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Communication during lane changes on motorway slip roads

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Abstract

One of the key factors for smooth and safe road traffic is successful communication between road users. This applies in particular to so-called ‘space sharing conflicts’, situations in which several road users intend to occupy the same space in the near future (Markkula et al., 2020). Examples of this include junctions without a clear right of way, pedestrians wanting to cross a traffic-ridden road or changing lanes on a motorway slip road to a busy destination lane. Depending on the situation, different means of communication can be used to resolve these situations. In slower inner-city traffic, implicit means like aspects of driving dynamics such as early braking are supplemented by explicit means of communication such as eye contact or gestures. In faster traffic like on motorways slip roads, these implicit means play a major role. As the communication content of driving dynamics is not necessarily intentional and cannot be separated from its actual purpose - the driving manoeuvre - it is classified as an implicit means of communication. The consideration of human communication in road traffic is gaining new relevance due to the increasing automation of vehicles. When automated vehicles share the road with human drivers in mixed traffic, it is essential that they are able to perceive, interpret and imitate human communication behaviour. The focus of the first three studies in this thesis is on communication via driving dynamics. First, in Study 1 the perception of lateral driving dynamics by other road users is investigated using an online video study: participants experienced the behaviour of a vehicle on a motorway slip road from the perspective of rearward traffic. In addition to the evaluation of different lateral driving dynamics, it is investigated whether the perception of these depends on whether the vehicle is labelled as automated with and eHMI (status eHMI). Studies 2 and 3 then investigate the perception of longitudinal driving dynamics and the influence of a status eHMI, initially in a German sample and in Study 3 as a replication study in the UK. The latter is intended to investigate cultural influences on behavioural assessment and the generalisability of the results. Finally, Study 4 looks at an automated system that is designed to overcome the hurdles of communication between automated vehicles and human drivers by preferentially cooperating with other automated vehicles through connectivity. The extent to which a short-term reduction in speed is accepted to enable another vehicle to merge onto the motorway is investigated. In addition, the relevance of internal communication about the reasons for the speed reduction to the occupants of the vehicle is analysed.

The results of the studies show that defensive behaviours such as slow lane changes in the middle of the acceleration lane and deceleration of the interaction partner are preferred. These findings are independent of whether the vehicle is automated or manual. The same behaviour of vehicles with and without status eHMI is either rated the same or automated vehicles are perceived more positively. In most cases, the status eHMI does not lead to deviating behaviour; in one situation, a greater safety distance was maintained from automated vehicles. When two connected automated vehicles agree on a cooperative driving manoeuvre, users accept minor personal restrictions, while medium and greater speed restrictions lead to a reduction in acceptance. Although an HMI that communicates the system status only has a minor influence on direct acceptance, it is still desired by users and has a positive influence on trust in the system. The results have implications both for the development of automated vehicles and for research into cooperation and communication in road traffic. Recommendations for development as well as an outlook for future research are discussed.

Kurzfassung

Einer der Schlüsselfaktoren für einen reibungslosen und sicheren Straßenverkehr ist die erfolgreiche Kommunikation zwischen Verkehrsteilnehmern. Dies gilt insbesondere für sogenannte „space sharing conflicts“, Situationen in denen mehrere Verkehrsteilnehmer in naher Zukunft den selben Raum für sich beanspruchen wollen (Markkula et al., 2020). Beispiele hierfür sind Kreuzungen ohne klare Vorfahrtsregelung, Fußgänger, die eine befahrene Straße queren wollen oder auch der Spurwechsel an der Autobahnauffahrt auf eine befahrene Zielspur. Je nach Situation können unterschiedliche Kommunikationsmittel zum Einsatz kommen, um diese aufzulösen. Während im langsameren innerstädtischen Verkehr explizite Kommunikationsmittel wie Blickkontakt oder Gesten um Aspekte der Fahrdynamik wie frühzeitiges Abbremsen ergänzt werden, spielt die Fahrdynamik im schnelleren Verkehr an Autobahnauffahrten eine Hauptrolle. Da der Kommunikationsgehalt der Fahrdynamik nicht zwingend intentional ist und nicht von ihrem eigentlichen Zweck – dem Fahrmanöver – zu trennen ist, fällt sie unter die impliziten Kommunikationsmittel. Neue Relevanz erhält die Betrachtung menschlicher Kommunikation im Straßenverkehr durch die zunehmende Automatisierung von Fahrzeugen. Sollen diese in einem Mischverkehr mit menschlichen Fahrern die Straße teilen, ist es elementar, dass sie das menschliche Kommunikationsverhalten als solches wahrnehmen, interpretieren und auch imitieren können. In den ersten drei Studien dieser Arbeit wird der Fokus auf die implizite Kommunikation mittels Fahrdynamik gelegt. Zunächst wird anhand einer Online-Videostudie die Wahrnehmung von lateraler Fahrdynamik durch andere Verkehrsteilnehmer untersucht: Probanden erleben das Verhalten eines Fahrzeuges auf der Autobahnauffahrt aus der Perspektive des rückwärtigen Verkehrs. Neben der Bewertung verschiedener lateraler Fahrdynamiken wird untersucht, ob die Wahrnehmung dieser davon abhängt, ob das Fahrzeug mittels eHMI als automatisiert gekennzeichnet ist (status eHMI). In Studien zwei und drei wird dann die Wahrnehmung longitudinaler Fahrdynamik und der Einfluss eines status eHMI untersucht, zunächst in einer deutschen Stichprobe und in Studie drei als Replikationsstudie in Großbritannien. Mit dieser sollen kulturelle Einflüsse auf die Verhaltensbewertung und der Generalisierbarkeitsanspruch der Ergebnisse untersucht werden. In Studie vier wird letztlich ein automatisiertes System betrachtet, das die Hürden der Kommunikation zwischen automatisierten Fahrzeugen und menschlichen Fahrern umgehen soll, indem es mittels Vernetzung bevorzugt mit anderen automatisierten Fahrzeugen kooperiert. Es wird untersucht, in welchem Ausmaß eine kurzfristige Geschwindigkeitsreduktion in Kauf genommen wird, um einem anderen Fahrzeug die Auffahrt auf die Autobahn zu

ermöglichen. Zudem wird die Relevanz der internalen Kommunikation der Gründe für die Geschwindigkeitsreduktion an die Insassen des Fahrzeugs betrachtet.

Die Ergebnisse der Studien zeigen, dass defensive Verhaltensweisen wie langsame Spurwechsel in der Mitte der Beschleunigungsspur sowie ein Bremsen des Interaktionspartners präferiert werden. Diese Erkenntnisse sind unabhängig davon, ob es sich bei dem Fahrzeug um ein automatisiertes oder ein manuelles Fahrzeug handelt. Gleiches Verhalten von Fahrzeugen mit und ohne status eHMI wird entweder gleich bewertet oder automatisierte Fahrzeuge werden positiver wahrgenommen. In den meisten Fällen führt das status eHMI nicht zu abweichendem Verhalten, in einer Situation wurde ein größerer Sicherheitsabstand zu automatisierten Fahrzeugen eingehalten. Verabreden zwei vernetzte automatisierte Fahrzeuge ein kooperatives Fahrmanöver, akzeptieren Nutzer kleine persönliche Einschränkungen, während mittlere und stärkere Geschwindigkeitseinbußen zu einer Reduktion der Akzeptanz führen. Ein HMI, das den Systemstatus kommuniziert, hat zwar nur einen geringen Einfluss auf die direkte Akzeptanz, ist aber dennoch von Nutzern gewünscht und beeinflusst das Vertrauen in das System positiv. Die Ergebnisse haben Implikationen sowohl für die Entwicklung automatisierter Fahrzeuge als auch die Forschung zu Kooperation und Kommunikation im Straßenverkehr. Es werden Empfehlungen für die Entwicklung als auch ein Ausblick auf zukünftige Forschung diskutiert.

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List of Abbreviations

AV	Automated Vehicle
CCAM	Cooperative, Connected and Automated Mobility
dHMI	dynamic Human-Machine Interface
DLC	Discretionary Lane Change
eHMI	external Human-Machine Interface
GDP	Gross Domestic Product
HMI	Human-Machine Interface
MLC	Mandatory Lane Change
MV	Manual Vehicle
NDS	Naturalistic Driving Study
ODD	Operational Design Domain
RQ	Research Question
SA	Situation Awareness
SAE	Society of Automotive Engineers
StVO	Straßenverkehrsordnung (German Road Traffic Act)
TAM	Technology Acceptance Model
THW	Time Headway
V2V	Vehicle-to-Vehicle

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1 Introduction

1.1 Motivation

The introduction of automated driving presents us with numerous challenges. Many of these challenges are of technical nature, which is why many of the solutions presented so far have been purely technical. However, such solutions harbour the risk of neglecting the human factor. In the long term, this would lead to a technically functional system, but ultimately it would not be accepted by its human users, e.g. because the technically optimised driving manoeuvre is unpleasant or disregards the implicit social rules of the road. The lack of acceptance of a system can lead to it either being disused or misused (Zhang et al., 2021).

In addition to the technical capabilities, the introduction of automated driving functions is dependent on legal requirements, such as prescribed safety distances. At the same time, research shows that human behaviour does not always follow these guidelines. For example, safety distances are regularly undercut when entering the motorway (Daamen, Loot, & Hoogendoorn, 2010; Kusuma, Liu, Choudhury, & Montgomery, 2015; van Beinum, Farah, Wegman, & Hoogendoorn, 2018). The gradual introduction of automated driving functions resulting in mixed traffic consisting of automated vehicles (AVs) and manually controlled vehicles (MVs) can consequently lead to conflicts. For this reason, it is essential that not only the technical possibilities and legal framework conditions are considered in the development of AVs, but also understanding human interaction and communication behaviour and incorporating the findings into the development. It can be tempting to avoid the difficulties of the interaction of MVs with AVs by adapting human behaviour directly for AVs. However, this would also involve copying behaviour patterns that are perceived as dangerous or at least undesirable by other road users. After analysing human communication behaviour, it is therefore important to first assess its desirability and only then derive recommendations for the development of human-oriented automated driving functions.

In this thesis, this approach is demonstrated in a motorway slip road scenario. Motorway slip roads are currently of particular interest in the context of automated driving because automating these driving task seems likely. In 2023, Mercedes Benz received the first approval for an SAE Level 3 driving function on German roads with the automated motorway assistant "DRIVE PILOT" (Mercedes-Benz Group, 2021). SAE Level 3 describes "conditional driving automation", in which the system independently takes over longitudinal and lateral control of the vehicle. The driver may temporarily switch to other activities but must be able to take over control at any time on request (SAE, 2021). So far, the "DRIVE PILOT" has a restricted Operational Design Domain (ODD), which is limited to driving on the motorway with a speed limit of 60km/h. The motorway slip road is currently out of the system's ODD but represents a logical next step following the expansion of the speed range.

Research into the communication behaviour of automated vehicles on motorway slip roads is not only relevant because of its topicality, but also represents an exciting use case from a scientific point of view. It is an example of a so-called "space sharing conflict", a situation in which “two or more road users are intending to occupy the same region of space at the same time in the near future” (Markkula et al., 2020, p. 736). These space sharing conflicts already represent a critical situation in human-human interaction (Beitel, Stipancic, Manaugh, & Miranda-Moreno, 2018; Liang, Meng, & Zheng, 2021). This makes them a particular challenge for the development of automated vehicles that are to cooperate successfully with MVs in mixed traffic. Resolving such a conflict requires an understanding of the communicative signals of other road users and successful communication of one's own behavioural intentions. Especially at high speeds, such as those prevailing on motorways, communication often takes place via implicit signals (Moore, Currano, Strack, & Sirkin, 2019; Schaarschmidt et al., 2021), e.g. via driving dynamics. For instance, the intention to pull in behind another vehicle can be signalled by reducing one's own speed.

The aim of this thesis is to investigate communication to resolve a space sharing conflict at motorway slip roads. To this end, the evaluation of driving dynamics for communication purposes is analysed. It is examined which driving dynamics are preferred by other road users and whether expectations of the behaviour of the other vehicle depend on whether it is perceived as AV or MV. Before deriving implications for the development of automated vehicles, the generalisability of the results beyond Germany will also be surveyed. Furthermore, an alternative to the potentially error prone external communication via driving dynamics is presented: Connectivity between automated vehicles can replace the communication between road users but requires adapted internal communication with the vehicle's occupants.

1.2 Thesis Outline

In the following, first the theoretical background of the thesis is explained. This involves discussing automated driving in general and then defining the terms "cooperation" and "communication". In addition, the current state of research on communication behaviour and communication means in road traffic is presented. The research questions for the thesis are derived from this. The four scientific studies included in the thesis (see Table 1) are then briefly summarised; the original articles of the published studies can be found in the appendix. **Study 1** discusses the results of an online study in which the assessment of lateral driving dynamics of vehicles on the slip roads of motorways was investigated. In **Study 2** and **Study 3**, longitudinal driving dynamics as implicit means of communication at motorway slip roads were investigated in two driving simulator studies, with Study 2 presenting the results of the German sample and Study 3 comparing these with the results from the replication study in the UK. **Study 4** deals with the user acceptance of an Automated Motorway Access Assistant system that attempts to circumvent the potential conflicts in the direct interaction of MVs and AVs by connecting automated vehicles. Finally, the key findings of this work are discussed in the general discussion and the implications for research and the development of automated driving functions are considered.

Table 1: Overview over the included studies. Numbers in brackets indicate the number of levels of the independent variables.

Study	Independent Variables	Dependent Variables	Setting
Study 1	Duration of Lane Change (3) Position of Lane Change (3) eHMI (2)	Perceived Criticality Perceived Cooperation	Video-based
Study 2	Perspective (2) Behaviour (3) eHMI (2)	Perceived Criticality Perceived Cooperation Safety Distance (THW)	Simulator
Study 3	Perspective (2) Behaviour (3) eHMI (2) Country (2)	Perceived Criticality Perceived Cooperation Safety Distance (THW)	Simulator abroad
Study 4	Perspective (2) Speed (3) Availability of an HMI (2)	Acceptance Trust Perceived Safety	Simulator

2 Theoretical Background

2.1 Automated Driving

Automated driving describes the transfer of parts of the driving task or the entire driving task to the vehicle. The driver increasingly becomes a passenger and hands over more and more responsibility to the system. The extent of this transfer of responsibility is described using the levels of automation according to the Society of Automotive Engineers (SAE) (SAE, 2021). The SAE distinguishes between five levels of vehicle automation (see Figure 1). The term automated driving is used from level 3 (conditional automated driving), in which the driving task is completely taken over by the vehicle within the boundaries of defined criteria (Operational Design Domain, ODD). However, if the system reaches the limits of the ODD, the driver must be able to take over the driving task at any time on request.

Figure 1. Levels of driving automation according to SAE J3016 (SAE, 2021)

The first certification for a level 3 driving system was acquired in 2021 for an automated motorway assistant (Mercedes-Benz Group, 2021). Although reliable prognoses on the availability of higher levels of automation are lacking, there is widespread agreement that the introduction of further functions will be gradual (ERTRAC, 2019; Li & Wagner, 2019). More and more vehicles will be equipped with automated driving functions, while many others will continue to be controlled manually. This will result in mixed traffic consisting of AVs and MVs. In mixed traffic, space-sharing conflicts arise between AVs and MVs (Markkula et al., 2020). The resolution of such a conflict requires communication and cooperation between the road users involved.

Besides solving space-sharing conflicts between AVs and MVs, another approach is to avoid these conflicts from the start by prioritising interaction between AVs and other AVs. Cooperative, connected and automated mobility (CCAM) is seen as paving the way for widespread automated mobility and is expected to bring benefits in terms of safety, comfort, environment and energy efficiency (Alonso Raposo et al., 2018; ERTRAC, 2019). However, these benefits largely depend on whether and to what extent the technology is accepted and utilised by users (Grandsart et al., 2023). For this reason, a user-centred approach is needed in the development of AVs, regardless of whether they interact with MVs or AVs (see chapter 2.5).

2.2 Scenario definition: motorway slip roads

All studies in this thesis refer to the scenario of a motorway slip road. A motorway slip road is a junction that connects a motorway with at least two lanes with the downstream road network. There are many different layouts of motorway slip roads, which differ in the way they are routed towards the acceleration lane. For this thesis, the focus of the investigation is on the interaction between vehicles that are on the acceleration lane and vehicles that are already driving on the motorway. For this reason, the different layouts are not considered further at this point.

An acceleration lane on a German motorway usually has a length of 250m (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2019), in which it is parallel to the main road. In most cases it transitions into a hard shoulder, which may only be used in exceptional cases. The purpose of the acceleration lane is to adjust the speed of the vehicle to the traffic flowing on the motorway and then to merge into this traffic by changing lanes.

Lane changing manoeuvres are divided into discretionary lane changes (DLC) and mandatory lane changes (MLC), with motorway slip roads falling into the MLC category. They are characterised by a lack of an adequate alternative course of action, unlike, for example, changing lanes to overtake a slower vehicle (Ahmed, 1999). If another vehicle occupies the right-hand lane of the motorway at the time of the intended lane change, a space sharing conflict occurs (Markkula et al., 2020), see also Chapter 2.1. As already established there, the solution to this conflict requires cooperation and communication.

2.3 Communication and Cooperation

The first step is to define and differentiate between the terms "communication and cooperation". Both represent a form of interaction, which in turn "concerns two entities that determine each other's behaviour over time" (Bunge, 1979, as cited in Hornbæk & Oulasvirta, 2017, p. 5046). Markkula et al. offer a more specific definition for interaction in road traffic: It is defined as "a situation where the behaviour of at least two road users can be interpreted as being influenced by the possibility that they are both intending to occupy the same region of space at the same time in the near future" (Markkula et al., 2020, p. 737).

2.3.1 Cooperation

Even though the terms "interaction" and "cooperation" are often used synonymously, other sources make a difference in terms of the objective. While interaction can be antagonistic, cooperation has a common goal (Hoc, 2001; Khamis, Kamel, & Salichs, 2006). The definition in the Dictionary of Psychology also emphasises the common goal and reciprocity of cooperation: "Cooperation is characterised by a conscious and planned approach to collaboration and by processes of mutual agreement on specific goals. (...) Cooperation also assumes fair conditions for collaboration. This includes the basic idea of mutuality or reciprocity." (Spieß, 2021). Then again, cooperation can also be associated with altruistic behaviour (Khamis et al., 2006). The authors assume that the actions of cooperation partners can be classified as either "purely self-interested" or "partially or wholly altruistic", whereby in the latter case the interests of the entire group are prioritised over one's own goals. This does not precludes the reciprocity though - on the contrary, the authors use this as a further element of their typology of cooperation (Khamis et al., 2006).

In road traffic, cooperation plays a crucial role in increasing efficiency, comfort and safety (Benmimoun, Maag, & Neunzig, 2004). According to the authors, cooperation in road traffic is either partnership-based or professional, depending on the underlying motivation. The reasons for partnership-based cooperation lie in a sense of responsibility towards the individual and a positive cost-benefit analysis. Professional cooperation, on the other hand, is based on consideration for the system as a whole.

Direct reciprocity cannot always be given, e.g. when one driver enables another to change lanes from the acceleration lane onto the motorway by decelerating. Nonetheless, cooperative behaviour in such situations cannot be explained solely by pure altruism. If people cooperate because they can assume that they will also be met with cooperative behaviour in a comparable situation, it is referred to as reciprocal altruism (Trivers, 1971). Since people in a traffic system experience situations at short intervals - both those in which they can make a manoeuvre possible for others through cooperative driving behaviour and those in which the cooperative behaviour of others would increase their safety and comfort - it can be assumed that the overall system consists of a series of reciprocal altruistic actions.

The various sources regarding cooperation agree on one point: They emphasise the relevance of communication for successful interaction (Rickheit, 2008) or cooperation (Khamis et al., 2006; Spieß, 2021). For instance, the above definition of cooperation in the Dictionary of Psychology is supplemented by the following sentence: "The success of cooperation requires opportunities for the coordination of goals and the exchange of information, mutual communication and mutual support, (…)" (Spieß, 2021).

2.3.2 Communication

Communication as the basis for successful cooperation therefore implies that information about goals and intentions is exchanged between the communication partners. Many definitions and models address the topic of communication from different perspectives and different theoretical backgrounds. In the following, only those that bring us closer to understanding communication in road traffic will be considered.

Watzlawick, Bavelas, and Jackson (1967) proposed a set of axioms that describe the fundamental principles underlying human communication. These axioms provide a framework for understanding interpersonal communication and explanations for its failure.

The five Axioms read as follows (Watzlawick et al., 1967):

1. “One cannot not communicate”: Every behaviour is a form of communication. Since one cannot not behave, it follows that one cannot not communicate. Silence or inaction conveys information just as words or actions.

2. “Every communication has a content and relationship aspect”: Communication operates on two levels: the content level, which conveys the informational aspect of a message, and the relationship level, which conveys how the communicators view their relationship. The latter often influences the interpretation of the former.

3. “The nature of a relationship is dependent on the punctuation of the partners' communication procedures”: In communication, people tend to segment or "punctuate" interactions, attributing cause and effect. Yet communication is a chain of stimuli in response to an earlier stimulus. This can lead to differing interpretations of events, potentially resulting in conflicts or misunderstandings.

4. “Human communication involves both digital and analogue modalities”: Digital communication involves discrete symbols (such as language), while analogic communication involves nonverbal cues and expressions. Effective communication often requires the integration of both digital and analogic elements.

5. “Inter-human communication is either symmetric or complementary”: Communication patterns can be symmetrical, where participants mirror each other's behaviour (e.g., mutual agreement or disagreement), or complementary, where participants' behaviours complement each other (e.g., a dominant and a submissive role).

Watzlawick et al. (1967) thus emphasise the relational aspect of communication - if communication is unavoidable and every communication conveys a relational aspect in addition to the content aspect, there is also a relationship, albeit sometimes a brief one, between all interaction partners. The 4th axiom also addresses a concept that plays a major role in communication in road traffic: non-verbal communication. According to Argyle (1972), non-verbal communication has three functions: 1. ‘Managing the immediate social situation’, 2. ‘Sustaining verbal communication’ and 3. ‘replacing speech’ (Argyle, 1972, p. 267). The last function is essential for road traffic. Since the possibilities of using speech are severely limited, communication is restricted to non-verbal means. Thus, all the means of communication in road traffic presented in chapter 2.4.2 are non-verbal.

Based on the work of Watzlawick, Schulz von Thun developed his four-sides model (Schulz von Thun, 1996). He assumes that every message contains four different facets: the factual content (information), the self-revelation (what the sender reveals about themselves), the relationship aspect (what the sender thinks about the recipient and their relationship) and the appeal (what the sender wants from the recipient). Furthermore, a message can be interpreted by the receiver on each of these facets and the receiver can react not only to the content level but also to the other aspects of the message. Furthermore, messages can be explicit or implicit on all four sides of the message. Explicit communication involves the direct and clear transmission of information, while implicit communication conveys underlying attitudes and emotions through tone of voice, context and non-verbal cues. The model helps to understand the complexity of interpersonal communication and the potential for misinterpretation when different facets are emphasised or neglected by the sender or receiver. The distinction between implicit and explicit communication also matters in road traffic and is therefore addressed again in the next chapter.

In contrast to this emphasis on the interpersonal relationship, Shannon and Weaver (1949) use an information technology approach in their model (see Figure 2). Initially designed to improve the efficiency of communication over telecommunication systems, this model has been widely adapted to understand various forms of human communication.

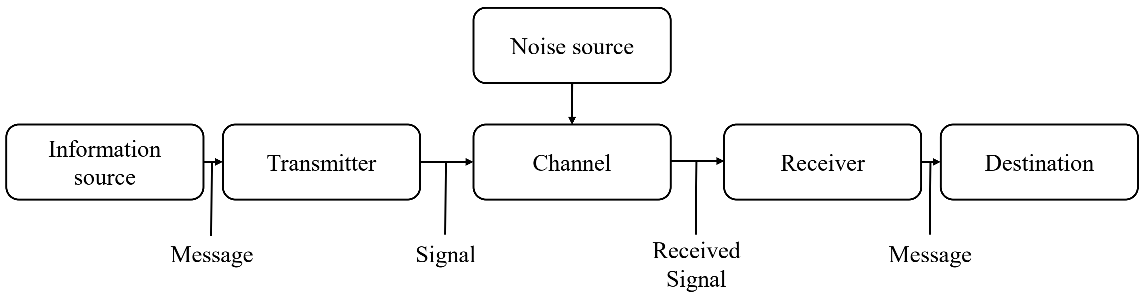

Figure 2. Shannon-Weaver model (Shannon & Weaver, 1949)

It comprises of six essential components. The information source generates the message to be communicated. In human communication, this is typically the sender or communicator who originates the thought or idea. The transmitter encodes the message into signals that can be transmitted over the chosen communication channel. This process involves converting the message into a suitable format for transmission, such as sound waves for verbal communication or digital signals for electronic communication. The channel is the medium through which the encoded message is transmitted from the transmitter to the receiver. This could be a physical medium like a telephone line, airwaves for speech transmission, or even digital networks. Noise refers to any interference or distortion that affects the message as it travels through the channel. Noise can be external, such as background sounds, or internal, such as psychological factors affecting the sender or receiver. The receiver is the device or person that decodes the transmitted signals back into a comprehensible message. In human communication, the receiver interprets and understands the message. The destination is the final target of the message. It is the person or group for whom the message is intended. While the original Shannon-Weaver model is linear, later adaptations introduced the concept of feedback, which allows the receiver to respond to the sender, thereby creating a more interactive and cyclical process of communication.

Although the Shannon-Weaver model is often applied to interpersonal communication, the criticisms levelled at the model highlight the limitations of using an information technology model in human-to-human communication. Firstly, the success of communication depends on the interpretative performance of the recipient (Bowman & Targowski, 1987; Merten, 1977) and not only on the absence of noise. This aspect is emphasised clearly in the interpersonal models of communication. Secondly, the model does not include the context dependency of messages (Zwicker, Petzoldt, Schade, & Schaarschmidt, 2019). For example, a signal (e.g. the headlight flasher) can be understood as a request for action ('I give you the right of way') in one situation and as a warning signal ('obstacle behind the bend') in another. This dependence on interpretation and context is further reinforced by cultural differences. For this reason, a separate chapter is dedicated to the cultural aspects of this research (see 2.6). Nonetheless, the model is often applied to human-human communication due to its low complexity, partly also in combination with the other models presented, and also represents a valuable approach to communication in road traffic for this dissertation.

2.4 Communication in road traffic

2.4.1 Theories related to communication in road traffic

The transferability of human-to-human communication, as described in the previous chapter, to road traffic is limited by three constraints of communication processes in road traffic: 1. non-verbality, 2. anonymity and 3. complexity of the situation (Merten, 1977). These limit communication in road traffic to very short communications on the visual channel, as the acoustic-verbal channel is (except for the horn) not available, and the volatility of the situation requires a high degree of economy in the transmission of messages. For this reason, Merten (1977) developed a communication model that relates specifically to communication in road traffic. The basic assumption of the model is that motivation for communication in road traffic always lies in the solution of a problem. It also assumes that, for economic reasons, an attempt is always first made to solve the problem without communication. There are four ways of doing so: *schematic action* attempts to deduce the future behaviour (e.g. accelerating) of a road user from their characteristics (e.g. sports car). *Pre-emptive action* describes the anticipation of the desired action by gradually carrying out the intended manoeuvre and thus informing other road users of the desired manoeuvre. *Communication avoidance* by means of information maximisation is based on reassuring oneself with multiple glances and waiting until no information speaks against an action. And finally, *collective orientation* involves imitating the behaviour of other road users in order to solve the problem, for example by having several drivers follow the first vehicle to leave the motorway via a dirt track in a traffic jam (Merten, 1977).

While these communication avoidance strategies can be applied to the motorway slip road scenario, the applicability of the actual communication process is severely limited. According to Merten (1977), the communication process in road traffic is based on establishing eye contact. This is followed by a complex non-verbal communication process which, depending on the occurrence of misunderstandings and frustrations, leads either to the resolution of the problem or to conflict, which in turn results in the utilisation of verbal communication. Due to the speed and the unfavourable angle of the vehicles to each other, eye contact is no relevant factor on motorway slip roads. The question therefore arises as to whether communication via driving dynamics, which is one focus of this thesis, can be understood as a communication avoidance strategy in the form of pre-emptive behaviour.

Two aspects oppose this assumption. Firstly, the first axiom of Watzlawick et al. (1967), according to which an attempt to avoid communication would also be communication. This would call into question the entire concept of communication avoidance; the avoidance strategy would always be communication at the same time. Secondly, a purely pre-emptive action without the possibility of feedback from the interaction partner would be considered at least uncooperative, if not risky, especially in the case of a motorway slip road. Although it can be assumed that this strategy might still be used to change lanes on motorway slip roads, it seems too short-sighted to assume that the driving dynamics cannot contain any communicative content as such.

Another limitation of Merten's model is its high complexity, which makes it difficult to utilise for automated vehicles. It is therefore worth taking another look at the Shannon-Weaver Model (Shannon & Weaver, 1949) presented in Chapter 2.3.2. The information technology approach allows individual or even all components of the model to be handled by technical rather than human entities. It also relates primarily to a simple directional communication, which is prevalent due to the speed of road traffic.

Applying the Shannon-Weaver model to the motorway slip road situation (see Figure 3), the information source would be the driver of the vehicle on the slip road or the driver of the vehicle in the destination lane. The destination would be the other driver. With the introduction of AVs, the information source or destination or even both could also be an AV. The signal would be communication media such as driving dynamics, indicators, or brake lights, which would be recognised by the receiver via visual perception or, in the case of AVs, via sensors. An optical channel is therefore used; in the case of AVs, connected functions in the sense of V2V communication (see 2.4.3.3) may also be available. However, the model does not make any statements about the type of communication means. These are therefore considered separately in chapter 2.4.2. The noise sources that can interfere with communication at the motorway slip road can be factors such as distraction, inattention, ambiguity of the transmitted signal or poor visibility.

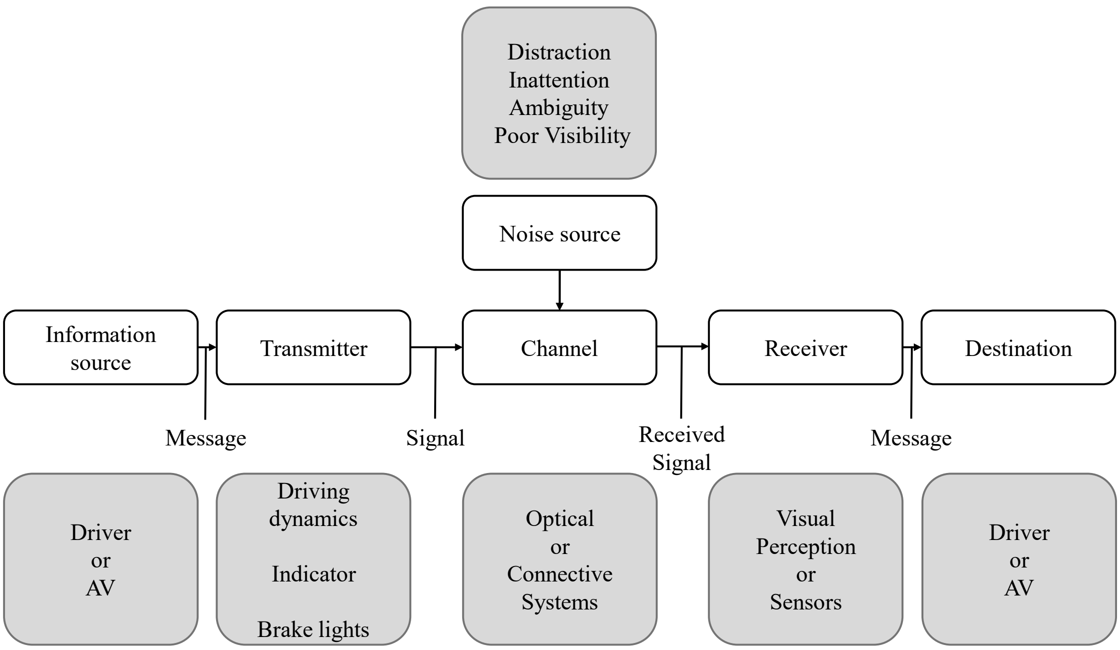

Figure 3. Shannon-Weaver model (Shannon & Weaver, 1949) in road traffic

For communication in road traffic to succeed, all road users therefore need to use signals that can be correctly interpreted by others and be able to interpret the signals of other road users. In mixed traffic, AVs must consequently select signals that people can understand on a channel that is open to humans (e.g. the optical channel). Moreover, they must be able to correctly interpret the signals of human road users.

One difficulty in using the Shannon-Weaver model in road traffic lies in identifying the recipient of the message (Schaarschmidt et al., 2021). The model implies a single, clearly identifiable receiver. In road traffic, however, a signal is potentially received by many people, namely every road user who can see the sending vehicle. Furthermore, not all signals are generated with a communication intention (Schaarschmidt et al., 2021). While signals such as indicators or flashing lights are used explicitly for communication, unintentional implicit communication signals are also permanently sent by means of driving dynamics. Implicit signals are received and interpreted by the receiver, even if the sender does not send them to transmit specific information. For example, strong acceleration on the motorway slip road can be interpreted by a driver in the target lane as a signal that the driver of the accelerating vehicle wants to merge into the target lane in front of the vehicle, even if acceleration was not carried out for communication purposes. The intentional use of driving dynamics for communication purposes is also discussed in other works, e.g. Risto, Emmenegger, Vinkhuyzen, Cefkin, and Hollan (2017).

The purpose of communication in road traffic is to ensure smooth traffic (Schaarschmidt et al., 2021) and to increase safety (Markkula et al., 2020). One link between communication and these goals lies in the situation awareness (SA): The internal communication of MVs and AVs to the occupants about the system status or the detection of the vehicle sensors ("Indicator usage detected for vehicle in front") can improve the perception of the current situation. And if a road user communicates his behavioural intention, this can help others to better understand his current behaviour ("He is indicating because he wants to take the next exit. This is an explanation for the fact that he is braking"). It can also enable others to make better predictions about future behaviour ("if he flashes now, he will probably change lanes shortly").

According to the model, SA is the basis for decision-making and the subsequent performance of actions, whereby it is dependent on various factors (see Figure 4). These include individual factors such as cognitive resources (information processing mechanisms, long-term memory, and automaticity), which in turn are influenced by abilities and training. Other individual factors are current goals and expectations. In addition, SA is influenced by system factors such as complexity and automation (Endsley, 1995). These factors are both particularly relevant in road traffic. The fact that road traffic is a fundamentally complex situation has already been established earlier (Merten, 1977). The introduction of automated driving functions can further impair the SA of road users.

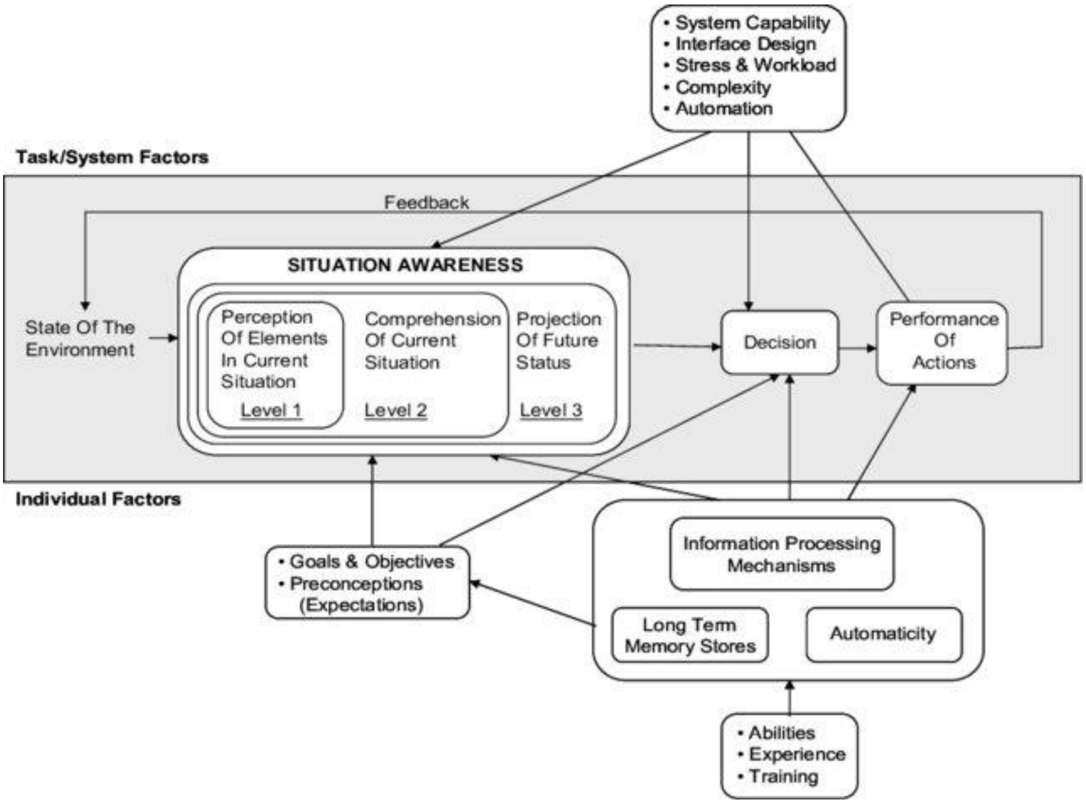

Figure 4. Situation Awareness Model (Endsley, 1995) as cited in Salerno, Hinman, and Boulware (2004)

If they turn their gaze away from the road during semi-automated driving and are inattentive to their surroundings and the system actions, the reduced SA can lead to problems when the system requests to take over (Endsley, 2018). Internal communication between the automated system and the occupants should therefore be suitable for supporting the SA, particularly in the context of handovers.

2.4.2 Means of communication in road traffic

In road traffic, a number of specific means of communication have been established which form the foundation of successful cooperation between human road users. Schaarschmidt et al. (2021) provide an overview of the means of communication used (see Figure 5).

Eye contact	Physical gestures	Direction indicator	Driving dynamics	Brake lights	Flashing lights	Hazard warning lights	Horn

Figure 5. Means of Communication in Road Traffic (Schaarschmidt et al., 2021)

Not all these means of communication are relevant in the motorway slip road scenario. Due to the high speed and since the vehicles are at an unfavourable angle to each other for this form of communication, eye contact and physical gestures do not play a significant role on motorway slip roads. The relevance of using indicators on motorway slip roads has already been shown before (Stoll, Weihrauch, & Baumann, 2020b). However, indicator usage is mandatory in this situation. The communicative value of brake lights is closely linked to driving dynamics. In addition, they are only visible when driving behind the vehicle, which is often not the case in the cooperation situation on the motorway slip road. For these reasons, the brake lights are not considered separately below. The use of flashing lights on motorway slip roads is determined by culture: While in Germany the flashing light may only be used outside built-up areas to indicate overtaking (§16 StVO), in the UK, for example, it is a common signal to allow the other vehicle to merge. In the context of this work, flashing lights are not considered further. The hazard warning lights, and horn are also not relevant, as these may only be used as warning signals in dangerous situations (although country-specific differences also apply here). This leaves driving dynamics as a relevant means of communication on motorway slip roads and are therefore considered in detail in this thesis. Driving dynamics include lateral and longitudinal driving manoeuvres, e.g. the lateral position in the lane or acceleration and deceleration.

To simplify the analysis of the multitude of means of communication, various authors have attempted to categorise them. For example, attempts have been made to classify the means of communication according to their modality (technology-supported vs. gesture-supported), their formality (formal vs. informal), their intentionality (explicit vs. implicit) or their selectivity (directed vs. undirected) (Schaarschmidt et al., 2021). The classification of driving dynamics is particularly interesting with regard to intentionality. Implicit means of communication are not sent out intentionally by the sender but are more of an accessory to the intended action (e.g. accelerating on the slip road to change lanes). Nevertheless, this action can be interpreted by the receiver (e.g. as a signal of intention to change lanes in front of another vehicle). At the same time, it is being discussed whether driving dynamics should be used intentionally for communication, especially in the context of automated driving (Bengler, Rettenmaier, Fritz, & Feierle, 2020; Risto et al., 2017). It is debatable whether driving dynamics will thus change from an implicit to an explicit means of communication. Although the intention would suggest it is explicit communication, at the same time the signals still have to be understood and interpreted by the receiver in the sense of implicit communication. Due to the necessary interpretation independent of the existence of an intention, driving dynamics are categorised in this work as an implicit means of communication.

2.4.3 Communication of automated vehicles

The introduction of automated vehicles extends the dyadic communication of MV drivers with other road users to include the AV, which communicates with both its passengers and other road users (Schieben, Wilbrink, Kettwich, Madigan, et al., 2019). Communication in automated vehicles is therefore divided into internal and external communication. This communication is realised by means of human-machine interfaces (HMI).

2.4.3.1 External Communication

External HMI (eHMI), which the AV uses to communicate with other road users, are divided into four categories according to Schieben, Wilbrink, Kettwich, Madigan, et al. (2019).

Category A - *information about vehicle driving mode* - includes external displays of the vehicle that inform surrounding traffic about the driving mode of the vehicle. Usually, it is displayed when the vehicle is in an automated driving mode. Other sources refer to these displays as 'status eHMI' (Faas, Mathis, & Baumann, 2020; Stange, Kühn, & Vollrath, 2022).

The question of whether the vehicle driving mode should be communicated to the outside world is the subject of controversial debate. On one hand, some studies show that pedestrians, cyclists and other drivers behave differently towards AVs (Faas et al., 2020; Hagenzieker et al., 2020; Lundgren et al., 2017). It is argued that status eHMI are important to give other road users the opportunity to adjust their expectations and behaviour to the potentially deviating behaviour of AVs (Stanton, Eriksson, Banks, & Hancock, 2020). There is also evidence that status eHMI could increase the acceptance of automated vehicles (Fuest, Feierle, Schmidt, & Bengler, 2020). Stange et al. (2022) even assume that continuous interaction with AVs with status eHMI can lead to other road users building a mental model of the behaviour of AVs in the long term and thus making more correct assumptions about the future behaviour of the AV and improving their situation awareness. At the same time, a growing body of research is emerging about the risk of AVs being outmanoeuvred or even bullied by drivers of MVs (Liu, Du, Wang, & Da Young, 2020; Moore, Currano, Shanks, & Sirkin, 2020). Other studies, however, find no difference in attitudes and behaviour between MVs and AVs (Fuest et al., 2020; GATEway Project, 2017; Joisten et al., 2020; Stange et al., 2022).

Category B according to Schieben, Wilbrink, Kettwich, Madigan, et al. (2019) includes all *information about the vehicle's next manoeuvres*, e.g. the intention to brake, accelerate or change lanes. In addition to the means of communication presented in 2.4.2, which can also be adapted by AVs, the use of further external communication is discussed. Active eHMI, for example in the form of a modified indicator that shows whether a lane change is planned or imminent, could increase the perceived cooperativeness of AVs (Haar, Haeske, Kleen, Schmettow, & Verwey, 2022).

Category C describes HMI that communicate *information about the perception of the environment*. Here, the previous interpersonal interaction through e.g. eye contact or hand gestures, which showed other road users that they were being perceived by the driver, is replaced by technical displays.

Category D contains *information about cooperation capabilities* of the AV. This refers to HMI that indicate to other road users that the AV will give them the right of way or, for example, requests pedestrians to cross the road in front of them.

In addition to the categories, Schieben, Wilbrink, Kettwich, Madigan, et al. (2019) also provides an overview of design options for external HMIs and their advantages and disadvantages. Visual HMIs, which can take the form of text, light patterns or symbols, are widely used. They represent a form of explicit communication that can be clearly traced back to their sender. However, their understanding is often not intuitive, which requires standardisation. In addition, their visibility in different scenarios poses a problem. Acoustic HMIs in the form of spoken words or sounds also fall under explicit eHMIs. However, they are rare due to the poor identifiability of the sender and the limitations in noisy or complex situations. Another design option is implicit communication through vehicle behaviour. Here, the communication via driving behaviour of AVs discussed in 2.4.2 is adapted. This has the advantage that this form of communication is already familiar to other road users, unlike artificial communication through visual or acoustic eHMIs. One disadvantage, however, lies in cultural differences in expected vehicle behaviour. This point is addressed in more detail in chapter 2.6. Other sources also refer to this type of HMI as dynamic HMI (dHMI) (Bengler et al., 2020).

One focus of the scientific papers in this dissertation is on the investigation of status eHMIs that fall into Category A. Here, a visual HMI in the form of a light band is considered. The second focus of the thesis is the investigation of the communication of behavioural intention (Category B) by means of vehicle behaviour, specific driving dynamics. The evaluation of the communication of behavioural intention at motorway slip roads, as well as the influence of a status eHMI on the evaluation of driving behaviour by other road users is examined in studies 1 - 3.

2.4.3.2 Internal Communication

Internal communication refers to the communication of AVs with the occupants of the vehicle. There are major similarities in the information that is communicated via internal and external HMI. However, while the usefulness of external communication about the vehicle driving mode is debated, it is undisputed that this information is elementary in internal communication. To ensure safe transitions between the different driving modes of the vehicle, the driver must be aware of the current mode at all times (Bengler et al., 2020). Information about the next driving manoeuvres and the perception of the environment, on the other hand, are designed to strengthen acceptance of and trust in the system. These aspects are considered in more detail in chapter 2.5.

Internal HMIs can consist of visual, auditory and tactile elements (Bengler et al., 2020), which can be combined. In addition, vehicle behaviour can also be seen as part of internal communication, as this is interpreted not only by the environment, but also by the occupants of the vehicle.

In Study 4, an internal HMI communicating information about the vehicle status and a cooperation agreed by the system with another AV is considered. It consists of a combination of visual and auditory elements.

2.4.3.3 V2X Communication

In addition to internal and external communication with other human interaction partners, AVs feature another communication channel, namely V2X communication. V2X stands for ‘vehicle to everything’, whereby X can be other AVs (V2V), the infrastructure (V2I) or the network (V2N). The connectivity of vehicles with their environment is seen as one of the conditions for the successful implementation of automated driving and is expected to be accompanied by safety, as well as environmental and efficiency benefits (Alonso Raposo et al., 2018). Study 4 of this dissertation examines the acceptance of a system that uses V2V communication to agree a cooperative driving manoeuvre with another AV.

2.5 Acceptance and related concepts

The successful introduction of automated driving functions is largely dependent on user acceptance. The Technology Acceptance Model (TAM; Davis, 1989) and its further developments offer a framework for understanding the factors influencing user acceptance of new technologies, including automated driving.

The original TAM by Davis (1989) was designed to explain and predict user acceptance of information technology. The model posits that two primary factors determine an individual's intention to use a technology: perceived usefulness and perceived ease of use. Perceived usefulness refers to the belief as to whether the system can improve one's task performance (in the case of automated driving functions, the task of controlling a vehicle). The perceived ease of use represents the conviction that using the technology will be free of effort. The easier a system is to use, the more likely it is to be accepted by potential users. These two beliefs influence an individual's attitude towards using the technology, which subsequently affects their behavioural intention to use it, ultimately determining actual system use.

The further development of the model, the TAM2 (Venkatesh & Davis, 2000) extends the original TAM by including the factors of social influence and cognitive instrumental processes as influencing factors on perceived usefulness. Social influence includes the variables subjective norm (the perceived social pressure to use or not to use the system), image (the influence of system use on a person's status) and voluntariness. In addition, “experience” as an influencing factor on the before-mentioned variables “subjective norm” and “image”, was introduced. The cognitive instrumental processes include job relevance, which reflects the degree to which the technology is applicable to one’s task; output quality, which is the degree to which the technology performs the task well; and result demonstrability, which is the tangibility of the results of using the technology. As in the TAM, perceived ease of use not only directly influences behavioural intention, but also perceived usefulness.

The third iteration, TAM3 (see Figure 6), was developed by Venkatesh and Bala (2008) as an integrative model that combines elements of TAM2 and the Model “Determinants of Perceived Ease of Use” (Venkatesh, 2000). TAM3 thus extends TAM2 by the two variable groups "Anchor" and "Adjustment", which explain how the perception of the perceived ease of use is formed.

All models share the common assumption that the actual use of a system depends largely on the intention to use it, which in turn is influenced by the main variables "perceived usefulness" and "perceived ease of use". If the system is not accepted in the other direction, there is no intention to use it, which means that the potential effects of increased road safety and comfort do not materialise. These relations are also apparent when considering automated driving: perceived usefulness, perceived ease of use, perceived trust and social influence are predictors of the intention to own or use autonomous vehicles, with perceived usefulness having the strongest influence (Panagiotopoulos & Dimitrakopoulos, 2018). In their study, the authors expand the TAM to include the influencing factors ‘Perceived Trust’ and ‘Social Influence’. In line with other studies, they show the close relation of the concepts of trust and user acceptance (Ghazizadeh, Peng, Lee, & Boyle, 2012; Kaur & Rampersad, 2018; J. D. Lee & See, 2004; Panagiotopoulos & Dimitrakopoulos, 2018; Zhang et al., 2021).

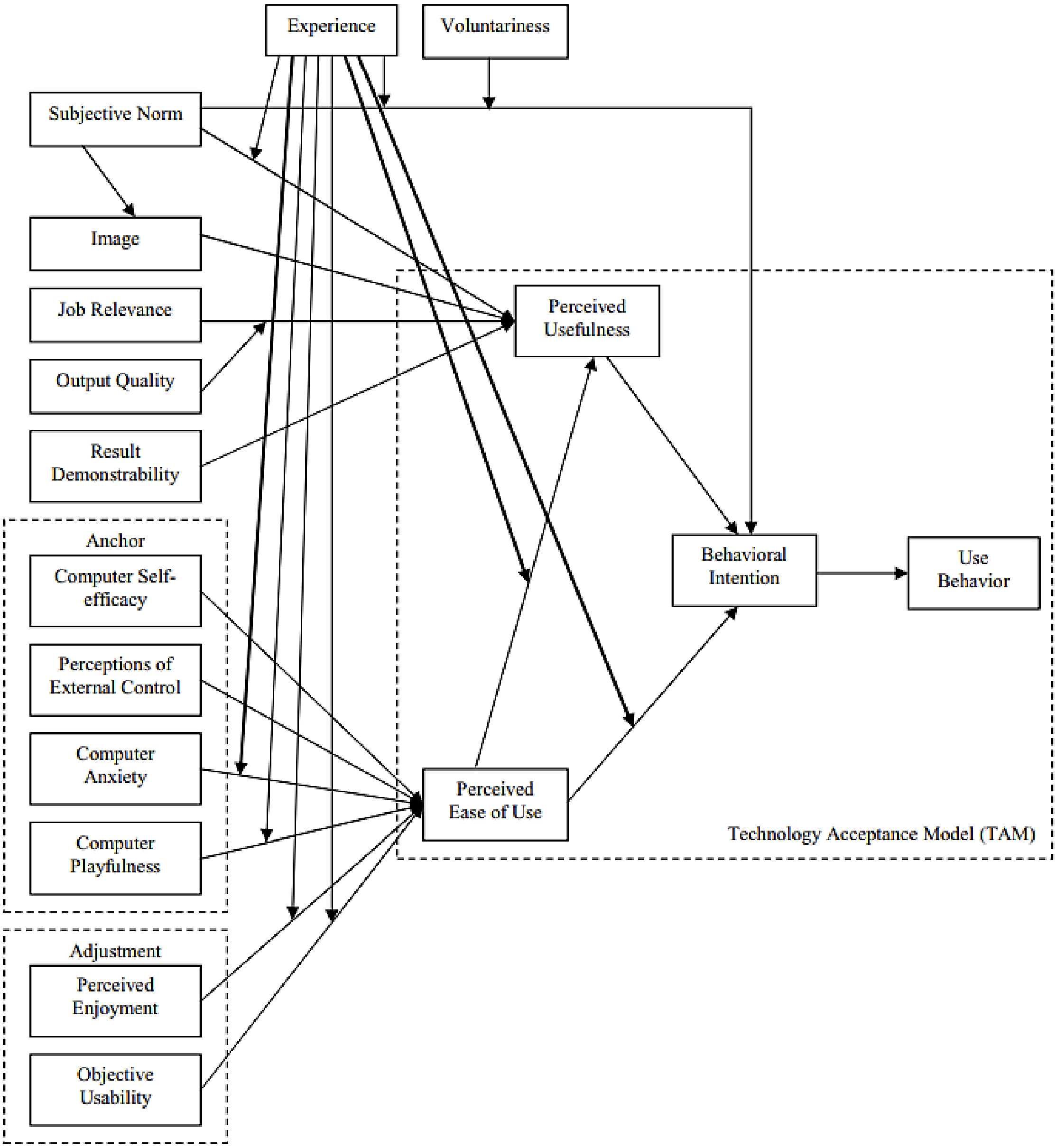

Figure 6. Technology Acceptance Model (TAM3; Venkatesh & Bala, 2008, p.280)

Trust is intersecting significantly with TAM constructs: It has a direct effect on perceived usefulness and perceived risk and subsequently behavioural (Choi & Ji, 2015). According to Ghazizadeh, Peng, et al. (2012), both perceived usefulness and perceived ease of use have a positive influence on trust, and both having a direct positive influence on behavioural intention. Regardless of the direction of the correlation, trust correlates with the frequency of use of automated driving functions (Dikmen & Burns, 2017). Positive experiences with automated vehicles, on the other hand, increase trust, perceived usefulness and perceived ease of use and therefore the acceptance of the system (Ghazizadeh, Lee, & Boyle, 2012; Zhang et al., 2021).

As mentioned above, the influence of trust on behavioural intention is partly mediated by perceived risk (Choi & Ji, 2015). Perceived risk, in turn, correlates highly with perceived criticality in studies on time headways in road traffic (Siebert, Oehl, & Pfister, 2014; Tscharn, Naujoks, & Neukum, 2018). Perceived criticality describes how critical a distance between one's own vehicle and another vehicle is perceived to be. If a high perceived criticality is associated with an increased perceived risk, it can therefore be assumed that this is also associated with lower trust and therefore lower acceptance in the long term.

2.6 Cultural Aspects and Generalizability

In addition to the aspects discussed in the last chapter, the acceptance of AVs depends on cultural factors (Edelmann, Stümper, & Petzoldt, 2021; Muzammel, Spichkova, & Harland, 2024; Schoettle & Sivak, 2014; Tolbert & Nojoumian, 2023). Besides acceptance, cultural aspects influence the explicit and implicit rules of the road and thus the question of which driving behaviour is accepted (Özkan, Lajunen, Chliaoutakis, Parker, & Summala, 2006). These cultural differences have also been observed in relation to the acceptance of the behaviour of AVs (Edelmann et al., 2021). Cultural aspects also influence the interpretation of means of communication (Y. M. Lee et al., 2021). In Germany, for example, the use of flashing lights by a vehicle in the fast lane is interpreted as a signal indicating the intention to overtake and is often perceived as aggressive. In the UK, on the other hand, the signal is used to indicate that another vehicle will be enabled to change lanes.

According to one definition, culture is “the collective programming of the mind that distinguishes the members of one group or category of people from another” (Hofstede, 2001). Based on this definition, Hofstede derived five cultural dimensions. *Power distance* refers to the degree to which a society accepts and expects that power is distributed unequally. The dimension *Individualism vs. Collectivism* measures the extent to which individuals are integrated into groups. *Masculinity vs. femininity* refers to the distribution of emotional roles between genders, with masculine cultures valuing competitiveness and assertiveness, and feminine cultures valuing care and cooperation. *Uncertainty avoidance* indicates the extent to which members of a culture feel threatened by ambiguous or unknown situations. And *indulgence* refers to the extent to which a society allows relatively free gratification of basic human desires, while *restraint* refers to a society that suppresses gratification and regulates behaviour through strict norms (Hofstede, 2011).

Studies show the association between Hofstede's dimensions and AV acceptance: power distance correlates positively with the acceptance of AVs (Muzammel et al., 2024; Taniguchi, Enoch, Theofilatos, & Ieromonachou, 2022; Yun, Oh, & Myung, 2021), as does uncertainty avoidance (Muzammel et al., 2024; Yun et al., 2021). In countries with a high degree of individualism, the acceptance of AVs is lower (Muzammel et al., 2024; Yun et al., 2021). There are contradictory research results with regard to the relation between masculinity and the acceptance of AVs (Muzammel et al., 2024; Taniguchi et al., 2022; Yun et al., 2021). Correlations are also reported between the cultural dimensions and accepted behaviours in road traffic: For example, power distance correlates positively and individualism negatively with non-speeding violations, whereby after controlling for GDP (gross domestic product), only individualism is significantly associated with non-speeding violations (Üzümcüoğlu, Özkan, & Lajunen, 2018).

The available research therefore suggests that cultural aspects influence both the acceptance of AVs and the acceptance of certain road behaviour. At the same time, most AV acceptance studies are currently being conducted in the US, China and Germany (Zhang et al., 2021). For successful global adoption of AVs, it is essential to develop AVs that are widely accepted and effective in different cultural contexts. The generalisability of study results from individual countries therefore needs to be constantly challenged and confirmed. Otherwise, there is a risk that AVs developed in one country will lead to traffic disruption and lack of acceptance after export or in the context of cross-regional journeys.

In this thesis, the generalisability claims of the results obtained in Germany is partially analysed by means of a replication study in the UK (see Study 3). This comparison was chosen for several reasons: firstly, there are great similarities but also some differences between the two countries on Hofstede's dimensions. This is a circumstance that applies to the comparison of many European countries. At the same time, there are significant differences in terms of the infrastructure of the two countries. In Germany, like the rest of Europe, right-hand traffic is the rule, while in the UK people drive on the left-hand side of the road. Nevertheless, there is active inter-regional traffic between the UK and mainland Europe, which is a challenge even without taking automated driving into account, partly because the vehicles are built differently due to the respective infrastructure. The comparison of the two countries is therefore based on the hypothesis that a generalisability claim of results from Germany for the UK implies that this also holds for countries with smaller cultural and infrastructural differences. Consequently, in future works it would be worthwhile to examine how high this is for countries with greater cultural differences.

2.7 Research Questions

Based on the literature discussed above, six research questions are derived which are intended to bring us closer to understanding communication at motorway slip roads:

RQ1: How are lateral driving dynamic communication means evaluated by other road users at motorway slip roads?

RQ2: How are longitudinal driving dynamic communication means evaluated by other road users at motorway slip roads?

RQ3: Is the evaluation of lateral and longitudinal driving dynamics by other road users dependent on whether the vehicle is perceived as MV or AV and does it influence their behaviour?

RQ4: Can the findings on the evaluation of driving dynamics on motorway slip roads and the influence of a status eHMI be generalised beyond Germany?

RQ5: Under which conditions is an alternative approach to the interaction of AVs and MVs, a cooperative automated motorway access assistant based on V2V communication, accepted?

RQ6: What influence does internal communication via HMI have on the acceptance of an automated motorway access assistant?

The research questions were answered by four studies, as already described in chapter 1.2. Research question 1 and 3 are considered in Study 1 in an online study. Study 2 considers Research Question 2 and again Research Question 3 in a driving simulator study. In a replication study of Study 2, Research Question 2 and 3 are reconsidered and complemented by an analysis regarding Research Question 4. And finally, in another driving simulator study (Study 4) Research Questions 5 and 6 are regarded. The four studies are presented in the following chapters.

3 Study 1: Evaluation of the communication means of lateral driving dynamics at motorway slip roads

The first study of this thesis deals with the evaluation of lateral driving dynamics on motorway slip roads. This study considers these behaviours under the premise that they are used as a means of communicating behavioural intent (Felbel, Dettmann, Lindner, & Bullinger, 2021; Schaarschmidt et al., 2021). Driving dynamics are an implicit means of communication (Schaarschmidt et al., 2021) and must therefore first be decoded by other road users. As previously established, human drivers usually manage this instinctively (Kauffmann, Winkler, Naujoks, & Vollrath, 2018). More research is needed, however, to enable AVs to understand these means of communication and use them in a way that is acceptable to other road users. Two relevant lateral driving dynamics during lane changes on motorway slip roads are position and the speed of the lane change. The former has so far only been considered in a study on unforced lane changes (Kauffmann, Winkler, et al., 2018), in which speed influenced perceived cooperativeness but not criticality. The position of lane change on motorway slip roads was previously only investigated with regard to gap acceptance (Choudhury, Ramanujam, & Ben-Akiva, 2009; Marczak, Daamen, & Buisson, 2013a). This study examines how cooperatively and critically variations in the position and speed of lane changes on motorway slip roads are perceived by traffic approaching from behind on the right lane of the motorway (RQ1). With regard to RQ3, it also examines whether the evaluation of the behaviour depends on whether the vehicle is labelled as an AV or not.

The following Subchapters *3.1 Introduction, 3.2 Theoretical Background, 3.3 Methods 3.4 Results, 3.5 Discussion and 3.6 Conclusion* with their respective sub-chapters are full citations form the publication

Ehrhardt, Graeber, Strelau, and Deml (2023). Evaluation of the communication means of lateral driving dynamics at motorway slip roads. *at - Automatisierungstechnik, 71(4)*, 269-277. https://doi.org/10.1515/auto-2022-0159.

For this purpose, the numbering of the chapters, figures and tables were adapted to the numbering of the thesis. In addition, the citation style was adapted to the citation style of the rest of the dissertation. All co-authors of the published article have declared that they will not use the publication in the context of another academic examination.

3.1 Introduction

"According to a study by Statista (2022), every one in ten vehicles will be driving autonomously in 2030. At the same time, 90 % of vehicles will only be partially automated or not automated at all. This results in mixed traffic of automated and manually controlled vehicles. To ensure safe and incident-free traffic, these vehicles will have to cooperate with each other. For this reason, there is a great need to understand human communication behaviour in road traffic and to develop concepts to transfer this behaviour to automated vehicles. The development of automated driving functions on the motorway is already rather advanced due to the comparatively lower complexity of the driving task compared to inner-city traffic. In 2021, for example, the first vehicle in Germany received certification for a SAE Level 3 function for the motorway driving mode (Mercedes-Benz Group, 2021). SAE level 3 is also referred to as "conditional driving automation" (On-Road Automated Driving Committee, 2021) and includes the execution of all aspects of the driving task by an automated driving function. The driver still must be able to take control at any time when requested. So far, automated driving is only possible on the motorway, not on the slip road. To implicate it on slip roads, a broad understanding of the interaction between human drivers is a necessity. Up to now, there has been a large gap in research on implicit communication behaviour at motorway slip roads and the evaluation of this behaviour by the cooperation partners.

In this paper, we present the results of an online study on how cooperative and critical different variations of lateral lane-changing behaviour (duration and position of the lane change) are evaluated. In addition, it will be investigated whether the results can be transferred to communication with vehicles marked as automated.

3.2 Theoretical Background

Safe, incident-free traffic is based on constant communication between road users. Usually, the communication in traffic is short and directed, and can be well described by the Shannon-Weaver Model (Shannon & Weaver, 1949). The model is a universal communication model, which is particularly suitable for use in automated driving because the aspects of the model can be implemented by technical devices (Schaarschmidt et al., 2021). It states that a message is encoded by a transmitter and then received and decoded by a receiver. In between, noise can interrupt or distort the transmission of the signal. A vehicle on a motorway slip road (transmitter) may express its intention to move to the right lane in the current gap by making a lateral movement (Felbel et al., 2021). The receiver, usually a vehicle in the right lane of the motorway, must first recognise this signal and comprehend it in addition. In between, factors such as rain or backlighting can distort the signal (noise). Automated vehicles should also be able to use their lateral position as a means of communication or register and interpret the movements of others via their sensor technology.

Schaarschmidt et al. (2021) provide an overview of the possible types of signals used in road traffic for communication purposes. The list refers to traffic in general, so not all of them are relevant to the situation of motorway slip roads. For example, the list includes physical gestures and eye contact, which do not play a role due to the speed on motorways. Relevant, on the other hand, are driving dynamics as a means of communication (Felbel et al., 2021). This includes acceleration, braking and lateral movements. In addition to the Shannon-Weaver Model and the means of communication according to Schaarschmidt, communication in road traffic can be categorised into explicit and implicit communication (Imbsweiler, Ruesch, Heine, et al., 2018; Lagstrom & Lundgren, 2015). Explicit communication may include hand gestures or flashing lights. Implicit communication includes aspects of driving dynamics such as lateral and longitudinal movements of a vehicle. In this paper, the focus is on the investigation of implicit communication through driving dynamics, especially through lateral movement.

Although a large research gap exists regarding communication on slip roads, more work has been done on lane changes on motorways. The motorway slip road is a special case of lane change as it is a forced lane change. Most other lane changes are unforced changes, for example during an overtaking manoeuvre (Choudhury et al., 2009). A driving simulator study investigated driving dynamics as a means of communication during unforced lane changes on motorways (Kauffmann, Winkler, et al., 2018). The influence of waiting time (time between the indicator set and the start of the lane change) and longitudinal acceleration as well as lane change duration on the evaluation of the situation was investigated. The results showed that a longer duration of the lane change leads to a more positive evaluation of the cooperation. However, no significant differences were found in subjective criticality ratings. For criticality the longitudinal acceleration was decisive as a delayed longitudinal acceleration led to higher ratings of perceived criticality. In line with the findings of Kauffmann, Winkler, et al. (2018) for unforced lane changes, we assume that a slower lane change is also evaluated more cooperatively for forced lane changes. In addition, we expect that a fast lane change is perceived as more critical because we assume, that the situation of a forced lane change is viewed as more critical and a fast lane change enhances the sense of criticality.

Besides the duration of the lane change, the position on the slip road during lane change could also influence the evaluation of the situation. The position where the lane change takes place has been investigated in previous studies only from the driver's perspective on the acceleration lane, not of the cooperation partner on the right lane. According to Marczak et al. (2013a) the position of the driver on the acceleration lane is an important criterion for which gaps the driver rejects and which (s)he accepts. The closer the driver gets to the end, the more likely (s)he is to accept a smaller gap (Choudhury et al., 2009). This can cause vehicles in the target lane to decelerate or brake, increasing the effort required by the driver of the vehicle behind (Haar et al., 2022). We assume that this higher effort, which the cooperation partners have experienced in the past, influences the evaluation of the position of lane change. In addition, the lack of alternatives can also affect the evaluation: in the case of a late lane change, the cooperation partner may feel forced to enable the lane change. Our hypothesis is that a lane change at the end of the slip road is rated less cooperative and more critical than an earlier lane change.

For the modelling of the driving behaviour of automated vehicles, in addition to an understanding of human behaviour, it is important whether the expectations of the behaviour towards automated cooperation partners differ from those towards human cooperation partners. Therefore, influence of a labelling as an automated cooperation partner on the evaluation of the communication behaviour will be investigated. This labelling is provided by an external Human-Machine-Interface (eHMI) and comes, for instance, in the form of a light strip on the chassis (Schieben, Wilbrink, Kettwich, Dodiya, et al., 2019). The labelling is intended to increase the acceptance of automated vehicles in the event of norm-deviating behaviour (Maurer, Gerdes, Lenz, & Winner, 2015). It can include a function for explicit communication with other road users (e.g. through rhythmic flashing, cf. Schieben, Wilbrink, Kettwich, Dodiya, et al., 2019) or merely implicitly label a vehicle as automated (Joisten et al., 2020). A communicating eHMI has an influence on the interaction between the cooperation partners. Haar et al. (2022) investigated the influence of a communicating eHMI on a motorway in a driving simulator study. The signal of the indicator was modified in such a way that it also communicates whether a lane change is planned or imminent. They showed that the communicating eHMI increases the perceived cooperativeness of the two cooperating partners.

Studies regarding a status eHMI, on the other hand, do not find a significant effect on the behaviour or evaluation of other road users in inner-city traffic (GATEway Project, 2017; Joisten et al., 2020). Status eHMIs just indicate an automated driving mode to the environment but do not communicate further. In a study with pedestrians, a vehicle was labelled as automated or manual using an eHMI. The participants indicated when they would cross the road. Simple labelling without explicit communication did not result in a significant difference in behaviour (Joisten et al., 2020). The Gateway Project also concludes that a display indicating automation mode does not influence the behaviour of other road users (GATEway Project, 2017). The aim of this study is to investigate whether the findings on status eHMI from inner-city traffic can be transferred to the situation of the motorway slip road. If a status eHMI does not induce differences in the assessment of and behaviour toward automated vehicles, other findings from traffic research regarding manual traffic could be transferable to automated vehicles. In this study, two questions will be investigated: *1. How are the two implicit driving dynamic communication means duration and position of lane change evaluated at a motorway slip road in terms of cooperation and criticality? 2. What influence does a status eHMI have on the evaluation of the cooperative lane change?*

3.3 Methods

The research questions were addressed in an online study using videos from the first-person perspective of a driver in the right lane of a motorway, who encounters a vehicle entering the motorway (see Figure 7). The following chapter describes the experimental design, the video material, and the methodological approach to data collection. In the video material, three variables were systematically varied, leading to a 3 × 3 × 2 within-subject design. As the first independent variable, the duration of the change from the acceleration lane to the target lane was varied based on (Kauffmann, Winkler, et al., 2018). In adaptation to the setting of a video study, fast to medium fast lane changes (2 s, 4 s or 6 s) were made.

The second independent variable was the position in the acceleration lane at which the merging vehicle had completed its lane change. It was measured as the distance from the end of the acceleration lane. Since an acceleration lane in Germany is usually 250 m long, the distances chosen for the study are 0 m (end of the acceleration lane), 100 m (just past the middle of the acceleration lane), and 200 m (just past the beginning of the acceleration lane).

Thirdly, the appearance of the oncoming vehicle was varied. In the baseline condition, a grey Audi A4 estate car (see Figure 7) is chosen. A highly visible, surrounding turquoise light strip was added to this vehicle in half of the videos. The subjects were instructed that this status eHMI indicates that the vehicle is driving in automated driving mode and is not controlled by a human. The design of the status eHMI is adapted from Wilbrink, Lau, Illgner, Schieben, and Oehl (2021). The driving situations shown in the videos were evaluated by participants in an online video study. The combination of variables resulted in a total of 18 (3 x 2 x 2) videos, which were presented to all participants in a within-subject-design. In addition, a sample video was recorded for the instruction of the subjects.

3.3.1 Materials

The videos were created using the Silab® driving simulator software. A motorway section with a slip road was generated in which various scenarios could be created. Figure 7 shows a screenshot of the scenario. The video shows the driver's perspective of a vehicle in the right lane of a motorway with three lanes in both directions. There is increased traffic density, with a speed of 120 km/h on the left lane and 100 km/h on the middle lane. The traffic on these lanes was standardized in all videos. Traffic in the right lane is travelling at 80 km/h. A heavy vehicle is visible in front of the driver’s own vehicle (ego vehicle). No other instruments or mirrors are displayed; the own speed is shown in the lower right corner. In all videos, the speed of the ego vehicle was kept constant at 80 km/h, the distance between the merging vehicle and the ego vehicle is always the same at the time of the vehicle's lane change in the acceleration lane. The distance to the heavy vehicle in front of the ego vehicle is also constant. The merging vehicle accelerates evenly from 50 km/h to 80 km/h in all videos. It reaches the speed of 80 km/h at the time when the lane change is completed. Since the lane change ends at different positions (0 m, 100 m, 200 m before the end of the acceleration lane), the acceleration is different in the three situations. As soon as the merging vehicle changed lanes, the ego vehicle decelerated to restore the safety distance. The deceleration phase was similar in all videos, but not identical since the ego vehicle was controlled manually. After deceleration, the ego vehicle accelerated again to 80 km/h. The length of the videos was 20 - 22 s, starting several meters before the acceleration lane and ending right behind the end of the acceleration lane.

3.3.2 Data collection

Subjects completed an online survey created by the tool LimeSurvey. The survey took about 15 min to complete. The subjects were recruited via the institute's subject database. As an incentive, three 20€ Amazon vouchers were randomly awarded to the participants. The requirement for participation in the study was the possession of a driving licence that allows the operation of passenger cars. Participants were instructed to complete the survey on a tablet or desktop computer and were not allowed to participate on smaller devices such as a mobile phone.

Figure 7. Screenshot from the sample video with an enlarged picture of the cooperation partner with eHMI (Ehrhardt, Graeber, et al., 2023)

The survey began with a request for demographic information such as age, gender, years of holding a driving licence and driving experience (kilometres driven per year). Additionally, the personal attitude towards automated driving was asked (-5 = very negative to 5 = very positive). The subjects were informed about the purpose of the study and the situation was introduced with a demo video. Following the demo video, the subjects had to indicate whether the merging vehicle in the video was an automated vehicle or not to test the understanding of the function of the eHMI.

After the demo, the 18 videos were presented in randomised order. The videos could only be viewed once each, it was not possible to pause them. After each video, two questions were asked as described by Neukum and Krueger (2003). Question 1: "How cooperative was the driver on the acceleration lane?" and question 2: "How critical did you find the situation?". Question 1 was answered on a 10-point scale, which was divided into 5 categories. The categories used were very low (1-2), low (3-4), medium (5-6), high (7-8) and very high (9-10). Question 2 was answered on an 11-point ordinal scale from 0-10. The scale was divided into the categories: nothing noticed

(0), noticeable (1-3), disruptive to driving (4-6) dangerous (7-9) and vehicle no longer controllable (10).

After the videos, the respondents were asked whether they had recognised the automated vehicles in each video. In addition, the question on the attitude towards automated driving was repeated. They were further asked if they expected a difference in behaviour between automated and manual vehicles. If this question was answered affirmatively, the participants had the opportunity to name the expected differences in a field of free text.

3.4 Results

The data set on which the analysis is based comprises 68 subjects (66% male, age range 18–78 years). Inclusion criteria were the complete response to the questionnaire, as well as the positive response to the question whether the subjects hold a driving licence. In addition, nine subjects who incorrectly answered to the control question about automatization following the sample video were excluded. Demographic data are shown in Table 2. Participation in the study did not significantly change attitudes towards automated driving (t (67) = - 0.12, p = 0.91).

Table 2: Means and standard deviations of demographic data (N = 68)

Variable	*M*	*SD*
age	29.53	13.74
years of holding a driver's licence	5.74	5.17
driving experience (in km per year)	6671.03	8068.08
attitude towards automated driving (pre)	1.44	2.68
attitude towards automated driving (post)	1.46	2.63

Note. *M* and *SD* represent mean and standard deviation, respectively

However, the attitude towards automated driving (pre study) correlates significantly with the age of the subjects (r = - 0.38, p < 0.01), the younger the subjects, the more positive their attitude. Furthermore, although participation in the study did not significantly change the subjects' attitudes towards automated driving, the difference in attitudes was correlated with age (r =−0.30, p = 0.012). The older the subjects, the more their attitude changed after the study to the positive.

During the evaluation of the three predictors (duration and position of lane change and status eHMI), a systematic error in the video recording became apparent: In the condition of the fast lane change (2 s) at the middle position (100 m) without eHMI, the ego vehicle braked down significantly more than in the other videos, particularly the corresponding video with status eHMI. Therefore, the status eHMI factor is first considered separately. If the two videos in question are excluded from the analysis, there is no significant difference between the factor levels of status eHMI for both criteria (t cooperation (67) = 1.17, p = 0.245; t criticality (67) = - 0.37, p = 0.716; see Figure 8). Since the factor 'status eHMI' does not show a significant effect and the systematic error occurs in the condition without status eHMI, all following analyses refer to the videos with status eHMI.

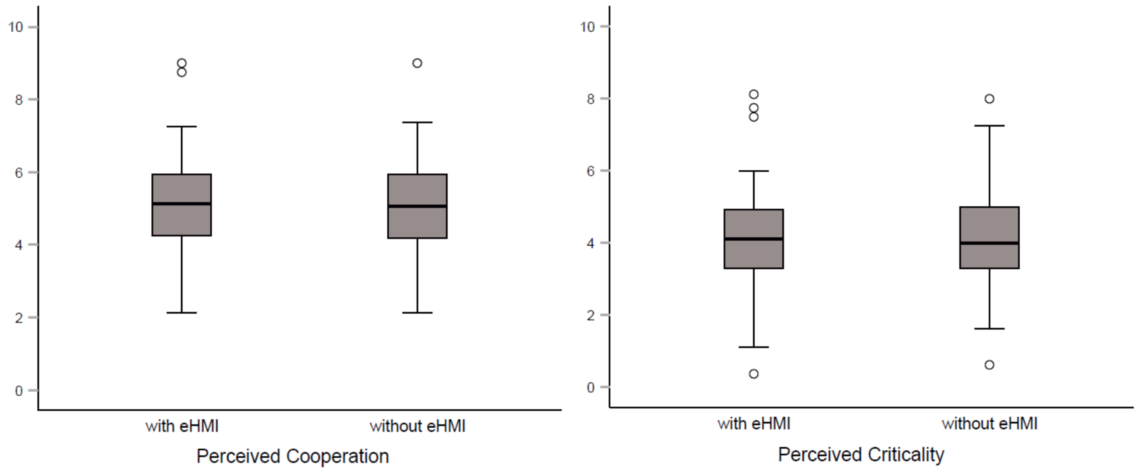

Figure 8. Boxplots of the influence of the eHMI on the dependent variables (Ehrhardt, Graeber, et al., 2023)

The influence of the two means of communication (duration and position of lane change) on the two criteria 'perceived cooperation' and 'perceived criticality' is calculated with two two-factor ANOVAs with repeated measures. Violations of the sphericity are corrected with the Greenhouse-Geisser adjustment. The results of the analysis are shown in Table 3.

Since a semi-disordinal interaction is present, the main effect 'duration of lane change' can be interpreted independently of the interaction effect for both criteria: a slower lane change leads to a more cooperative rating of the driving behaviour. The situation is assessed as less critical (see Table 4). This effect is not dependent on the position of the lane change. Post hoc tests show significant differences for all conditions and both dependent variables: The perceived cooperation for a 2 s and a 4 s lane change differed at $p < .001$ significance level and between 4 s and 6 s at $p = .002$. The perceived criticality differed at a significance level of $p < .001$ for both comparisons.

Table 3: Two-factor ANOVA with repeated measures with perceived cooperation and perceived criticality as the criteria

	Sum of Squares	***df***	***df*$_{error}$**	**Mean Square**	***F***	***p***	**partial η^2**
Perceived cooperation							
duration	543.79	2.00	134.00	271.89	107.58	<.001	.62
position	144.33	1.63	109.19	88.56	24.127	<.001	.27
duration x position	124.34	4.00	268.00	31.09	14.81	<.001	.18
Perceived criticality							
duration	850.27	2.00	134.00	425.13	165.41	<.001	.71
position	206.83	1.79	120.10	115.39	37.81	<.001	.36
duration x position	164.28	3.57	238.83	46.09	18.05	<.001	.21

Table 4: Means and standard deviations of the perceived cooperation and criticality for the duration of lane change (*N* = 68)

	Perceived cooperation			**Perceived criticality**		
Duration of lane change	*M*	*SD*	Category	*M*	*SD*	Category
2s	3,74	1,48	low	5,90	1,63	disruptive
4s	5,37	1,64	medium	3,80	1,55	disruptive
6s	5,97	1,56	medium	3,14	1,45	noticeable

Note. *M* and *SD* represent mean and standard deviation, respectively. The categorisation corresponds to the categories proposed by Neukum & Krüger (2003), which were presented in the questionnaire next to the numerical response option.

The main effect ‘position of the lane change’ can only be interpreted with regard to the interaction. For a fast lane change (2 s), there is an almost linear relationship with the position: If it is performed late (with a 0 m distance to the end of the acceleration lane), it is evaluated as less cooperative and more critical than if it is performed shorter before the end of the acceleration lane (100 m or 200 m). For a medium-fast (4 s) and slow lane change (6 s), however, there is an inverted U-shaped relationship with position: A lane change in the middle of the acceleration lane (100 m) is rated as more cooperative and less critical than an early (200 m) or late (0 m) lane change (see Figure 9).

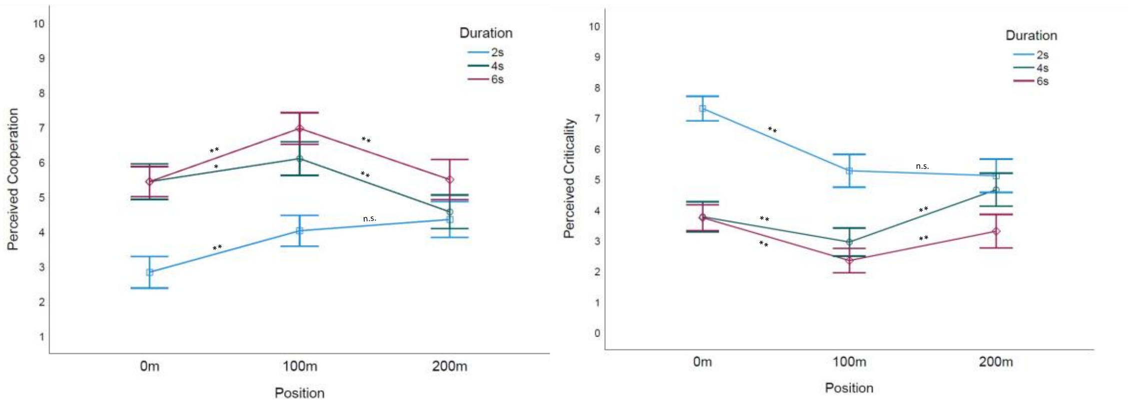

Figure 9. Diagram of the influence of the position of lane change on the dependent variables (Ehrhardt, Graeber, et al., 2023)

In the post-questionnaire, 72 % of the subjects stated that they expect a different behaviour from automated vehicles compared to those controlled by humans. However, the reasons given are controversial: on the one hand, automated vehicles are expected to behave in a more optimised (19 out of 49 inputs) and predictable (14 out of 49) way, while on the other hand, automated vehicles are also expected to behave unexpectedly or to malfunction (11 out of 49).

3.5 Discussion

The results show no significant influence of the eHMI on the evaluation of the situation. In contrary, the duration as well as the position of the lane change significantly influence the evaluation. A slower lane change is perceived as more cooperative and less critical. In the case of a medium-fast and slow lane change, a change in the middle of the acceleration lane is preferred. A fast lane change is perceived as uncooperative and critical, especially at the end of the acceleration lane. Thus, the results of our study are in line with the findings in the literature and our hypothesis. The status eHMI has no significant influence on the evaluation of the interaction, comparable to the results of Joisten et al. (2020) and Schieben, Wilbrink, Kettwich, Dodiya, et al. (2019). This finding suggests that results from studies on the evaluation of human behaviour in road traffic can be used for the development of automated vehicles.

The hypothesis that a faster lane change is perceived as more uncooperative and critical has also been confirmed. This result is consistent with previous findings from research on driving behaviour during an unforced lane change (Kauffmann, Winkler, et al., 2018). Unlike the study by Kauffmann, Winkler, et al. (2018) we were able to show an influence not only on the assessment of cooperativeness, but also on criticality. The duration of the lane change is thus considered more relevant for criticality in a forced lane change than in an unforced one. We assume that the slip road situation is perceived as more critical overall because of the lack of action alternatives. However, a slow lane change gives the rearward cooperation partner more time to react and increase the safety distance. A fast lane change shortens the reaction time, leading to a higher perception of criticality.

A nonlinear relationship is found between the position of the lane change and the evaluation: both an early lane change directly at the beginning of the acceleration lane and a late lane change at the end of the acceleration lane are evaluated as significantly more uncooperative and critical than one in the middle of the acceleration lane. However, this only applies in combination with a medium-fast or slow lane change. The more negative evaluation of the late lane change can be explained by the results of Marczak et al. (2013a) who found that the change at the end of the acceleration lane is considered as more enforced. Due to the lack of alternative actions, the situation is perceived as more critical and less cooperative. An early change, on the other hand, may be perceived as more unexpected and thus more critical and less cooperative.

Most of the subjects in the follow-up survey state that they expect different behaviour from automated vehicles than from manual vehicles. The qualitative evaluations show that most test persons expect optimised and more predictable behaviour from automated vehicles, thus the absence of human errors. The absence of a difference in the evaluation of the behaviour of the vehicles with eHMI, while the general expectations do, allows two conclusions to be drawn: First, one possible explanation for the identical evaluation is that both vehicles acted identically in the situation, and thus no expectations were fulfilled regarding human or technical errors. The evaluation of an irregular behaviour could therefore still be different. And secondly, it can be concluded from the result that in studies on expectations of automated vehicles, the evaluation of specific behaviours must be examined in addition to general expectations.

The present study is subject to some limitations. First, the results are based on the evaluation of video recordings in an online survey. Some of the problems of this study format were countered with control questions. For example, records of subjects who did not correctly answer the question about the presence of eHMI in a test video were excluded. Additionally, a minimum completion time for the questionnaire was set and replaying of the videos was prohibited. Studies also show that the perception of traffic situations in video studies is good (Imbsweiler, 2019). Nevertheless, the results should be replicated in a more realistic setting, such as a driving simulator study. A second limitation is the demographics of the sample: the average age of about 30 years is significantly below the population average. Furthermore, we found a negative correlation between age and attitudes towards automated driving. Since the sample consisted of more young subjects, the opinions of more critical persons are presumably underrepresented as a result. It is also interesting to note that although there is no significant difference in attitudes towards automated driving before and after the survey, the correlation with the age decreases: It is possible that a familiarisation with the topic can improve attitudes towards it, especially among older respondents.

Third, an error in the creation of a video without eHMI prohibited the analysis of the full experimental design. Nevertheless, valuable results could be found by focussing on the eHMI conditions. In addition to validating the results in a realistic setting, future research should address other aspects of implicit communication at motorway entrances: According to the list of Schaarschmidt et al. (2021), the means of driving dynamic communication include lateral movement, which was analysed in the present study, as well as longitudinal movements (braking and accelerating). This aspect should receive more attention in future research.

3.6 Conclusion

From the evaluation of the two implicit driving dynamic communication means "duration" and "position of the lane change", specific recommendations for actions can be derived: Lane changes at slip roads should be performed slowly, as this is perceived as more cooperative and less critical. Furthermore, it should be carried out in the middle of the acceleration lane. This applies especially to vehicles labelled as automated, since we were unable to test the full design regarding manual vehicles. These findings can help to develop automated vehicles whose behaviour is understood and accepted by other road users. Also, the results indicate that in the tested scenario, labelling of automated vehicles has no added value for other road users."

4 Study 2: Implicit communication on the motorway slip road: a driving simulator study

Following the consideration of lateral driving dynamics in the previous study, this study now focusses on longitudinal driving dynamics. Like lateral driving dynamics, these fall under the implicit means of communication that are used in road traffic to indicate one's own intention to manoeuvre (Schaarschmidt et al., 2021). Three means of communication via longitudinal driving dynamics at motorway slip roads were analysed: acceleration, deceleration, and maintaining speed. A driving simulator study was conducted to investigate how cooperative and how critical these behaviours are perceived by their interaction partners. As in Study 1, the appearance of the vehicles was also varied so that the participants assumed they were cooperating with either an MV or an AV. This made it possible to analyse whether the evaluation of AVs differs from the evaluation of MVs. The results can help to adapt the behaviour of AVs to the expectations of other road users and thus increase their acceptance.

The following Subchapters *4.1 Introduction, 4.2 Material and Methods, 4.3 Results, 4.4 Discussion and 4.5 Conclusion* with their respective sub-chapters are full citations form the publication

Ehrhardt, Roß, and Deml (2023). Implicit communication on the motorway slip road: a driving simulator study. In D. de Waard, V. *Hagemann*, L. Onnasch, A. Toffetti, D. Coelho, A. Botzer, M. de Angelis, K. Brookhuis, and S. Fairclough (2023). *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2023 Annual Conference* (pp. 95-106). Available from http://hfes-europe.org (ISSN 2333-4959).

For this purpose, the numbering of the chapters, figures and tables were adapted to the numbering of the thesis. All co-authors of the published article have declared that they will not use the publication in the context of another academic examination.

4.1 Introduction

“The more vehicles feature functions that enable semi-automated driving, the more frequent interactions between human-controlled and (temporarily) automated vehicles will become. Smooth, safe road traffic requires constant communication between all road users. There is now a moderately good understanding of what means of communication drivers use among themselves (for a list, see Schaarschmidt et al., 2021). However, how each is used in specific traffic situations is not yet fully understood. Understanding the importance of the communication tools and how they are evaluated is, however, important to ensure smooth traffic. Furthermore, it needs to be explored whether these communication tools are assessed in the same way in visibly automated vehicles and thus whether there is a transferability from findings regarding human-to-human communication on automated driving. In this paper, the assessment of implicit communication through driving dynamics (e.g., braking and accelerating) is considered in the situation of slip roads. Two research questions are studied: 1. How are different means of communication via driving dynamics evaluated at motorway slip roads? 2. Is this evaluation dependent on whether a vehicle is marked as automated?

4.1.1 Theoretical background

Especially at high speeds, where the time windows for mutual understanding are shorter, effective communication is crucial for safe and efficient driving. As a result, communication at motorways often occurs implicitly, e.g., via driving dynamics, to communicate one’s intentions (Moore et al., 2020; Risto et al., 2017; Schaarschmidt et al., 2021) . Driving dynamics include lateral movements as well as deceleration and acceleration. Human drivers rely on their experience to understand the message in the behaviour of other drivers. However, automated vehicles lack this experience, and it is necessary to implement implicit communication effectively for safe integration into highway traffic (Kauffmann, Naujoks, Winkler, & Kunde, 2018).

Research on the role of driving dynamics for communication purposes has been conducted for different traffic scenarios: In urban traffic, people tend to view slowing down as defensive behaviour, while accelerating or maintaining speed is seen as aggressive (Imbsweiler, 2019). In their naturalistic driving study, accelerating was found to be an unambiguous way to communicate the intention to make a manoeuvre ahead of another vehicle. However, participants rated this as rather uncooperative. Björklund and Åberg (2005) found that when approaching an intersection, maintaining speed and accelerating are associated with driving intention, while slowing down is perceived as yielding. Similar results have been found from a driving simulator study observing a bottleneck scenario: maintaining was understood as intention to drive while reducing speed was understood as yielding (Rettenmaier, Dinkel, & Bengler, 2021b). To identify implicit forms of cooperative behaviour on motorways, (Kauffmann, Naujoks, et al., 2018) investigated the evaluation of different behaviours conducted by the vehicle behind participants that changed lanes in dense traffic. They found that the harder the rear vehicle braked, the more cooperative and less critical the behaviour was perceived by the participants. The study, however, refers to lane changes on motorways which fall into the category of unforced lane changes. However, at motorway slip roads, forced lane changes take place as the acceleration lane ends. Further research is needed to investigate implicit cooperative behaviour during these forced lane changes.

In addition to the evaluation of longitudinal driving behaviour as a means of communication, this work will explore the impact of an external human-machine interface (eHMI). An eHMI which labels a car as automated (status eHMI) can increase acceptance of unexpected behaviour, similar to the markings of driving school cars (Fuest et al., 2020). Studies on the influence of eHMI in different traffic situations show no significant effects on the behaviour and evaluation of participants (Fuest et al., 2020; GATEway Project, 2017; Joisten et al., 2020). In a driving simulator study, no differences in gap size acceptance were found when participants encountered automated vs. manual vehicles (GATEway Project, 2017). And pedestrians in a controlled field experiment did not differ in their crossing behaviour when interacting with a vehicle equipped with a status eHMI. Also, their self-reported perceived safety did not differ significantly (Joisten et al., 2020). However, only the study by Fuest et al. (2020) refers to the interaction of two vehicles on the highway; the other two studies took place in urban traffic. In three different scenarios (road works, traffic jam, lane change) participants followed a car on the highway, which was either labelled as automated by an eHMI or not. The vehicle obeyed the traffic rules but doing so was a deviation from the rest of the traffic. The subjective opinion of the participants on the behaviour of the vehicle and the distance behaviour (Time Headway, THW) was surveyed. No significant influence of the eHMI was found. Yet, in Fuest et al. (2020), no cooperation between the participants and the vehicles with eHMI took place. This paper aims to fill this research gap.

4.2 Material and methods

Four hypotheses were derived from the literature and investigated in the present study:

- H1a. Drivers on the slip road perceive a deceleration of the cooperating vehicle in the right lane as more cooperative and less critical than acceleration and maintaining speed.
- H1b. Drivers in the right lane perceive deceleration of the cooperating vehicle on the slip road as more cooperative and less critical than acceleration and maintaining speed.
- H2a. There is no significant difference in the participants perceptions of cooperation and criticality between manual and automated vehicles with identical behaviour.
- H2b. There is no significant difference in the distance behaviour toward manual and automated vehicles with identical behaviour.

4.2.1 Independent and dependent variables

Three independent variables were investigated in the study: First, the level of automation of the cooperation partner which was manipulated using an eHMI. Participants were instructed that vehicles without eHMI were manually controlled by humans and vehicles with eHMI drove automatically (for information on the eHMI see subchapter "*Setting*"). Secondly, the behaviour of the cooperation partner was varied: After being at the same level as the participants at the beginning of the acceleration lane, they either accelerated, maintained their speed, or braked (for detailed information on cooperation partners' behaviour see subchapter "*Setting*"). Thirdly, the situation was examined from both perspectives; the participants drove onto the motorway themselves and passed another slip road on which a cooperation partner was driving. This resulted in a total of twelve situations (2x3x2), two of which were driven through in each lap of the test circuit. The six resulting test runs were randomised. Each test participant drives through all situations according to a within-subject design.

The dependent variables are perceived cooperativeness and criticality on the one hand and the participants' distance behaviour on the other. The perceived cooperativeness of the other road user was assessed on a seven-point Likert scale according to Imbsweiler (2019). It ranged from "very uncooperative" (1) to "very cooperative" (7). Perceived criticality was represented on an eleven-point scale from (0) to (10), which is derived from Neukum and Krueger (2003). The rating is divided into five categories. A rating of (0) corresponds to the category of nothing noticed, (1-3) falls into the category of noticeability, (4-6) describes an interference with driving, (7-9) classifies the situation as dangerous, and a rating of (10) classifies the vehicle as no longer controllable. The distance behaviour was determined using the "time headway" (THW). It is defined as the distance of the following vehicle to the vehicle in front, divided by the speed of the vehicle behind. It allows a statement about the distance behaviour in relation to the speed driven (Maurer et al., 2015).

4.2.2 Setting

The experiment was conducted in a static driving simulator based on a VW Golf 6 automatic. Unlike the original vehicle, the simulator has a speedometer display and centre console display, and the mirrors have been replaced by displays. A curved screen and three projectors provide a 180-degree field of vision (see Figure 10). The test track was realised with the simulation software SILAB 7.0®.

Figure 10. Driving simulator at Karlsruhe Institute for Technology (Ehrhardt, Roß, & Deml, 2023)

The track was designed as a circuit. The starting point is a country road that leads to a junction and then via an entry to a three-lane motorway. Overgrowth prevents an early view of the flowing traffic before the first cooperative on-ramp situation takes place on the slip road. The route then leads about two kilometres at a speed limit of 120 km/h past an obscured motorway car park, where the second cooperative on-ramp situation occurs. The route then leads along the motorway for a further stretch until an exit leads back onto the country road, the starting point of the route. On both slip roads only one vehicle was present (the participant’s vehicle or the cooperating vehicle). There was also only one vehicle in the right-hand lane in these situations.

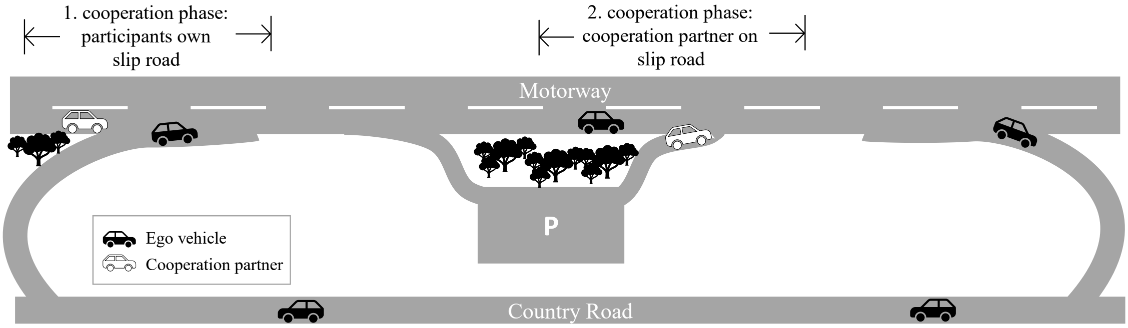

Figure 11. Overview over the track (Ehrhardt, Roß, & Deml, 2023)

Initially, the subjects drive a lap on the circuit without interacting with other road users for familiarisation purposes. For demonstration they drive past a parked vehicle that is marked as automated by eHMI. The eHMI consisted of a surrounding turquoise stripe (see Figure 12). The design was adapted from Wilbrink et al. (2021). Subjects were instructed that this eHMI indicates that the vehicle is driving autonomously.

Figure 12. Screenshot from the simulated cooperation vehicle with eHMI (Ehrhardt, Roß, & Deml, 2023)

Relevant for the study were the two slip road situations during the test drive: The first situation is the slip road of the participants onto the motorway. Here, the participants drive through a long right-hand curve restricted to 70 km/h onto the acceleration lane of the motorway, where a speed limit of 120 km/h applied. A cooperative vehicle is placed in the right lane of the motorway so that it is at the same level and travels at the same speed as the subject. After the two vehicles have been at the same level for about one second and the lane marking between the two lanes allows a lane change, the cooperative vehicle performs one of the following three actions:

- It accelerates from the subject's speed to about 130 km/h.
- It maintains exactly the last speed the subject was travelling at.
- It decelerates to 50 km/h from the initial speed of approx. 80 km/h.

The second relevant situation is when another road user enters the motorway. To guarantee that the participants are in the right lane in this situation, they drive through a stretch of road with little traffic before the car park. At the beginning of the test drive, they are asked to respect the obligation to drive on the right. To make it difficult for the participants to evade into the middle lane, a convoy of three vehicles overtakes shortly before the car park with a significant speed difference and small distance between the individual vehicles. The vehicle on the slip road is positioned to be on the same level as the subject's vehicle and travelling at the same speed. It sets the indicator at the beginning of the lane and then performs one of the following three actions:

- It accelerates to 145 km/h and changes to the right lane at a predetermined point on the acceleration lane in front of the subject.
- It maintains the subject's speed for a further 50 metres. After 75% of the acceleration lane, it brakes sharply and then merges onto the motorway behind the subject.
- It decelerates until it is driving about 15% slower than the participant. Then it changes to the right lane of the motorway.

4.2.3 Procedure

To be included, participants had to hold a valid driving licence to drive a passenger car. The acquisition of participants took place in associations and interest groups close to the university. The participants were first informed about the purpose of the study and informed consent was given. This was followed by the collection of demographic data using the LimeSurvey questionnaire software. During this, the eHMI was introduced as well as the scales for the later rating of cooperativeness and criticality. This was followed by the familiarisation phase in the driving simulator. During the entire drive, the experimenter sat in the passenger seat. At first, the experimenter instructed the participants to adhere to the traffic rules, especially the obligation to drive on the right. This was followed by the test drive, during which the experimenter asked the participants to rate their cooperativeness and criticality after each cooperative situation. Finally, the subjects completed a short post-survey.

4.3 Results

Thirty-six participants participated in the study, four of whom had to discontinue the test due to simulator sickness. Of the remaining 32 participants, ten were female (31%), the mean age of the participants was M = 25.44 years (SD = 3.72) with an average driving experience of M = 7.15 years (SD = 3.58).

4.3.1 First-person perspective of the slip road

First, the perspective of the own slip road is analysed: The two-factor MANOVA with repeated measures showed a statistically significant influence of the cooperation vehicles' behaviour on the combined dependent variables (F (4,28) = 7.97, p < .001, η_p^2 = .533). The behavioural pattern 'accelerating' was rated as significantly more critical compared to 'decelerating' (F (1,31) = 7.60, p = .010, η_p^2 = .197). 'Maintaining speed' was not rated differently from the other two behaviours in terms of criticality (F (1,31) < 1, p = .740, η_p^2= .004; see Figure 13a). Accordingly, 'accelerating' was rated less cooperative (F (1,31) = 13.41, p < .001, η_p^2 = .302) compared to 'decelerating'. Furthermore, 'maintaining speed' was rated significantly less cooperative than 'decelerating' (F (1,31) = 7.48, p = .010, η_p^2 = .194; see Figure 13b).

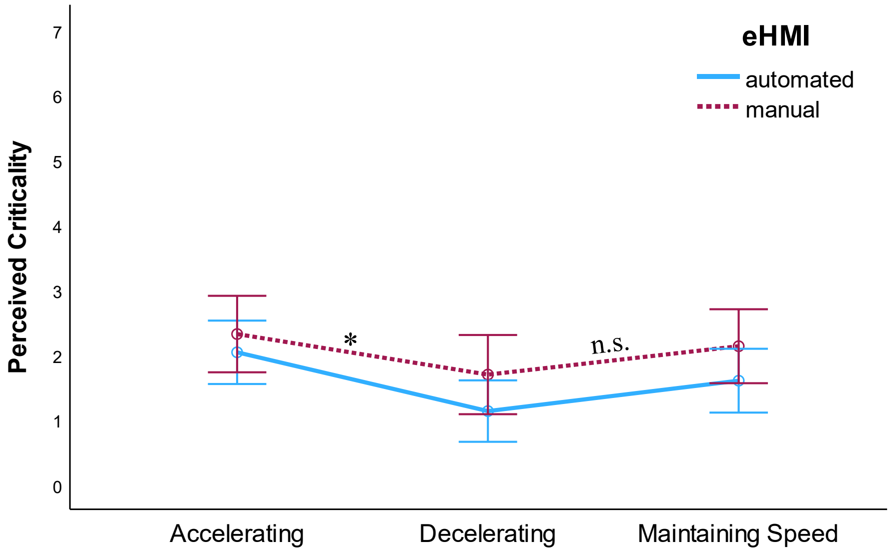

Figure 13a. Influence of the behaviour of the cooperation partner, who was driving on the motorway, on perceived criticality. Circles reflect mean ratings; error bars reflect standard deviations. ** p < .001, * p = .010, n.s. = not significant (Ehrhardt, Roß, & Deml, 2023)

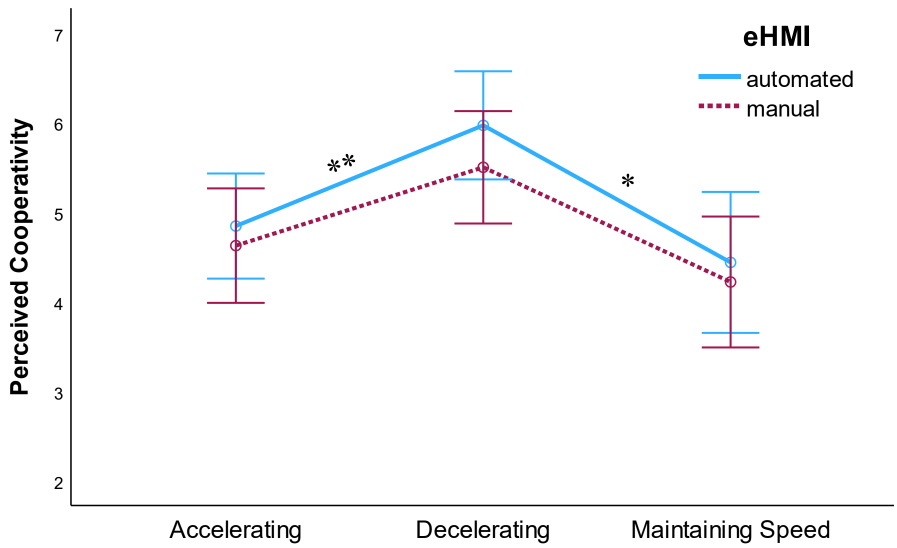

Figure 13b. Influence of the behaviour of the cooperation partner, who was driving on the motorway, on perceived cooperativity. Circles reflect mean ratings; error bars reflect standard deviations. ** p < .001, * p = .010, n.s. = not significant (Ehrhardt, Roß, & Deml, 2023)

Across all behaviours, the behaviour of the vehicle marked as automated via eHMI was rated as less critical (F (1,31) = 8.32, p = .007, η_p^2 = .212). The assessment of the cooperativeness of the partner did not differ significantly between manual and automated vehicles (F (1,31) = 3.13, p = .087, η_p^2 = .092). However, there is no significant interaction effect between the behaviour rating and the presence of the eHMI (F (4,28) = 0.22, p = .924).

4.3.2 Slip Road of the cooperation partner

A significant influence of the cooperation partners' behaviour on the two independent variables is also shown for the cooperation partners' slip road (F (4,27) = 16.97, p < .001, η_p^2 = .715). The behavioural pattern ‘decelerating’ was rated significantly less critical than ‘accelerating’ (F (1,30) = 13.62, p < .001., η_p^2 = .312) and ‘maintaining speed’ (F (1,30) = 20.11, p < .001., η_p^2 = .401; see Figure 14a). The evaluation of the criticality of ‘accelerate’ and ‘maintaining speed’ did not differ significantly (p = .211). The behavioural pattern ‘decelerating’ was rated the most cooperative, significantly more cooperative than ‘accelerating’ (F (1,30) = 16.40, p < .001., η_p^2 = .353). The latter, in turn, was rated significantly more cooperative than ‘maintaining speed’ (F (1,30) = 44.76, p < .001., η_p^2 = .599; see Figure 14b).

In contrast to the slip road from a first-person perspective, for the third-party driveway the degree of automation of the cooperative vehicle has no significant influence on the evaluation of criticality and cooperation (F (2,29) = 0.73, p = .488, η_p^2 = .048). As with own driveway, there is no significant interaction effect between the degree of automation and behaviour (F (4,27) = 0.39, p = .816, η_p^2 = .054).

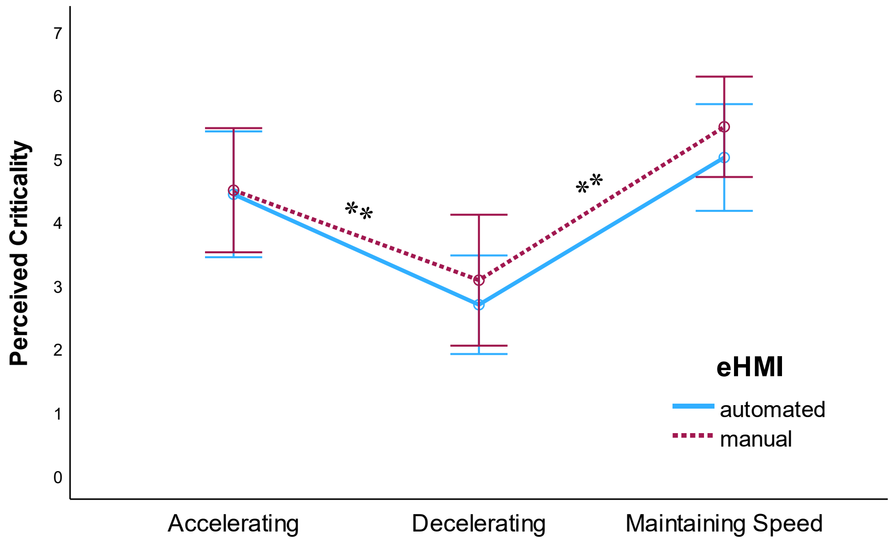

Figure 14a. Influence of the behaviour of the cooperation partner, who was driving on the slip road, on perceived criticality. Circles reflect mean ratings; error bars reflect standard deviations. ** p < .001 (Ehrhardt, Roß, & Deml, 2023)

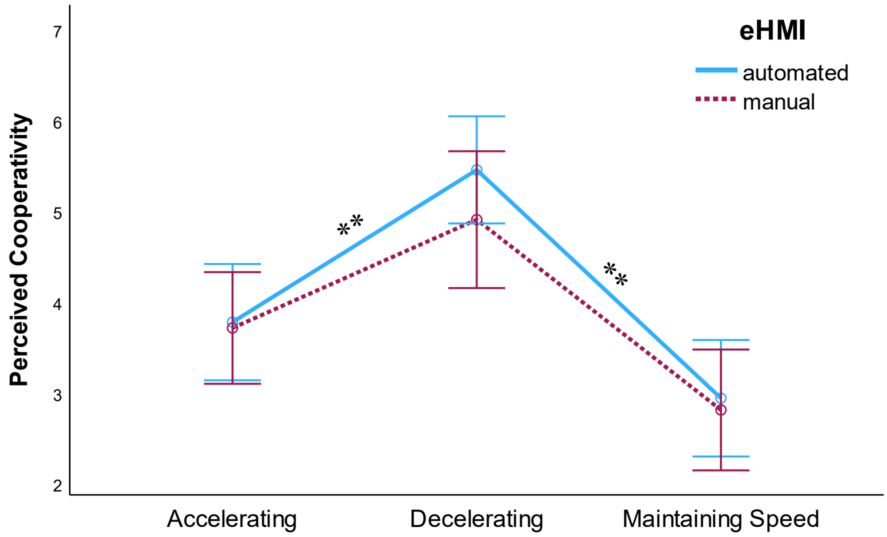

Figure 14b. Influence of the behaviour of the cooperation partner, who was driving on the slip road, on perceived cooperativity. Circles reflect mean ratings; error bars reflect standard deviations. ** p < .001 (Ehrhardt, Roß, & Deml, 2023)

4.3.3 Influence of the eHMI

The influence of the degree of automation indicated by the eHMI on participants' evaluation of the cooperation was already evaluated in the multivariate models for the analysis of behaviour (see earlier subchapters). The analysis showed an influence of the eHMI on the evaluation of the cooperation partner when the subjects were on the slip road themselves, but not when the cooperation partner was on the slip road. In addition to the influence of the eHMI on the participants' evaluation, the influence on their distance behaviour (time headway, THW) was also investigated.

In the case of the motorway slip road from a first-person perspective, there is no significant difference in distance behaviour compared to automated vehicles (F (1, 31) <1, p = .894). However, when the cooperation partner is on the slip road, participants maintain a significantly greater distance from vehicles with eHMI (F (1, 19) = 11.99, p = .003, η_p^2 = .387). From both perspectives, the behaviour of the cooperating vehicle has a statistically significant influence on the THW. When driving on the slip road themselves (F (2, 62) = 44.36, p < .001, η^2 = .589), the greatest distance is kept from vehicles that decelerate (M = 2.01 seconds), a slightly lower distance for the 'accelerate' behaviour pattern (M = 1.44 seconds), and maintaining speed resulted in the lowest THW (M = 0.74 seconds). When the other vehicle was merging (F (1.498, 28.458) = 6.039, p = .011, η^2 = 0.441), only the conditions of 'accelerating' and 'maintaining speed' differed, 'maintaining speed' resulted in significantly greater THW ($M_{\text{accelerate}}$ = 0.47, M_{maintain} = 0.76, p = .002).

4.4 Discussion

The results of the driving simulator study show that the preferred behaviour of the cooperating partner is independent of the factor 'deceleration'. This is perceived as both more cooperative and less critical than accelerating or maintaining speed. A constraint exists for the first-person perspective of the slip road in terms of criticality, as there is no significant difference between "decelerating" and "maintaining speed" here. Hypothesis H1b can thus be accepted, Hypothesis H1a can only be accepted with one constraint. The results are consistent with findings from the literature, according to which accelerating or holding speed were judged as uncooperative and aggressive (Imbsweiler, 2019; Kauffmann, Naujoks, et al., 2018) and signalled the intention to drive (Björklund & Åberg, 2005; Rettenmaier et al., 2021b). In conclusion, at motorway slip roads, the willingness of drivers on the slip road as well as on the right lane to give way to the other vehicle is perceived as more cooperative and safer than speeding up or holding speed to indicate that one wants to drive or merge in front of the cooperative partner. However, this leads to a dilemma: if participants from both perspectives prefer that the cooperation partner brakes and gives way to the other person, only one of the two cooperation partners can act according to that preference. Otherwise, a conflict would arise. To give automated vehicles a concrete instruction for action in this scenario, the next step would be to investigate which behaviour is appropriate if both cooperation partners brake initially. However, the qualitative data show that beyond the preference towards a deceleration or acceleration behaviour, an evasive lane change may be the preferred behaviour.

Secondly, the influence of the eHMI on the evaluation of the behaviour was examined. The evaluation depends on the perspective: If the participants were on the motorway, an eHMI on the merging vehicle had no influence on the evaluation. However, if the participants were on the motorway slip road, the identical behaviour of a vehicle marked as automated was assessed as more cooperative and less critical. Hypothesis 2a is thus rejected; in one out of two situations, the eHMI has an influence on the evaluation of behaviour. This is inconsistent with previous studies, according to which a status eHMI has no influence on the participants' behaviour evaluation (Fuest et al., 2020; GATEway Project, 2017; Joisten et al., 2020). The reasons for the deviation compared to the literature could be that the previous studies partly took place in urban traffic and the criticality of the situation was possibly assessed differently due to the lower speed. And in contrast to Fuest et al. (2020), the behaviour of the cooperating vehicle potentially influenced the participant's own safety, which may have led to the behaviour being analysed in greater detail.

Hypothesis 2b is also rejected: contrary to previous findings (Fuest et al., 2020; GATEway Project, 2017; Joisten et al., 2020), in some cases the eHMI had a significant effect on participants' behaviour. This effect is also dependent on perspective. Participants kept a significantly greater distance from merging vehicles with eHMI than from those without eHMI. There was no difference in distance behaviour when the participants drove onto the motorway themselves. However, the influence of perspective may also result from the situation: When driving onto the motorway themselves, the possibility of increasing the safety distance to the vehicle in the right lane was limited due to the programming of the cooperation partner. Nevertheless, it is worth noting that the behaviour of the participants is not consistent with their evaluation of the cooperation partner. Participants kept a significantly greater distance to oncoming vehicles with eHMI, while they did not rate their behaviour differently. When entering the motorway themselves, the behaviour of the cooperating partners with eHMI was perceived as more cooperative and less critical, but the distance did not differ significantly. This may indicate that subjects' explicit and implicit attitudes toward automated driving differ. Future research should look more deeply into how this divergence can be explained.

4.4.1 Limitations

The present study is subject to some limitations: Although the implementation in the driving simulator allows a high standardisation of the situation, it also leads to a limitation in the external validity. Ultimately, the results have to be validated in real traffic. Secondly, the sample was obtained in a university environment and is not representative of the population in terms of age and level of education. Furthermore, all participants were habituated to German traffic. Studies show a cultural influence on the acceptance of certain driving behaviours (Edelmann et al., 2021) and on the acceptance on automated vehicles in general (Schoettle & Sivak, 2014). The generalisability of the results beyond Germany will be investigated in a following study.

4.5 Conclusion

An important result of the present study is the clear preference for the other vehicle to visibly decelerate, regardless of whether the participants themselves drive onto the motorway or interact with the cooperation partner on the slip road. The influence of the eHMI, on the other hand, is not as clear: it can influence both the participants' evaluation of the behaviour as well as their own behaviour, but not in all situations. The results provide a first basis for the implementation of implicit communication for automated vehicles on motorway slip roads, although further research is certainly needed."

5 Study 3: Comparing implicit communication via longitudinal driving dynamics: A cross-cultural study in Germany and the UK

This study is a replication of the previously presented Study 2, in which longitudinal driving dynamics were investigated as a means of communication at motorway slip roads. The purpose of the replication was to investigate the generalisability of the results beyond Germany. For this purpose, an additional UK sample was collected at the University of Leeds and the results were compared with the results from the German sample.

The comparison between these two countries is particularly interesting because major differences in infrastructure meet great cultural proximity. The biggest infrastructural difference is certainly the right-hand traffic vs. left-hand traffic. The countries also differ in terms of road layout and speed limits. In addition to the infrastructure, however, the accepted driving behaviour in a country is also influenced by cultural aspects (Özkan et al., 2006). The cultural differences and similarities between two countries are illustrated by Hofstede's (2011) cultural dimensions, for example. Germany and the UK show great similarities here: While the two countries have similar to identical values in the dimensions "power-distance", "individualism vs collectivism", "masculinity vs femininity" and "long term orientation", they only differ in the dimensions "uncertainty avoidance" and "indulgence" (Culture Factor Group, 2023).

Despite the differences in infrastructure, this great cultural similarity led us to the hypothesis that the two samples do not differ in the evaluation of implicit communication by means of longitudinal driving dynamics and also in the cooperation partners' perceptions of cooperation and criticality between manual and automated vehicles with identical behaviour. The implications of the results for the development and use of automated driving functions across national borders are discussed.

The following Subchapters *5.1 Introduction, 5.2 Material and Methods, 5.3 Results, 5.4 Discussion and 5.5 Conclusion* with their respective sub-chapters are full citations from the publication

Ehrhardt, Merat, Daly, Solernou Crusat, and Deml (2024). Comparing implicit communication via longitudinal driving dynamics: A cross-cultural study in Germany and the UK. *Transportation Research Part F: Traffic Psychology and Behaviour, 102*, 278-293.

For this purpose, the numbering of the chapters, figures and tables were adapted to the numbering of the thesis. All co-authors of the published article have declared that they will not use the publication in the context of another academic examination.

5.1 Introduction

"Successful communication between all road users is one of the key contributors to safe and smooth road traffic. Communication of drivers can either be explicit (e.g., through indicators, flashing lights or hand signals), or implicit (Ceunynck et al., 2013; Imbsweiler, Ruesch, Weinreuter, Puente León, & Deml, 2018; Y. M. Lee et al., 2021). Implicit means of communication in road traffic primarily include vehicle dynamics, i.e., lateral or longitudinal movements like decelerating or accelerating (Schaarschmidt et al., 2021). In a previous study, the evaluation of these tangential movements for implicit communication at motorway slip roads was investigated, using a sample of German drivers (Ehrhardt, Roß, & Deml, 2023). In addition to using three communicative behaviour patterns (decelerating, accelerating, and maintaining speed), the influence of a status eHMI, that labelled the vehicle as automated, was investigated. The aim of the study was to investigate if participants have different expectations on the implicit communication of automated vehicles than for human drivers. The present study adds one more aspect to these questions, namely that of cultural influence. To this end, the original German study was replicated in the UK and the results from both driving simulator studies are compared in this paper. The findings are aimed at contributing to the design of more human-centred automated vehicles by determining which implicit means of communication are preferred and whether this preference applies equally to manual and automated vehicles. The results are also expected to provide indications as to whether automated vehicles need to have country-specific modes or whether the similarities between at least some countries are similar enough to allow the vehicles to cross national borders without the need for adaptation.

5.1.1 Theoretical Background

The gradual introduction of automated driving is already leading to the presence of partially automated vehicles (AVs; SAE Level 2 or higher) on our roads, sharing the traffic infrastructure with manually controlled vehicles (MVs). This results in a mixed traffic setting. According to Markkula et al. (2020), this mixed traffic will lead to so-called "space-sharing conflicts" between AVs and MVs. Space-sharing conflicts are defined as situations in which "two or more road users are intending to occupy the same region of space at the same time in the near future" (Markkula et al., 2020, p. 736). A particular example of a space-sharing conflict is a motorway slip road. These often include merging path conflicts and represent a critical traffic situation in human-human interactions. At the same time, driving on the motorway is one of the first driving situations where automated driving is possible. In 2021, the first vehicle in Germany received approval for automated driving at SAE Level 3 for the "Drive Pilot" (Mercedes-Benz Group, 2021), an automated assistant for driving on the highway up to 60 km/h. SAE level 3 refers to "conditional driving automation" (On-Road Automated Driving Committee, 2021) and describes a driving function in which the vehicle takes over longitudinal and lateral control, but the driver must be ready to take control at all times. The Operational Design Domain (ODD) of the "Drive Pilot" is currently limited to the motorway itself, while motorway slip roads lie outside the ODD.

5.1.1.1 Communication on motorway slip roads

Communication in road traffic is often described using the Shannon-Weaver model (Shannon & Weaver, 1949), which was originally developed to improve telecommunications. The model can be applied very well to automated driving, as it is used to describe short, directed messages, which are often prevalent in fast-moving traffic. According to the model, a message is encoded by a transmitter, decoded by the receiver, and possibly impaired by noise during transmission. In the case of the motorway slip roads, for example, the vehicle on the slip road is the transmitter, communicating the intention to change lanes behind another vehicle by braking slightly. This signal must be understood and correctly interpreted by the receiver (drivers of adjacent vehicles). Such communication may of course be impaired by poor visibility or distraction of the driver. For automated vehicles to be part of a successful communication with human drivers, they must be able to encode the manually driven vehicle's behavioural intention, as humans do. In addition to the communication just described above via driving dynamics (braking to indicate the intention to perform an action after another person), there are many other means of communication used by humans in road traffic. For a list, see Schaarschmidt et al. (2021).

These means of communication are often divided into implicit and explicit. Hand gestures, headlight flashes or indicators are seen as explicit communication, while driving dynamics (e.g. braking, accelerating) are classified as implicit communication (Ceunynck et al., 2013; Imbsweiler, 2019; Kauffmann, Winkler, et al., 2018; Rettenmaier & Bengler, 2021). According to Y. M. Lee et al. (2021) and Ceunynck et al. (2013), implicit communication is the most commonly used, while explicit communication signs rarely occurred in the examined scenario.

The perception of vehicle dynamics as a means of communication between drivers has mainly been investigated in urban traffic (Björklund & Åberg, 2005; Imbsweiler, 2019; Rettenmaier & Bengler, 2021; Rettenmaier, Dinkel, & Bengler, 2021a). According to Imbsweiler (2019), accelerating or maintaining speed tends to be perceived as an aggressive signal by other road users, whereas braking is perceived as defensive. In a naturalistic driving study, they found that accelerating is understood as a clear signal of the intention to perform a manoeuvre in front of another road user, in this case driving through an intersection before another vehicle. Accelerating is also rated as less cooperative than yielding in unambiguous situations, while being considered more cooperative in complex situations (Imbsweiler, 2019). Other studies also show that accelerating or maintaining speed is associated with the intention to drive (first), while braking is understood as yielding (Björklund & Åberg, 2005; Rettenmaier et al., 2021a). As the studies just mentioned all relate to urban traffic, we will attempt a further approach to implicit communication on motorway slip roads through the following study considering lane changes on the motorway.

In a driving simulator study Kauffmann, Winkler, et al. (2018) investigated the effect of lateral driving dynamics on perceived willingness to cooperate and perceived criticality during lane change on motorways. They found that a slower lane change duration on the motorway is perceived as more cooperative, but the duration of the lane change does not influence drivers' perceived criticality. In this study, the longitudinal acceleration affected drivers' perceived criticality, with a delayed longitudinal acceleration being perceived as more critical. In a second study, the participants changed lanes in heavy traffic and evaluated the behaviour of the vehicle in front of which they were merging (Kauffmann, Winkler, et al., 2018). The more the vehicle in the rear braked when the participants changed lanes, the more cooperative and less critical its driving behaviour was rated. However, both studies relate to unforced lane changes (which are not mandatory but serve the comfort or the maintenance of the speed), while lane changes on motorway slip roads are considered forced lane changes (Balal, Cheu, Gyan-Sarkodie, & Miramontes, 2014).

Using a video-based setup, Ehrhardt, Graeber, et al. (2023) investigated lateral driving dynamics at motorway slip roads, to study the effect of the position and duration of the lane change on the rating of cooperativity and criticality. Results showed that a slow lane change (6 s) is rated as more cooperative and less critical than a quick lane change (2 s). In addition, a lane change in the middle of the acceleration lane is rated most positively.

Stoll, Weihrauch, and Baumann (2020a) investigated the preference for drivers' own longitudinal driving behaviour on motorway slip roads. They found that drivers preferred to decelerate when a vehicle was next to them on the motorway slip road. The original study to this present replication study investigated the other perspective of this situation, namely which longitudinal driving behaviour is preferred in the cooperating vehicle (Ehrhardt, Roß, & Deml, 2023). It was shown that participants on the slip road consider decelerating or maintaining the speed of vehicles which are already on the motorway to be the least critical and the most cooperative. When driving on the motorway themselves, they rated deceleration by vehicles on the slip road as less critical and more cooperative than when the merging vehicles accelerated.

5.1.1.2 Status external human-machine interfaces (eHMIs)

External HMIs are part of the external communication of automated vehicles. Based on their function, they can be divided into four categories (Schieben, Wilbrink, Kettwich, Madigan, et al., 2019): eHMIs in the first category (A) inform other road users about the vehicle's driving mode (also known as status eHMI). The other three categories (B-D) include more active information, such as information about future driving manoeuvres, the AV's perception of the environment and cooperation capabilities. The status eHMI (Category A) is particularly relevant for this paper. Discussions are currently taking place on whether automated vehicles should be required to display such a status display as soon as they are no longer driven by a human (Stilgoe, 2022). One argument in favour of this display status is that automated vehicles cannot always be reliably identified by surrounding traffic even if their driving behaviour deviates (Stanton et al., 2020). The authors suspect that this has a negative impact on road safety, as drivers use implicit means of communication on the road that an automated vehicle may not be able to understand and utilise. They therefore recommend using a status eHMI to enable drivers of manually controlled vehicles in the surrounding traffic to adapt their expectations and their own behaviour to the driving mode of the AVs. Stange et al. (2022) expect long-term effects from status eHMIs. For example, they suggest that continuing interaction with marked AVs can help us to successively build a mental model of their driving behaviour. Creating the right mental model of an AV’s behaviour during space-sharing scenarios would allow drivers of manually controlled vehicles to make more accurate predictions about the AV’s future behaviour and enhancing their situation awareness (Endsley, 1995). On the other hand, some studies that suggest that vehicles labelled as automated could be outsmarted by other drivers, as it is assumed that the AVs act more passively (Liu et al., 2020; Moore et al., 2020).

In view of this discussion, it is important to understand how a status eHMI from an AV affects other road users' response and behaviour. A number of studies have considered the effect of such status eHMI on the perception and behaviour of vulnerable road users, such as pedestrians and cyclists (Faas et al., 2020; Hagenzieker et al., 2020; Lundgren et al., 2017). For example, Faas et al. (2020) showed that a status eHMI resulted in pedestrians feeling significantly safer when interacting with an AV and indicating more positive ratings of trust and user experience, than when the eHMI was absent. However, results are missed and other studies have failed to find such effects, especially in relation to the evaluation and behaviour by other drivers (Ehrhardt, Graeber, et al., 2023; Fuest et al., 2020; GATEway Project, 2017; Stange et al., 2022).

For example, using a driving simulator study, Stange et al. (2022) investigated the effect of different penetration rates of AVs and the influence of a status eHMI on perceived safety, comfort, and perceived efficiency, as well as measuring drivers' average speed and minimum time headways. The results showed that, although the status eHMI helped drivers identify the automated vehicles in traffic, it had no influence on the subjective ratings or driving behaviour of the participants. In another driving simulator study (Fuest et al., 2020), participants followed a lead vehicle through three scenarios (roadworks, traffic jam, lane change). The lead vehicle was either labelled as automated with a status eHMI or non-automated. Regardless of the eHMI it strictly adhered to the traffic rules throughout the journey, making it stand out from the surrounding traffic. The eHMI had no significant influence on the subjective assessment of driving behaviour or distance behaviour (Time Headway, THW). Similarly, other studies did not find an effect of an eHMI on factors like gap acceptance (GATEway Project, 2017) or on the perceived criticality and perceived cooperation (Ehrhardt, Roß, & Deml, 2023). However, the latter found that in one of the two examined situations, the participants kept a significantly greater safety distance to vehicles with eHMI.

5.1.1.3 Intercultural Aspects

Vehicles in general, but also automated vehicles, are usually not only used in the country in which they were originally manufactured, but also (e.g. for holiday trips or through sales) in neighbouring countries or even around the world. The two countries analysed, the UK and Germany, have close relations, but at the same time differences exist in terms of infrastructure (e.g. left-hand vs. right-hand traffic). The question therefore arises as to whether the similarities or differences in traffic conditions and culture outweigh and whether automated vehicles could operate in the two countries without programming adjustments. The selected countries are very well suited to answering the question in that there is a high degree of cultural similarity, whereas apparent differences exist in the infrastructure. If cultural proximity outweighs differences in infrastructure, communication in countries with similar cultural proximity and smaller differences in infrastructure should be even more similar and, by implication, the implicit external communication of automated vehicles should also work in neighbouring countries.

Differences in road traffic between countries can be attributed to various causes. One aspect is the different infrastructure in different countries. The main difference in the road layout between Germany and the UK is obvious: in Germany, vehicles drive on the right, in the UK on the left. This results in the layout being mirrored. The structure of motorway slip roads differ beyond this aspect in that they are generally single-lane and often curved in Germany. In the UK, they mostly have two lanes and a straighter layout. The speed on motorways also differs between the two countries. In the UK a speed limit of 70 mph (approx. 114 km/h) applies, whereas in Germany there is no general speed limit on motorways, but a recommended speed of 130 km/h (approx. 81 mph).

However, this is only part of the picture, as in addition to infrastructural aspects, the culture of traffic significantly influences what is considered acceptable driving behaviour (Özkan et al., 2006). In psychological and sociological research, cultural differences are often classified according to the cultural dimensions of Hofstede (2011): Six relevant cultural dimensions are used to categorise a country's culture: (1) power-distance, (2) individualism vs collectivism, (3) masculinity vs femininity, (4) uncertainty avoidance, (5) long term orientation, and (6) indulgence. The UK and Germany have very similar or even identical values in four of the scales. They differ in the two scales "uncertainty avoidance" and "indulgence" (Culture Factor Group, 2023). Germany has a substantially higher score in "uncertainty avoidance", which is reflected in a greater need for control and less flexibility. This is also apparent in the road traffic regulations of the two countries, with Germany’s being much more detailed and extensive than the UK’s. “Indulgence” is much more pronounced in the UK than in Germany, which means that there is a greater tendency in this culture to act on impulse, to be optimistic, and to enjoy pleasure and leisure (Culture Factor Group, 2023).

While intrinsic (e.g. age or gender) and extrinsic factors such as formal traffic rules, as well as informal norms influence driving behaviour (Edelmann, Stümper, & Petzoldt, 2021; Özkan et al., 2006; Tennant et al., 2021), we do not anticipate differences in these factors between Germany and the UK, given their geographical proximity and similar scores in Hofstede's dimensions. None of the studies analysed the difference in traffic culture between the UK and Germany, but the following individual aspects are of relevance to the present study: German road culture places a high value on safety on the one hand (Wang, Cheng, Li, André, & Jiang, 2019), but also on individual freedom on the other. This can be observed in the widespread resistance to a general speed limit for motorways. British drivers score very low in terms of aggressive offences on the road, but are more likely than other countries to be guilty of “speeding on the motorway” and “pulling out, and forcing your way out” (Özkan et al., 2006). Beyond the aspects named above, culture not only has an influence on driving behaviour and road safety, but also on the perception of automated driving (Edelmann et al., 2021; Tolbert & Nojoumian, 2023). However, no comparison was made between the UK and Germany here.

The aim of the study was to investigate whether differences between the two countries exist in the evaluation of implicit means of communication on motorways. Even though some of the studies mentioned above suggest that differences may be found, due to the high similarity in the Hofstede dimensions and the geographical and cultural proximity, we hypothesise no differences in the results of the two samples.

5.1.2 Hypotheses

The following hypotheses were derived from the literature, whereby hypotheses H1 & H2 were adapted from the German to the UK study (cf. Ehrhardt, Roß, & Deml, 2023):

- H1a. Drivers on the slip road perceive a deceleration of the vehicle in the nearside lane as more cooperative and less critical than acceleration and maintaining speed.
- H1b. Drivers in the nearside lane of the motorway perceive deceleration of the merging vehicle on the slip road as more cooperative and less critical than acceleration and maintaining speed.
- H2a. There is no significant difference in the cooperation partners’ perceptions of cooperation and criticality between manual and automated vehicles with identical behaviour.
- H2b. There is no significant difference in the distance behaviour towards manual and automated vehicles with identical behaviour.
- H3. There are no differences in the result profiles between the German and UK samples.

5.2 Material and methods

The current study is a replication of the study previously published in Ehrhardt, Roß, and Deml (2023) in which a German sample of drivers were recruited. An ethics approval for both studies was obtained from the Ethics Council of the Karlsruhe Institute of Technology. The results from the original study are used to assess the effect of cultural differences on the dependent variables. In the following section, the methodology of data collection in the UK is described, differences to the methodology in Germany are discussed in 5.2.7.

5.2.1 Participants

Participants were recruited via the institute's own database, and through various local Facebook groups. Inclusion criteria were possession of a UK driving licence, fluency in English and an age range of 20-40 years. The last condition was chosen to match the German sample. A power analysis performed with G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) based on the effect sizes of the original study resulted in a target sample size of 28 participants.

Data from 27 participants in the UK sample were included in the analysis. Four participants were female (15%) and 19 were male (85%). The original study from Germany included 32 participants, of whom ten (31%) were female (Ehrhardt, Roß, & Deml, 2023). Descriptive statistics of both samples can be found in Table 5. Sample differences were calculated using a t-Test.

Table 5: Means and standard deviations of demographic data for both samples.

Variable	UK Sample (*N* = 27)		German Sample (*N* = 32)		Differences
	M	SD	M	SD	p
Age	26.07	5.42	25.44	3.72	.600
Driving licence possession (in years)	6.74	4.97	7.15	3.58	.715

Note. *M* and *SD* represent mean and standard deviation, respectively.

5.2.2 Setting

Data from the UK sample was collected in the University of Leeds Driving Simulator (UoLDS). The simulator consists of a Jaguar S-Type in a spherical projection dome with a projection angle of 300° (see Figure 15). In addition, the wing mirrors are equipped with screens. Furthermore, the simulator has a motion system with eight degrees of freedom. However, this was not used in the study to ensure compatibility with the study using the German sample. At the KIT in Germany, on the other hand, a static driving simulator based on a VW Golf 6 automatic was used, which features a modernised digital speedometer display. A curved screen and three projectors provide a 180-degree field of vision, while the view to the rear is made possible by displays in the mirrors (see Figure 15). For a more detailed description of the setup in Germany, please see Ehrhardt et al. (2023).

Figure 15. University of Leeds Driving Simulator (UoLDS; left) and KIT Driving Simulator (right) (Ehrhardt, Merat, et al., 2024)

Each test run consisted of two individual scenarios. The first began on the slip lane of a motorway junction, from where the participants merged into the traffic on the three-lane motorway. The first cooperation situation with a drone car took place during the merging situation. The "drone car" is the vehicle whose behaviour and appearance were manipulated for the purpose of the study and with which the participants interacted at the slip roads. After approximately 2 km (1.2 miles) on the motorway, the participants passed an exit slip road and then 1.3 km (0.8 miles) later reached a second entry slip road on which a drone car was located. The second cooperation took place as the second drone car drove along the slip road onto the motorway. The participants were instructed to stay in the nearside lane of the motorway to ensure the interaction. Additionally, traffic adapted to the speed of the participants prevented them from changing to the adjacent lane. Shortly after this situation, the scenario ended with a grey screen. For an overview of the test track, see Figure 16. As there were 2 x 3 x 2 independent variables overall (see 5.2.3), each participant completed 12 scenarios over six runs.

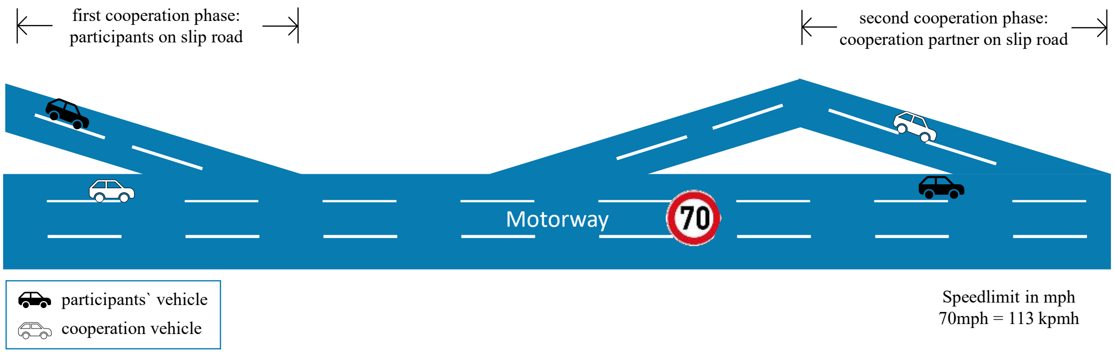

Figure 16. Overview of the test track (Ehrhardt, Merat, et al., 2024)

5.2.3 Independent Variables

To test the hypotheses, three independent variables were manipulated: the participants perspective, the behaviour of the cooperation partner and the presence of labelling of the automated vehicle with a status eHMI. In addition, the study was conducted with samples from two countries (Germany and the UK) to investigate the cultural influence on behaviour assessment, resulting in a 2 x 3 x 2 x 2-Design.

5.2.3.1 Perspective

Motorway slip roads are experienced by drivers from two perspectives: firstly, they use them to join the flowing traffic on the motorway themselves. Secondly, on a longer journey on the motorway, drivers pass many other slip roads on which there may be other vehicles that want to merge into the driver's lane. Their expectations and motivation may differ in these two situations. In this study, each participant first merged from the slip road onto the motorway while interacting with an approaching car in the left lane. After a stretch on the motorway, they passed another slip road, from which a car drove onto the participant’s lane. Thus, both perspectives on a motorway slip road were covered: their own slip road as well as the slip road of another vehicle while driving in the left lane of the motorway (in the German sample, the participants were on the right lane, of course, due to right-hand traffic). Because of the layout of the test track, this independent variable was not randomised; the participants experienced the two perspectives alternately, starting with their own slip road.

5.2.3.2 Behaviour

Three longitudinal communication behaviours emerge from the literature, which are associated with different behavioural intentions and were perceived as different desirable in previous studies. We therefore manipulated the behaviour of the vehicles with which the test subjects interacted at the slip roads in three ways: the vehicles accelerated, maintained the participants speed, or decelerated. In each of the three conditions, the drone car initially matched its speed to that of the participants so that they travelled side by side for a certain distance until a decision point. From the decision point, the behaviour varied as shown in Table 6. The decision point was at the end of the right (offside) lane of the two-lane slip road, at the first position where the lane change becomes possible. The three behaviour patterns were completely randomised between participants.

5.2.3.3 eHMI

In addition to the behaviour of the drone cars, their appearance was also manipulated: An external status HMI (eHMI) was added in the form of a surrounding turquoise light band (see Figure 17). Previous studies suggest that these status eHMI do not influence the participants evaluation of and behaviour towards the labelled vehicles (Ehrhardt, Graeber, et al., 2023; Fuest et al., 2020; GATEway Project, 2017; Stange et al., 2022). Confirmation of these results is important both for the political decision for or against mandatory labelling and for the question of whether the results of research on human interaction behaviour can be used in the development of automated vehicles. Following Maurer et al. (2015), this light band was to indicate that the vehicle was in automated driving mode. Vehicles without eHMI were equivalent to human drivers. The participants were instructed about the meaning of the eHMI before the start of the study and were shown sample images of vehicles with and without status eHMI. They were instructed that these labelled vehicles are not controlled by humans, but entirely by an automated system. The display of the eHMI was randomised, with either the first half (1-6) or the second half (7-12) of the scenarios being run with eHMI.

Table 6: Behaviour of the drone cars on the nearside lane of the motorway and the slip road, respectively.

	Participant on slip road	**Participant on nearside lane, passing a slip road**
Accelerating	Accelerate to 130 km/h (approx. 80 mph)	Accelerate to 130 km/h, then join the nearside lane of the motorway at the end of the slip road
Maintaining Speed	Maintain participants' speed (speed at the decision point)	Maintain the participants' speed (speed at the decision point), then join the nearside lane of the motorway at the end of the slip road
Decelerating	Decelerate to 50 km/h (approx. 31 mph)	Decelerating to 50 km/h, then join the nearside lane of the motorway at the end of the slip road

Figure 17. Drone car on the nearside lane of the motorway with eHMI (Ehrhardt, Merat, et al., 2024)

5.2.4 Dependent Variables

To measure the evaluation of the drone cars' behaviour, two subjective and one objective dependent variable were captured. After each scenario, the participants were asked to rate the criticality of the situation on an eleven-point Likert scale from (0) "not at all critical" to (10) "extremely critical", based on Neukum and Krueger (2003). The rating is divided into five categories. A rating of (0) corresponds to the category "nothing noticed", (1-3) falls into the category "noticeable", (4-6) describes impaired driving, (7-9) classifies the situation as dangerous and a rating of (10) describes the vehicle as no longer controllable. They were also asked to rate the cooperativeness of the interaction partner. This was done on a seven-point Likert scale from (1) "very uncooperative" to (7) "very cooperative" as defined by Imbsweiler (2019). The participants completed the rating verbally via radio while they continued driving. The scales were presented to the participants during the pre-questionnaire and the experimenter repeated the respective scale each time the rating was requested.

As an objective measure, the time headway (THW) was analysed. THW was calculated by dividing the distance between the two vehicles at the time of the lane change by the participant's speed (Maurer et al., 2015). It allows a statement about the safety distance maintained in relation to the speed driven.

5.2.5 Collection of descriptive data

In addition to age, sex and driving experience (possession of a driving licence in years), technical affinity, the attitude towards automated driving and the driving style were measured in a pre-questionnaire before the test drive. To capture technical affinity, the validated “TA-EG” questionnaire (Karrer, Glaser, Clemens, & Bruder, 2009) was adapted to reflect the affinity for assistance systems in motor vehicles. The number of items was reduced by selecting two questions from the four item categories (enthusiasm, complexity, positive attitude, negative attitude) to facilitate adaptation to the narrower topic of "driver assistance systems". The internal consistency of the shortened questionnaire is satisfying, with Cronbach’s alpha = .70.

Agreement on these questions is asked on a seven-level Likert scale from (1) “strongly disagree” to (7) “strongly agree”. The attitude towards automated driving was recorded with the item “What is your general attitude towards automated driving?” The 7-point Likert scale ranged from (1) “very negative” to (7) “very positive”. Driving style was collected in the self-report, whereby the participants were asked to rate their own driving style on a scale from (1) “very calm” to (7) “very sporty”.

After driving in the driving simulator, the participants were given a short post-questionnaire. They were asked which of the three behaviours they would prefer in the two perspectives by choosing one of the three behaviours as the one they would like to see most in the other vehicle.

5.2.6 Procedure

Upon arrival, the participants were informed about the procedure and purpose of the study and gave their informed consent for data collection. Subsequently, the demographic data was collected, and the participants were instructed about the function of the eHMI. In addition, the scales for evaluating the driving situations were presented. In the simulator, the participants first drove a familiarisation phase during which the experimenter sat in the vehicle with them to answer any questions that arose. This phase was approx. 10 min long. The experimenter then left the simulator dome, allowing the participant to drive in isolation, although they were in contact with the experimenter by radio, when required. These were used to query the rating after each interaction situation. After the experiment, participants answered the follow-up questionnaire and received £10.

5.2.7 Intercultural aspects and disparities in study execution

Probably the most significant difference between the two data collections is that Germany has right-hand traffic, whereas the UK has left-hand traffic. For this reason alone, the simulated test tracks differed. In addition, routes were created in the respective simulations according to the valid road layout specifications. Also, different speed limits applied to take account of country-specific circumstances: In the German study, a speed limit of 130 km/h (approx. 81 mph) applied, in the UK study a speed limit of 70 mph (approx. 113 km/h). In addition to the country-specific differences in road traffic, there are also variations due to the technical realisation of the two driving simulators, but care was taken to achieve the greatest possible similarity in the simulation. Due to a technical limitation, the circuit realised in the German study could not be implemented in the UK simulator, so the circuit was divided into six individual scenarios. A final country-specific difference can be found in the wording of the questions. These were translated with great care, but a slightly different understanding of the questions cannot be ruled out.

5.2.8 Data Analysis

Due to the confounding of the variable "country" described in 5.2.7, the data are not analysed in a joint analysis, but separately and the results of the two analyses are contrasted. We present the results of two separate two-factor MANOVAs for the two perspectives, each compared to the results of the German sample.

5.3 Results

Besides gender (see 5.2.1), the UK sample differed from the German sample in technical affinity and the attitude towards automated driving: Both variables had significantly lower values in the British sample (see Table 7). Sample differences were calculated using a t-Test. However, there is no significant gender difference in the attitude towards automated driving (t (57) = 0.13, p = .894, d = 0.04) or technical affinity (t (57) = 1.31, p = .197, d = 0.40). The self-reported driving style did not differ significantly between the samples. There is also no significant gender effect (t (57) = 2.00, p = .051, d = 0.61).

Table 7: Means and standard deviations of demographic data for both samples.

Variable	UK Sample (N = 27)		German Sample (N = 32)		Differences	Effect Size
	M	SD	M	SD	p	d
Technical Affinity	4.46	0.94	5.06	1.04	.036	0.56
Attitude towards automated driving	4.30	1.46	5.28	1.22	.007	0.74
Driving style	3.19	0.96	3.44	1.34	.418	0.73

Note. *M* and *SD* represent mean and standard deviation, respectively. Technical affinity, attitude towards automated driving and driving style were measured on 7-point-likert scales from 1 to 7.

5.3.1 First-person perspective of the slip road

5.3.1.1 Subjective Measures: perceived criticality & perceived cooperation

The influence of the behaviour of the vehicle on the nearside lane while the test persons were driving on the slip road and the influence of the presence of a status eHMI on the evaluation by the participants was investigated using a two-factor MANOVA (see Table 8). There is neither a significant effect of the two predictors "eHMI" and "behaviour" on the dependent variables "perceived criticality" and "perceived cooperation", nor is the interaction of the predictors significant. However, a significant difference emerges in the post hoc tests: "Maintaining Speed" was rated as significantly less cooperative than the other two behaviours. The criticality rating, though, does not differ significantly. This result differs from the results of the German sample, for which accelerating of the cooperation partner was rated as significantly more critical than decelerating, while maintaining speed was rated similar to decelerating (see Figure 18). In addition, deceleration was assessed as significantly more cooperative than the other two behaviours (see Figure 19). In both samples, there are no significant differences between the two eHMI conditions for the three behaviours investigated.

Table 8: Two-factor MANOVA with repeated measures with perceived criticality and perceived cooperation as the criteria for the first-person perspective on the slip road in the UK sample.

	Sum of Squares	***df***	***df***	**Mean Square**	***F***	***p***	**partial η²**
				Perceived criticality			
Main Effects							
eHMI	0.22	1	26	0.22	0.02	.879	.001
behaviour	16.09	2	52	8.04	1.78	.179	.064
eHMI x behaviour	3.59	2	52	1.80	0.55	.580	.021
Post Hoc Tests							
Accelerating x Decelerating	1.82	1	26	1.82	0.31	.585	.012
Decelerating x Maintaining Speed	15.57	1	26	15.57	5.11	.096	.164
Maintaining Speed x Accelerating	6.75	1	26	6.75	1.48	.472	.048
				Perceived cooperation			
Main Effects							
eHMI	2.47	1	26	2.47	0.71	.406	.027
behaviour	25.15	2	52	12.57	2.54	.089	.089
eHMI x behaviour	1.86	2	52	0.93	0.33	.723	.012
Post Hoc Tests							
Accelerating x Decelerating	4.90	1	26	4.90	0.88	.526	.033
Decelerating x Maintaining Speed	25.04	1	26	25.04	7.40	**.033**	.222
Maintaining Speed x Accelerating	7.79	1	26	7.79	1.31	.526	.048

Note. p-Values of the post hoc tests are corrected for alpha-Error by Bonferroni-Holm correction (Holm, 1979).

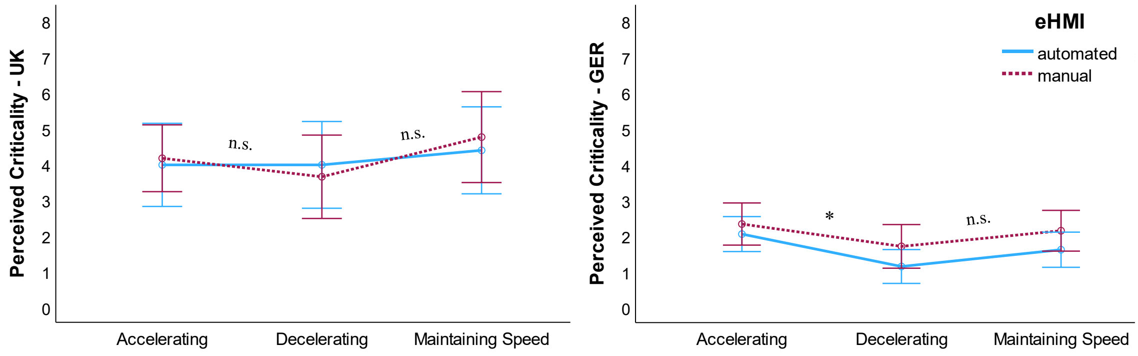

Figure 18. Influence of the behaviour of the cooperation partner, who is driving on the motorway, on perceived criticality for the UK sample (left) and German sample (right). Circles reflect mean ratings; error bars reflect standard deviations. Significance information refer to the differences between the behaviours. * p < .05, n.s. = not significant. (Ehrhardt, Merat, et al., 2024)

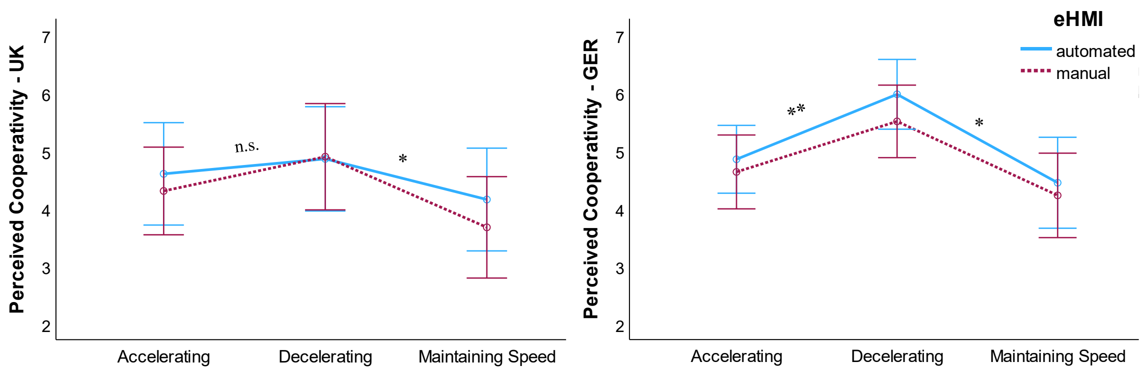

Figure 19. Influence of the behaviour of the cooperation partner, who is driving on the motorway, on perceived cooperativity for the UK sample (left) and German sample (right). Circles reflect mean ratings; error bars reflect standard deviations. Significance information refer to the differences between the behaviours. ** p < .001, * p < .05, n.s. = not significant. (Ehrhardt, Merat, et al., 2024)

5.3.1.2 Objective Measure: Time headway

The eHMI has no significant influence on the time headway (THW) during the participants first-person perspective of the slip road (see Figure 20). This applies to both the UK sample (t (24) = -1.09, p = .285) and the German sample (t (31) = 0.13, p = .894). The THW also does not differ significantly between the two countries ($t_{\text{automated}}$ (56) = -1.93, p = .059; t_{manual} (55) = -1.01, p = .319). One accident (THW = 0) was recorded during the study in the UK, however, when interacting with a vehicle with eHMI that showed the "acceleration" behaviour. No accidents were recorded in the German study. Both samples have a reduced number of degrees of freedom for analysing the THW, as the THW could only be calculated if the ego vehicle and the drone car were directly in front of or behind each other after the lane change.

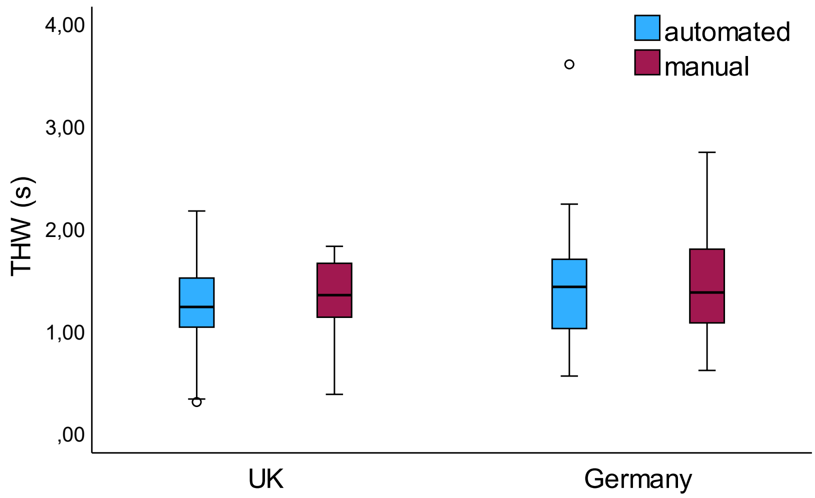

Figure 20. Time Headway (THW) for the first-person perspective on the slip road, divided after the eHMI condition. (Ehrhardt, Merat, et al., 2024)

5.3.1.3 Position of the participant

The position of the participants after the lane change (in front of or behind the drone car) is shown in Figure 21. In the German sample, the results are unambiguous: the participants always merged behind accelerating drone cars and in front of decelerating drone cars. If the drone car maintained its speed, the participants merged in front of the drone more often than behind it. There are no relevant differences due to the eHMI. In the UK sample, on the other hand, some participants merged in front of the accelerating drone and behind the decelerating drone car. In addition, more participants in the UK than in the German sample decided to merge behind a drone that maintained its speed. A noticeable eHMI-related difference can be observed for this behaviour in the UK sample: If the vehicle was marked as automated, the participants drove in front of the drone vehicle more often.

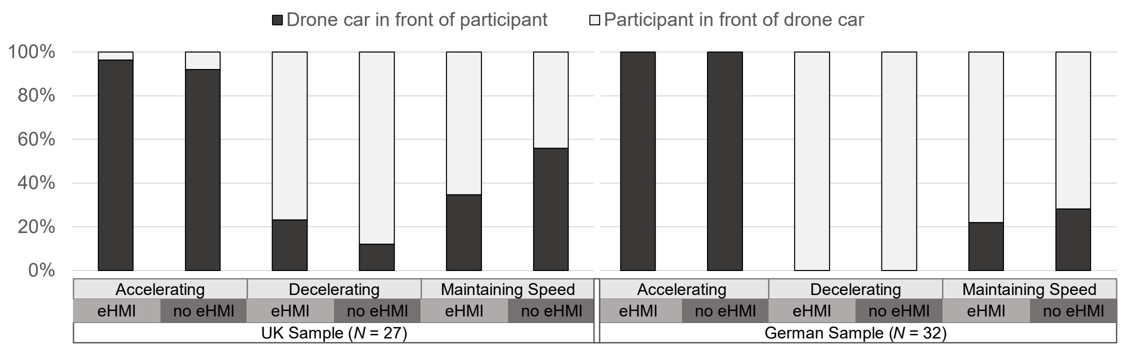

Figure 21. Position of the participant after the lane change for the first-person perspective on the slip road for both samples (Ehrhardt, Merat, et al., 2024)

5.3.2 Slip road of the cooperation partner

5.3.2.1 Subjective Measures: perceived criticality and perceived cooperation

The second analysis regards the other perspective on motorway slip roads, where the participants are in the nearside lane of the motorway while a drone car is next to them on the slip road. The eHMI has no significant effect on perceived criticality, but it does influence perceived cooperativity (see Table 9). Vehicles with eHMI are rated as significantly more cooperative under identical behaviour. Post-hoc tests show that this significant main effect can only be attributed to the "maintaining speed" condition (t (26) = 1.84, p = .039). The difference is not significant for the other two behavioural patterns. The main effect of behaviour is significant for both dependent variables. The post-hoc tests show that this is the result of the behavioural pattern "decelerating" being rated as significantly less critical and significantly more cooperative than the other two behaviours. There is no significant difference between maintaining speed and accelerating. The results for this perspective are in line with the results from the German sample (see Figure 22 & 23).

Table 9: Two-factor MANOVA with repeated measures with perceived criticality and perceived cooperation as the criteria for the slip road of the cooperation partner in the UK sample.

	Sum of Squares	***df***	***df*_{error}**	**Mean Square**	***F***	***p***	**partial η²**
				Perceived criticality			
Main Effects							
eHMI	5.93	1	26	5.93	2.00	.169	.071
behaviour	419.27	2	52	209.64	35.20	**<.001**	.575
eHMI x behaviour	2.83	2	52	1.41	0.36	.699	.014
Post Hoc Tests							
Accelerating x Decelerating	240.01	1	26	240.01	48.10	**<.001**	.649
Decelerating x Maintaining Speed	374.08	1	26	374.08	76.48	**<.001**	.746
Maintaining Speed x Accelerating	14.82	1	26	14.82	1.86	.185	.067
				Perceived cooperation			
Main Effects							
eHMI	8.00	1	26	8.00	4.95	**.035**	.160
behaviour	268.15	2	52	134.57	42.88	**<.001**	.623
eHMI x behaviour	0.93	2	52	0.46	0.27	.767	.010
Post Hoc Tests							
Accelerating x Decelerating	222.45	1	26	222.45	95.92	**<.001**	.787
Decelerating x Maintaining Speed	178.90	1	26	178.90	43.33	**<.001**	.625
Maintaining Speed x Accelerating	2.37	1	26	2.27	0.80	.380	.030

Note. p-Values of the post hoc tests are corrected for alpha-Error by Bonferroni-Holm correction (Holm, 1979).

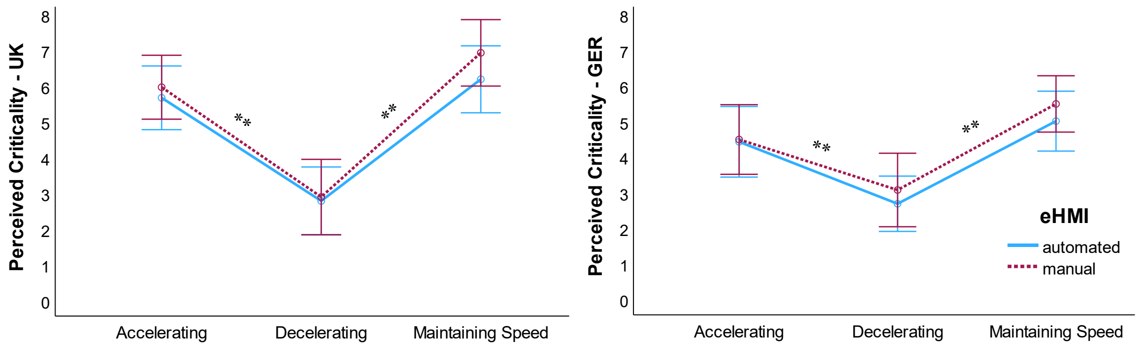

Figure 22. Influence of the behaviour of the cooperation partner, who is driving on the slip road, on perceived criticality for the UK sample (left) and German sample (right). Circles reflect mean ratings; error bars reflect standard deviations. Significance information refer to the differences between the behaviours. ** p < .001 (Ehrhardt, Merat, et al., 2024)

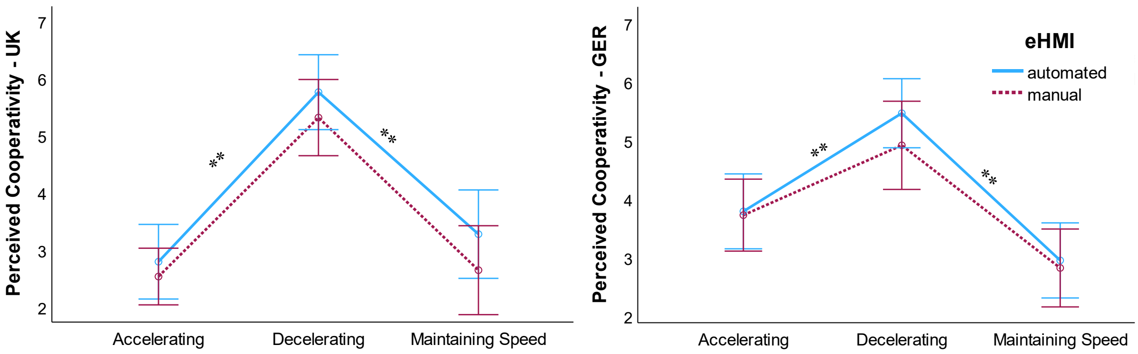

Figure 23. Influence of the behaviour of the cooperation partner, who is driving on the slip road, on perceived cooperativity for the UK sample (left) and German sample (right). Circles reflect mean ratings; error bars reflect standard deviations. Significance information refer to the differences between the behaviours. ** p < .001 (Ehrhardt, Merat, et al., 2024)

5.3.2.2 Objective Measure: Time headway

While the eHMI has no influence on the THW in both samples in the first-person perspective, there is a significant difference in this perspective, but only for the German sample (t (19) = 3.46, p = .003; see Figure 24). In the UK sample, there is again no difference in the THW towards vehicles with and without eHMI (t (12) = 0.72, p = .484). On the other hand, three accidents (THW = 0) were recorded in the UK sample, all of which occurred when vehicles on the slip road maintained their speed. One of the vehicles involved in the accident was equipped with an eHMI, the other two were manual vehicles.

The THW of the two countries differed significantly, both in the interaction with automated (t (39) = 21.79, p < .001) and with manual vehicles (t (18) = 15.42, p < .001). The safety distances in the UK sample were higher in both cases. The lower degrees of freedom again result from both vehicles not always travelling directly in front of or behind each other after the lane change. In most cases, this was because the participants were driving too close in front of or behind another vehicle so that the vehicle on the slip road was unable to merge there. In other cases, the participants managed to change lanes despite another vehicle blocking their path to clear the way for the vehicle on the slip road.

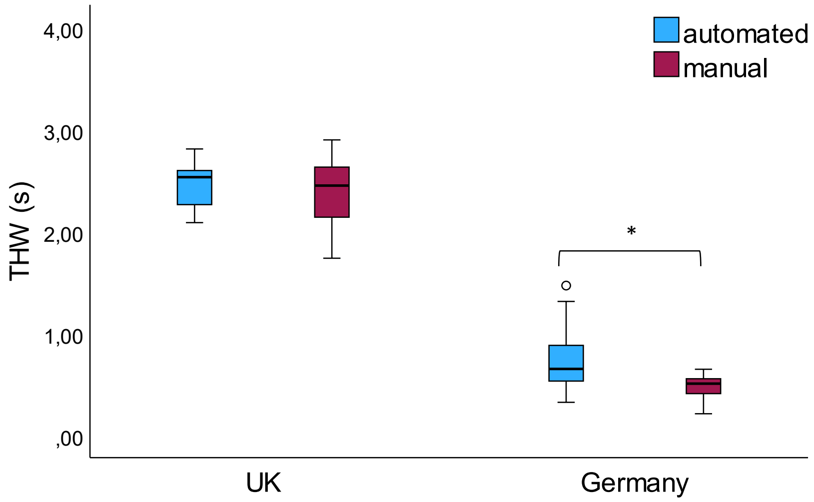

Figure 24. Time Headway (THW) for the slip road of the cooperation partner, divided after the eHMI condition (Ehrhardt, Merat, et al., 2024)

5.3.2.3 Position of the participant

Figure 25 shows the position of the participant after the lane change (either in front or behind the drone car) for the two samples. As with the first-person perspective of the slip road, the picture of the position of the participants after the slip road is less ambiguous in the German sample. The participants always allowed accelerating drone cars to merge in front of them on the slip road, while decelerating drone cars changed lanes behind their own vehicle. If the drone car maintained its speed, most of the participants in the German sample accelerated so that the drone car could merge in behind them. The eHMI has no influence on the sequence. The picture in the UK sample is more ambiguous: firstly, individual participants managed to drive faster than the accelerating drone car on the slip road, so that the drone car merged behind them. Secondly, when the drone car decelerated, around a third of the participants in the UK decelerated so sharply that the drone car ultimately merged in front of them. If the drone car maintained its speed on the slip road, UK participants allowed the vehicle to merge in front of them significantly more often than in the German sample. If they were labelled with an eHMI, this happened more frequently than if they did not have an eHMI.

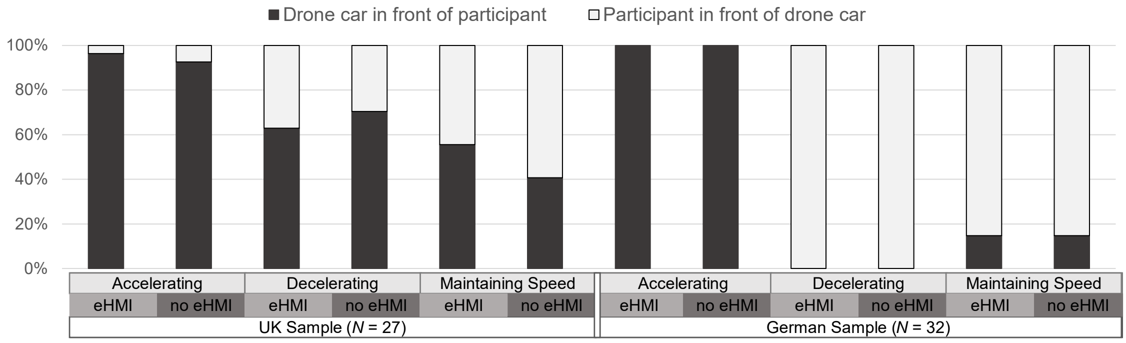

Figure 25. Position of the participant after the lane change for the slip road of the cooperation partner for both samples (Ehrhardt, Merat, et al., 2024)

5.3.3 Preferred behaviour

In the follow-up survey, the participants were asked which of the three behaviours they would prefer in the two scenarios. The results are shown in Figure 26. Whereas in the UK, the preferred behaviour for the vehicle in the target lane is to slow down or maintain speed, in Germany it is expected that the cooperation vehicle will accelerate or maintain speed. The results of the two samples also differ for the second perspective: in the UK, the vehicle on the slip road is expected to accelerate, followed in second place by decelerating. In Germany, on the other hand, decelerating is clearly the preferred behaviour.

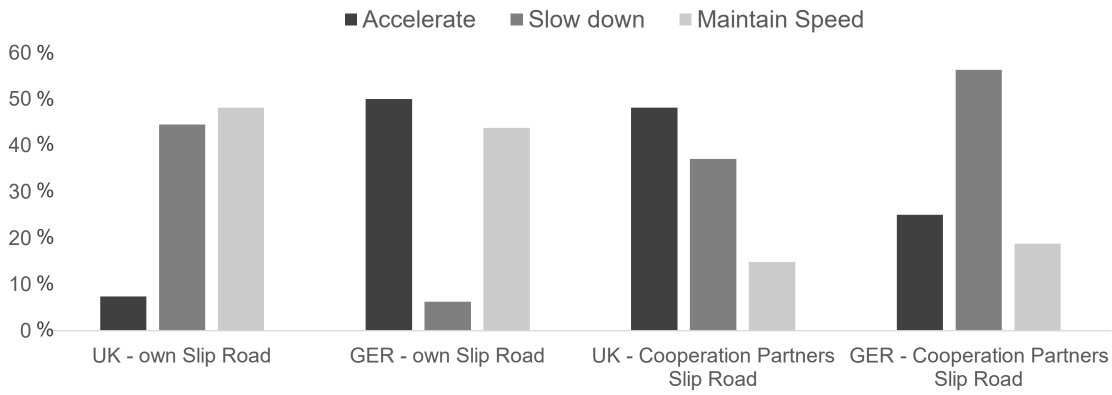

Figure 26. Preferred behaviour of the cooperation partner, as indicated in the post questionnaire (Ehrhardt, Merat, et al., 2024)

5.4 Discussion

5.4.1 Evaluation of longitudinal driving dynamic behaviours

The first aim of the study was to find out how implicit communication through three longitudinal driving dynamic behaviours is evaluated by other drivers. No clear picture emerges for the first-person perspective on the slip road. The ratings of the three behaviours did not differ significantly in the UK sample, which is contrary to our first hypothesis. There are various possible reasons for this. Firstly, it is possible that there is no preference for one of the behaviours in the UK. The follow-up survey shows, however, that maintaining speed or braking is clearly favoured over accelerating. Another reason may lie in the road layout and the implementation of the study. In line with the usual UK slip road layout, the slip road had two lanes. To ensure that the drone car drove at the same speed as the test person for a while, as in the German study, the vehicle only indicated the differences in behaviour towards the end of the right lane of the slip road. Some participants tried to force a lane change from right-hand lane of the slip road to the motorway, even if the drone car blocked their way. Therefore, they only experienced the behavioural variation to a limited extent. This can also be seen in the position of the participants after the lane change: in the UK sample, a few participants got in front of accelerating and behind braking drone cars, which did not occur in the German sample. This shows above all that it is very important to take the different road layouts into account when designing automated driving functions.

For the slip road of the cooperation partner, on the other hand, a clear result emerged: Deceleration of the drone car and pulling in behind the participants vehicle is viewed most cooperatively and least critically. This is in line with our hypothesis, and applies to both the UK and the German sample (Ehrhardt, Roß, & Deml, 2023). These results match the findings of Kauffmann, Winkler, et al. (2018) and Imbsweiler (2019), in which braking was perceived as particularly cooperative, while accelerating and maintaining speed were perceived as aggressive and uncooperative.

In the follow-up questionnaire, however, the participants partially contradicted the results. If the participants were on the slip road themselves, the follow-up questionnaire revealed that UK participants preferred the vehicles in the target lane to maintain their speed. However, this behaviour was rated as the least cooperative in the study. Decelerating, which was favoured by vehicles on the slip road in the driving simulator, only came second in the ranking after accelerating. However, this may only be because vehicles on the acceleration lane are always expected to accelerate first, while braking is only appropriate in some situations. This primarily shows that mere questioning is often not sufficient, but that the situation in question must be experienced.

5.4.2 Influence of the status eHMI

Our second aim was to find out whether the implicit communication of vehicles labelled as automated is evaluated differently than when subjects assume they are interacting with a human. For the first-person perspective of the slip road, the eHMI has no significant influence on the behavioural assessment and also not on the safety distance (THW). This applies to both countries. The results for the first-person perspective of the slip road are therefore in line with the results from previous studies (Ehrhardt, Graeber, et al., 2023; Fuest et al., 2020; GATEway Project, 2017; Stange et al., 2022). In the UK sample, however, decelerating vehicles on the slip road are perceived as significantly more cooperative with identical behaviour if they are labelled as automated. This is remarkable, as it contradicts earlier findings and also our hypothesis. This effect does not exist in Germany, too. We suspect that this difference is due to a difference in the two samples: the attitude towards automated driving in the UK sample was more negative than in the German sample. UK participants may therefore have been positively surprised by the cooperative driving behaviour of the vehicles labelled as automated and rated them more positively.

However, there is also a different sex distribution in the two samples. We did not find any difference in attitudes towards autonomous driving between the genders in our samples. Previous studies have found a more critical attitude towards automated driving among women though (Hőgye-Nagy, Kovács, & Kurucz, 2023; Hulse, Xie, & Galea, 2018). Another study shows that the gender gap in the willingness to use, buy or activate an automated driving function is culturally influenced (Torrao, Lehtonen, & Innamaa, 2024). However, they categorise both the UK and Germany in the group with a significant gender gap.

As hypothesised, UK drivers did not keep a different safety distance from vehicles with eHMI. The descriptive evaluation shows the effect of the eHMI on the position of the participants after the lane change: the participants more frequently merged in front of vehicles with an eHMI in the "maintaining speed" behaviour pattern than when no eHMI was present. This effect can also be seen in the German sample, but to a lesser extent. If the drone car decelerates, the eHMI increases the probability that the participants will still change lanes behind the drone car. If the drone car was on the slip road, a drone car with eHMI that maintained its speed was more likely enabled to change lanes in front of the participants. If it decelerated, the participants were less likely to brake hard enough to stay behind the drone car. From this perspective, the eHMI had no influence for the German sample. This result of the UK sample is also inconsistent with the cited literature, which assumes no influence of an eHMI on the behaviour of other drivers (Fuest et al., 2020; GATEway Project, 2017).

5.4.3 Intercultural aspects

The third aim was to find out whether the answers to the two previous questions (evaluation of the means of communication and influence of eHMI) differ between the UK and Germany, and whether the results of the first study can be generalised across different countries.

Since differences were found in the result profiles of the two samples, full applicability of the findings between the countries is not possible. At the same time, major similarities were found in the results. These are congruent with assertions of the Culture Factor Group (2023), according to which the two countries show no relevant differences in four of the six Hofstede dimensions. The countries achieve different scores in the dimensions "uncertainty avoidance" and "indulgence". The lower values for "uncertainty avoidance" in the UK provide a possible explanation for several of the differences found: In addition to the differences in road layout, this uncertainty avoidance may also play a role in the fact that there is no preference for one type of behaviour in the first-person perspective of the slip road in the UK sample. While "deceleration" is preferred in Germany, which is a clear behaviour pattern, different behaviour patterns and thus "uncertainty" appear to be accepted in the UK.

Another difference between the two samples lies in the position of the participant after lane change: remarkably, some participants in the UK sample remained behind braking drone cars, which did not occur in the German sample. Özkan et al. (2006) attested UK drivers a very low score for aggressive offences on the road, i.e. a rather passive behaviour, which may explain this result. At the same time, however, Özkans study also provides a clue to the explanation for the fact that some UK drivers got in front of accelerating drone cars (which did not occur in the German sample) by reporting that UK drivers are more likely than other countries to be guilty of "speeding on the motorway" and "pulling out and forcing your way out". However, future research should analyse the general differences in driving behaviour between the two countries in more detail.

Only minor differences were found in the evaluation of automated vehicles. Our results thus differ from those of Edelmann et al. (2021), in which culture had a major influence on the perception of automated driving. However, their results related to China, Germany, Japan and the United States, i.e. countries with greater cultural differences. Future research could consider whether there are clusters in the perception of automated driving (e.g. Europe) or whether the perception must be considered at country level.

5.4.4 Limitations

Even though great care was taken in the planning and execution of the study, it is still subject to some limitations: The biggest is likely the use of two different driving simulators, which was unavoidable due to the data collection in two countries. Although the track design and the execution were standardised as far as possible (for more details see 5.2.7), differences in vehicle control and perception of the environment cannot be ruled out. In addition, translated questionnaires have the inherent problem of slight differences in understanding the wording. Furthermore, both samples are not representative of the population in terms of age and gender. In particular, the unbalanced sex distribution in both samples is a limitation (as discussed in further detail in 5.4.2) and should be addressed in detail in future studies.

5.5 Conclusion

The study showed that there is a clear behavioural preference towards vehicles on motorway slip roads, namely, to decelerate and pull in behind the vehicle in the target lane. This was seen as the most cooperative and least critical type of behaviour in both countries. For the first-person perspective on the slip road, results are ambiguous, with only a slight preference for "decelerating". The eHMI has only a small influence on the behavioural assessment in the UK; vehicles with eHMI are rated as more cooperative when decelerating on the slip road. In Germany, a greater safety distance was maintained from vehicles with eHMI on the slip road; in the UK there were no differences in this respect.

Even if the results barely differ between the countries in many important aspects, there are still certain cultural influences on the assessment of behaviour. For this reason, it is important to consider the cultural aspect in the development of automated driving functions. At the same time, the differences appear to be small enough to allow cross-regional traffic to function across national borders without having to change the driving behaviour of the vehicles. It can also be assumed that previous research results can be generalised to a certain extent beyond the country in which they were collected, even if future research must provide further data.”

6 Study 4: User Expectations for an Automated Motorway Access Assistant System

The aim of Studies 1-3 was to analyse the implicit communication of human drivers on motorway slip roads to make it applicable to AVs. An alternative to this is to avoid the interaction of AVs with MVs by means of connected cooperative autonomous mobility (CCAM). CCAMs connect with other vehicles and can exchange data and agree to cooperate to enable or simplify a driving manoeuvre by one or both vehicles. This cooperation agreement is often based on reciprocal altruism – one vehicle enables the other to perform a manoeuvre and puts itself at an immediate disadvantage, assuming they will experience the same level of cooperation from others in a similar situation (Trivers, 1971). In this driving simulator study, an Automated Motorway Access Assistant System is considered. It was investigated what disadvantage the occupants of an automated vehicle accept on the motorway to allow another CCAM to enter this motorway. The disadvantage described is a reduction in speed, which in the scenario should enable the two vehicles to meet at the slip road. The subjects experienced the situation from both perspectives, one time they had to accept the speed reduction in order to allow others to merge, another time they themselves benefited from the cooperative behaviour of another CCAM. It was also investigated whether internal communication via an HMI that displays the reason for the speed adjustment could increase acceptance.

The following Subchapters *6.1 Introduction, 6.2 Methods, 6.3 Results, 6.4 Discussion and 6.5 Conclusion* with their respective sub-chapters are full citations form the publication

Ehrhardt, Martin, Hild, and Deml (2024). User expectations for an automated motorway access assistant system. *Frontiers in Future Transportation*, *5.* https://doi.org/10.3389/ffutr.2024.1420073.

For this purpose, the numbering of the chapters, figures and tables were adapted to the numbering of the thesis. In addition, the text has been converted from American English to British English to match the rest of the dissertation. All co-authors of the published article have declared that they will not use the publication in the context of another academic examination.

6.1 Introduction

"Motorway access is considered a critical situation for manual vehicles. It is identified as one of the key causes of traffic jams on German motorways (Treiber & Kesting, 2010). For automated vehicles, this situation is even more demanding. This is partly because interaction with human partners proves to be difficult. There is a comprehensive body of research on human behaviour at motorway slip roads, for example on slip road speed (Choudhury et al., 2009; Kondyli & Elefteriadou, 2010; van Beinum et al., 2018) or gap acceptance (Choudhury et al., 2009; Marczak, Daamen, & Buisson, 2013b). However, those papers show above all that the safety distance is frequently undercut (Daamen et al., 2010; Kusuma et al., 2015; van Beinum et al., 2018) and ramping drivers force merging to the target lane (Choudhury et al., 2009). While human drivers usually accept this to enable merging, the legal situation does not allow it for automated vehicles (Dolianitis, Chalkiadakis, Mylonas, & Tzanis, 2019).

A promising approach to solve this problem is connected cooperative driving. It avoids cooperation with human partners. Instead, other automated vehicles open a sufficient gap for safe and legally compliant merging. The effectiveness of such a system was shown by Rios-Torres and Malikopoulos (2017) in a simulation study. They report a reduction in fuel consumption and travel time as well as the prevention of congestion and accidents. However, a coincidental encounter between two automated vehicles in the short time window of an on-ramp to the motorway is unlikely with low penetration rates. The meeting must be arranged. Therefore, a speed adjustment of both cooperating partners is needed, including the non-benefiting partner (the one already on the motorway). Our contribution deals with the question of how to design such a connected cooperative motorway access assistant to ensure that both partners accept the required speed adjustments. The questions investigated by our study are:

- What is the maximum acceptable speed reduction while cooperating?
- Does an HMI have an influence on the maximum accepted speed reduction?

Various contributions demonstrate the benefits of connected cooperative driving in different scenarios. As described in the introduction, Rios-Torres and Malikopoulos (2017) showed in a simulation that by implementing cooperative connected vehicle coordination at motorway slip roads, both fuel consumption and travel time can be reduced significantly, while congestion and collisions are avoided. Zheng, Ran, Qu, Zhang, and Lin (2020) used a cooperative strategy for connected and automated vehicles to optimize traffic safety and traffic flow at lane changes on motorways. Further analyses showed a positive influence of connected vehicles on the stability of the traffic flow as well as on the throughput by preventing the formation of shock waves and their propagation (Talebpour & Mahmassani, 2016)). Calvert, Schakel, and van Lint (2017) argue that mere connectivity will initially have a negative impact on traffic flow, as the required time gaps of automated vehicles are higher. Only an increasing penetration rate of cooperative AVs can reverse this negative effect. As a limitation, these approaches have in common that the results have been obtained exclusively from simulations and disregard human factors such as user acceptance and trust.

Arguably, the most well-known acceptance model is the Technology Acceptance Model (TAM) by Davis (1989) and its further developments. It assumes that the "Attitude Toward Using" is determined by two variables: the "Perceived Usefulness", i.e., the assessment of whether a technology is useful for the user, and the "Perceived Ease of Use", i.e., whether the technology is easily usable. A positive assessment of these factors leads to the user's intention to use the technology. Conversely, a lack of acceptance leads to a system not being used, which in terms of automated driving means that the intended increase in road safety is no longer given. A concept closely related to acceptance is trust (Kaur & Rampersad, 2018; J. D. Lee & See, 2004). Trust in the context of human-machine interaction is defined by as "the attitude that an agent will help achieve an individual's goals in a situation characterized by uncertainty and vulnerability" (J. D. Lee & See, 2004). Trust is also correlated with the frequency of use of an automated driving system (Dikmen & Burns, 2017).

Fank, Knies, and Diermeyer (2021) highlighted the importance of an HMI for user acceptance of a cooperative system. They developed a user interface for cooperative truck overtaking and evaluated it in a driving simulator study with thirty truck drivers. They were able to show that drivers were willing to use a cooperative system, particularly, if they are provided with a suitable HMI. They concluded that the success of a cooperative system depends on driver acceptance and trust towards the system. The influence of an HMI on acceptance and trust in the automation was also investigated by Forster, Naujoks, and Neukum (2017). They compared the effect of a non-specific warning tone with a semantic speech output during the execution of different automatic driving manoeuvres in a driving simulator. The results showed that describing an automatic function appropriately to the driver increases their trust in automation as well as acceptance of the system. Haar et al. (2022) considered lane changes on motorways in a driving simulation study with N = 52 participants. They investigated how the willingness to cooperate can be supported by means of vehicle-to-vehicle communication. The results showed that a head-up display providing additional information about the cooperation partners` intentions supplementary to the regular turn signal might be beneficial. Their approach appeared to lead to behaviour that is more permissive, makes drivers perceive other drivers as more cooperative and reduces the overall ambiguity in the lane change situation.

The approach we propose in the present contribution demands drivers to selflessly accept a speed reduction to allow others to enter the motorway safely and comfortably and to trust the systems speed adaption decisions. A similar approach was taken by Reinolsmann et al. (2021). They developed an active gap metering signalization system that indicates drivers in the right lane to actively reduce their speed and adjust their headway so that vehicles coming from the driveway can merge safely. In a driving simulator study with 64 participants, they showed that the safety distances were significantly improved with the help of the signalizations. The idea that people in road traffic are not solely motivated by their own advantage, but also show selfless behaviour, was already considered by Kesting, Treiber, and Helbing (2007). Their lane change model presents the decision to change lanes as a trade-off between the expected own advantage and the disadvantage imposed on other drivers when changing lanes. The politeness parameter included in their model allows the motivation for the lane change to vary from purely selfish to selfless. However, to the authors' knowledge, there are no studies on user acceptance of a system that reduces speed below the speed limit over a longer period for altruistic reasons.

The literature, thought, provides evidence that allows the generation of hypotheses: As shown earlier, according to the TAM, acceptance is determined by, i.a., "Perceived Usefulness" (Davis, 1989). Accordingly, a system that significantly reduces the speed without the user deriving any personal benefit should not be accepted, or acceptance should at least be significantly higher if a personal benefit is present. In further development of the model (TAM2; Venkatesh & Davis, 2000), however, the factor "Subjective Norm" was added, among others. One social norm in road traffic is that of mutual consideration. The Kesting et al. (2007) lane change model also shows that social factors such as "politeness" have an influence on our decisions in road traffic. Thus, there appears to be a trade-off between personal benefit (or the reduction of benefit by the amount of speed reduction) and the benefit of others. One can assume that this trade-off is more likely to be due to the disadvantage of the acceptance of the system with a stronger personal restriction (i.e., stronger speed reduction). In addition, the research literature shows a positive effect of an HMI on acceptance and trust in automated systems. From those findings, the following hypotheses were derived:

H1: The degree of acceptance of the system depends on the speed during the cooperation phase. Acceptance decreases the more the automation decreases the speed during the cooperation phase.

H2: The degree of acceptance depends on the user's perspective. Acceptance is higher when the user benefits from the cooperation when they are on the slip road than when they are on the highway and not benefitting.

H3: The degree of acceptance depends on the HMI. The availability of an HMI leads to higher user acceptance. It also moderates the effect of speed on acceptance: The HMI can reduce the negative influence of reduced speed on acceptance.

6.2 Methods

To address these hypotheses, a user study in a driving simulator was conducted. On a simulated test track, the participants experienced the Automated Motorway Access Assistant System from both viewpoints: Entering the motorway as well as driving on the motorway and letting someone else enter. In both cases, the coordination partner was a scripted car. The speed of the ego vehicle changed in a randomized pattern while cooperating on the highway to simulate the required adjustments for the cooperation to succeed. Both HMI and randomized speeds were varied in multiple laps on the circuit. Figure 27 shows an overview of the track.

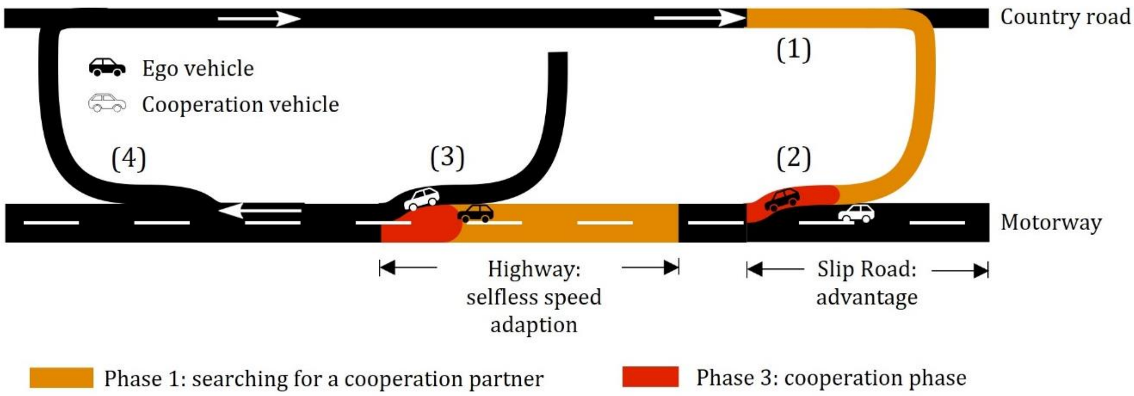

Figure 27. Overview of the study concept and track. Test participants (black) experience the cooperative motorway assistant on a circuit starting on a country road (1), followed by a motorway on-ramp (2), a stretch on the motorway where another on-ramp is passed (3) and an exit (4), after which the turn is made back onto the country road (1). Cooperation phases are marked in orange (phase 1: searching for a cooperation partner) and red (phase 3: cooperation phase). On the motorway, test participants are confronted with varying speed changes to simulate the control loop necessary to meet the cooperation partner (white) at the right time (Ehrhardt, Martin, et al., 2024)

6.2.1 Independent and dependent variables

Three independent variables are examined in this experiment. The study design is a within-subject design (2 x 3 x 2), allowing all subjects to perform with all independent variables and their combinations. The first is "availability of an HMI", with the two levels "with HMI" and "without HMI", respectively. The second is "speed during the cooperation phase" with the three levels "70-90 km/h", "90-110 km/h" and "110-130 km/h". Speed fluctuates in the indicated ranges simulating a realistic adaptation to the speed of the cooperating partner. A speed limit of 130 km/h was applied in the relevant section of the motorway. Thirdly, the driver's perspective is evaluated: The subjects experienced the system both from the perspective of the vehicle on the slip road and as a cooperating partner in the right lane. The condition order of the availability of an HMI was randomized: Every second participant started with a block of three laps (according to the three levels of the speed condition) with HMI, the other half without HMI. The variable "speed during the cooperation phase" was thoroughly randomized within the HMI condition. The perspective is conditioned by the track: subjects experience the two perspectives alternately, starting with their own slip road.

The dependent variables are acceptance, trust, and perceived safety. Acceptance is operationalized by two means: Firstly, the subjects were instructed to terminate the cooperation by taking over control if they did not accept the systems decisions. Standardized questionnaires for measuring technology acceptance like the TAM (Davis, 1989) usually consist of several items. This serves to capture different aspects of acceptance and to increase reliability. In the present study, however, acceptance is surveyed while driving, which makes it impossible to answer several items for reasons of time and distraction. Therefore, acceptance was measured through a one-item questionnaire, which is asked after each cooperation situation. A machine voice asked how satisfied they were with the cooperation. Subjects answered the question on a 5-point scale ranging from "very unsatisfied" to "very satisfied" on the touch display in the centre console.

Trust is captured by a "Trust in Automated Systems Questionnaire" (Pöhler, Heine, & Deml, 2016). Perceived safety is captured by the Godspeed V (Bartneck, Kulić, Croft, & Zoghbi, 2009). The variables were rated on a scale from 1 (very low) to 6 (very high). Finally, users were asked whether they preferred the version with HMI or without HMI. If they took over control during the experiment, they were also asked to state the reason in an open question.

6.2.2 Apparatus

The driving simulator consists of an Audi A3 with full functionality of all inputs such as steering wheel, gearshift, and pedals (see Figure 28). The car is surrounded by three screens onto which high-resolution projectors cast projections of the simulated driving environment. The exterior mirrors are equipped with displays, and there is a large screen behind the vehicle for a realistic impression when looking in the rear-view mirror. The driving simulation is realized using the simulation software SILAB® 6.5.

The system allows switching between manual control and autonomous driving mode. A user initiates takeover from the autonomous mode by taking over the steering wheel or using the pedals. To give control back to the autonomous mode, the user pushes a button in the centre console. An icon in the instrument cluster indicates the autonomous driving mode to the user.

Figure 28. Driving Simulator frontal projection screens (left) and interior of the simulator vehicle (right) (Ehrhardt, Martin, et al., 2024)

6.2.3 Experimental system

The HMI of the Automated Motorway Access Assistant System was designed as follows. It consists of two main elements: An animated icon, and an audio signal. The assistant system covers four phases: 1) Looking for a cooperation partner, 2) finding a cooperation partner, 3) the cooperation period itself and 4) the end of the cooperation. When the cooperation is terminated by the driver the HMI disappears. Table 10 shows the representation of the two elements (icon and signal) in each phase. The turquoise colour chosen for the animation of the icons regards previous work recommending this colour for the display of automated driving (Faas, S. M., & Baumann, M., 2019; Werner, 2019). The HMI was identical for either perspective - both when merging onto the motorway themselves, and while driving on the motorway when cooperation with a simulated cooperation partner was arranged. The HMI was displayed in the digital instrument cluster between the speedometer and rev counter. Figure 28 shows a picture of the basic configuration of the vehicle. For the study, the display of the speedometer and rev counter was reduced in size so that these two displays and the HMI each took up about a third of the screen. The HMI was developed in an iterative process to optimize comprehensibility. In the follow-up survey, the comprehensibility of the system was rated on a scale from 1 (not comprehensible at all) to 7 (fully comprehensible) with M = 6.00 (SD = .99).

6.2.4 Test task

In order to test the hypotheses, a driving simulation test task was designed and implemented. It consists of a circuit (Figure 27), starting on a country road (1), followed by a motorway on-ramp (2), a stretch on the motorway where another on-ramp is passed (3) and an exit (4), after which the turn is made back onto the country road (1). In each lap, the subjects experience two cooperation phases. The first while entering the motorway themselves; the second while passing the second slip road. The motorway contains three lanes in each direction with a speed limit of 130 km/h indicated by signs. Other vehicles were simulated on all lanes, creating an average traffic density. The distance between the cooperation partners vehicles was identical in all situations.

Table 10: The four phases of the Automated Motorway Access Assistant System with the respective HMI elements.

Phase	Icon	Translation	Animation	Audio signal
1: searching		searching for cooperation partner	blinking of the connecting bars	2 short beeps (pitches: low medium)
2: finding		cooperation ongoing please do not take over	icon turns turquoise	2 short beeps (pitches: medium high)
3: cooperation		cooperation ongoing please do not take over	no animation	no audio
4: end		Thank you!	icon disappears	2 short beeps (pitches: low medium)

During cooperation, either a human-machine interfaces (HMI) is presented to the test persons (see subsection 6.2.3), or they go through the cooperation scenario without an HMI. While driving on the motorway during the second cooperation phase, the automated system reduces the speed of the vehicle to either 110-130, 90-110, or 70-90 km/h, respectively. Each speed level occurs for two laps, one with and one without HMI. This way, the speed reduction simulates the necessary speed adjustment which guarantees that the two cooperating vehicles would meet at the slip road.

6.2.5 Procedure

41 test persons (*Mean* age = 28.05, *SD* = 10.02; mean years of holding a driving license = 9.78, *SD* = 8.77; 29% female) participated. They were recruited via two distribution lists of our research institutes or via walk-in acquisition and were paid 15 Euro compensation each. The procedure started with a pre-survey in which the subjects filled in demographic data and the Godspeed questionnaire (Bartneck et al., 2009) on the topic of perceived safety. This was used to record the baseline of the current general perception of safety. After that, an introduction to the driving simulator followed.

In a training phase, the subjects drove manually on a country road, which was not part of the simulated test track, to get used to the simulation environment as well as the control of the vehicle. They also trained handover scenarios between manual control and an automated driving mode. After familiarization, the subjects were informed about the aim of the study, and the functionality of the Automated Motorway Access Assistant System was introduced. In order not to confound the condition "no HMI first", the HMI was not mentioned in the instruction. Rather, it was referred to as "two versions of the assistant" that were to be compared. In addition, subjects were instructed to take control if they felt unsafe or did not like the behaviour of their vehicle, but after a short time to return control to the automation so that the experiment could continue.

After the instruction, the subjects performed the test phase where they drove six laps on the circuit. They were assigned randomly to drive the block of three laps with or without HMI first. Within the blocks, the order of the speed levels was also randomized between the test persons. This results in an order randomization of the HMI variable and a complete randomization of the speed level variable. The driver’s perspective is not randomized in this design, as the participants always drive the same lap, starting with their own slip road.

After each cooperation, the subjects were asked to rate their acceptance, as stated in Section 6.2.1. After three laps, they came to a stop at a stop sign and were asked to rate their perceived control and their trust in the system (c.f. 6.2.1 Independent and dependent variables). After the last lap, the test persons completed the post questionnaire. It consisted of questions about the subjects' understanding and preference of HMI components. Also, they again rated their trust in the system as well as their system acceptance and retook the Godspeed questionnaire on perceived safety. Finally, they rated the system with HMI and the system without HMI on a scale from 1 (do not like it at all) to 10 (do like it very much) and named which version of the system they preferred (with or without HMI). Each user session lasted approximately 1.5 h.

6.3 Results

6.3.1 H1: Speed during the cooperation phase

To answer hypothesis 1, the influence of speed reduction on the two operationalization's of acceptance was analysed. Only the cooperation situations while driving on the motorway were included in the analysis, as the change in speed only occurred here. Please note that the inclusion of data from the other perspective still led to significant results in the main effect as well as the contrasts. An ANOVA with repeated measures shows a significant influence of the speed level on the rating of acceptance in the questionnaire (F (2, 80) = 35.08, $p < .001$, $\eta_p^2 = .47$). The contrast analysis between the speed levels "70-90 km/h" and "90-110 km/h" (F (1, 40) = 23.16, $p < .001$, $\eta_p^2 = .37$) as well as "90-110 km/h" and "110-130 km/h" (F (1, 40) = 14.28, $p < .001$, $\eta_p^2 = .26$) are significant and show a higher acceptance the lower the speed reduction (see Figure 29).

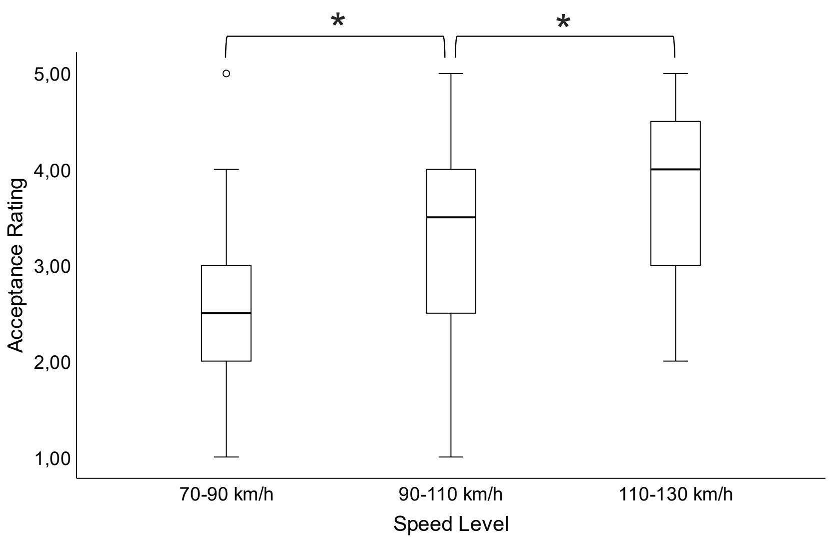

Figure 29. Acceptance rating of the three speed intervals. Error bars represent 95% confidence interval. * Significant difference within speed level, $p < .001$ (Ehrhardt, Martin, et al., 2024)

The analysis of the number of cooperation terminations was carried out using the McNemar test (McNemar, 1947), with pooled data over both HMI conditions and perspectives. The second operationalization of acceptance also shows a significant influence of the speed level: At speed level "110-130 km/h", the cooperation is interrupted only 3 times, at speed level "90-110 km/h" significantly more often with 15 times (p = .006). At the highest speed reduction ("70-110 km/h"), however, the number of terminations (19) no longer increases significantly (p = .687, see Figure 30).

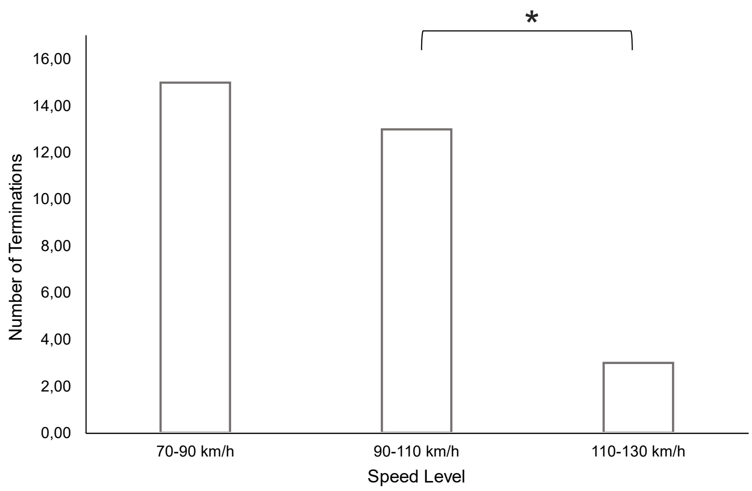

Figure 30. Number of cooperation terminations during the cooperation phase on the motorway perspective. Error bars represent 95% confidence interval. * Significant difference within speed level, p = .006 (Ehrhardt, Martin, et al., 2024)

6.3.2 H2: Perspective

Hypothesis 2 deals with the influence of perspective (slip road vs. motorway) and thus the personal benefit from cooperation. For this purpose, the "perspective" factor was included in the analysis, resulting in a two-way ANOVA with repeated measures. The perspective has a significant influence on the acceptance rating: F (1, 40) = 28.86, $p < .001$, $\eta_p^2 = .42$. The rating is significantly more positive if no personal restrictions in the form of a speed reduction had to be accepted (see Figure 31). The interaction term of speed level and perspective is also significant: F (2, 80) = 25.82, $p < .001$, $\eta_p^2 = .39$. Analysis of within-subject contrasts shows the following: Only in the case of the lowest restriction (speed level "110-130 km/h"), the acceptance rating does not differ significantly between the two perspectives (t (40) = 1.20, p = .12). In the other two conditions, the system was rated significantly worse when subjects drove on the motorway, ergo did not benefit themselves: t (40) = 3.94, $p < .001$ for speed level "90-110 km/h" and t (40) = 7.56, $p < .001$ for speed level "70-90 km/h".

Similarly, the number of cooperation terminations depends on the perspective: While driving onto the motorway, the cooperation was terminated 3 times, while driving on the motorway 37 times ($p < .001$).

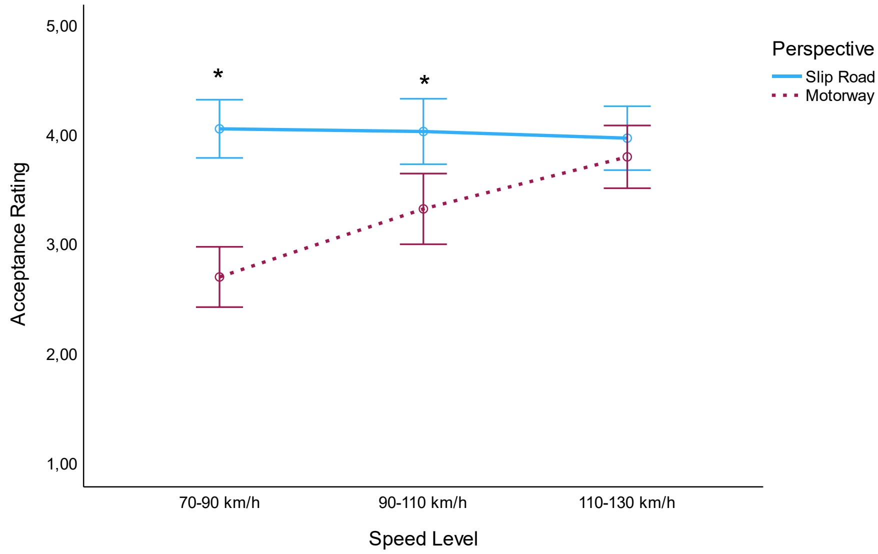

Figure 31. Acceptance rating of the three speed intervals for both perspectives. Error bars represent 95% confidence interval. * Significant difference within speed level, $p < .001$ (Ehrhardt, Martin, et al., 2024)

6.3.3 H3: HMI

The third hypothesis regards the influence of an HMI on the acceptance of the system. The factor HMI is included in the ANOVA. Contrary to the assumption, the HMI does not lead to a significantly different acceptance rating in the questionnaire: F (1, 40) = 0.002, $p = .967$, $\eta_p^2 = .00$. The interaction terms with the other variables also show no significant interaction effects ("Speed Level": F (2, 80) = 0.38, $p = .686$, $\eta_p^2 = .01$; "Perspective": F (1, 40) = 0.43, $p = .515$, $\eta_p^2 = .01$). However, the McNemar test reveals a significant effect of the HMI on the number of terminations at speed level "90-100 km/h" ($p = .006$). For the other two speed levels, no significant effect was found (see Table 11).

Table 11: Influence of the availability of an HMI on the number of terminations of the cooperation.

Speed Interval	**Terminations with HMI**	**Terminations without HMI**	***p***
70-90 km/h	6	13	.065
90-110 km/h	3	13	.006
110-130 km/h	2	3	1.000

To rule out the possibility that the results of the number of terminations were due to a carry-over effect from the previous condition, a further analysis was carried out. In the style of a between-subject-design, the differences in the first block of the experiment between the two HMI conditions were analysed. Similarly, this analysis only shows a significant influence of the HMI on the number of terminations for the speed level "90-100 km/h" (p = .039).

6.3.4 Further analyses

Due to the lack of hypotheses, the analyses in this chapter are α-error corrected. The interim survey after the first three laps showed the following results. Perceived safety is independent of the availability of the HMI (z (23) = -0.53, p = .598). However, the HMI has a significant influence on trust in the automation. Trust is significantly higher with HMI (t (40) = -3.38, p < .001), and distrust is significantly lower (t (40) = 5.02, p < .001).

19 of the 41 subjects (46.3%) took over vehicle control at least once during the cooperation phases. The most frequently mentioned reasons in an open question format were "ego vehicle too slow" (12 mentions), "too little distance to other vehicles" (5), "behaviour of the ego vehicle not comprehensible" (2) and "abrupt braking or acceleration" (2).

The motorway access assistant with HMI is rated significantly better (t (40) = -9.26, p < .001) in the post-questionnaire. The visual cooperation symbol is rated as the most helpful component of the HMI (M = 4.39, SD = 0.89), followed by the text (M = 4.17, SD = 1.07) and the sound effect (M = 3.88, SD = 1.27). Moreover, three other suggestions for improving the HMI were rated on a scale from "1 = not at all helpful" to "5 = very helpful". The option "reason for vehicle speed adjustment" is considered most helpful (M = 4.00, SD = 1.31), followed by "position of cooperation partner" on a map (M = 3.57, SD = 1.33) and "speed of cooperation partner" (M = 3.38, SD = 1.25). In an open question, five people additionally expressed the demand for more information for identifying the cooperation partner, and four people expressed the demand for a countdown to the completion of the cooperation phase.

6.4 Discussion

The presented study shows that the acceptance of the cooperative connected motorway slip road assistant depends on the extent of the speed restrictions that are required to ensure the function of the assistant. Only at the lowest speed restriction (speed level “110-130 km/h”) the acceptance of the test persons was as high as at their own motorway entrance when they benefit from the system themselves. This is also reflected in the number of interventions in the system: The greater the reduction in speed, the more frequently cooperation is terminated. In contrast, during the driver's own joining of the motorway, control is only very rarely taken over to override the assistant. Contrary to the hypothesis, the HMI has only a very small influence on the acceptance of the assistant: The rating in the questionnaire does not differ on any speed interval. However, in the intermediate speed interval (“90-110 km/h”), the HMI reduces the number of cancellations. Such a tendency is also evident for the slowest interval (“70-90 km/h”). Both with and without HMI, cooperation is rarely terminated at 110-130 km/h.

Therefore, the first hypothesis can be considered confirmed: Acceptance decreases with the reduction of speed during the cooperation phase. The second hypothesis is also accepted, acceptance is higher when users benefit from the assistant. The assistant is evaluated not worse on the motorway compared to during the slip road only at the lowest speed restriction. The third hypothesis is largely not confirmed: The HMI does not lead to a better acceptance rating and does not moderate the effect of speed on acceptance. Only at one speed level (90-110 km/h), the HMI can reduce the intervention in the system. However, it was shown that the availability of an HMI can increase the trust in an automated system.

Similar to the finding in the research literature (Kesting et al., 2007; Reinolsmann et al., 2021), subjects in the present study show partly selfless behaviour to increase the safety and comfort of others. Although the assistant is rated better when the subjects themselves benefit from it, overall cooperation is rarely terminated. Out of 246 laps in which cooperation could have been terminated in favour of faster driving, subjects did so only 40 times.

However, contrary to what is inferred from the literature (Fank et al., 2021; Forster et al., 2017; Haar et al., 2022), an HMI had no significant influence on the systems acceptance. The HMI only led to less frequent interruptions of the cooperation in the medium speed interval (“90-110 km/h”). There may be several reasons for this. Firstly, it is possible that the HMI used in the study provided too little or not the relevant information for the test persons; hence, they might not have paid attention to it. Another potential reason is that the test persons relied so much on the automated vehicle control that they did not need any further information to accept the system. Thirdly, the HMI may have played a much smaller role for the subjects than the speed reduction of the vehicle. The question about the acceptance of the system may, therefore, have been based exclusively on speed. This is also supported by the fact that the HMI had a significant influence on the trust in the system. This result is consistent with (Forster et al., 2017), who found the availability of an informative HMI to be an important factor for trust and acceptance in the automated system. Beyond the existing literature, the study provides data on the acceptance of variable speed reduction to enable a cooperative motorway access.

The study is inherently subject to some limitations. Even though the validity of driving simulators has been repeatedly confirmed in the literature (e.g. Godley, Triggs, & Fildes, 2002; Shechtman, Classen, Awadzi, & Mann, 2009), the generalizability of the results is constrained. A naturalistic driving study should be carried out at a later stage of the system development to evaluate the validity of the results. The lack of actual time pressure from the experimental scenario may also have had an impact on the subjects' patience and thus their willingness to engage in altruistic behaviour. In addition, only the initial contact with the system was investigated in the approximately one-hour driving time. Future research should investigate how acceptance develops after a period of greater familiarization and how the relevance of the HMI develops, when the user is familiar with the system. Furthermore, only one draft of an HMI was used. It should be further developed in the future with the help of the user feedback collected in this study.

6.5 Conclusion

We presented a study on an Automated Motorway Access Assistant System. The focus of the study was the acceptance of speed changes to facilitate the cooperation as well as the influence of an HMI on the acceptance of the assistance system overall. The data provides evidence that users accept a connected cooperative system even if it does not act solely for their own benefit. The acceptance was highest when drivers benefited themselves by joining the motorway unrestrictedly. Similar acceptance could only be achieved for small restrictions when driving on the motorway letting others join cooperatively. Larger speed reductions facilitating the cooperation led to decreased acceptance of the system. While an HMI does not increase the reported acceptance, it can increase tolerance for moderate restrictions, and it also increases trust in the system. The results are promising, and they provide a solid base for further development of such a system that can improve safety and comfort at motorway slip roads."

7 General Discussion and Outlook

7.1 Key Findings

Before discussing the implications of the results for research and development, the key findings of the four studies will be discussed in relation to the research questions raised in Chapter 2.7.

Research Question 1 deals with the question of how different forms of lateral driving dynamics are evaluated. Study 1 investigates this topic with the help of a video study. The position and speed of the lane change were analysed. Slow lane changes were rated as more cooperative and less critical. Fast lane changes, on the other hand, were seen as less cooperative and more critical. For the position of the lane change, an interaction effect with speed was found. Lane changes at the beginning or end of the acceleration lane were considered more critical and less cooperative than in the middle, especially if they were carried out slowly or at medium speed. Fast lane changes were rated negatively, especially at the end of the acceleration lane.

Imbsweiler (2019) categorised behaviour observed in inner-city road traffic as offensive and defensive. Defensive driving comprises driving practices aimed at reducing the risk of accidents by anticipating potential hazards and making safe, well-informed decisions on the road. In a naturalistic driving study (NDS), defensive behaviours were perceived as more cooperative while more offensive behaviours were rated less cooperative. This also influenced the behaviour of the participants, who were more likely to perform a manoeuvre in front of the cooperation partner in a space sharing conflict if the partners driving behaviour was more defensive and to drive after the cooperation partner if their driving behaviour was more offensive (Imbsweiler, 2019).

Such a categorisation can also be made in relation to the speed and position of the lane change: A slower lane change can be categorised as defensive, a faster lane change as offensive. This means that a more defensive behaviour of the cooperation partner is preferred. Regarding the position of the lane change, a lane change directly at the beginning of the acceleration lane can be interpreted as offensive behaviour, while a later lane change would be more defensive. However, the classification of lane changes at the end of the acceleration lane is ambiguous. On the one hand, it could be argued that the later a lane change takes place, the more defensive the behaviour is. On the other hand, a lane change at the end of the acceleration lane means that there is no longer an alternative course of action, which contradicts the definition of defensive driving ('reducing the risk of accidents by anticipating potential hazards'). If a driver changes to the right-hand lane at the end of the acceleration lane, he might force a driver in this lane to take an active action, namely, to decelerate to enable the lane change. Behaviour that forces other road users to behave defensively cannot be defensive itself, which means that a late lane change is offensive again. So here too, defensive behaviour in form of a lane change in the middle of the acceleration lane is ultimately perceived as more cooperative and less critical.

Research Question 2 examines the evaluation of longitudinal driving dynamics. These were analysed in studies 2 and 3. Here, also, a preference for defensive behaviour patterns can be identified: In most cases, a deceleration of the cooperation partner was rated as less critical and more cooperative than accelerating or maintaining speed. One exception is the own driveway in the UK sample. In this situation, the three behaviours are not rated differently in terms of their criticality, and only maintaining speed is rated slightly less cooperative than the other two behaviours. The possible reasons for this difference to the German sample are discussed in detail in Ehrhardt, Roß, and Deml (2023).

The question of whether deceleration fundamentally represents defensive driving behaviour is debatable. The results of both studies showed that the participants usually want their cooperation partner to decelerate for both perspectives of the motorway slip road when they get into a space sharing conflict. However, if both interaction partners decelerated, the situation could not be resolved, and a potentially critical situation would arise. Considering driving behaviour as a means of communication, which, according to Schulz von Thun (1996), always contains an appeal, might help here. In this case, the appeal of a decelerating driver is that the cooperating partner should accelerate and pull in front of their own vehicle. If, on the other hand, both vehicles decelerate and maintain the behaviour, this would be a failed communication - both would not follow the other's appeal, which is what creates the critical situation in the first place. Stoll (2022) therefore also concludes that accelerating, if it is intended to open a suitable gap behind the vehicle to change lanes, can be considered cooperative behaviour. The preference for the 'deceleration' behaviour can also express the desire to resolve the situation cooperatively, while maintaining speed can be interpreted as neglecting the need for coordination and accelerating as withdrawing from the situation. Future research should examine how a communication situation in which the same action is initially chosen can be resolved satisfactorily.

Research Question 3 considers the influence of the status eHMI on the evaluation of communication by means of driving dynamics. The three studies provide differing answers to this question:

In Study 1, the eHMI had no significant influence on the evaluation of lateral driving dynamics. In study 2, on the other hand, identical behaviour of AVs on their own driveway was rated as more cooperative and less critical than that of MVs, while the status eHMI had no influence on the behaviour of the test subjects. Conversely, a greater safety distance was maintained from AVs on the slip road than from MVs, while the behavioural assessment did not differ significantly. A discrepancy between the rating and the behaviour can therefore be observed here. In study 3, no difference in behaviour towards AVs was observed. There was also no influence of the eHMI status on the behaviour rating when driving onto the motorway (deviating from study 2). However, the behaviour of AVs was rated as more cooperative when the cooperation partner drove onto the motorway (deviating from study 2); there was no difference for cooperativeness (consistent with study 2).

Research question 3 therefore cannot be answered conclusively: depending on the situation, a status eHMI either has no influence on the behavioural evaluation or AVs are evaluated more positively than MVs. In most cases, a status eHMI does not appear to influence the distance behaviour of the participants, but in individual situations participants maintain a greater distance from AVs. These contradictory findings are also reflected in previous research. While some sources find differences in the evaluation and behaviour towards vehicles labelled as automated (Faas et al., 2020), many sources report that there are no differences (Fuest et al., 2020; GATEway Project, 2017; Joisten et al., 2020; Stange et al., 2022).

Depending on the results, different conclusions can be drawn about whether human behaviour is an adequate model for the development of AVs. The studies in this thesis provide evidence in favour of the adoption of AV behaviour from MVs. Since the AVs with identical behaviour were either not rated differently from MVs or even as more cooperative, human behaviour can be a good model for AVs. A more important factor is to copy human behaviour that is perceived as cooperative and desirable, which applies to defensive driving behaviour (see RQ 1&2). If the status eHMI caused a change in behaviour at all, then in the studies of this work it was a greater safety distance from AVs, ultimately a more defensive and therefore safer driving behaviour.

In research question 4, the generalisability of the results beyond Germany is explored. No clear answer can be given to this question either. Even though many of the results of the two samples were consistent, there were some differences. For example, the behavioural assessment matched in one of the two perspectives observed (the cooperation partner's sip road). In the second situation, no difference between the behavioural patterns could be identified in the UK sample. However, as the pattern of results was also not contradictory, it can be assumed that an AV that was developed on the basis of the preferences in the German sample would also be accepted in the UK. Deviating programming beyond the differences in infrastructure would therefore not be necessary in this case.

The results of the two samples also differed in some areas regarding the influence of eHMI status: No influence on behaviour was observed in the UK, but some ratings differed, while in Germany different behaviour was shown towards AVs to some extent. Here too, however, were no contradictory results and the recommendation for both countries would be the same: visible labelling does not appear to have any negative effects, so AVs should be labelled with an eHMI.

Nevertheless, the results also show that the evaluation of behaviours can differ even between cultures that are largely similar according to Hofstedes (2001) definition. Previous research has shown that the differences in the perception and acceptance of AVs are even greater in countries with greater cultural differences (Edelmann et al., 2021; Louw et al., 2021; Öztürk, Wallén Warner, & Özkan, 2024; Zhang et al., 2021). A comprehensive generalisability of the results of the studies in this thesis, but also of other earlier research, is therefore not given, but must be examined in detail and the systems adapted accordingly. At the same time, it can be assumed that studies on cultural differences will also regularly reveal major commonalities that enable an uniform behavioural model for supra-regional areas or even - possibly only in relation to individual driving situations - even allow a generally valid compromise.

Research Question 5 deals with the acceptance of a cooperative automated motorway access assistant based on V2V communication as an alternative to interaction between AVs and MVs. Such a system requires users to accept short-term restrictions in the sense of reciprocal altruism to enable the system to agree on a cooperative manoeuvre. The results show that the system is generally accepted, especially if the participants themselves benefit from the system. Minor reductions in speed did not worsen acceptance in comparison to the situation of personal advantage. Only when the speed was reduced moderately or significantly the system was no longer accepted, which was reflected in a poorer evaluation and more frequent oversteering of the system.

The study shows that, up to a certain point, CCAM systems also seem to be able to utilise the fact that reciprocal altruism prevails in road traffic, i.e. that road users allow others to make certain manoeuvres while accepting short-term personal restrictions on the assumption that they will be met with similar behaviour in the same situation. The acceptance of AV passengers that the automated system will act in accordance with this reciprocal altruism is a basic prerequisite for CCAM. Only if altruistic driving manoeuvres are accepted and are not overridden by the users connected driving functions that agree on joint manoeuvres with other AVs are possible. In the study presented here, only a brief explanation of the benefits of the driving function provided to the users. This was sufficient for the participants to accept a small restriction, but not a larger one. If the acceptance of greater restrictions is necessary for a system to function, additional incentivisation may be required. The incentivisation of cooperative or altruistic behaviour in road traffic was investigated in previous research, for example, using a credit system (Bi, Shang, Chen, Yu, & Ochieng, 2022) or financial incentives (Merugu, Prabhakar, & Rama, 2009).

The last research question (RQ 6) focused on the question of whether the acceptance of the automated motorway access assistant depends on the internal communication via HMI in addition to the behaviour of the system. In contrast to previous research on the relevance of HMI for the acceptance of AVs (e.g. (Fank et al., 2021; Forster et al., 2017; Haar et al., 2022), study 4 did not show any significant influence on the acceptance rating. Chapter 3.4.4 and Ehrhardt, Martin, et al. (2024) discuss possible reasons for this result.

Regardless of the reasons for the lack of a significant influence on the acceptance rating, the result should not be interpreted as an argument against internal communication of the system status of a CCAM system. Firstly, although the HMI had no significant influence on the rating, it did have an influence on the behaviour of the participants in one of the three speed levels: in the medium speed reduction, the HMI significantly reduced the number of terminations. In addition, trust in the system was significantly higher with the HMI. The answer to Research Question 6 is therefore nuanced. Although internal communication has no influence on the selected operationalisation of an acceptance evaluation, it can influence the behaviour of the participants in favour of altruistic behaviour in the case of a moderate restriction. In addition, internal communication of the system status has a positive influence on trust in the system, which is closely related to user acceptance (see chapter 2.5). The use of suitable internal communication is therefore still recommended.

The key findings presented have an impact on research, as they highlight research gaps and contribute to the evaluation of existing theories for applicability in the research field, as well as on the development of AVs, for which concrete recommendations can be derived. These implications will therefore be discussed separately below.

7.2 Implications

7.2.1 Implications for research

The implications of the results just described relate to both cooperation and communication in road traffic. Study 4 demonstrates that subjects show altruistic behaviour in a situation in which they themselves would benefit from the system in similar circumstances. This is not only a good example of reciprocal altruism. It also shows that it can be applied not only to direct human interaction, but also mediated by automated systems. To date, however, there has been little research on reciprocal altruism in road traffic and, to the best of the author's knowledge, no work regarding CCAM. Since the functionality of CCAM is largely based on the idea that reciprocal altruism can also be applied to AVs, a substantial research gap exists here.

This work also highlights the need for further research in the application of general communication theories to road traffic. For example, we assume that, based on Watzlawick's first axiom, driving dynamics without communication intention also has a communication content. However, this assumption should be tested in the future. Is the communicative content of driving dynamics perceived by other road users? And is this behaviour also seen as an appeal in the sense of Schulz von Thun’s (1996) appeal side of a message?

Further discussions are also necessary on the question of the applicability of the Shannon-Weaver model (Shannon & Weaver, 1949) for communication in road traffic in general and motorway access in particular. As already mentioned in 2.4.1, the simplicity of the model and its good transferability to automated driving speaks in favour of this. In the case of the motorway slip road, there is an unambiguous transmitter and receiver, but as this is not always the case in more complex traffic situations, this is a significant weakness of the model. Another relevant point of criticism is the lack of a feedback loop. This is also relevant in the case of the motorway slip road, as this is the only way to depict conflicting communication or misunderstandings in communication. Misunderstandings can also arise from the fact that, contrary to the model, sometimes not only one channel is used and that messages from different channels can also be contradictory. This becomes particularly obvious when one considers the number and variance of the means of communication in road traffic presented in chapter 2.4.2. Ultimately, the use of driving dynamics for communication purposes in particular reveals a large scope for interpretation (cf. Bowman & Targowski, 1987), which is only increased by cultural differences. Here the model finally meets its limits.

Even the only model explicitly referring to road traffic communication (Merten, 1977) can only deal with the problem of different interpretations to a limited extent. Other weaknesses of the model, such as the reliance on eye contact in communication, have already been discussed in chapter 2.4.1, thus only one point of discussion will be dealt with here. Merten (1977) describes the so-called 'pre-emptive action' as a way to avoid error-prone (and eye contact-based) communication. It has already been questioned whether driving dynamics as 'pre-emptive action' can be understood as a communication avoidance strategy in Merten's sense. In addition to the two aspects already discussed - the contradiction to Watzlawick et al. (1967), according to whom one cannot not communicate, and the acceptance problem of this strategy - the problematic aspects of this assumption become apparent when taking a closer look at the various forms of driving dynamics. The investigated offensive behaviours may still be in line with Merten's pre-emptive action, although, as suspected, a lack of acceptance is evident here. The defensive driving dynamics, on the other hand, do not represent a pre-emptive action, which according to Merten (1977) is intended to avoid communication, but are considered cooperative behaviour in studies 1-3. And since successful communication is a prerequisite for cooperation, defensive driving dynamics cannot be categorised as a means of avoiding communication. The implication of these findings is an insufficient description of communication in road traffic based on existing theories. There is an urgent need for a theory that both comprehensively describes human communication in road traffic and is also applicable to automated driving.

In addition to the implications for cooperation and communication, two further aspects should be addressed. Firstly, the studies presented show differences in the explicit attitudes reported by questionnaire and implicit measures such as the THW. This underlines the relevance of behavioural measures in acceptance research. Secondly, this aspect is not sufficiently considered especially in research on cultural differences in the acceptance of AVs. For economic reasons, these studies are often based exclusively on questionnaires, which means that only explicit attitudes are surveyed. In a next step, the results need to be verified for example using driving simulator studies.

Besides the implications for research, implications for the development of AVs can also be derived. Here, too, further research is necessary, but in contrast to the implications discussed so far, with a focus on practical applications.

7.2.2 Implications AV development

Based on the results presented, implications for the development of automated driving functions in general and for automated motorway access in particular can also be derived. In general, a defensive driving behaviour is preferred for the interaction partner, regardless of its degree of automation. For the motorway slip road, this means that the 'perfect' interaction partner decelerates on the slip road when another vehicle is driving on the destination lane and then slowly changes lanes in the middle of the acceleration lane. Vehicles in the right-hand lane of the motorway should initially decelerate if a space sharing conflict with a vehicle in the acceleration lane occurs and a lane change to another lane is not possible. These recommendations apply to both MVs and AVs.

In the discussion about whether AVs should be visibly labelled from the outside, which was discussed by Stilgoe (2022) and others, the data in this study speaks in favour of labelling, as there were either no differences in evaluation and behaviour, or the evaluation was even more positive, and the driving behaviour was more defensive and therefore safer.

If users must accept certain compromises to use cooperative driving functions, they seem to be willing to do so to a certain extent. Small reductions in speed do not yet lead to poorer acceptance, only larger restrictions lead to the system no longer being used. Even if the internal communication of the system status via HMI does not have a major influence on the acceptance rating of the system, a system with HMI is favoured by users with a high degree of agreement in retrospect. In terms of design, there is a clear preference for displays in the form of a symbol or text (or both), while a sound signal is viewed ambivalently.

The main general implication for the development of AVs is the relevance of the consideration of the human factor. In most of the scenarios studied, the participants had a clear preference for the behaviour of an AV and this preference does not necessarily have to correspond to algorithmically optimised driving behaviour. As user acceptance is crucial for the actual use of a system, this should be reassessed as technical development progresses. The current investigations were carried out with today's ideas of a status eHMI and with today's expectations of the functionalities of CCAM. When these developments are closer to market maturity, they should be reconsidered to cover changes in designs and functionalities. As with research, an important implication for human subject studies in the development process is that it is not sufficient to ask subjects about their preferences, but that studies with practical scenarios are also necessary because explicit views and implicit attitudes reflected in behaviour do not always coincide.

7.3 Limitations and Outlook

The studies in this dissertation are subject to some limitations that should be addressed in future research. A common characteristic of the studies is that they are simulation studies. This method was chosen because it has the advantage of high standardisation: each subject experiences identical behaviour of the interaction partner as well as identical behavioural manipulations. Potential confounding variables such as the behaviour of uninvolved road users, traffic density or the weather can be controlled. In addition, the simulation enables the investigation of more extreme behaviours without endangering the safety of the participants. In a systematic review, Wynne, Beanland, and Salmon (2019) showed that around half of the driving simulator studies investigated achieved absolute or relative validity. To ensure the transferability to real traffic, the results should therefore be validated in future with the help of naturalistic driving studies (NDS).

In addition, the generalisability of the results beyond Germany has so far only been examined for the UK. This is not sufficient to conclusively assess whether there are cultural differences in communication via driving dynamics and how extensive these differences are. Future research could address the question of whether automated vehicles need to have country-specific or even region-specific programming regarding their communication behaviour.

A further limitation of the studies is the isolated consideration of individual means of communication. In studies 1-3 the driving dynamics alone were considered separately without, for example, varying factors such as the onset time of the indicator. In addition, the lateral and longitudinal driving dynamics were considered individually. Further research should analyse the interactions of the driving dynamics with each other and with other means of communication. So far, only the external perspective has been considered regarding driving dynamics. This is important for the acceptance of AVs in general and the question of whether other road users trust them as interaction partners. However, the internal perspective is particularly relevant for behavioural intention, thus whether the driving behaviour is also accepted by the passengers of the AV. Future work should consider this, especially when technological development allows a realistic representation of these behavioural patterns in real traffic.

8 Conclusion

This dissertation considered communication at motorway slip roads in different aspects. External communication was examined, both in the form of driving dynamics and as a status eHMI for displaying the vehicle driving mode. The internal communication of a CCAM system at a motorway slip road, which is intended to overcome the challenges of the communication between AVs and MVs described in the other studies, was also researched. Based on these investigations, recommendations were made both for the development of AVs and for future research in the field.

The key findings include a preference for defensive behaviours such as slow lane changes in the middle of the acceleration lane and deceleration, regardless of whether the vehicle is an AV or an MV. Identical behaviour of vehicles with and without status eHMI is either rated identically or AVs are perceived more positively. In most cases, the eHMI does not lead to deviating behaviour, in one situation, a greater safety distance to AVs was maintained. If the interaction between AVs and MVs should be replaced by a CCAM system, users accept small personal restrictions in the sense of reciprocal altruism. Although an HMI that communicates the system status only has a minor influence on direct acceptance, it is still desired by users and has a positive influence on trust in the system.

The findings presented in this disseration can help to improve communication between MVs and AVs or AVs and their users and improve acceptance and trust in AVs so that they can contribute to improving road safety and traffic flow.

References

Ahmed, K. I. (1999). *Modeling drivers' acceleration and lane changing behavior.* Massachusetts Institute of Technology; Massachusetts Institute of Technology. Retrieved from https://dspace.mit.edu/handle/1721.1/9662

Alonso Raposo, M., Grosso, M., Fernández Macías, E., Galassi, C., Krasenbrink, A., Krause, J., . . . Ciuffo, B. (2018). *An analysis of possible socio-economic effects of a Cooperative, Connected and Automated Mobility (CCAM) in Europe*. Retrieved from https://core.ac.uk/download/pdf/157830385.pdf

Argyle, M. (1972). Non-verbal Communication in Human Social Interaction. In R. A. Hinde (Ed.), *Non-verbal communication* (pp. 243–269). Cambridge: Cambridge Univ. Press.

Balal, E., Cheu, R. L., Gyan-Sarkodie, T., & Miramontes, J. (2014). Analysis of Discretionary Lane Changing Parameters on Freeways. *International Journal of Transportation Science and Technology*, *3*(3), 277–296. https://doi.org/10.1260/2046-0430.3.3.277

Bartneck, C., Kulić, D., Croft, E., & Zoghbi, S. (2009). Measurement Instruments for the Anthropomorphism, Animacy, Likeability, Perceived Intelligence, and Perceived Safety of Robots. *International Journal of Social Robotics*, *1*(1), 71–81. https://doi.org/10.1007/s12369-008-0001-3

Beitel, D., Stipancic, J., Manaugh, K., & Miranda-Moreno, L. (2018). Assessing safety of shared space using cyclist-pedestrian interactions and automated video conflict analysis. *Transportation Research Part D: Transport and Environment*, *65*, 710–724. https://doi.org/10.1016/j.trd.2018.10.001

Bengler, K., Rettenmaier, M., Fritz, N., & Feierle, A. (2020). From HMI to HMIs: Towards an HMI Framework for Automated Driving. *Information*, *11*(2), 61. https://doi.org/10.3390/info11020061

Benmimoun, A., Maag, C., & Neunzig, D. (2004). Effizienzsteigerung durch professionnelles/partnerschaftliches Verhalten im Strassenverkehr. In *181*. Retrieved from https://trid.trb.org/view/967153

Bi, H., Shang, W.-L., Chen, Y., Yu, K., & Ochieng, W. Y. (2022). An Incentive Based Road Traffic Control Mechanism for Covid-19 Pandemic Alike Emergency Preparedness and Response. *IEEE Transactions on Intelligent Transportation Systems*, *23*(12), 25092–25105. https://doi.org/10.1109/tits.2022.3191161

Björklund, G. M., & Åberg, L. (2005). Driver behaviour in intersections: Formal and informal traffic rules. *Transportation Research Part F: Traffic Psychology and Behaviour*, *8*(3), 239–253. https://doi.org/10.1016/j.trf.2005.04.006

Bowman, J. P., & Targowski, A. S. (1987). Modeling the Communication Process: The Map is Not the Territory. *Journal of Business Communication*, *24*(4), 21–34. https://doi.org/10.1177/002194368702400402

Bunge, M. (1979). *Causality and modern science* (Fourth revised edition). Abingdon, Oxon, New York, NY: Routledge. https://doi.org/10.4324/9781315081656

Calvert, S. C., Schakel, W. J., & van Lint, J. W. C. (2017). Will Automated Vehicles Negatively Impact Traffic Flow? *Journal of Advanced Transportation*, *2017*, 1–17. https://doi.org/10.1155/2017/3082781

Ceunynck, T. de, Polders, E., Daniels, S., Hermans, E., Brijs, T., & Wets, G. (2013). Road Safety Differences between Priority-Controlled Intersections and Right-Hand Priority Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, *2365*(1), 39–48. https://doi.org/10.3141/2365-06

Choi, J. K., & Ji, Y. G. (2015). Investigating the Importance of Trust on Adopting an Autonomous Vehicle. *International Journal of Human-Computer Interaction*, *31*(10), 692–702. https://doi.org/10.1080/10447318.2015.1070549

Choudhury, C. F., Ramanujam, V., & Ben-Akiva, M. E. (2009). Modeling Acceleration Decisions for Freeway Merges. *Transportation Research Record: Journal of the Transportation Research Board*, *2124*(1), 45–57. https://doi.org/10.3141/2124-05

Culture Factor Group (2023, November 27). Country comparison tool. Retrieved from https://www.hofstede-insights.com/country-comparison-tool?countries=germany%2Cunited+kingdom

Daamen, W., Loot, M., & Hoogendoorn, S. P. (2010). Empirical Analysis of Merging Behavior at Freeway On-Ramp. *Transportation Research Record: Journal of the Transportation Research Board*, *2188*(1), 108–118. https://doi.org/10.3141/2188-12

Davis, F. D. (1989). Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology. *MIS Quarterly*, *13*(3), 319. https://doi.org/10.2307/249008

Dikmen, M., & Burns, C. (2017). Trust in autonomous vehicles: The case of Tesla Autopilot and Summon. In *2017 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*. IEEE. https://doi.org/10.1109/smc.2017.8122757

Dolianitis, A., Chalkiadakis, C., Mylonas, C., & Tzanis, D. (2019). How Will Autonomous Vehicles Operate in an Unlawful Environment? - The Potential of Autonomous Vehicles for Disregarding the Law. *6th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS)*, 1–10.

Edelmann, A., Stümper, S., & Petzoldt, T. (2021). Cross-cultural differences in the acceptance of decisions of automated vehicles. *Applied Ergonomics*, *92*, 103346. https://doi.org/10.1016/j.apergo.2020.103346

Ehrhardt, S., Graeber, D., Strelau, N.-R., & Deml, B. (2023). Evaluation of the communication means of lateral driving dynamics at motorway slip roads. *at - Automatisierungstechnik*. (4), 269–277. https://doi.org/10.1515/auto-2022-0159

Ehrhardt, S., Martin, M., Hild, J., & Deml, B. (2024). User expectations for an automated motorway access assistant system. *Frontiers in Future Transportation*, *5*. https://doi.org/10.3389/ffutr.2024.1420073

Ehrhardt, S., Merat, N. [Natasha], Daly, M., Solernou Crusat, A., & Deml, B. (2024). Comparing implicit communication via longitudinal driving dynamics: A cross-cultural study in Germany and the UK. *1369-8478*, *102*, 278–293. https://doi.org/10.1016/j.trf.2024.03.008

Ehrhardt, S., Roß, R., & Deml, B. (2023). Implicit communication on the motorway slip road: a driving simulator study. *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2023 Annual Conference*, 95–106. Retrieved from https://www.hfes-europe.org/

Endsley, M. R. (1995). Toward a Theory of Situation Awareness in Dynamic Systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *37*(1), 32–64. https://doi.org/10.1518/001872095779049543

ERTRAC (2019). *Connected Automated Driving Roadmap 2019*. Retrieved from https://www.ertrac.org/wp-content/uploads/2022/07/ERTRAC-CAD-Roadmap-2019.pdf

Faas, S. M., Mathis, L.-A., & Baumann, M. (2020). External HMI for self-driving vehicles: Which information shall be displayed? *Transportation Research Part F: Traffic Psychology and Behaviour*, *68*, 171–186. https://doi.org/10.1016/j.trf.2019.12.009

Faas, S. M., & Baumann, M. (2019). Light-Based External Human Machine Interface: Color Evaluation for Self-Driving Vehicle and Pedestrian Interaction. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. Advance online publication. https://doi.org/10.1177/1071181319631049

Fank, J., Knies, C., & Diermeyer, F. (2021). After You! Design and Evaluation of a Human Machine Interface for Cooperative Truck Overtaking Maneuvers on Freeways. In *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 90–98). New York, NY, USA: ACM. https://doi.org/10.1145/3409118.3475139

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/BF03193146

Felbel, K., Dettmann, A., Lindner, M., & Bullinger, A. C. (2021). Communication of Intentions in Automated Driving – the Importance of Implicit Cues and Contextual Information on Freeway Situations. In (pp. 252–261). Springer, Cham. https://doi.org/10.1007/978-3-030-78358-7_17

Forschungsgesellschaft für Straßen- und Verkehrswesen (2019). *Richtlinien für die Markierung von Straßen* (Ausgabe 2019). *FGSV: 330A*. Köln: FGSV.

Forster, Y., Naujoks, F., & Neukum, A. (2017). Increasing anthropomorphism and trust in automated driving functions by adding speech output. In *2017 IEEE Intelligent Vehicles Symposium (IV)*. IEEE. https://doi.org/10.1109/ivs.2017.7995746

Fuest, T., Feierle, A., Schmidt, E., & Bengler, K. (2020). Effects of Marking Automated Vehicles on Human Drivers on Highways. *Information*, *11*(6), 286. https://doi.org/10.3390/info11060286

GATEway Project (2017). Driver responses to encountering automated vehicles in an urban environment: Project report PPR807. *Transport Research Foundation*. Retrieved from https://trl.co.uk/Uploads/TRL/Documents/D4.6_Driver-responses-to-encountering-automated-vehicles-in-an-urban-environment_PPR807.pdf

Ghazizadeh, M., Lee, J. D., & Boyle, L. N. (2012). Extending the Technology Acceptance Model to assess automation. *Cognition, Technology & Work*, *14*(1), 39–49. https://doi.org/10.1007/s10111-011-0194-3

Ghazizadeh, M., Peng, Y., Lee, J. D., & Boyle, L. N. (2012). Augmenting the Technology Acceptance Model with Trust: Commercial Drivers' Attitudes towards Monitoring and Feedback. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 56*(1), 2286–2290. https://doi.org/10.1177/1071181312561481

Godley, S. T., Triggs, T. J., & Fildes, B. N. (2002). Driving simulator validation for speed research. *Accident Analysis & Prevention, 34*(5), 589–600.

Grandsart, D., Cornet, H., Loukea, M., Coeugnet-Chevrier, S., Metayer, N., Anund, A., & Dahlman, A. S. (2023). Citizen and Stakeholder Engagement in the Development and Deployment of Automated Mobility Services, as Exemplified in the SHOW Project. In E. G. Nathanail, N. Gavanas, & G. Adamos (Eds.), *Lecture Notes in Intelligent Transportation and Infrastructure, Smart Energy for Smart Transport: Proceedings of the 6th Conference on Sustainable Urban Mobility, CSUM2022, August 31-September 2, 2022, Skiathos Island, Greece* (1st ed., pp. 468–481). Cham: Springer Nature Switzerland; Imprint Springer. https://doi.org/10.1007/978-3-031-23721-8_39

Haar, A., Haeske, A. B., Kleen, A., Schmettow, M., & Verwey, W. B. (2022). Improving clarity, cooperation and driver experience in lane change manoeuvres. *Transportation Research Interdisciplinary Perspectives*, *13*, 100553. https://doi.org/10.1016/j.trip.2022.100553

Hagenzieker, M. P., van der Kint, S., Vissers, L., van Schagen, I. N. L. G., Bruin, J. de, van Gent, P., & Commandeur, J. J. F. (2020). Interactions between cyclists and automated vehicles: Results of a photo experiment. *Journal of Transportation Safety & Security*, *12*(1), 94–115. https://doi.org/10.1080/19439962.2019.1591556

Hoc, J.-M. (2001). Towards a cognitive approach to human–machine cooperation in dynamic situations. *International Journal of Human-Computer Studies*, *54*(4), 509–540. https://doi.org/10.1006/ijhc.2000.0454

Hofstede, G. (2001). *Culture's consequences: Comparing values, behaviors, institutions, and organizations across nations*. Thousand Oaks, Calif., London: SAGE.

Hofstede, G. (2011). Dimensionalizing Cultures: The Hofstede Model in Context. *Online Readings in Psychology and Culture*, *2*(1). https://doi.org/10.9707/2307-0919.1014

Hőgye-Nagy, Á., Kovács, G., & Kurucz, G. (2023). Acceptance of self-driving cars among the university community: Effects of gender, previous experience, technology adoption propensity, and attitudes toward autonomous vehicles. *Transportation Research Part F: Traffic Psychology and Behaviour*, *94*, 353–361. https://doi.org/10.1016/j.trf.2023.03.005

Holm, S. (1979). A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics*, 65–70.

Hornbæk, K., & Oulasvirta, A. (May 2017). What Is Interaction? In G. Mark (Ed.), *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (pp. 5040–5052). New York: Association for Computing Machinery. https://doi.org/10.1145/3025453.3025765

Hulse, L. M., Xie, H., & Galea, E. R. (2018). Perceptions of autonomous vehicles: Relationships with road users, risk, gender and age. *Safety Science*, *102*, 1–13. https://doi.org/10.1016/j.ssci.2017.10.001

Imbsweiler, J. (2019). Kooperation im Straßenverkehr in innerstädtischen Pattsituationen. Retrieved from https://d-nb.info/1188321765/34

Imbsweiler, J., Ruesch, M., Heine, T., Linstedt, K., Weinreuter, H., León, F., & Deml, B. (2018). Die Rolle der expliziten Kommunikation im Straßenverkehr. *Arbeit (S). Wissen. Schaf (F) T–Grundlagen Für Management & Kompetenzentwicklung.* (64). Retrieved from https://www.researchgate.net/profile/jonas-imbsweiler/publication/323365310_die_rolle_der_expliziten_kommunikation_im_strassenverkehr/links/5a901bee45851535bcd478c8/die-rolle-der-expliziten-kommunikation-im-strassenverkehr.pdf

Imbsweiler, J., Ruesch, M., Weinreuter, H., Puente León, F., & Deml, B. (2018). Cooperation behaviour of road users in t-intersections during deadlock situations. *Transportation Research Part F: Traffic Psychology and Behaviour*, *58*, 665–677. https://doi.org/10.1016/j.trf.2018.07.006

Joisten, P., Alexandi, E., Drews, R., Klassen, L., Petersohn, P., Pick, A., . . . Abendroth, B. (2020). Displaying Vehicle Driving Mode – Effects on Pedestrian Behavior and Perceived Safety. In (pp. 250–256). Springer, Cham. https://doi.org/10.1007/978-3-030-27928-8_38

Karrer, K., Glaser, C., Clemens, C., & Bruder, C. (2009). TA-EG Fragebogen zur Technikaffinität – Einstellung zu und Umgang mit elektronischen Geräten: Der Mensch Im Mittelpunkt Technischer Systeme. *Berliner Werkstatt Mensch-Maschine-Systeme*, *29*, 196–201.

Kauffmann, N., Naujoks, F., Winkler, F., & Kunde, W. (2018). Learning the "Language" of Road Users - How Shall a Self-driving Car Convey Its Intention to Cooperate to Other Human Drivers? In (pp. 53–63). Springer, Cham. https://doi.org/10.1007/978-3-319-60366-7_6

Kauffmann, N., Winkler, F., Naujoks, F., & Vollrath, M. (2018). "What Makes a Cooperative Driver?" Identifying parameters of implicit and explicit forms of communication in a lane change scenario. *Transportation Research Part F: Traffic Psychology and Behaviour*, *58*, 1031–1042. https://doi.org/10.1016/j.trf.2018.07.019

Kaur, K., & Rampersad, G. (2018). Trust in driverless cars: Investigating key factors influencing the adoption of driverless cars. *0923-4748*, *48*, 87–96. https://doi.org/10.1016/j.jengtecman.2018.04.006

Kesting, A., Treiber, M., & Helbing, D. (2007). General Lane-Changing Model MOBIL for Car-Following Models. *Transportation Research Record: Journal of the Transportation Research Board*, *1999*(1), 86–94. https://doi.org/10.3141/1999-10

Khamis, A. M., Kamel, M. S., & Salichs, M. A. (2006). Cooperation: Concepts and General Typology. In *2006 IEEE International Conference on Systems, Man and Cybernetics*. IEEE. https://doi.org/10.1109/icsmc.2006.384929

Kondyli, A., & Elefteriadou, L. (2010). Driver behavior at freeway-ramp merging areas based on instrumented vehicle observations. *Conference: 5th International Congress on Transport Research*.

Kusuma, A., Liu, R., Choudhury, C., & Montgomery, F. (2015). Lane-changing characteristics at weaving section. In *Transportation Research Board 94th Annual Meeting*.

Lagstrom, T., & Lundgren, V. M. (2015). *AVIP-Autonomous vehicles interaction with pedestrians*. Retrieved from https://scholar.google.de/citations?user=dltva04aaaaj&hl=de&oi=sra

Lee, J. D., & See, K. A. (2004). Trust in automation: Designing for appropriate reliance. *Human Factors*, *46*(1), 50–80. https://doi.org/10.1518/hfes.46.1.50_30392

Lee, Y. M. [Yee Mun], Madigan, R. [Ruth], Giles, O., Garach-Morcillo, L., Markkula, G. [Gustav], Fox, C., . . . Merat, N. [Natasha] (2021). Road users rarely use explicit communication when interacting in today's traffic: Implications for automated vehicles. *Cognition, Technology & Work*, *23*(2), 367–380. https://doi.org/10.1007/s10111-020-00635-y

Li, D., & Wagner, P. (2019). Impacts of gradual automated vehicle penetration on motorway operation: A comprehensive evaluation. *European Transport Research Review*, *11*(1), 1–10. https://doi.org/10.1186/s12544-019-0375-3

Liang, X., Meng, X., & Zheng, L. (2021). Investigating conflict behaviours and characteristics in shared space for pedestrians, conventional bicycles and e-bikes. *Accident; Analysis and Prevention*, *158*, 106167. https://doi.org/10.1016/j.aap.2021.106167

Liu, P., Du, Y., Wang, L., & Da Young, J. (2020). Ready to bully automated vehicles on public roads? *Accident; Analysis and Prevention*, *137*, 105457. https://doi.org/10.1016/j.aap.2020.105457

Louw, T., Madigan, R. [Ruth], Lee, Y. M. [Yee Mun], Nordhoff, S., Lehtonen, E., Innamaa, S., . . . Merat, N. [Natasha] (2021). Drivers' Intentions to Use Different Functionalities of Conditionally Automated Cars: A Survey Study of 18,631 Drivers from 17 Countries. *International Journal of Environmental Research and Public Health*, *18*(22), 12054. https://doi.org/10.3390/ijerph182212054

Lundgren, V. M., Habibovic, A., Andersson, J., Lagström, T., Nilsson, M., Sirkka, A., . . . Saluäär, D. (2017). Will There Be New Communication Needs When Introducing Automated Vehicles to the Urban Context? *Advances in Human Aspects of Transportation*, *484*, 485–497. https://doi.org/10.1007/978-3-319-41682-3_41

Marczak, F., Daamen, W., & Buisson, C. (2013a). Key Variables of Merging Behaviour: Empirical Comparison between Two Sites and Assessment of Gap Acceptance Theory. *Procedia - Social and Behavioral Sciences*, *80*, 678–697. https://doi.org/10.1016/j.sbspro.2013.05.036

Marczak, F., Daamen, W., & Buisson, C. (2013b). Merging behaviour: Empirical comparison between two sites and new theory development. *Transportation Research Part C: Emerging Technologies*, *36*, 530–546. https://doi.org/10.1016/j.trc.2013.07.007

Markkula, G. [G.], Madigan, R. [R.], Nathanael, D. [D.], Portouli, E., Lee, Y. M. [Y. M.], Dietrich, A. [A.], . . . Merat, N. [N.] (2020). Defining interactions: A conceptual framework for understanding interactive behaviour in human and automated road traffic. *Theoretical Issues in Ergonomics Science*, *21*(6), 728–752. https://doi.org/10.1080/1463922X.2020.1736686

Maurer, M., Gerdes, J. C., Lenz, B., & Winner, H. (2015). *Autonomes Fahren*. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-45854-9

McNemar, Q. (1947). Note on the sampling error of the difference between correlated proportions or percentages. *Psychometrika*, *12*(2), 153–157. https://doi.org/10.1007/bf02295996

Mercedes-Benz Group (2021). Erste international gültige Systemgenehmigung: Hochautomatisiertes Fahren | Mercedes-Benz Group. Retrieved from https://group.mercedes-benz.com/innovation/produktinnovation/autonomes-fahren/systemgenehmigung-fuer-hochautomatisiertes-fahren.html

Merten, K. (1977). Kommunikationsprozesse im Straßenverkehr. In Bundesanstalt für Straßenwesen (Ed.), *Symposium 77* (pp. 115–126). Köln.

Merugu, D., Prabhakar, B. S., & Rama, N. S. (2009). An incentive mechanism for decongesting the roads: A pilot program in bangalore. *Proc. Of ACM NetEcon Workshop, Citeseer*.

Moore, D., Currano, R., Shanks, M., & Sirkin, D. (2020). Defense Against the Dark Cars. In T. Belpaeme, J. Young, H. Gunes, & L. Riek (Eds.), *HRI '20: Proceedings of the 2020 ACM/IEEE International Conference on Human Robot Interaction : March 23-26, 2020, Cambridge, United Kingdom* (pp. 201–209). New York, NY: The Association for Computing Machinery. https://doi.org/10.1145/3319502.3374796

Moore, D., Currano, R., Strack, G. E., & Sirkin, D. (2019). The Case for Implicit External Human-Machine Interfaces for Autonomous Vehicles. In *ACM Digital Library, Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 295–307). New York,NY,United States: Association for Computing Machinery. https://doi.org/10.1145/3342197.3345320

Muzammel, C. S., Spichkova, M., & Harland, J. (2024, April 3). *Cultural influence on autonomous vehicles acceptance*. Retrieved from http://arxiv.org/pdf/2404.03694v1

Neukum, A., & Krueger, H. (2003). Fahrerreaktionen bei Lenksystemstoerungen - Untersuchungsmethodik und Bewertungskriterien [Driver reaction to steering system failures - methodology and criteria for evaluation]. *VDI-Berichte*, *1791*. Retrieved from https://trid.trb.org/view/954756

On-Road Automated Driving Committee (2021). *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles.*

Özkan, T., Lajunen, T., Chliaoutakis, J. E., Parker, D., & Summala, H. (2006). Cross-cultural differences in driving behaviours: A comparison of six countries. *Transportation Research Part F: Traffic Psychology and Behaviour*, *9*(3), 227–242. https://doi.org/10.1016/j.trf.2006.01.002

Öztürk, İ., Wallén Warner, H., & Özkan, T. (2024). Preferred level of vehicle automation: How technology adoption, knowledge, and personality affect automation preference in Türkiye and Sweden. *Cogent Psychology*, *11*(1), 2314840. https://doi.org/10.1080/23311908.2024.2314840

Panagiotopoulos, I., & Dimitrakopoulos, G. (2018). An empirical investigation on consumers' intentions towards autonomous driving. *Transportation Research Part C: Emerging Technologies*, *95*, 773–784. https://doi.org/10.1016/j.trc.2018.08.013

Pöhler, G., Heine, T., & Deml, B. (2016). Itemanalyse und Faktorstruktur eines Fragebogens zur Messung von Vertrauen im Umgang mit automatischen Systemen. *Zeitschrift für Arbeitswissenschaft*, *70*(3), 151–160. https://doi.org/10.1007/s41449-016-0024-9

Reinolsmann, N., Alhajyaseen, W., Brijs, T., Pirdavani, A., Hussain, Q., & Brijs, K. (2021). Investigating the impact of a novel active gap metering signalization strategy on driver behavior at highway merging sections. *Transportation Research Part F: Traffic Psychology and Behaviour*, *78*, 42–57. https://doi.org/10.1016/j.trf.2021.01.017

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

Rettenmaier, M., Dinkel, S., & Bengler, K. (2021a). Communication via motion - Suitability of automated vehicle movements to negotiate the right of way in road bottleneck scenarios. *Applied Ergonomics*, *95*, 103438. https://doi.org/10.1016/j.apergo.2021.103438

Rettenmaier, M., Dinkel, S., & Bengler, K. (2021b). Communication via motion - Suitability of automated vehicle movements to negotiate the right of way in road bottleneck scenarios. *Applied Ergonomics*, *95*, 103438. https://doi.org/10.1016/j.apergo.2021.103438

Rickheit, G. (Ed.) (2008). *Handbooks of applied linguistics: Vol. 1. Handbook of communication competence*. Berlin: Mouton de Gruyter. https://doi.org/10.1515/9783110199000

Rios-Torres, J., & Malikopoulos, A. A. (2017). Automated and Cooperative Vehicle Merging at Highway On-Ramps. *IEEE Transactions on Intelligent Transportation Systems*, *18*(4), 780–789. https://doi.org/10.1109/TITS.2016.2587582

Risto, M., Emmenegger, C., Vinkhuyzen, E., Cefkin, M., & Hollan, J. (2017). Human-Vehicle Interfaces: The Power of Vehicle Movement Gestures in Human Road User Coordination. *Driving Assessment Conference*, *9*(2017), 186–192. https://doi.org/10.17077/drivingassessment.1633

SAE (2021). Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles: J3016_202104. Retrieved from https://saemobilus.sae.org/content/j3016_202104

Salerno, J., Hinman, M., & Boulware, D. (2004). Building a framework for situation awareness. *Proceedings of the 7th International Conference on Information Fusion*. Retrieved from https://apps.dtic.mil/sti/citations/ada524360

Schaarschmidt, E., Yen, R., Bosch, R., Zwicke, L., Schade, J., & Petzoldt, T. (Eds.) (2021). *Berichte der Bundesanstalt für Strassenwesen - Fahrzeugtechnik (F): Vol. 138. Grundlagen zur Kommunikation zwischen automatisierten Kraftfahrzeugen und Verkehrsteilnehmern: [Fundamentals of communication betweeen automated vehicles and road users]* (1. Auflage). Bremen: Fachverlag NW in Carl Ed. Schünemann KG. Retrieved from https://bast.opus.hbz-nrw.de/opus45-bast/frontdoor/deliver/index/docId/2497/file/F138_barrFrei.pdf

Schieben, A. [Anna], Wilbrink, M., Kettwich, C., Dodiya, J., Weber, F., Sorokin, L., . . . Kaup, M. (2019). Testing external HMI designs for automated vehicles – An overview on user study results from the EU project interact. In *9. Tagung Automatisiertes Fahren*. Retrieved from https://mediatum.ub.tum.de/1535145

Schieben, A. [Anna], Wilbrink, M., Kettwich, C., Madigan, R. [Ruth], Louw, T., & Merat, N. [Natasha] (2019). Designing the interaction of automated vehicles with other traffic participants: Design considerations based on human needs and expectations. *Cognition, Technology & Work*, *21*(1), 69–85. https://doi.org/10.1007/s10111-018-0521-z

Schoettle, B., & Sivak, M. (2014). *A survey of public opinion about autonomous and self-driving vehicles in the U.S., the U.K., and Australia* (University of Michigan, Ann Arbor, Transportation Research Institute). Retrieved from University of Michigan, Ann Arbor, Transportation Research Institute website: https://deepblue.lib.umich.edu/handle/2027.42/108384

Schulz von Thun, F. (1996). *Miteinander reden 1: Störungen und Klärungen: Allgemeine Psychologie der Kommunikation*. Retrieved from https://ixtheo.de/record/1121062636

Shannon, C. E., & Weaver, W. (1949). A mathematical model of communication. *Urbana, IL: University of Illinois Press*. (11), 11–20.

Shechtman, O., Classen, S., Awadzi, K., & Mann, W. (2009). Comparison of driving errors between on-the-road and simulated driving assessment: A validation study. *Traffic Injury Prevention*, *10*(4), 379–385. https://doi.org/10.1080/15389580902894989

Siebert, F. W., Oehl, M., & Pfister, H.-R. (2014). The influence of time headway on subjective driver states in adaptive cruise control. *1369-8478*, *25*, 65–73. https://doi.org/10.1016/j.trf.2014.05.005

Spieß, E. Kooperation. In Markus A. Wirtz (Ed.), *Dorsch. Lexikon der Psychologie*. Bern. Retrieved from https://dorsch.hogrefe.com/stichwort/kooperation* (Original work published 2021).

Stange, V., Kühn, M., & Vollrath, M. (2022). Manual drivers' experience and driving behavior in repeated interactions with automated Level 3 vehicles in mixed traffic on the highway. *Transportation Research Part F: Traffic Psychology and Behaviour*, *87*, 426–443. https://doi.org/10.1016/j.trf.2022.04.019

Stanton, N. A., Eriksson, A., Banks, V. A., & Hancock, P. A. (2020). Turing in the driver's seat: Can people distinguish between automated and manually driven vehicles? *Human Factors and Ergonomics in Manufacturing & Service Industries*, *30*(6), 418–425. https://doi.org/10.1002/hfm.20864

Statista (2022, November 9). Jedes zehnte Fahrzeug fährt bis 2030 autonom. Retrieved from https://de.statista.com/presse/p/autonomes_fahren_2020/

Stilgoe, J. (2022, May 14). It will soon be easy for self-driving cars to hide in plain sight. We shouldn't let them. *MIT Technology Review*. Retrieved from https://www.technologyreview.com/2022/05/14/1052250/labeling-self-driving-cars/

Stoll, T. (2022). *Cooperation in traffic: influence of situational factors in cooperative situations*. Universität Ulm: Doctoral dissertation. Retrieved from https://oparu.uni-ulm.de/xmlui/handle/123456789/46324

Stoll, T., Weihrauch, L., & Baumann, M. (2020a). After you: Merging at Highway On-Ramps. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *64*(1), 1105–1109. https://doi.org/10.1177/1071181320641266

Stoll, T., Weihrauch, L., & Baumann, M. (2020b). After you: Merging at Highway On-Ramps. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *64*(1), 1105–1109. https://doi.org/10.1177/1071181320641266

Talebpour, A., & Mahmassani, H. S. (2016). Influence of connected and autonomous vehicles on traffic flow stability and throughput. *Transportation Research Part C: Emerging Technologies*, *71*, 143–163. https://doi.org/10.1016/j.trc.2016.07.007

Taniguchi, A., Enoch, M., Theofilatos, A., & Ieromonachou, P. (2022). Understanding acceptance of autonomous vehicles in Japan, UK, and Germany. *Urban, Planning and Transport Research*, *10*(1), 514–535. https://doi.org/10.1080/21650020.2022.2135590

Tolbert, S., & Nojoumian, M. (2023). Cross-Cultural Expectations from Self-Driving Cars. Advance online publication. https://doi.org/10.21203/rs.3.rs-2432387/v1

Torrao, G., Lehtonen, E., & Innamaa, S. (2024). The gender gap in the acceptance of automated vehicles in Europe. *Transportation Research Part F: Traffic Psychology and Behaviour*, *101*, 199–217. https://doi.org/10.1016/j.trf.2023.11.002

Treiber, M., & Kesting, A. (2010). Stauentstehung und Stauausbreitung. In M. Treiber & A. Kesting (Eds.), *Springer-Lehrbuch. Verkehrsdynamik und -simulation* (pp. 257–266). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-05228-6_17

Trivers, R. L. (1971). The Evolution of Reciprocal Altruism. *The Quarterly Review of Biology*, *46*(1), 35–57. https://doi.org/10.1086/406755

Tscharn, R., Naujoks, F., & Neukum, A. (2018). The perceived criticality of different time headways is depending on velocity. *1369-8478*, *58*, 1043–1052. https://doi.org/10.1016/j.trf.2018.08.001

Üzümcüoğlu, Y., Özkan, T., & Lajunen, T. (2018). The relationships between cultural variables, law enforcements and driver behaviours across 37 nations. *1369-8478*, *58*, 743–753. https://doi.org/10.1016/j.trf.2018.07.009

Van Beinum, A., Farah, H., Wegman, F., & Hoogendoorn, S. (2018). Driving behaviour at motorway ramps and weaving segments based on empirical trajectory data. *Transportation Research Part C: Emerging Technologies*, *92*, 426–441. https://doi.org/10.1016/j.trc.2018.05.018

Venkatesh, V. (2000). Determinants of Perceived Ease of Use: Integrating Control, Intrinsic Motivation, and Emotion into the Technology Acceptance Model. *Information Systems Research*, *11*(4), 342–365. https://doi.org/10.1287/isre.11.4.342.11872

Venkatesh, V., & Bala, H. (2008). Technology Acceptance Model 3 and a Research Agenda on Interventions. *Decision Sciences*, *39*(2), 273–315. https://doi.org/10.1111/j.1540-5915.2008.00192.x

Venkatesh, V., & Davis, F. D. (2000). A Theoretical Extension of the Technology Acceptance Model: Four Longitudinal Field Studies. *Management Science*, *46*(2), 186–204. https://doi.org/10.1287/mnsc.46.2.186.11926

Wang, W., Cheng, Q., Li, C., André, D., & Jiang, X. (2019). A cross-cultural analysis of driving behavior under critical situations: A driving simulator study. *Transportation Research Part F: Traffic Psychology and Behaviour*, *62*, 483–493. https://doi.org/10.1016/j.trf.2019.02.007

Watzlawick, P., Bavelas, J. B., & Jackson, D. D. (1967). *Pragmatics of human communication: A study of interactional patterns, pathologies, and paradoxes.*

Werner, A. (2019). New Colours for Autonomous Driving: An Evaluation of Chromaticities for the External Lighting Equipment of Autonomous Vehicles. *Colour Turn*, *0*(1). https://doi.org/10.25538/tct.v0i1.692

Wilbrink, M., Lau, M., Illgner, J., Schieben, A. [Anna], & Oehl, M. (2021). Impact of External Human–Machine Interface Communication Strategies of Automated Vehicles on Pedestrians' Crossing Decisions and Behaviors in an Urban Environment. *Sustainability*, *13*(15), 8396. https://doi.org/10.3390/su13158396

Wynne, R. A., Beanland, V., & Salmon, P. M. (2019). Systematic review of driving simulator validation studies. *Safety Science*, *117*, 138–151. https://doi.org/10.1016/j.ssci.2019.04.004

Yun, Y., Oh, H., & Myung, R. (2021). Statistical Modeling of Cultural Differences in Adopting Autonomous Vehicles. *Applied Sciences*, *11*(19), 9030. https://doi.org/10.3390/app11199030

Zhang, T., Zeng, W., Zhang, Y., Da Tao, Li, G., & Qu, X. [Xingda] (2021). What drives people to use automated vehicles? A meta-analytic review. *Accident; Analysis and Prevention*, *159*, 106270. https://doi.org/10.1016/j.aap.2021.106270

Zheng, Y., Ran, B., Qu, X. [Xu], Zhang, J., & Lin, Y. (2020). Cooperative Lane Changing Strategies to Improve Traffic Operation and Safety Nearby Freeway Off-Ramps in a Connected and Automated Vehicles Environment. *IEEE Transactions on Intelligent Transportation Systems*, *21*(11), 4605–4614. https://doi.org/10.1109/tits.2019.2942050

Zwicker, L., Petzoldt, T., Schade, J., & Schaarschmidt, E. (2019). Kommunikation zwischen automatisierten Kraftfahrzeugen und anderen Verkehrsteilnehmern - was brauchen wir überhaupt? In R. Bruder & H. Winner (Eds.), *Hands off, Human Factors off? Welche Rolle spielen Human Factors in der Fahrzeugautomation? 9. Darmstädter Kolloquium* (pp. 47–57).

List of Publications

This is the doctoral candidate's complete list of scientific publications. The publications included in the publication-based doctoral thesis are printed in bold and are followed by the respective CRediT author statement.

Ehrhardt, S., Martin, M., Hild, J., & Deml, B. (2024). User expectations for an automated motorway access assistant system. *Frontiers in Future Transportation, 5.* https://doi.org/10.3389/ffutr.2024.1420073

CRediT author statement:

Sofie Ehrhardt: Conceptualization, Data Curation, Investigation, Methodology, Formal analysis, Writing – Original Draft, Visualization. **Manuel Martin:** Conceptualization, Software, Writing - Review & Editing. **Jutta Hild:** Conceptualization, Writing - Review & Editing. **Barbara Deml:** Funding Acquisition, Resources, Supervision, Writing - Review & Edit

Ehrhardt, S., Merat, N., Daly, M., Crusat, A. S., & Deml, B. (2024). Comparing implicit communication via longitudinal driving dynamics: A cross-cultural study in Germany and the UK. *Transportation Research Part F: Traffic Psychology and Behaviour, 102,* 278-293.

CRediT author statement:

Sofie Ehrhardt: Writing – Original Draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Natasha Merat:** Writing – Review & Editing, Resources, Project administration. **Michael Daly:** Writing – Review & Editing, Software. **Albert Solernou Crusat:** Software. **Barbara Deml:** Writing – Review & Editing, Supervision, Conceptualization.

Ehrhardt, S., Roß, R., & Deml, B. (2023). Implicit communication on the motorway slip road: a driving simulator study. In D. de Waard, V. Hagemann, L. Onnasch, A. Toffetti, D. Coelho, A. Botzer, M. de Angelis, K. Brookhuis, and S. Fairclough (2023). *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2023 Annual Conference* (pp. 95-106). Available from http://hfes-europe.org (ISSN 2333-4959).

CRediT author statement:

Sofie Ehrhardt: Conceptualization, Methodology, Formal analysis, Writing – Original Draft, Visualization. **Raphael Roß:** Software, Investigation, Data Curation, Formal analysis. **Barbara Deml:** Resources, Supervision, Writing - Review & Editing.

Ehrhardt, S., Graeber, D., Strelau, N. & Deml, B. (2023). Evaluation of the communication means of lateral driving dynamics at motorway slip roads. at - Automatisierungstechnik, 71(4), 269-277. https://doi.org/10.1515/auto-2022-0159

CRediT author statement:

Sofie Ehrhardt: Conceptualization, Methodology, Formal analysis, Writing – Original Draft, Visualization. **Daniel Graeber:** Software, Investigation, Data Curation. **Nadine-Rebecca Strelau:** Formal analysis, Writing - Review & Editing. **Barbara Deml:** Resources, Supervision.

Ziehn, J. R., Baumann, M. V., Beyerer, J., Buck, H. S., Deml, B., **Ehrhardt, S**., . . . Vortisch, P. (2023). Cooperative automated driving for bottleneck scenarios in mixed traffic. In 35th IEEE Intelligent Vehicles Symposium (IV 2023), Anchorage, AK, USA, June 4-7, 2023.

Baumann, M. V., Buck, H. S., **Ehrhardt, S**., Roschani, M., & Vortisch, P. (2021). Simulation-based traffic assessment of a connected automated driving function. In ETC conference papers 2021: online.

Ehrhardt, S., Baumann, M. V., Buck, H. S., Li, Y., Deml, B., & Vortisch, P. (2021). Gap Acceptance at Blocked Lanes on Urban Two-Way Roads and Evaluation of a Bottleneck Assistant (No. TRBAM-21-01297).

Schneeberger, T., **Ehrhardt, S.**, Anglet, M. S., & Gebhard, P. (2019). Would you Follow my Instructions if I was not Human? Examining Obedience towards Virtual Agents. In 2019 8th International Conference on Affective Computing and Intelligent Interaction (ACII) (pp. 1-7). IEEE