better adapt to the bike. On the one hand, the focus was on making these interactions clear and easy to recognize. On the other hand, they should allow adapting to the respective situation. For each situation, it is calculated how critical this situation is in terms of needed communication to avoid, for example, a possible close passing of VRU. This required communication is calculated as variable NOC. It is based on the risk of a collision, the people's awareness of the ADB, and the people's density around the bike. This quantification allows the generation of adapted interactions for each situation. As the last point, the interactions were given the possibility to indicate a kind of feedback to the VRU in the form of a focus point aligned to the person's position.

They can be configured independently from the rest of the interaction. These interactions were implemented on a prototype and evaluated in a study with x subjects.

The requirements were approached and solved as follows:

- unambiguous: The interactions have been given color groups so that similar interactions differ but simultaneously express their respective (non-) criticality.
- appropriate: By introducing NOC as a measure of the urgency of a given interaction, each interaction can look different depending on how critical the situation is considered to be.
- feedback: A feedback system has been developed which provides a focus point for each person in the interaction and is based on the person's position and distance from the cargo bike. The animation and color of the focus point change depending on the interaction.

3. How should the realization of such a concept be designed?

The implementation includes integrating the signal hardware, the interface to the PC, and the software for processing and generating the interactions. In the implementation of the signal hardware and its connection to the PC, attention was paid to a faithful implementation from the evaluated concept of the studies, and a precise and fast activation was given. The main aspect lies in the software module, which realizes a connection to ROS and, thus, to the rest of the software system of the autonomous cargo bike. The data from the bike system are used to identify traffic situations based on which the interaction types are generated and timed. In this process, the position and movement data of the VRU are taken into account in order to include the safety or sense of safety of the VRU in the design of the interactions. All the processes of the main module that process the environment, such as the design of the interactions, are parameterized and thus fully configurable during or between the uses of the HMI. In concrete terms, the requirements are answered again in detail in the following:

Requirements

- traffic: different interaction types are used for different traffic situations to reflect the respective dynamics of the cargo bike in the respective situation.

- safety: the position and movement data of VRU is taken into account in the generation of interactions and increases the attention generation if needed.
- configurability: extensive parameterization allows changing the system's assessment of criticality and definition of traffic situations, the interaction expression itself, and the framework in which it may adaptively adjust to the situation.
- response: the asynchronous processing of the data prevents blocking of the interaction generation and thus enables a constant generation of interactions.
- reliability: the use of various fallback strategies allows the system to get by with very little to hardly any data, even in the short term, and still generate a meaningful interaction.

7.2 Future Work

Ultimately, we want to work out the aspects of the thesis which offer possibilities for improvements or extensions to improve the previous work in a meaningful way.

There are possibilities to improve the hardware of the HMI. On the one hand, the visibility of the signaling to the rear is poor. Here, one could imagine an extension similar to the cargo box with a small LED strip around the rear luggage carrier. However, the same features cannot be used on this small signaling device as on the large LED strip. For example, due to the lack of space, the visibility of focus points are strongly reduced. Here, an intermediate solution must be found. Besides, there were some things that could have been improved in the study regarding the visibility of the LED strips. Here it could still be clearly clarified whether the problem is due to the recording technology of the camera or whether an equally serious visibility problem also exists in persona, and if so, this should be addressed accrodignly. In this case, other strips or diffusers should be considered and evaluated.

Regarding the framework, some improvement can be made concerning the calculation of the human awareness. This is of particular difficulty and relevance at the same time. Currently, the analysis is done solely on the aspect of whether a person has seen the bicycle and, if so, at what moment. However, human perception is much more than just a simple glance. Here, one could measure not the direct glance but a general reaction to the interaction on the one hand. An additional aspect is an assumption that people in a certain radius heard the bicycle as soon as the bike interaction made a noise. However, this is difficult to generalize since many people wear earphones and earmuffs or are hard of hearing in public spaces. How such an inclusion of acoustic signals can be included in the measurement of perception would be a fascinating field of investigation.

Furthermore, it is of enormous importance that the interactions themselves are further investigated. The studies could not make a meaningful statement for or against an interaction scheme. This needs to be investigated further to determine whether this is due to the minor differences in the interaction schemes, the study design, and implementation, or the design of the prototype design itself. On the other hand, legislation at the national and international levels is becoming increasingly active in regulating the field of autonomous driving. And it is expected that restrictions will result from this concerning color or animation, or even hardware to be used.

8 Appendix

8.1 Fuzzy Logic and Controller

A fuzzy controller is a controller that uses fuzzy logic as a basis. Fuzzy logic currently finds some application outside of control systems[41][208]. For example, it helps physicians to make a decision based on image data [66, 74] or in the field of neuro-fuzzy where fuzzy logic is used within artificial neural networks [124]. Fuzzy logic is, in contrast to the classical boolean two valued logic. This means that for statements now admissible truth values instead of the two-element set $\{0,1\}$ is now the unit element $[0,1]$ [138].

As an example, the 'class of all young people' is not a set in the classical mathematical sense, but such an imprecisely defined class plays an essential role in human understanding of the surrounding world. To stay with the example, we call young a linguistic value that is applied to age, and the age we call a linguistic variable. In boolean logic, a person would be considered either young or not young; that is, the statement that person is young is true or false; in fuzzy logic, it is different; here, gradual membership is allowed; that is, the person is young to a certain extent, and that extent need not be 0 or 1, but any value in between. This is much more in line with the human understanding of membership[227].

These membership functions are called membership functions, formerly called compatibility functions[227]; these membership functions define fuzzy sets; unlike ordinary sets where an element is either part of the set or not, fuzzy sets have a membership range defined by the membership function. For example, an age function with all numbers from 0 to 100 as input (0-100 defines all possible ages) must have an output value for all of them, indicating to which degree of membership it corresponds. As a result, the fuzzy set of all young people is defined on the set of all people.

So if we start with the example of the age as a finite discrete set of single objects $X = \{x_1, \ldots, x_n\}$, a fuzzy set can be specified by directly specifying the membership $\mu(x)$ for each element $x \in X$, see 8.1[138]. To keep the visualization simple, this is continuous, but it all applies to continuous as well as discrete fuzzy sets. Here, the slopes where elements have nonzero membership and no full membership are called boundaries, and the midpoints where the elements have full membership are called core[128].

$$\mu \hat{=} \{(x_1, \mu(x_1)), \ldots, (x_n, \mu(x_n))\} \tag{8.1}$$

Thereby membership functions can take any shape. The example 8.4 triangle, trapezoid and ramp. These examples also have the property that they are *normal*, meaning they have at least one element in x full membership. Functions that do not have this property are called *subnormal*.

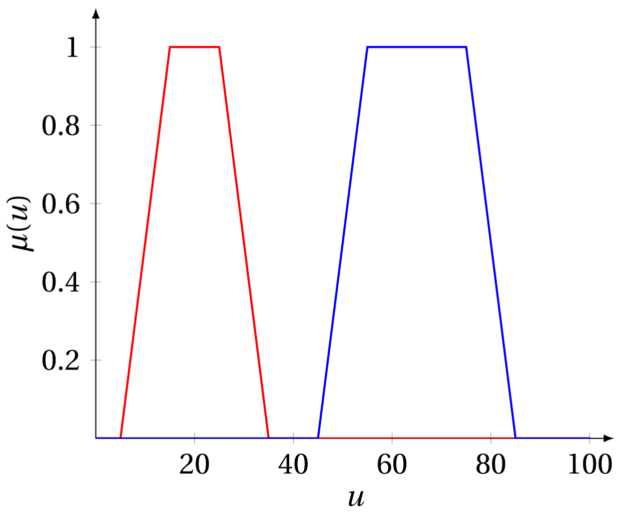


Figure 8.1: Membership function for young as red graph and old as blue graph

In contrast, in classical set theory, one can apply operators to fuzzy sets. For example, consider the definition set up by L. Zadeh[226], who introduced the fuzzy sets and their operators.

Definition Union: The membership function $\mu_{A\cup B}$ of the union $A \cup B$ is pointwise defined for all $u \in U$ by

$$\mu_{A\cup B}(u) = \max\{\mu_A(u), \mu_B(u)\} \tag{8.2}$$

Definition Intersection: The membership function $\mu_{A\cap B}$ of the intersection $A \cap B$ is pointwise defined for all $u \in U$ by

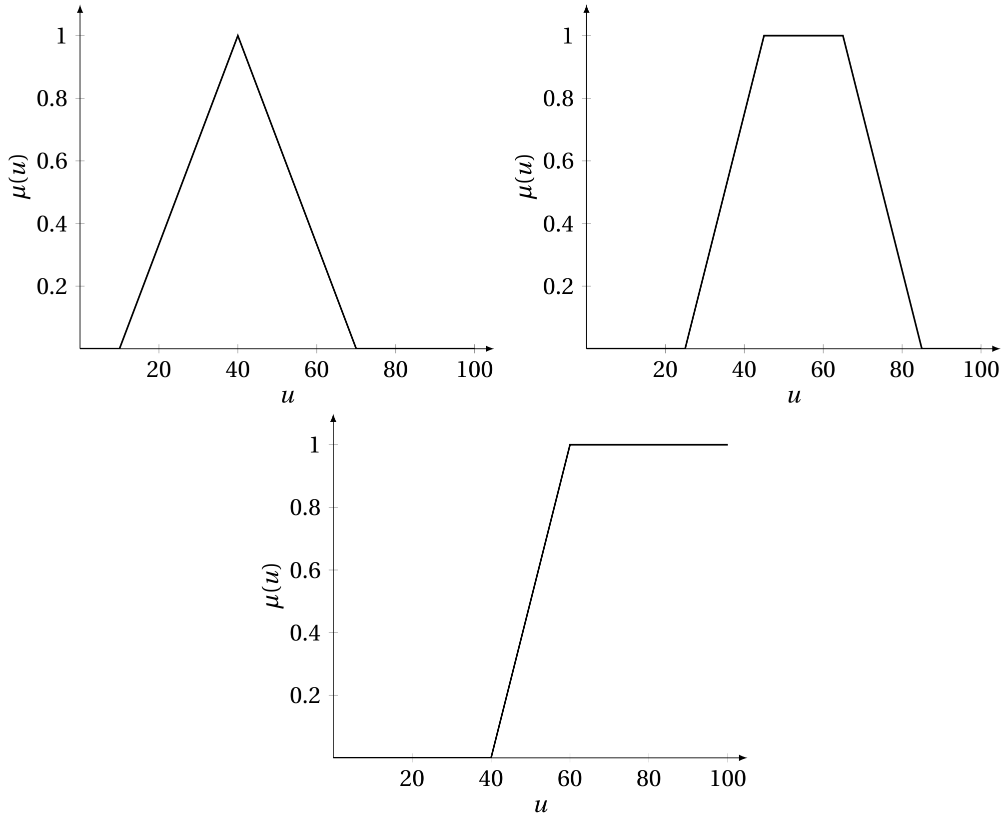


Figure 8.2: Examples of membership functions in shape of a triangle, trapaezoid and ramp

$$\mu_{A \cap B}(u) = \min\{\mu_A(u), \mu_B(u)\} \tag{8.3}$$

Definition Complement: The membership function $\mu_{\bar{A}}$ of the complement of a fuzzy set A is pointwise defined for all $u \in U$ by

$$\mu_{\bar{A}}(u) = 1 - \mu_A(u) \tag{8.4}$$

However, these definitions are not the same everywhere. For each operator one can define a different truth function than the ones given above for maximum 8.2, minumum 8.3 and negation 8.4. As an illustration serves me the operation of implication, which can be defined as a truth-value function the *Łukasiewicz-implication*8.5 and the *Gödel-implication*8.6 among others[138]. By this freedom of the definition of the truth value functions to the respective operator, it is usually before use of the operators to bring any definition with before, as to see in Bellmann et al.[44].

$$\omega_{\rightarrow}(\alpha,\beta) = \min\{1-\alpha+\beta, 1\} \tag{8.5}$$

$$\omega_{\rightarrow}(\alpha,\beta) = \begin{cases} 1, & \text{if } \alpha \leq \beta \\ \beta, & \text{otherwise} \end{cases} \tag{8.6}$$

Next, we come to the introduction of the conditional statements by L. Zadeh[228]. As a basic idea, he took the description of two interdependent variables in quantity system analysis, such as *if x is 7 then y is 12.* Here, he replaced the variables with linguistic variables and the numerical values with the values of the fuzzy variables. Thus, the fuzzy conditional statements of 8.7 arise.

IF x is *large* THEN y is *very small* (8.7)

IF x is *not large* and *not small* THEN y is *not very small* (8.8)

Mamdani controller

With the presented fuzzy logic operators and conditional statements, it was possible to build a fuzzy control system. One of the first and, until today, the most well-known fuzzy controllers is from Mamdani et al.[156]. This was designed for the application in a steam engine. For the demonstration of the Mamdani controller, the derivation from the book by Kruse et al. [138]. Here, the conditional statements are considered as rules R of a rule set $R \in \mathcal{R}$. These rules are named if-then-rules.

$$\begin{aligned} R: \quad & \text{If } x_1 \text{ is } \mu_R^1 \text{ and} \dots \text{and } x_n \text{ is } \mu_R^n \\ & \text{then } y \text{ is } \mu_R \end{aligned} \tag{8.9}$$

Here, $x_1,\dots,x_n$ represent input variables and y the output variable. Where μ_R represent the linguistic values such as *not large*, *very small* and *negatively big*.

The rule set $\mathcal{R}$ consisting of the rules $R_1, \dots, R_n$ will be understood as a piecewise definition of a fuzzy function.

$$f(x_1, \dots, x_n) \approx \begin{cases} \mu_{R_1} & \text{falls } x_1 \approx \mu_{R_1}^1 \text{and} \dots \text{and} x_n \approx \mu_{R_1}^n \\ \vdots & \\ \mu_{R_r} & \text{falls } x_1 \approx \mu_{R_r}^1 \text{and} \dots \text{and} x_n \approx \mu_{R_r}^n \end{cases} \tag{8.10}$$

The graph corresponds to the formula:

$$grapth(f) = \bigcup_{i=1}^{r} (\hat{\pi}_1(\{x_i^{(1)}\}) \cup \dots \cup \hat{\pi}_n(\{x_i^{(n)}\}) \cup \hat{\pi}_y(\{y_i\})) \tag{8.11}$$

A summary of the functionality of the Mamdani controller is shown in the visualization 8.3.

Fuzzification

The next step is fuzzification. The previously defined mathematical functions are used for the respective operators. In this case, we use the average, the minimum, and the maximum(supremum) for the union, as in the formulas 8.3 and 8.2. Thus, we obtain the fuzzy set as a fuzzy graph of the function described by the finite set of rules $R \in \mathcal{R}$.

$$\begin{aligned} \mu_{\mathcal{R}} : X_1 \times \dots \times X_n \times Y \to [0,1], \\ (x_1, \dots, x_n, y) \to \sup_{R \in \mathcal{R}} \{\min\{\mu_{R_i^1}(x_1), \dots, \mu_R^n(x_n) \mu_R(y)\} \end{aligned} \tag{8.12}$$

The insertion of an input vector for the input variables results in a fuzzy set as the output value.

$$\mu_{\mathcal{R}, a_1, \dots, a_n}^{output} : Y \to [0,1], \qquad y \mapsto \mu_{\mathcal{R}(1_1, \dots, a_n, y)} \tag{8.13}$$

Defuzzification

In the last step, the output value must be converted into a crisp value. This process is called defuzzification. In contrast to fuzzification, a crisp value is transformed into a fuzzy value. For the defuzzification, first, all fuzzy quantities of the output variable are merged so that only one fuzzy quantity is left, as seen in equation 8.14.

$$\underset{\sim}{C}_k = \bigcup_{i=1}^{k} \underset{\sim}{C}_i = \underset{\sim}{C} \tag{8.14}$$

For the defuzzification are again different stratgies or functions which make this possible. They have different properties and result in different output values. The selection should always consider the system in which the controller works. An example for a defuzzification function is the *height method* or also max membership principle called[128], to see in figure 8.5. Here only the fuzzy quantity with the highest membership portion is relevant. It is given by the following algebraic expression.

$$\mu_{\underset{\sim}{C}}(u^*) \geq \mu_{\underset{\sim}{C}}(u) \qquad \text{for all} \quad u \in U. \tag{8.15}$$

Another example is the *centroid method*, also known as center of area (COA) or center of gravity (COG). Here we try to find point u^* where a vertical line would separate the aggregated fuzzy sets into two equal masses. The method is usually limited to symmetric membership functions, and the centroids of the respective function are used as the maximum membership. Cases where the function is applied to unsymmetrical functions and various scalar outputs can be seen in Sugeno et al. [204][128]. Figure 8.6 shows a visualization of the method. it is given by the discrete algebraic expression.

$$u^* = \frac{\sum_{i=1}^{n} \mu_{\underset{\sim}{C}}(u_i) * u_i}{\sum_{i=1}^{n} \mu_{\underset{\sim}{C}}(u_i)}. \tag{8.16}$$

Another example is the *weighted average method*, shown in figure 8.7. This is a widespread and simple, and efficient method to implement. Here, each membership function is weighted according to the value of the highest membership of that function. It is given by the discrete algebraic expression.

$$u^* = \frac{\sum_{i=1}^{n} \mu_{\underset{\sim}{C}}(u_i) * (u_i)}{\sum_{i=1}^{n} \mu_{\underset{\sim}{C}}(u_i)}. \tag{8.17}$$

Additionally, the *centroid* and *weighted average method* can never reach the outer ranges of the output range, which comes from the nature of their calculation.

At the same time, the *membership method* allows this if the point of maximum membership is precisely at the edge of the output range.

The figure 8.8 shows the activation of a Mamdani rule set in the matlab fuzzy logic designer[128][**?**]. On the right are the outputs of each rule as a fuzzy set and below the accumulated output value as a fuzzy quantity. The red bar shows the COG based on the crisp value of y calculated as 0.341.

After the insight into fuzzy logic, fuzzy quantities, and the Mamdani fuzzy controller, we can now look at how we can use this knowledge in the eHMI system. Here we have the input parameters of ROC, HD and HA and on the other side we need the output value NOC. The value that should express with which urgency our communication has to take place.

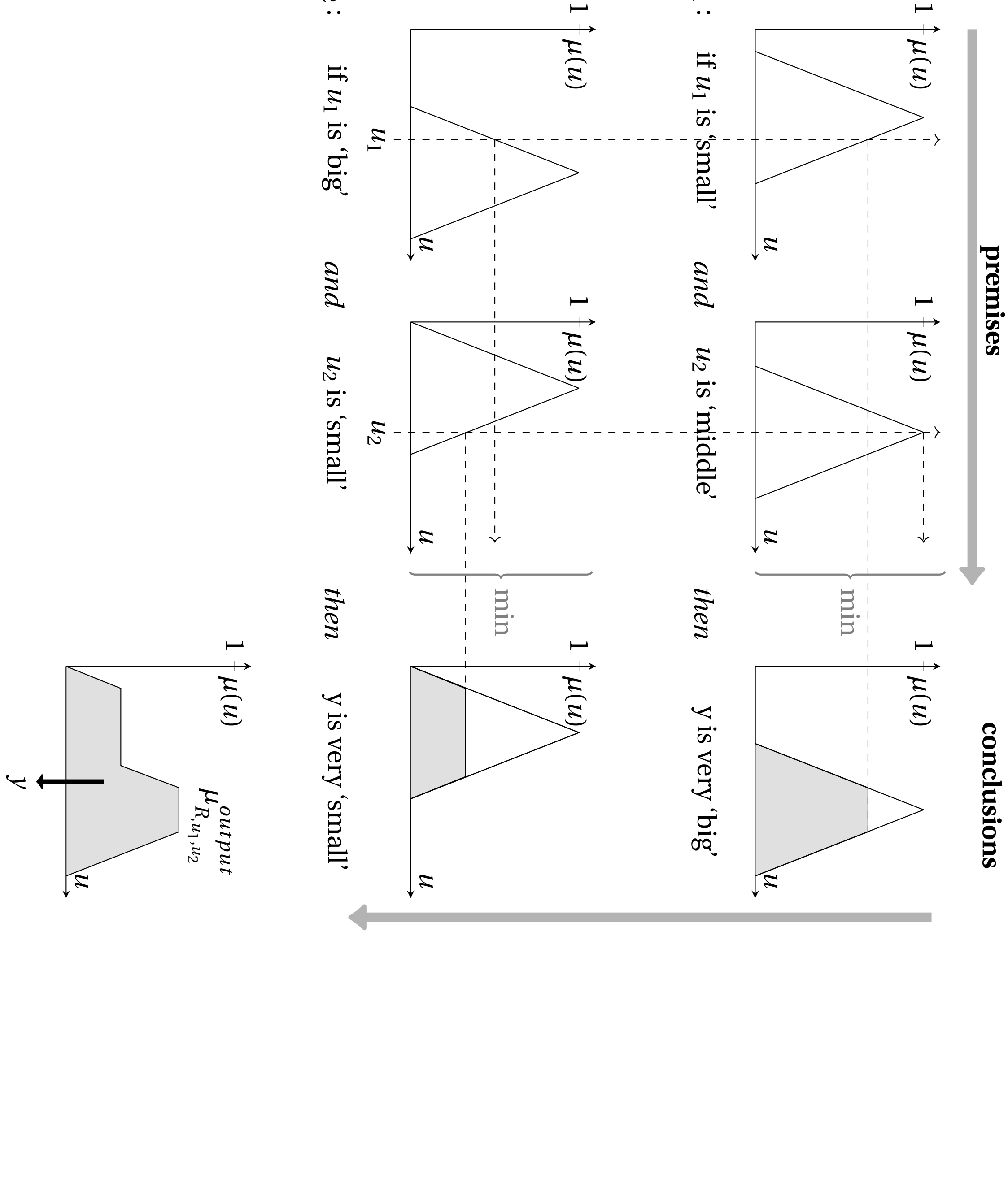


Figure 8.3: Visualisation of the operating principle of mamdani controler. Based on Kruse et al.[138]

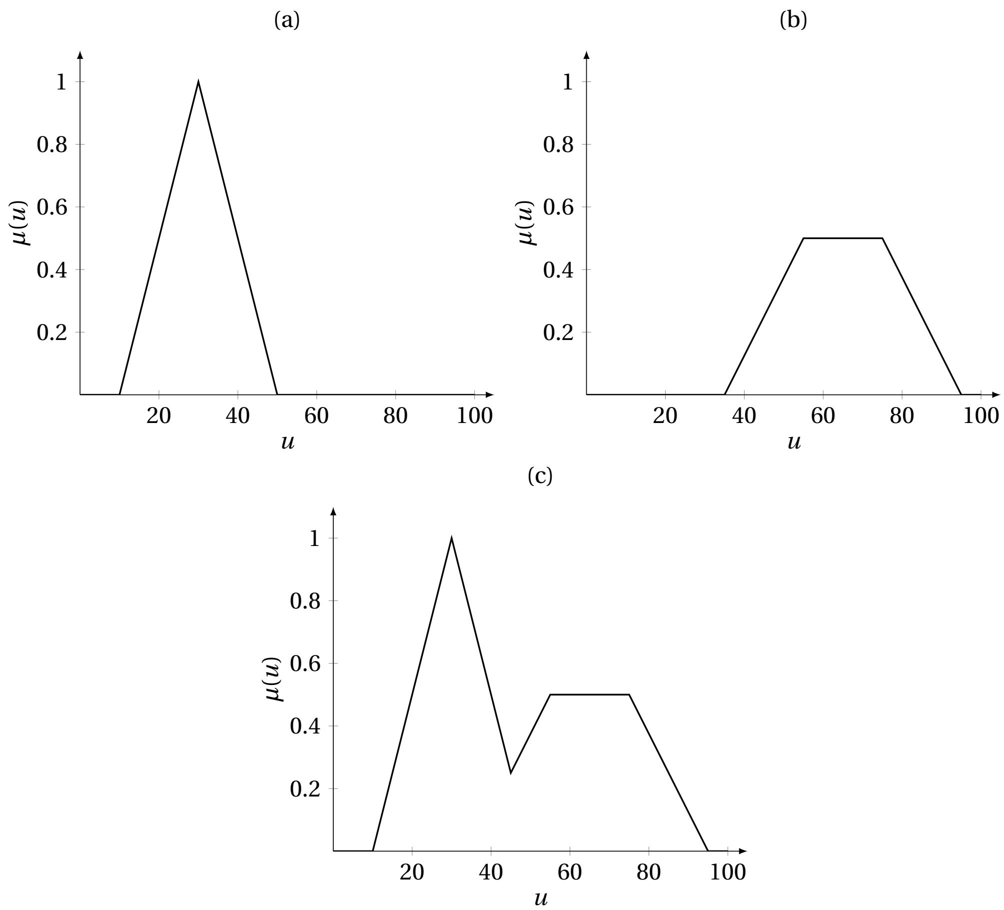


Figure 8.4: Accumulated fuzzy output:(a) first part of fuzzy output; (b) second part of fuzzy output; and (c) union of both parts

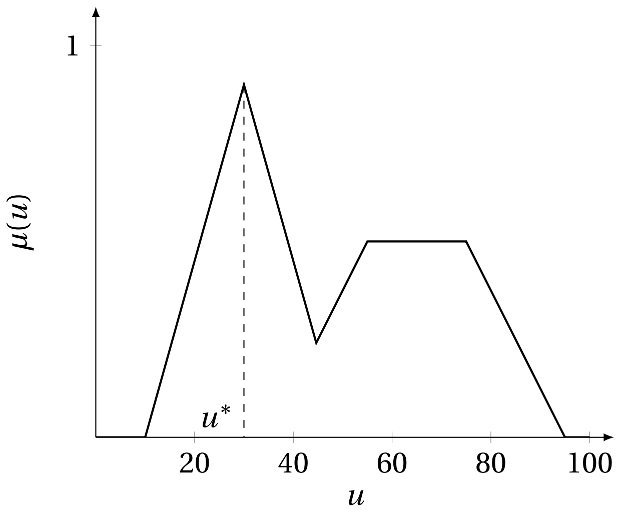


Figure 8.5: Visualisation of height method of defuzzification

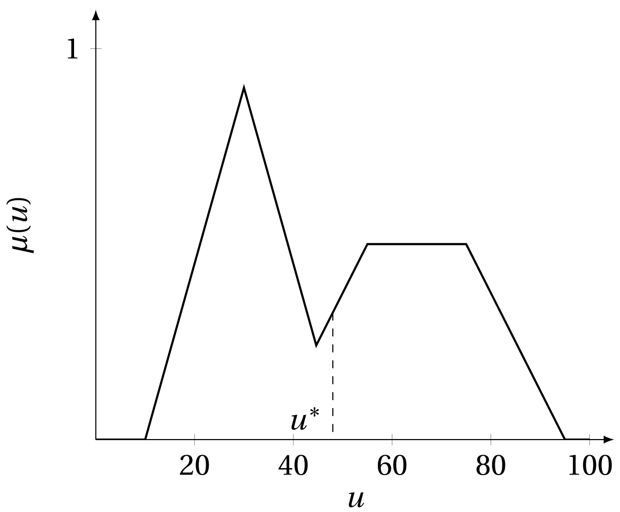


Figure 8.6: Visualisation of centroid method of defuzzification

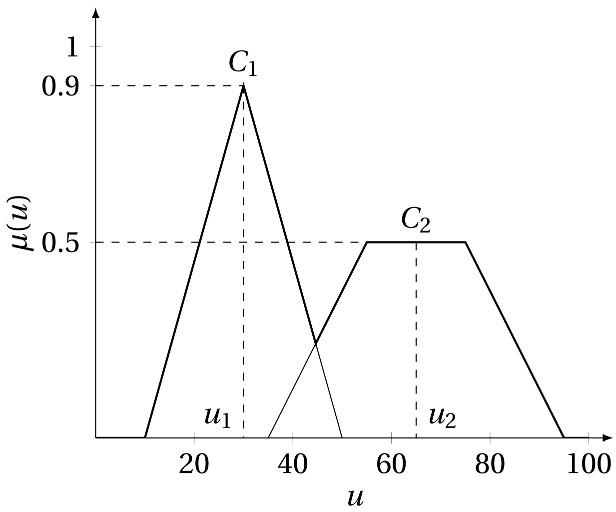


Figure 8.7: Visualisation of weighted average method of defuzzification

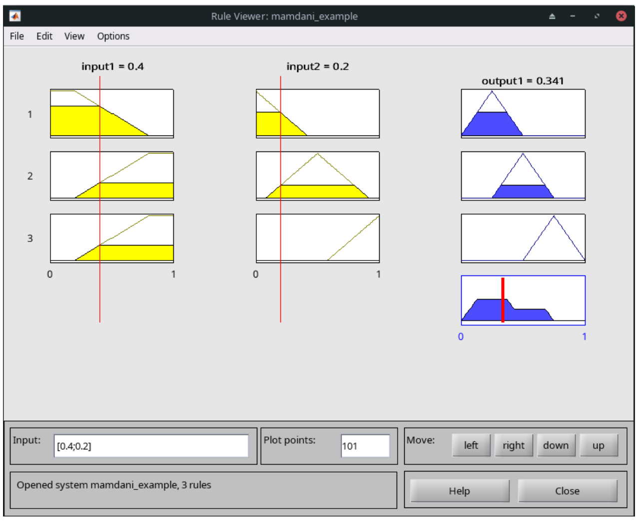


Figure 8.8: Matlab's Fuzzy Logic Designer showing a mamdani rule set activation with example input

8.2 Early Study eHMI Concepts

Table 8.1: Images of rotating beacon

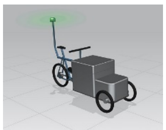
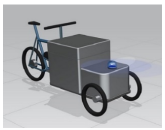
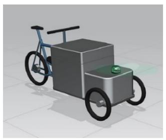
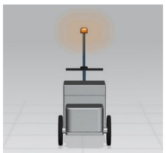
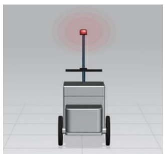
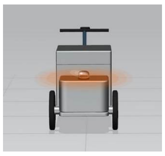
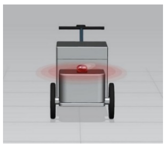
Scenario	Placement	Rotating Beacon	
		1	2
Scenarios 1 status	Tower		
	Front box		
Scenarios 2 attention	Tower		
	Front box		
Scenarios 3 direction	Tower	-	-
	Front box	-	-
Scenarios 4 stop	Tower		-
	Front box		-
Scenarios 5 start	Tower		
	Front box	-	-

Table 8.2: Images of display

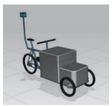
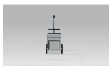
Scenario	Placement	Display				
		1	2	3	4	5
Scenarios 1 status	Tower				-	-
	Front box				-	-
Scenarios 2 attention	Tower				-	-
	Front box				-	-
Scenarios 3 direction	Tower		-			-
	Front box					
Scenarios 4 stop	Tower				-	-
	Front box				-	-
Scenarios 5 start	Tower				-	-
	Front box				-	-

Table 8.3: Appendix color of led

		LED	
		1	2
Scenarios 1 status	Tower	blue	green
	Front box	blue	green
Scenarios 2 attention	Tower	yellow	red
	Front box	yellow	red
Scenarios 3 direction	Tower	-	yellow
	Front box	yellow	yellow
Scenarios 4 stop	Tower	red	-
	Front box	red	-
Scenarios 5 start	Tower	blue	green
	Front box	blue	green

Table 8.4: Visualisation of the scenarios

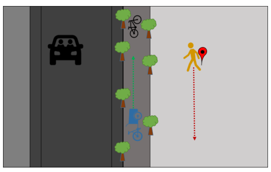
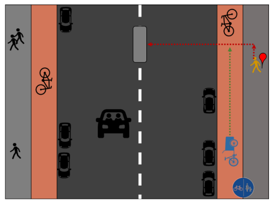
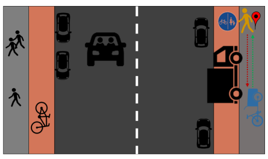
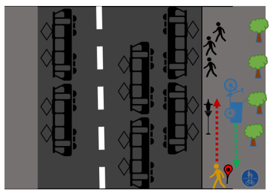
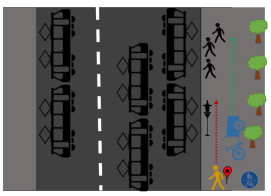
Scenario	Visualisation	Scenario	Visualisation
1. Scenario Status		2. Scenario Attention	
3. Scenario Direction		4. Scenario Stop	
5. Scenario Start			

Table 8.5: Color of rotating beacon

Scenario	Placement	Rotating Beacon	
		1	2
Scenarios 1 status	Tower	blue	green
	Front box	blue	green
Scenarios 2 attention	Tower	yellow	red
	Front box	yellow	red
Scenarios 3 direction	Tower	-	-
	Front box	-	-
Scenarios 4 stop	Tower	red	-
	Front box	red	-
Scenarios 5 start	Tower	blue	green
	Front box	-	-

Table 8.6: Appendix content of display

Scenario	Placement	Symbols				
		1	2	3	4	5
Scenarios 1 status	Tower	blue	blue	A blue	-	-
	Front box	blue	blue	AUTONOM blue	-	-
Scenarios 2 attention	Tower	yellow	!!! yellow	yellow	-	-
	Front box	yellow	!!! ACHTUNG yellow	yellow	-	-
Scenarios 3 direction	Tower	left / right led column yellow	-	yellow	yellow	-
	Front box	yellow	yellow, green	yellow	yellow	yellow
Scenarios 4 stop	Tower	red	red	STOP red	-	-
	Front box	red	1 km/h red	STOP red	-	-
Scenarios 5 start	Tower	blue	green	1 km/h green	-	-
	Front box	blue	green	1 km/h green	-	-

8.3 Codes Snippets

Listing 8.1: Structure of Sound Service. Comments has been removed for better readability.

```
Sound.srv
{
  bool horn
  string file
  uint8 volume
  ---
  # Response

  bool not_found
  bool not_supported
}
```

Listing 8.2: Structure of LED Stripe Service. Comments has been removed for better readability.

```
LEDStripe.srv
{
  # Request
  LEDBlock left
  LEDBlock right

  ---
  # Response

  # empty
}
```

Listing 8.3: Structure of LED Block Message. Comments has been removed for better readability.

```
LEDBlock.msg
{
  ColorHSV color
  bool fade_color
  uint8 blinking_frequency
  bool fade_blinking
}
```

Listing 8.4: Structure of LED Focus Service. Comments has been removed for better readability.

```
LEDFocus.srv
{
  # Request
  ColorHSV        focus_hsv
  ColorHSV        background_hsv
  float64         focus_degree
  uint8           fade_channel
  uint8           blink_frequency
  uint16          focus_point_width
  uint16          slope_to_focus_point_width
  ---
  # Response

  # empty
}
```

Listing 8.5: Structure of policy. Comments has been removed for better readability.

```
struct Policy
{
  bool m_remote_toggle = true;
  bool m_ignore_world = false;
  float m_threshold_distance_danger = 3;
  float m_threshold_distance_attention = 20;
  int m_threshold_amount_humans_close = 10;
  int m_threshold_time_attention = 5000;
  int m_threshold_time_danger = 2000;
  int m_threshold_time_human_forgot_bike = 5000;
  ...
}
```

Listing 8.6: Structure of signal configuration. Comments has been removed for better readability.

```
struct SignalConfig
{
  float MaxColorIntensity = 1.0;
  float MinColorIntensity = 0.5;
  int MaxBlinkFrequency = 10;
  int MinBlinkFrequency = 1;
  int MaxAcousticVolume = 10;
  int MinAcousticVolume = 0;
  std::string AcousticFileBell;
  std::string AcousticFileHorn;
  ...
}
```

Listing 8.7: Example and structure of Interaction Parameter. Comments has been removed for better readability.

```
struct InteractionParameter
{
  EnableDynamic           : true
  BaseColorSaturation     : 1.0
  BaseColorValue          : 0.5
  EnableFocus             : true
  FocusFadeChannel        : 3
  FocusWidth              : 6
  FocusSlopeWidth         : 3
  FocusBlinkTarget        : 1
  EnableAcoustic          : true
  AcousticVolume          : 80
  SoundPlaybackDuration   : 2000
  ...
}
```

8.4 Statistical Results of the Study

Table 8.7: List of questions the subjects received after each scenario

Code	Statements	Answer posib.
SI01	Ich würde mich in der Nähe des autonomen Transportrades sicher fühlen.	1-5 Likert scale
SI02	Das autonome Transportrad ist verlässlich.	1-5 Likert scale
SI03	Ich habe das Signal des autonomen Transportrades in der Situation als hilfreich empfunden.	1-5 Likert scale
SI04	Das autonome Transportrad bietet Sicherheit.	1-5 Likert scale
SI05	Das autonome Transportrad hat sich so verhalten, wie ich es erwartet habe.	1-5 Likert scale
SI06	Ich kann dem autonomen Transportrad vertrauen.	1-5 Likert scale
SI07	Die Nutzung des autonomen Transportrad wird Schaden mit sich bringen.	1-5 Likert scale
EM01	Emotionaler Zustand zwischen ängstlich und entspannt.	1-5 Likert scale
EM02	Emotionaler Zustand zwischen aufgewühlt und ruhig.	1-5 Likert scale
EM03	Emotionaler Zustand zwischen still und überrascht.	1-5 Likert scale

	n0	mean0	n1	mean1	u-value	z-value	p-value	r-value
SI07_01	28	4.8571429	119	3.6134454	2956.0	-6.7418951	0.0000000	0.5560621
SI07_03	28	4.6071429	119	4.1008403	2133.5	-2.5026903	0.0123253	0.2064184
SI07_05	28	4.3928571	119	3.7983193	2303.5	-3.3153736	0.0009152	0.2734474
SI07_06	28	4.5000000	119	3.6386555	2506.0	-4.3657206	0.0000127	0.3600786
EM07_01	28	4.5714286	119	4.0000000	2197.0	-2.7942951	0.0052013	0.2304696
EM07_02	28	4.3928571	119	4.1092437	1951.0	-1.5066103	0.1319106	0.1242631
EM07_03	28	2.6428571	119	2.7647059	1588.0	-0.4012987	0.6882002	0.0330986

Table 8.8: Results of the comparison between the online study using the Elbedome color scheme and the Elbedome study in the scenario *Start up*

	n0	mean0	n1	mean1	u-value	z-value	p-value	r-value
SI01	119	3.6722689	119	3.6134454	7375.0	-0.5940871	0.5524539	0.03850895
SI02	119	3.6554622	119	3.6554622	7012.5	-0.1379481	0.8902815	0.00894185
SI03	119	3.9915966	119	4.1008403	6731.0	-0.7023639	0.4824522	0.04552749
SI04	119	3.5714286	119	3.6218487	7001.5	-0.1586583	0.8739381	0.01028429
SI05	119	3.7983193	119	3.7983193	7046.0	-0.0698655	0.9443007	0.00452871
SI06	119	3.6890756	119	3.6386555	7273.5	-0.3865307	0.6991037	0.02505506
SI07	119	2.3949580	119	2.4285714	6986.5	-0.1871392	0.8515515	0.01213043
EM01	119	4.0336134	119	4.0000000	7285.5	-0.4081407	0.6831704	0.02645583
EM02	119	4.0420168	119	4.1092437	6868.5	-0.4240945	0.6714969	0.02748996
EM03	119	2.7226891	119	2.7647059	6910.0	-0.3318570	0.7399973	0.02151109

Table 8.9: Results of the comparison between the new interaction scheme(group 0) and Elbedome interaction scheme(group 1) in the scenario *Start up*

	n0	mean0	n1	mean1	u-value	z-value	p-value	r-value
SI05_01	28	3.7500000	119	3.5378151	1871.0	-1.0758323	0.2820023	0.08873315
SI05_03	28	4.0714286	119	4.0840336	1667.0	-0.0052708	0.9957945	0.00043473
SI05_05	28	3.4642857	119	3.8739496	1396.0	-1.4396666	0.1499617	0.11874170
SI05_06	28	4.0357143	119	3.5798319	2085.5	-2.1724928	0.0298185	0.17918419
EM05_01	28	3.6428571	119	3.5882353	1689.0	-0.1173909	0.9065503	0.00968224
EM05_02	28	3.6785714	119	3.6218487	1712.5	-0.2379311	0.8119345	0.01962423
EM05_03	28	3.5714286	119	3.0504202	2095.5	-2.1876704	0.0286936	0.18043602

Table 8.10: Results of the comparison between the online study using the Elbedome color scheme and the Elbedome study in the scenario *Stop as confrontation*

	n0	mean0	n1	mean1	u-value	z-value	p-value	r-value
SI01	119	3.6218487	119	3.5378151	7476.5	-0.7907544	0.4290873	0.05125699
SI02	119	3.7647059	119	3.7394958	7155.0	-0.1493639	0.8812665	0.00968182
SI03	119	4.0168067	119	4.0840336	6713.5	-0.7372841	0.4609496	0.04779103
SI04	119	3.6722689	119	3.6218487	7225.5	-0.2903704	0.7715329	0.01882192
SI05	119	3.9243697	119	3.8739496	7445.5	-0.7323784	0.4639376	0.04747304
SI06	119	3.6554622	119	3.5798319	7437.5	-0.7131218	0.4757704	0.04622482
SI07	119	2.4621849	119	2.4453782	7207.5	-0.2518555	0.8011528	0.01632537
EM01	119	3.7226891	119	3.5882353	7555.5	-0.9258268	0.3545360	0.06001244
EM02	119	3.6722689	119	3.6218487	7296.0	-0.4207034	0.6739717	0.02727015
EM03	119	3.0672269	119	3.0504202	7156.5	-0.1474371	0.8827870	0.00955693

Table 8.11: Results of the comparison between the new interaction scheme(group 0) and Elbedome interaction scheme(group 1) in the scenario *Stop as confrontation*

	n0	mean0	n1	mean1	u-value	z-value	p-value	r-value
SI09_01	28	4.3846154	119	3.4705882	2353.0	-4.3587479	0.0000131	0.3595035
SI09_03	28	4.7200000	119	2.9579832	2725.5	-6.7546711	0.0000000	0.5571159
SI09_05	28	4.2400000	119	3.6890756	2057.0	-3.2313373	0.0012321	0.2665162
SI09_06	28	4.2692308	119	3.3949580	2314.0	-4.1687361	0.0000306	0.3438316
EM09_01	28	3.9642857	119	3.8319328	1776.0	-0.5681318	0.5699455	0.0468587
EM09_02	28	3.9642857	119	3.9579832	1640.5	-0.1321866	0.8948367	0.0109026
EM09_03	28	3.1071429	119	2.5714286	2122.5	-2.3170717	0.0204998	0.1911089

Table 8.12: Results of the comparison between the online study using the Elbedome color scheme and the Elbedome study in the scenario *Drive by*

	n0	mean0	n1	mean1	u-value	z-value	p-value	r-value
SI01	119	3.4285714	119	3.4705882	6949.0	-0.2623778	0.7930302	0.01700742
SI02	119	3.5546218	119	3.5210084	7187.5	-0.2163937	0.8286809	0.01402672
SI03	119	2.9663866	119	2.9579832	7205.5	-0.2454225	0.8061293	0.01590838
SI04	119	3.4369748	119	3.3445378	7366.0	-0.5696136	0.5689398	0.03692257
SI05	119	3.7478992	119	3.6890756	7363.0	-0.5712534	0.5678279	0.03702886
SI06	119	3.4957983	119	3.3949580	7534.5	-0.9055375	0.3651807	0.05869728
SI07	119	2.5546218	119	2.5630252	7028.0	-0.1045699	0.9167171	0.00677826
EM01	119	3.9159664	119	3.8319328	7427.5	-0.6850024	0.4933424	0.04440211
EM02	119	3.9495798	119	3.9579832	7051.0	-0.0583980	0.9534316	0.00378538
EM03	119	2.6554622	119	2.5714286	7343.0	-0.5120263	0.6086326	0.03318974

Table 8.13: Results of the comparison between the new interaction scheme(group 0) and Elbedome interaction scheme(group 1) in the scenario *Drive by*

	n0	mean0	n1	mean1	u-value	z-value	p-value	r-value
SI11_01	28	4.8571429	119	3.5210084	2964.0	-6.7305997	0.00000000	0.5551305
SI11_06	28	4.7142857	119	3.4957983	2848.0	-6.1047205	0.00000000	0.5035089
EM11_01	28	4.8571429	119	3.7310924	2652.0	-5.1302881	0.00000029	0.4231390
EM11_02	28	4.6071429	119	3.7731092	2411.5	-3.8602968	0.00011325	0.3183919
EM11_03	28	2.4285714	119	2.9243697	1291.0	-1.9032873	0.05700307	0.1569805

Table 8.14: Results of the comparison between the online study using the Elbedome color scheme and the Elbedome study in the scenario *Crossing*

	n0	mean0	n1	mean1	u-value	z-value	p-value	r-value
SI01	119	3.6050420	119	3.5210084	7371.0	-0.5793438	0.5623572	0.03755328
SI02	119	3.6386555	119	3.5462185	7423.0	-0.6874914	0.4917731	0.04456345
SI03	119	4.0000000	119	3.8739496	7471.0	-0.7777783	0.4366997	0.05041588
SI04	119	3.4537815	119	3.5630252	6492.5	-1.1653951	0.2438591	0.07554134
SI05	119	3.8571429	119	3.7563025	7726.5	-1.3106316	0.1899822	0.08495563
SI06	119	3.5546218	119	3.4957983	7264.5	-0.3645824	0.7154231	0.02363237
SI07	119	2.5462185	119	2.5462185	7089.5	-0.0177418	0.9858448	0.00115003
EM01	119	3.8151261	119	3.7310924	7221.0	-0.2753317	0.7830614	0.01784711
EM02	119	3.7563025	119	3.7731092	6909.5	-0.3357420	0.7370654	0.02176292
EM03	119	2.9495798	119	2.9243697	7151.0	-0.1371511	0.8909114	0.00889018

Table 8.15: Results of the comparison between the new interaction scheme(group 0) and Elbedome interaction scheme(group 1) in the scenario *Crossing*

	n0	mean0	n1	mean1	u-value	z-value	p-value	r-value
SI01	119	3.7563025	119	3.7647059	6996.5	-0.1664969	0.8677659	0.01079239
SI02	119	3.5882353	119	3.5798319	6978.5	-0.2028345	0.8392644	0.01314781
SI03	119	3.0252101	119	3.0168067	7122.0	-0.0819120	0.9347167	0.00530957
SI04	119	3.5966387	119	3.5714286	7060.0	-0.0406943	0.9675396	0.00263782
SI05	119	3.5378151	119	3.7058824	6345.0	-1.4516021	0.1466123	0.09409339
SI06	119	3.7142857	119	3.5630252	7635.5	-1.1120824	0.2661027	0.07208560
SI07	119	2.4789916	119	2.4369748	7250.0	-0.3324687	0.7395354	0.02155074
EM01	119	4.1932773	119	4.2521008	6724.0	-0.7347298	0.4625041	0.04762546
EM02	119	4.2352941	119	4.2773109	6779.5	-0.6222435	0.5337818	0.04033406
EM03	119	2.3445378	119	2.2100840	7688.0	-1.1878183	0.2349050	0.07699482

Table 8.16: Results of the comparison between scenarios containing blinking response type with the focus response type

	n0	mean0	n1	mean1	u-value	z-value	p-value	r-value
SI01	119	3.6722689	119	3.7647059	6741.5	-0.6743080	0.5001155	0.04370890
SI02	119	3.5714286	119	3.5798319	6936.5	-0.2859164	0.7749422	0.01853321
SI03	119	3.0672269	119	3.0168067	7267.5	-0.3673347	0.7133694	0.02381077
SI04	119	3.5210084	119	3.5714286	6786.0	-0.5841385	0.5591272	0.03786407
SI05	119	3.4705882	119	3.7058824	6079.5	-1.9682781	0.0490360	0.12758452
SI06	119	3.5546218	119	3.5630252	6991.0	-0.1782193	0.8585508	0.01155224
SI07	119	2.4285714	119	2.4369748	7081.0	-0.0009816	0.9992168	0.00006363
EM01	119	4.0924370	119	4.2521008	6263.0	-1.6628234	0.0963478	0.10778483
EM02	119	4.1512605	119	4.2773109	6309.5	-1.5723130	0.1158780	0.10191791
EM03	119	2.5630252	119	2.2100840	8365.0	-2.4988340	0.0124603	0.16197535

Table 8.17: Results of the comparison between scenarios containing blinking response type with none response type

	n0	mean0	n1	mean1	u-value	z-value	p-value	r-value
SI01	119	3.6722689	119	3.7563025	6814.0	-0.5274804	0.5978600	0.03419148
SI02	119	3.5714286	119	3.5882353	7033.5	-0.0937652	0.9252957	0.00607790
SI03	119	3.0672269	119	3.0252101	7227.0	-0.2863165	0.7746357	0.01855914
SI04	119	3.5210084	119	3.5966387	6794.5	-0.5659257	0.5714443	0.03668352
SI05	119	3.4705882	119	3.5378151	6784.0	-0.5839905	0.5592267	0.03785448
SI06	119	3.5546218	119	3.7142857	6453.5	-1.2428771	0.2139131	0.08056376
SI07	119	2.4285714	119	2.4789916	6907.0	-0.3403030	0.7336283	0.02205857
EM01	119	4.0924370	119	4.1932773	6622.0	-0.9255036	0.3547040	0.05999149
EM02	119	4.1512605	119	4.2352941	6615.5	-0.9424202	0.3459776	0.06108803
EM03	119	2.5630252	119	2.3445378	7822.5	-1.4418870	0.1493342	0.09346366

Table 8.18: Results of the comparison between scenarios containing blinking response type with the focus response type

8.5 Miscellaneous

Attribute	Value facets
Right of way	AV
	HRU
	Undefined
AV's intention regating right of way	Let HRU go first
	Go First
HRU's intention regating right of way	Let AV go first
	Go First
HRU Character	Vehicle drivers
	Cyclist
	Pedestrians
Longitudinal distance (Headway)	<3m
	3-10m
	>10m
Lateral distance	0m
	≤ 3m
	>3m
Attention HRU	Yes
	No
Impairment of the HRU's perception	View
	Acoustic
	Both(view and acoustic)
	No impairment
Speed AV	0 km/h
	30 km/h
	50 km/h
	130 km/h
Speed HRU	0 km/h
	4.4km/h
	17.5 km/h
	30 km/h
	50 km/h
	130 km/h
Driving direction AV	Driving fowards
	Reverse
Perspective (from the perspective of the AV)	Ahead
	Sideways diagonal
	Backward

Table 8.19: Overview of all attributes and value facets from Fuest et al.[98]

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