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# Principles for External Human–Machine Interfaces

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**Abstract:** Automated vehicles will soon be integrated into our current traffic system. This development will lead to a novel mixed-traffic environment where connected and automated vehicles (CAVs) will have to interact with other road users (ORU). To enable this interaction, external human–machine interfaces (eHMIs) have been shown to have major benefits regarding the trust and acceptance of CAVs in multiple studies. However, a harmonization of eHMI signals seems to be necessary since the developed signals are extremely varied and sometimes even contradict each other. Therefore, the present paper proposes guidelines for designing eHMI signals, taking into account important factors such as how and in which situations a CAV needs to communicate with ORU. The authors propose 17 heuristics, the so-called eHMI-principles, as requirements for the safe and efficient use of eHMIs in a systematic and application-oriented manner.

**Keywords:** interaction with automated vehicles; external human–machine interface; design of communication signals for CAV; interaction of automated vehicles and other road users; guidelines for eHMI



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## 1. Introduction

The introduction of connected automated vehicles (CAVs) into our traffic system will lead to a novel mixed-traffic environment where CAVs will coexist with other road users (ORU) [1]. This mixed-traffic environment creates new challenges for CAVs since they need the ability to interact with ORU in a safe and efficient way. Therefore, all traffic participants need to build up a common understanding of the ability and intentions of others [2]. Considering how humans interact in traffic environments, implicit and explicit communication are two promising methods for designing interactions between CAVs and ORU. Implicit communication needs to be interpreted by the receiver and often contains no obvious information (e.g., vehicle movements). Furthermore, implicit information is broadcast into the environment and is not directly addressed to one receiver. On the other hand, explicit communication is directed to a particular traffic participant and can involve different modalities (e.g., auditory, visual) to transfer further information (e.g., hand gestures and the use of turn indicators).

Research results in the fields of human–machine interaction and traffic psychology reveal the great potential of external human–machine interfaces (eHMIs). These eHMIs can play a significant role in enabling safe and efficient interactions between CAVs and

ORU, as they will enhance the current forms of communication and compensate for deficits in implicit communication, e.g., [3–5]. In the literature, a huge variety of different eHMI designs have been proposed and tested in various traffic scenarios [6]. These concepts differ in the number and modality (mostly visually) of signals, and in the directionality (signal for only one receiver vs. broadcast for the environment) of the information, as well as the taken perspective in which the messages are formulated (vehicle's point of view: "I am stopping"; pedestrian perspective: "You can cross the street"). Most of the empirical studies found benefits of eHMI concepts in terms of comprehensibility, safety, efficiency, and acceptability [7]. However, the variability in the eHMI concepts makes it hard to compare and transfer results between the studies. When considering the interaction between CAVs and ORU from a holistic point of view, a pure focus on explicit communication via eHMI seems insufficient. Therefore, the importance of the interplay between eHMIs and the vehicle's movement patterns, the so-called dynamic HMI (dHMI, e.g., acceleration and deceleration), should be highlighted.

## 2. Approval Aspects and Existing Guidelines

Currently, recommendations are organized as checklists or guidelines addressing product developers in the automotive and supplier industry. However, a surprisingly low number of design recommendations and legal requirements exist for eHMI signals.

In the USA, the Federal Motor Vehicle Safety Standard 108 regulates the installation and properties of "automotive lighting systems, signaling, and reflective devices" [8]. Among other things, the regulation prescribes the colors of emitting lights for different zones of the vehicle (e.g., white or amber is allowed in the front area of a vehicle). In addition, FMVSS 108 requires new lighting systems to be installed away from existing devices so that any confusion regarding light signals can be avoided. The UNECE document R48, authoritative for many countries in Europe, Asia, and beyond, regulates the integration of new external visual communication systems more restrictively [9]. In the current version, additional visual communication systems are not permitted. However, the question of whether and in what form CAVs should communicate with ORU has been discussed for several years in different working groups (e.g., the "Taskforce on Autonomous Vehicle Signaling Requirements", set up by the UNECE [10]). While the discussions in this panel proceed controversially, standardization institutes such as SAE and ISO have described concrete aspects for future communication between CAVs and ORU.

With the "recommended practice" J3134, SAE International has proposed an "Automated Driving System Marker Lamp" that lights up in cyan [10]. The lamp should be installed in the front area of the vehicle and light up permanently when automated driving is activated.

The International Organization for Standardization is also publishing documents that are to be understood as building blocks for future standardization. The Technical Report ISO/TR 23049 ("Road Vehicles—Ergonomic aspects of external visual communication from automated vehicles to other road users") analyzes communication patterns in non-automated traffic and compiles design dimensions that need to be considered when developing future eHMIs (e.g., communication of the driving mode, vehicle state, and vehicle's intention) [11]. Currently in preparation is the standard ISO/AWI PAS 23735 ("Road vehicles—Ergonomic design guidance for external visual communication from automated vehicles to other road users"), which deals with so-called design parameters for safe and well-accepted communication between CAVs and ORU. Among other things, a distinction is made as to which information should be transmitted on which communication media and in which concrete design. It is planned for the document to also contain an extensive list of traffic scenarios and use cases.

A harmonization of eHMI signals in a traffic system can play a major role regarding the acceptance of CAVs and traffic safety while interacting with them. Only if eHMI signals are consistent between vehicle manufacturers and traffic situations can ORU build up a matching mental model of CAVs and understand their present and future behavior.

## 3. Method for Deriving eHMI-Principles

Multiple approaches were followed to create the present list of eHMI-principles. As a first approach, the authors evaluated the existing research papers and literature reviews in the field of HMI and human factors for automated vehicles. Based on the research results, eHMI-principles were derived iteratively. As another approach, focus groups with drivers were conducted to discuss the need for, functionality, and design of eHMIs from a user's perspective. Finally, project partners identified open research questions and conducted over 40 user studies and expert workshops gaining new insights on the topic of eHMI as a main result of the German project @CITY-AF [12]. Over a period of 2 years, the authors revised the eHMI-principles iteratively based on these two approaches in several expert workshops.

## 4. Goal and Structure of the eHMI-Principles

Since guidelines for designing eHMI signals are still missing, the authors propose 17 heuristics, the so-called eHMI-principles, as requirements for the safe and efficient use of eHMIs in a systematic and application-oriented manner.

However, the eHMI-principles neither claim to be normative in the sense of homologation guidelines nor are they intended as instructions for detailed product designs and concrete design implementations. Rather, the eHMI-principles represent an application-oriented catalogue of recommendations that can be used to support the development and evaluation of eHMIs in a targeted manner.

The eHMI-principles are structured in two different sections covering the questions "How should a CAV communicate?" (category A) and "In which situations should a CAV communicate?" (category B). Accordingly, the eHMI-principles contain ten principles for "category A" and seven principles for "category B", each scientifically justified with an explanation and a rationale, and illustrated with examples of good or bad implementations. Finally, each eHMI-principle indicates open questions and areas for future research. Some of the eHMI-principles focus only on the interaction of external communication through eHMI, while others also take the more implicit communication through the vehicle's movement patterns (dHMI, e.g., acceleration and deceleration) into account; see [11]. The numeration and order of the eHMI-principles have no hierarchal character and are not based on each other. The principles are independent of each other and stand for themselves.

## 5. eHMI-Principles

The following section contains the eHMI-principles (see Table 1) starting with category A (how should a CAV communicate?) followed by eHMI-principles in category B (in which situation should an eHMI communicate).

**Table 1.** Overview of the eHMI-principles.

| Principle ID | Name of Principle |
|---|---|
| A1 | Clarity and unambiguity of used communication signals |
| A2 | Side effects of communication |
| A3 | Prosocial communication |
| A4 | Consistency across different vehicle types |
| A5 | Consistency of dHMI and eHMI |
| A6 | Expectation conformity of dHMI communication signals |
| A7 | Consideration of physical–psychological states |
| A8 | Adaptivity to (traffic) environment |
| A9 | Communication with passengers about the status of current external communication |
| A10 | Changed intentions |

**Table 1.** *Cont.*

| Principle ID | Name of Principle |
|---|---|
| B1 | Identification of the automation level |
| B2 | Communication of intent |
| B3 | Mixed traffic |
| B4 | Informal traffic rules |
| B5 | Restricted communication via the dHMI |
| B6 | Minimal-risk condition |
| B7 | External communication with other automated systems |

### *5.1. Category A—How Should a CAV Communicate?*

#### 5.1.1. Principle A1: Clarity and Unambiguity of Used Communication Signals

«All signals sent through dHMI and eHMI should be as clear, distinct, and unambiguous as possible.»

Explanations: The signals sent by the CAV through dHMI and eHMI to ORU should be as clear, distinct, and unambiguous as possible. Ideally, the signals are standardized worldwide and uniform across manufacturers.

Rationale: The signals from the CAV must be clear and consistent. No ambiguous or contradicting messages should be sent to avoid accidents, conflicts, and uncertainties regarding the CAV's behavior.

Example of effective implementation: A CAV signals that it is yielding to allow pedestrians to cross before the CAV by slowing down and simultaneously showing a pulsing light signal on a standardized light band in a fixed monotone color and frequency.

Example of ineffective implementation: An already stationary CAV uses a non-uniform, manufacturer-specific light color and frequency on a light band to signalize that it will yield for ORU.

Open questions and areas for research: There is a particular need for research on the temporal coordination of dHMI and eHMI signals in different scenarios that contribute to the efficient design of interactions. Various subject groups (e.g., children, older adults) and their specific needs should be considered (e.g., different perspectives due to small body size) as well as possible cultural differences in various countries.

References: [13–24].

#### 5.1.2. Principle A2: Side Effects of Communication

«When communicating via an eHMI, possible negative effects on ORU should be considered.»

Explanations: In order to exclude undesired or negative side effects, the explicit signals communicated by the CAV should be evaluated with regards to their effect on ORU.

Rationale: Phenomena related to the human–machine interaction such as "over-trust" and "controllability of automation failures" must be considered during the design of eHMI signals. Likewise, a falsely created feeling of being addressed by the eHMI must be prevented.

Example of effective implementation: A CAV communicates through a spatially directed eHMI which of the surrounding road users are detected and are being addressed by the eHMI signal.

Example of ineffective implementation: Non-addressed road users feel addressed by the eHMI signals. This spurious feeling of being addressed can lead to misunderstandings, uncertainty, and, ultimately, to accidents.

Open questions and areas for research: There is a particular need for research in complex traffic scenarios with multiple road users being present. Furthermore, the influence of learning aspects and long-term use on the behavior of road users in terms of "over-trust" and "controllability of automation failures" should be investigated.

References: [20,25–29].

#### 5.1.3. Principle A3: Prosocial Communication

«Prosocial messages are to be sent to ORU via eHMI.»

Explanations: When determining the signals sent to ORU via eHMI, priority should be given to prosocial messages (e.g., "I give priority to you", "I am considerate of you", "I let you go first", "Thank you kindly").

Rationale: According to §1 (1) of the German Road Traffic Act (StVO), participation in road traffic requires constant caution and the mutual consideration of road users. Ideally, traffic participants behave in a way that helps each other share the traffic space, communicate, and act prosocially—this should also apply to communication via eHMIs. The contagious effect of role models in road traffic has been known for a long time in traffic psychology; see, e.g., [30]. Prosocial communication via an eHMI could serve as a role model for ORU and thus encourage considerate behavior on the road.

Example of effective implementation: In an ambiguous situation on a parking lot, the CAV communicates via eHMI that it will yield (e.g., when another vehicle is driving in reverse on a parking lot), allowing another vehicle to merge into its lane. The communication of the vehicle's intention via eHMI is visible for ORU and adds a benefit beyond the pure dHMI (e.g., deceleration/yielding) by providing a prosocial reason for its behavior.

Example of ineffective implementation: The CAV does not communicate its prosocial intention to let another vehicle merge into its lane on the eHMI. The yielding behavior of the CAV creates an ambiguity because the ORU cannot grasp the vehicle's prosocial behavior.

Open questions and areas for research: The principle is also applicable for "reverse" situations where CAVs benefit from the cooperative behaviors of ORU. In this case, the CAV could express "thank you" as a dialog display, which is common in manual traffic, e.g., via waving or smiling. However, the extent to which eHMIs can express gestures of saying thank you and which communicative problems may be associated with this still requires systematic analysis. Based on the current knowledge, it is advised to communicate the intention of giving priority to others.

References: [30–32].

#### 5.1.4. Principle A4: Consistency across Different Vehicle Types

«The basic characteristic (e.g., modalities, designs) of an eHMI should be consistent across different vehicle types (e.g., bus, car, shuttles).»

Explanations: The eHMI signals of CAVs should be consistent across different vehicle types.

Rationale: CAVs may differ in size and vehicle type, but to avoid potential accidents, conflicts, and uncertainties, they should not differ in the basic characteristics of the eHMI to enable a predictable environment and the development of consistent mental models by ORU.

Example of effective implementation: CAVs of different types identically signal future behaviors and intentions. Vehicle type-specific signals (e.g., for busses or shuttles) fit consistently and without contradiction into other vehicle types' existing communication patterns.

Example of ineffective implementation: A conventional-sized CAV communicates its intention to yield for ORU differently than a bus or shuttle.

Open questions and areas for research: There is a particular need for research in complex traffic scenarios with multiple, simultaneously present CAVs of different types. Additionally, the influence of possible vehicle type-specific signals (e.g., bus: departure at a stop) should be investigated.

References: [22,33–35].

#### 5.1.5. Principle A5: Consistency of dHMI and eHMI

«The signals communicated through an eHMI should be in line with dHMI signals.»

Explanations: Vehicle signals communicated by dHMI (e.g., braking/accelerating) shall not contradict eHMI signals.

Rationale: The communication of the CAV must be consistent and shall not send any contradicting messages to avoid a feeling of uncertainty. In most scenarios, vehicle behavior (dHMI) affects the behavior of ORU. Therefore, the eHMI output should be adapted to the dHMI.

Example of effective implementation: A CAV signals through an eHMI its intention to stop in order to give priority. At the same time, the vehicle gradually slows down in a clearly perceptible manner.

Example of ineffective implementation: A CAV signals via the eHMI that it intends to yield and give priority. However, the intention of the CAV is not indicated by its approaching behavior (e.g., by showing an early braking behavior or lateral deviation from the road center).

Open questions and areas for research: There is a particular need for research on the synchronization of dHMI and eHMI signals in different scenarios. For example, an eHMI signal, such as the intention to brake, could be displayed as an announcement before the actual braking happens. The braking must occur in a narrow time span for vehicle behavior to be considered as decision guidance. In the event of discrepancies, trust and perceived safety will decrease.

References: [6,17,18,22,36–40].

#### 5.1.6. Principle A6: Expectation Conformity of dHMI Communication Signals

«The dHMI signals of CAVs should be based on existing dHMI signals for manual driving.»

Explanations: The signals communicated by CAVs through dHMI (e.g., braking/accelerating, gap selection) should be oriented as closely as possible to the already established and familiar dHMI signals (assuming established dHMI is in line with the respective law) in order to avoid confusion/irritation and disruptions of established routines.

Rationale: According to §1 of the German Road Traffic Act (StVO), all road users should behave in such a way that no one is endangered, harmed, hindered, or disturbed. Therefore, CAVs must show predictable behavior, as disruptions of the usual interaction can otherwise occur. Variations can be offered within an accepted range of expected behavior; for example, through selectable automated driving style variants such as dynamic/defensive.

Example of effective implementation: When turning left with opposing traffic, a CAV selects a gap acceptable to both the vehicle occupants and ORU. It neither waits too long (thereby hindering traffic) nor chooses gaps that are too narrow, which would be perceived as aggressive or risky.

Example of ineffective implementation: A CAV turns left sharply and at high speed in front of approaching opposing traffic. From a technical viewpoint, the maneuver may not be critical because the gaps for the calculated execution are large enough. However, the fast turning is perceived as uncomfortable by the passengers of the vehicle, and the opposing traffic is forced to brake as a precaution.

Open questions and areas for research: Using subject tests, accepted parameters for specific (frequent) maneuvers can be determined. However, this is not possible for every scenario in real traffic. The parameters could be validated, extended, and adjusted, for example, by means of machine learning methods and real driving data.

References: [19,23,25,41–47].

#### 5.1.7. Principle A7: Consideration of Physical–Psychological States

«The signals transmitted via eHMI should be designed in terms of sensory modality and representation format to ensure safe and efficient communication between the system and ORU.»

Explanations: In the event that an eHMI can output different sensory modalities (e.g., visual and auditory) and/or different representation formats (e.g., linguistic vs.

non-linguistic), the information format that allows for the most reliable transmission of information shall be selected depending on the current physical–psychological state of the communication partner. To ensure maximum consistency in the behavior of the eHMI, switches between different modalities and representation formats should follow simple and clear rules.

Rationale: The success of communication between a sender (in this case: the eHMI) and a receiver (here: ORU) depends on the information receiver's current psychological and physiological state. If the person's attention is not focused on the CAV but on other objects, or if the person is in a state of intoxication or fatigue, different modalities may prove to be differentially successful means of communication. Furthermore, it is known from cognitive psychology that simultaneously occurring tasks that access the same processing mechanisms (e.g., codes for processing linguistic information) result in poorer performance than tasks that access different processing codes (e.g., for processing linguistic information on the one hand and pictorial information on the other). Based on these insights, multimodal eHMI concepts are to be developed in a way that ensures reliable and safe information acquisition and processing.

Example of effective implementation: A connected and automated bus wants to inform ORU about the departure at a bus stop. The system recognizes that the waiting people at the bus stop are distracted by other activities. In addition to the visual signal, an acoustic signal is emitted as well.

Example of ineffective implementation: The CAV's detection system detects that a guide dog and a visually impaired person are at the pedestrian crossing. By default, the vehicle can only communicate visually, resulting in an impossible interaction with the person.

Open questions and areas for research: It should be examined in detail under which conditions an eHMI, which reacts differently depending on the situation, is perceived as understandable and reliable.

References: [28,48–52].

#### 5.1.8. Principle A8: Adaptivity to (Traffic) Environment

«The eHMI signal should be adapted to the prevailing environmental conditions.»

Explanations: The eHMI signal should be adapted to the environmental conditions that are primarily determined by weather influences, time of day (e.g., brightness), infrastructure (e.g., terrain), and traffic context (e.g., occlusions and noise level) in order to ensure that the signal stands out from them and is always easily perceptible (ensuring the salience of the signal).

Rationale: Regarding explicit communication, it is essential that signals are perceivable, so ORU can be informed efficiently and safely. Adapting the eHMI signal to the respective environmental conditions ensures that ORU are able to perceive the intended signal. This can be supported by having redundant elements in the eHMI that guarantees that the signal is perceptible from various angles.

Example of effective implementation: An eHMI light strip that is mounted 360° around the vehicle, adapting its luminosity to the prevailing environmental conditions and is always visible regardless of the environment. The light strip adjusts its brightness during nighttime to avoid dazzling ORU and increases its intensity during intense sunlight.

Example of ineffective implementation: The luminosity of the eHMI light strip does not adapt to the ambient conditions making it hard for ORU to perceive information coming from the eHMI light strip. Furthermore, the eHMI is only mounted on the front of the vehicle, making it difficult to detect communication signals when a person stands at the side of the vehicle.

Open questions and areas for research: The interaction between the eHMI and other (visual) signals attached to the vehicle (such as turn signals and headlights) must be validated through testing in lighting laboratories and in real-world traffic.

References: [46,53–55].

#### 5.1.9. Principle A9: Communication with Passengers about the Status of Current External Communication

«Signals shared with ORU through eHMI should be visible and understandable to passengers.»

Explanations: eHMI signals from CAVs should also be displayed for passengers inside the vehicle.

Rationale: By providing feedback from the CAV regarding the signals sent through eHMI, improved transparency regarding the behavior of the CAV can be achieved. This improves the situational awareness of the passengers, reduces subjective uncertainty regarding the vehicle's behavior, and enables a predictable environment with uniform mental models among road users.

Example of effective implementation: The CAV signals via eHMI that it will yield for an ORU. At the same time, this information is presented to the passengers inside the CAV. Passengers can then understand the reason for the deceleration.

Example of ineffective implementation: The CAV signals via eHMI that it will yield for an ORU. However, this information is not communicated to the passengers. Since the reason for the deceleration is not immediately clear, passengers will feel uncertain and may assume a possible malfunction of the CAV.

Open questions and areas for research: Novel, unobtrusive display and interaction concepts for system feedback (modality, timing, and positioning) remain to be investigated.

References: [56–59].

#### 5.1.10. Principle A10: Changed Intentions

«When the CAV communicates right of way/priority to ORU, it should not change its intention or external message during the interaction.»

Explanations: After the CAV communicates the right of way to ORU, it should not change its eHMI signal and should proceed with the communicated maneuver until the ORU or the CAV have left the interaction zone.

Rationale: ORU perceive the signals of the CAV, rely on their accuracy, and perform actions accordingly. A change in intention is either no longer perceived or it takes some time after the awareness to process the changed intention and to adjust one's reaction. This can lead to reduced road safety and can negatively affect the trust in and acceptance of CAVs.

Example of effective implementation: The CAV approaches a pedestrian, communicates the intention to yield, and maintains this intention. The pedestrian then crosses the road. After the road is clear, the CAV continues its journey.

Example of ineffective implementation: The CAV approaches a pedestrian and communicates its yielding intention. The pedestrian starts to cross the road. Meanwhile, the CAV changes its intention due to a misperception and insists on having the right of way. As a result, a critical situation arises.

Open questions and areas for research: Research is needed on the "controllability of automation failures" and the behavior of human interaction participants in the case of a change in intention of the CAV.

References: [17,18,59,60].

### *5.2. Category B—In Which Situation Should an eHMI Communicate?*

#### 5.2.1. Principle B1: Identification of the Automation Level

«If a CAV is driving at SAE level L3 (conditional driving automation) or higher, this driving mode should be permanently communicated to the outside through an eHMI.»

Explanations: When a vehicle is moving at automation level L3 (SAE) or higher, the person at the steering wheel is no longer responsible for the driving task, does not have a constant monitoring function, and is therefore not available as an immediate communication person. This condition should be communicated to all ORU in the immediate vicinity.

Rational: The labeling of CAVs is desired by the majority of users (see references), allows, if necessary, an adaptation of the behavior of ORU, as is possible with, e.g., driving school vehicles, enables learning experiences with CAVs in mixed traffic, and avoids possible unclear or conflict-prone situations if people at the driver's seat, for example, turn to driving-unrelated activities and this is perceived from the outside.

Example of effective implementation: An LED light strip is installed 360° around the vehicle and is constantly lit when the vehicle is driving at L3 or higher (e.g., Autobahn chauffeur). ORU can infer from this that this vehicle leaves larger gaps and refrains from making sudden lane changes without prior announcement by flashing.

Example of ineffective implementation: The person behind the steering wheel of a CAV (SAEL3 and above) is engaged with a smartphone and not monitoring the road scene. Without eHMI, ORU do not know if this driver is distracted or if the vehicle is currently in charge of the driving task.

Open questions and areas for research: There are various options for placing an eHMI, e.g., as a signal visible from all sides. In addition to a 360° LED strip, a signal on the roof would also be conceivable (e.g., as with taxis, driving schools, and emergency vehicles) and/or coupled with acoustic signals in special situations such as parking. The design of the signal should ideally not create any confusion with other signals, such as those from emergency vehicles.

References: [21,34,35,46,61–70].

#### 5.2.2. Principle B2: Communication of Intent

«The CAV should inform the environment via an eHMI about its intention and the behavior it will exhibit in certain situations.»

Explanations: The vehicle should inform the environment in situations where it will slow down, stop, grant priority, or start driving again via eHMI regarding its future intention. This allows ORU in the traffic environment of the CAV to perceive, understand, and adapt their behavior accordingly—without specific recommendations or instructions being given. The communication of the CAV's future intentions should be binding in this regard.

Rationale: The early communication of the intentions of the CAV creates a high sense of security for pedestrians and allows them to recognize the future behavior of the vehicle. As they can adapt their behavior accordingly, the overall efficiency of traffic flow is increased. Additionally, this prevents the vehicle from giving specific instructions to ORU. Messages instructing ORU to a specific behavior should be avoided as they raise legal and safety-related issues.

Example of effective implementation: A light signal in the front of the CAV informs the environment of the intention to stop. ORU perceive this signal and can adapt their behavior to the future trajectory of the CAV. They can rely on the information provided by the eHMI signal and do not have to wait until the vehicle shows the announced driving behavior.

Example of ineffective implementation: The CAV approaches ORU without informing them about its future behavior. The ORU has to wait until the vehicle actually slows down—e.g., communicates specifically through the dHMI.

Open questions and areas for research: Safety concerns need to be evaluated related to the resumption of the driving task when approaching the crosswalk after communicating with pedestrians via an eHMI. In addition, individual studies in the laboratory show that eHMIs that instruct a specific behavior and thus communicate from an egocentric perspective are understood more quickly and easily than those that provide information about the future behavior of the CAV (allocentric perspective). These findings should be verified in real-world traffic.

References: [4,6,17,18,20,22,34,40,69–76].

#### 5.2.3. Principle B3: Mixed Traffic

«As soon as a CAV is driving in mixed traffic, it should communicate with ORU via eHMI (mixed traffic = automated and non-automated road users, e.g., drivers, cyclists).»

Explanations: In mixed traffic, interaction between automated and non-automated road users is essential, and CAVs need to be able to communicate with ORU.

Rationale: The use of explicit communication by CAVs towards ORU becomes relevant when the vehicle moves in or enters mixed traffic. In segregated CAV networks, the use of explicit communication between CAVs would lead to efficiency losses because communication between the automated agents in these areas can be taken over more effectively and efficiently by other technologies (e.g., V2V communication interfaces). Furthermore, the use of explicit communication by CAVs in fully segregated traffic areas could negatively affect traffic safety, e.g., by distracting non-automated road users who are in the vicinity of this area.

Example of effective implementation: By leaving a delimited lane for automated road users and entering mixed traffic, the CAV will use the eHMI to communicate with non-automated road users.

Example of ineffective implementation: The CAV does not communicate with ORU through an eHMI in mixed traffic. Deadlocks can occur (e.g., in construction areas).

Open questions and areas for research: Open questions exist in the design of the HMIs of CAVs in the transitions between mixed traffic and fully separated areas.

References: [17,18,40,46,72,75,77].

#### 5.2.4. Principle B4: Informal Traffic Rules

«The CAV should communicate via the eHMI in traffic situations where informal rules of interaction are predominant.»

Explanations: Regarding communication between road users, both formal and informal rules are applied. While formal rules stem from laws (e.g., the German StVO), informal rules arise from the interaction of road users who want to optimize a certain system.

Rationale: Informal rules of interaction between road users are situation-specific and are interpreted according to the characteristics of the situation. Due to the need for the interpretation of communication signals in these situations, explicit communication can promote mutual understanding, increase traffic efficiency, and ensure the satisfaction or acceptance of road users.

Example of effective implementation: The CAV interacts with ORU at an equal, unregulated bottleneck, using the eHMI in addition to the dHMI (e.g., braking of the vehicle). The ORU recognize that the CAV is giving priority.

Example of ineffective implementation: The CAV interacts with ORU at an equal, unstructured bottleneck by braking and stopping without using the eHMI. There is no clarity about who should go first.

Open questions and areas for research: Open questions may relate to the influence of other situational characteristics and other influencing factors, such as cultural variables.

References: [17,18,72,78–80].

#### 5.2.5. Principle B5: Restricted Communication via the dHMI

«The CAV should communicate via the eHMI in scenarios in which communication via the dHMI is not clearly possible.»

Explanations: Communication through the dHMI (in particular, driving dynamics through acceleration and braking performed by the vehicle) can be limited or even impossible due to the driving environment conditions, especially at lower speeds. In these situations, a CAV should communicate explicitly through the eHMI.

Rationale: Explicit communication positively influences the willingness to cooperate and contributes to mutual understanding between road users in cooperative situations. Cooperative behavior in road traffic can minimize individual and global costs (e.g., optimize traffic flow) and contributes to fairness among road users. Especially at low speeds, it can be difficult for ORU to identify the intention of the CAV when only communicated by its dHMI.

Example of effective implementation: The CAV drives in a low speed area such as a shared space. Since communication by the dHMI is very limited here, the CAV communicates its intention via dHMI and eHMI.

Example of ineffective implementation: In a "deadlock" situation, where all road users have come to a standstill, the CAV does not communicate through the eHMI to resolve the deadlock.

Open questions and areas for research: Open questions concern the offensive signals emitted by the CAV and signals that increase the willingness to cooperate among all road users.

References: [74,76,81–85].

#### 5.2.6. Principle B6: Minimal-Risk Condition

«The CAV should communicate through the eHMI when performing a minimal-risk maneuver.»

Explanations: A minimal-risk condition is defined as a stable, safe, or risk-minimizing state of a CAV, which it enters when a certain journey cannot or should not be continued. Through a minimal-risk maneuver, a CAV brings itself into a minimal-risk condition.

Rationale: In a minimal-risk condition, ORU should be informed and warned before the CAV performs the maneuver. This helps to maintain road safety, especially when the CAV performs unexpected maneuvers to achieve the minimal-risk condition. The means of explicit communication can also contribute to calibrating the trust of ORU in the CAV. Furthermore, explicit communication can support the identification of the intervention of a technical supervisor.

Example of effective implementation: A CAV bringing itself into a minimal-risk condition by exiting the lane and stopping on the emergency lane. During this maneuver, the vehicle informs ORU through the eHMI. When stopping on the emergency lane, the vehicle communicates its current state constantly to ORU.

Example of ineffective implementation: A CAV executes a minimal-risk maneuver without informing ORU through eHMI.

Open questions and areas for research: Open questions refer to the design of explicit signals during the implementation of a minimal-risk condition and the effects on road safety as well as on the attitudes (especially trust and acceptance) of ORU.

Reference: [86,87].

#### 5.2.7. Principle B7: External Communication with Other Automated Systems

«When a CAV communicates with other CAVs or the infrastructure, the eHMI should serve as an additional source of information for the environment.»

Explanations: Communication between CAVs and/or infrastructure should be transparent and visible through an eHMI. This is particularly important in situations where ORU actively participate in traffic and are dependent on what was communicated between the vehicles/infrastructure.

Rationale: For ORU to build adequate situational awareness, they should have access to all possible information for predicting future system behavior. If the communication between CAVs remains a "black box", it can lead to safety-critical situations.

Example of effective implementation: Two CAVs are facing each other at a two-way lane restriction. They communicate with each other to regulate priority. Pedestrians who want to cross the street at the same point are informed through the eHMIs of the CAVs as to which vehicle has priority. This allows ORU to predict the traffic situation and adjust their behavior accordingly.

Example of ineffective implementation: Two CAVs are facing each other at a two-way lane restriction. Although they communicate with each other to clarify who has priority, the surrounding traffic is not informed. For pedestrians who want to cross the street at the same point, this communication remains invisible, and they must wait until the traffic situation has been resolved.

Open questions and areas for research: The situation in which an eHMI communicates in the sense of a broadcast with people in the environment who are not direct recipients must be further examined.

References: [6,16,60].

## 6. Discussion

The eHMI-principles should support the development of eHMI communication strategies by providing high-level design recommendations and a heuristic checklist for the evaluation of eHMI communication strategies. However, a possible limitation of the method used for creating the eHMI-principles is that they are based on German cultural practices and norms. As a result, there is a high chance that the eHMI-principles are picked selectively and lack consideration for cultural diversity. Therefore, the proposed eHMI-principles may need some design adaptations when implemented in other countries. Additionally, the proposed eHMI-principles might not enclose a comprehensive range of accessibility considerations for users with impairments, disabilities, or special needs. Individuals with visual/hearing impairments, cognitive disabilities, or motor disabilities may require specific design adaptations. Moreover, all eHMI-principles must comply with the road traffic laws of the respective country. There may be legal or safety reasons where deviation from the original eHMI-principles is required. Furthermore, the eHMI-principles do not claim to cover the topic of eHMI to the full extent nor are all principles transferable to all kinds of traffic situations or countries. Quite the contrary, the eHMI-principles should be updated and reviewed with growing research and evaluation in the field of eHMI. Additionally, it may not always be useful to comply with all eHMI-principles at once, as long as the developer reflects on the principles and considers them when designing an eHMI.

Future research on the development of eHMI should use these principles as a basis for designing safe and efficient interaction strategies while contributing new results and principles to the existing collection. Furthermore, an evaluation of existing and upcoming eHMI-principles regarding ethical issues should be conducted.

## 7. Conclusions

The proposed 17 eHMI-principles primarily aim to help practitioners design safe and efficient eHMIs in an application-oriented manner. Thus, the principles are intended to be used as a rather high-level checklist for a heuristic evaluation of eHMIs. The checklist can help in both (1) evaluating existing eHMI solutions with regard to, e.g., non-intended side effects, and (2) avoiding potential issues at early stages in the development process of new eHMIs. The rather high degree of abstraction as “principles” was chosen to cover a great variety, including potential future eHMI solutions even beyond passenger cars. This decision, in turn, does not allow the specification of very detailed product design aspects such as, e.g., colors or patterns of eHMI signals. The principles neither claim to be normative in the sense of homologation guidelines nor are they intended as instructions for detailed product designs and concrete design implementations. However, in addition to their use as a heuristic checklist, the principles should stimulate scientific as well as application-related discussions about eHMI guidelines and are therefore related to parallel activities in, e.g., standardization institutions such as ISO and SAE.

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## References

1. Kauffmann, N.; Winkler, F.; Naujoks, F.; Vollrath, M. "What Makes a Cooperative Driver?" Identifying parameters of implicit and explicit forms of communication in a lane change scenario. *Transp. Res. Part F Traffic Psychol. Behav.* **2018**, *58*, 1031–1042. [CrossRef]
2. Färber, B. Communication and Communication Problems Between Autonomous Vehicles and Human Drivers. In *Autonomous Driving: Technical, Legal and Social Aspects*; Maurer, M., Gerdes, J.C., Lenz, B., Winner, H., Eds.; Springer Open: Berlin/Heidelberg, Germany, 2016; pp. 125–144, ISBN 978-3-662-48845-4.
3. Winter, J.; de Dodou, D. External human–machine interfaces: Gimmick or necessity? *Transp. Res. Interdiscip. Perspect.* **2022**, *15*, 100643. [CrossRef]
4. Tabone, W.; Winter, J.; de Ackermann, C.; Bärgman, J.; Baumann, M.; Deb, S.; Emmenegger, C.; Habibovic, A.; Hagenzieker, M.; Hancock, P.A.; et al. Vulnerable road users and the coming wave of automated vehicles: Expert perspectives. *Transp. Res. Interdiscip. Perspect.* **2021**, *9*, 100293. [CrossRef]
5. Schaarschmidt, E.; Yen, R.; Bosch, R.; Zwicker, L.; Schade, J.; Petzoldt, T. *Grundlagen zur Kommunikation zwischen automatisierten Kraftfahrzeugen und Verkehrsteilnehmern: Berichte der Bundesanstalt für Straßenwesen*; F138; Fachverlag NW: Bremen, Germany, 2021; ISBN 978-3-95606-570-5.
6. Dey, D.; Habibovic, A.; Löcken, A.; Wintersberger, P.; Pfleging, B.; Riener, A.; Martens, M.; Terken, J. Taming the eHMI jungle: A classification taxonomy to guide, compare, and assess the design principles of automated vehicles' external human-machine interfaces. *Transp. Res. Interdiscip. Perspect.* **2020**, *7*, 100174. [CrossRef]
7. Rouchitsas, A.; Alm, H. Corrigendum: External Human-Machine Interfaces for Autonomous Vehicle-to-Pedestrian Communication: A Review of Empirical Work. *Front. Psychol.* **2020**, *11*, 575151. [CrossRef] [PubMed]
8. National Highway Traffic Safety Administration, Department of Transportation. *Federal Motor Vehicle Safety Standards No. 108; Lamps, Reflective Devices, and Associated Equipment, Adaptive Driving Beam Headlamps*; 49 CFR Part 571; National Highway Traffic Safety Administration, Department of Transportation: Washington, DC, USA, 2022.
9. Economic Commission for Europe of the United Nations (UNECE). Regulation No 48—Uniform provisions concerning the approval of vehicles with regard to the installation of lighting and light-signalling devices—Uniform provisions concerning the approval of vehicles with regard to the installation of lighting and light-signalling devices [2016/1723]. *Off. J.* **2016**, 125–242. Available online: http://data.europa.eu/eli/reg/2016/1723/oj (accessed on 28 June 2023).
10. GRE AVSR. Report of the GRE Taskforce Autonomous Vehicle Signalling Requirements (AVSR): 8th Meeting, 17 October 2022. Available online: https://wiki.unece.org/display/trans/AVSR+-+8th+session%2C+2022-10-17 (accessed on 30 March 2023).
11. *ISO/TC 22/SC 39*; Ergonomics; Road Vehicles—Ergonomic Aspects of External Visual Communication from Automated Vehicles to Other Road Users. International Standards Organization (ISO): Geneva, Switzerland, 2018.
12. WES-Office. Automated Driving in the City. Available online: https://www.atcity-online.de/?language=en (accessed on 27 April 2023).
13. Gauß, E.-M. Stehen oder Gehen?—Wenn kein Mensch mehr kommuniziert. Kommunikation Eines automatisierten Fahrzeugs am Zebrastreifen in der Interaktion mit Kindern und Erwachsenen. Bachelor's Thesis, FernUniversität Hagen, Hagen, Germany, 2019.
14. Ackermann, C.; Beggiato, M.; Schubert, S.; Krems, J.F. An experimental study to investigate design and assessment criteria: What is important for communication between pedestrians and automated vehicles? *Appl. Ergon.* **2019**, *75*, 272–282. [CrossRef] [PubMed]
15. Deb, S.; Strawderman, L.J.; Carruth, D.W. Investigating pedestrian suggestions for external features on fully autonomous vehicles: A virtual reality experiment. *Transp. Res. Part F Traffic Psychol. Behav.* **2018**, *59*, 135–149. [CrossRef]
16. Habibovic, A.; Lundgren, V.M.; Andersson, J.; Klingegård, M.; Lagström, T.; Sirkka, A.; Fagerlönn, J.; Edgren, C.; Fredriksson, R.; Krupenia, S.; et al. Communicating Intent of Automated Vehicles to Pedestrians. *Front. Psychol.* **2018**, *9*, 1336. [CrossRef]
17. Rettenmaier, M.; Bengler, K. The Matter of How and When: Comparing Explicit and Implicit Communication Strategies of Automated Vehicles in Bottleneck Scenarios. *IEEE Open J. Intell. Transp. Syst.* **2021**, *2*, 282–293. [CrossRef]
18. Rettenmaier, M. Interaction between Automated Vehicles and Oncoming Human Drivers: Efficient and Safe Urban Driving in Bottleneck Scenarios. Ph.D. Thesis, Technical University of Munich, Munich, Germany, 2023.

19. Miller, L.; Leitner, J.; Kraus, J.; Baumann, M. Implicit intention communication as a design opportunity for automated vehicles: Understanding drivers' interpretation of vehicle trajectory at narrow passages. *Accid. Anal. Prev.* **2022**, *173*, 106691. [CrossRef]
20. Dey, D.; van Vastenhoven, A.; Cuijpers, R.H.; Martens, M.; Pfleging, B. Towards Scalable eHMIs: Designing for AV-VRU Communication Beyond One Pedestrian. In Proceedings of the 13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, Leeds, UK, 9–14 September 2021; ACM: New York, NY, USA, 2021; pp. 274–286.
21. Joisten, P.; Alexandi, E.; Drews, R.; Klassen, L.; Petersohn, P.; Pick, A.; Schwindt, S.; Abendroth, B. Displaying Vehicle Driving Mode—Effects on Pedestrian Behavior and Perceived Safety. In *Human Systems Engineering and Design II*; Ahram, T., Karwowski, W., Pickl, S., Taiar, R., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 250–256, ISBN 978-3-030-27927-1.
22. Lau, M.; Jipp, M.; Oehl, M. Toward a Holistic Communication Approach to an Automated Vehicle's Communication with Pedestrians: Combining Vehicle Kinematics with External Human-Machine Interfaces for Differently Sized Automated Vehicles. *Front. Psychol.* **2022**, *13*, 882394. [CrossRef] [PubMed]
23. Fuest, T.; Michalowski, L.; Schmidt, E.; Bengler, K. Reproducibility of Driving Profiles—Application of the Wizard of Oz Method for Vehicle Pedestrian Interaction. In Proceedings of the 2019 IEEE Intelligent Transportation Systems Conference (ITSC), Auckland, New Zealand, 27–30 October 2019; IEEE: New York, NY, USA; pp. 3954–3958.
24. Lee, Y.M.; Madigan, R.; Garcia, J.; Tomlinson, A.; Solernou, A.; Romano, R.; Markkula, G.; Merat, N.; Uttley, J. Understanding the Messages Conveyed by Automated Vehicles. In Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, Utrecht, The Netherlands, 21–25 September 2019; ACM: New York, NY, USA, 2019; pp. 134–143.
25. Lee, J.; Daimon, T.; Kitazaki, S. Negative Effect of External Human-Machine Interfaces in Automated Vehicles on Pedestrian Crossing Behaviour: A Virtual Reality Experiment. In *Proceedings of the 21st Congress of the International Ergonomics Association (IEA 2021)*; Black, N.L., Neumann, W.P., Noy, I., Eds.; Springer International Publishing: Cham, Switzerland, 2021; pp. 718–725, ISBN 978-3-030-74607-0.
26. Wilbrink, M.; Lau, M.; Illgner, J.; Schieben, A.; Oehl, M. Impact of External Human–Machine Interface Communication Strategies of Automated Vehicles on Pedestrians' Crossing Decisions and Behaviors in an Urban Environment. *Sustainability* **2021**, *13*, 8396. [CrossRef]
27. Hübner, M.; Feierle, A.; Rettenmaier, M.; Bengler, K. External communication of automated vehicles in mixed traffic: Addressing the right human interaction partner in multi-agent simulation. *Transp. Res. Part F Traffic Psychol. Behav.* **2022**, *87*, 365–378. [CrossRef]
28. Lanzer, M.; Koniakowsky, I.; Colley, M.; Baumann, M. Interaction Effects of Pedestrian Behavior, Smartphone Distraction and External Communication of Automated Vehicles on Crossing and Gaze Behavior. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems, Hamburg, Germany, 23–28 April 2023; Schmidt, A., Väänänen, K., Goyal, T., Kristensson, P.O., Peters, A., Mueller, S., Williamson, J.R., Wilson, M.L., Eds.; ACM: New York, NY, USA, 2023; pp. 1–18.
29. Dietrich, A.; Willrodt, J.-H.; Wagner, K.; Bengler, K. Projection-Based External Human Machine Interfaces—Enabling Interaction between Automated Vehicles and Pedestrians. In Proceedings of the Driving Simulation Conference 2018 Europe VR, Driving Simulation Association, Antibes, France, 5–7 September 2018.
30. Echterhoff, W. Lernen im Straßenverkehr durch gezielt angebotenes Modell-Verhalten: Ein Feldexperiment. *Z. Für Verk.* **1989**, *35*, 156–159.
31. Stern, J. Evaluation eines dynamischen Rückmeldesystems an Fußgängerüberwegen und an einem Bahnübergang. In *Fortschritte der Verkehrspsychologie*; Schade, J., Engeln, A., Eds.; VS Verlag für Sozialwissenschaften: Wiesbaden, Germany, 2008; pp. 103–122, ISBN 978-3-531-15956-0.
32. Schlag, B.; Stern, J.; Butterwegge, B.; Degener, S. *"Lob und Tadel": Wirkungen des Dialog-Display*; Forschungsbericht VV01; Gesamtverband der Deutschen Versicherungswirtschaft e. V.: Berlin, Germany, 2009.
33. Lau, M.; Jipp, M.; Oehl, M. Investigating the Interplay between eHMI and dHMI for Automated Buses: How Do Contradictory Signals Influence a Pedestrian's Willingness to Cross? In Proceedings of the 13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, Leeds, UK, 9–14 September 2021; ACM: New York, NY, USA, 2021; pp. 152–155.
34. Lau, M.; Jipp, M.; Oehl, M. One Solution Fits All? Evaluating Different Communication Strategies of a Light-based External Human-Machine Interface for Differently Sized Automated Vehicles from a Pedestrian's Perspective. *Accid. Anal. Prev.* **2022**, *171*, 106641. [CrossRef]
35. Oehl, M.; Lau, M.; Gehreke, L.; Wilbrink, M. Towards a Universal Explicit Communication Design of External Human-Machine Interfaces (eHMI) for Differently Sized Highly Automated Vehicles Evaluated by Different Pedestrian Age Groups. In *HCI International 2022—Late Breaking Posters*; Stephanidis, C., Antona, M., Ntoa, S., Salvendy, G., Eds.; Springer: Cham, Switzerland, 2022; pp. 391–398, ISBN 978-3-031-19681-2.
36. Hensch, A.-C.; Kreißig, I.; Beggiato, M.; Krems, J.F. The Effect of eHMI Malfunctions on Younger and Elderly Pedestrians' Trust and Acceptance of Automated Vehicle Communication Signals. *Front. Psychol.* **2022**, *13*, 866475. [CrossRef]
37. Holländer, K.; Wintersberger, P.; Butz, A. Overtrust in External Cues of Automated Vehicles. In Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, Utrecht, The Netherlands, 21–25 September 2019; ACM: New York, NY, USA, 2019; pp. 211–221.

38. Kaleefathullah, A.A.; Merat, N.; Lee, Y.M.; Eisma, Y.B.; Madigan, R.; Garcia, J.; de Winter, J. External Human-Machine Interfaces Can Be Misleading: An Examination of Trust Development and Misuse in a CAVE-Based Pedestrian Simulation Environment. *Hum. Factors* **2022**, *64*, 1070–1085. [CrossRef]
39. Bengler, K.; Rettenmaier, M.; Fritz, N.; Feierle, A. From HMI to HMIs: Towards an HMI Framework for Automated Driving. *Information* **2020**, *11*, 61. [CrossRef]
40. Dey, D.; Matviienko, A.; Berger, M.; Pfleging, B.; Martens, M.; Terken, J. Communicating the intention of an automated vehicle to pedestrians: The contributions of eHMI and vehicle behavior. *It—Inf. Technol.* **2021**, *63*, 123–141. [CrossRef]
41. Hensch, A.-C.; Beggiato, M.; Krems, J.F. Drive safely and comfortably—Gap Acceptance as a Basis for a user-centred Design of Driving Styles in Automated Vehicles. In Proceedings of the 7th HUMANIST Conference, Rhodes Island, Greece, 26–27 October 2021.
42. Hensch, A.-C.; Beggiato, M.; Krems, J.F. Drivers' gap acceptance during parking maneuvers as a basis for initiating driving actions in automated vehicles. *Transp. Res. Part F Traffic Psychol. Behav.* **2023**, *92*, 133–142. [CrossRef]
43. Domeyer, J.; Dinparastdjadid, A.; Lee, J.D.; Douglas, G.; Alsaid, A.; Price, M. Proxemics and Kinesics in Automated Vehicle–Pedestrian Communication: Representing Ethnographic Observations. *Transp. Res. Rec.* **2019**, *2673*, 70–81. [CrossRef]
44. Domeyer, J.E.; Lee, J.D.; Toyoda, H. Vehicle Automation–Other Road User Communication and Coordination: Theory and Mechanisms. *IEEE Access* **2020**, *8*, 19860–19872. [CrossRef]
45. Rettenmaier, M.; Dinkel, S.; Bengler, K. Communication via motion—Suitability of automated vehicle movements to negotiate the right of way in road bottleneck scenarios. *Appl. Ergon.* **2021**, *95*, 103438. [CrossRef] [PubMed]
46. Schieben, A.; Wilbrink, M.; Kettwich, C.; Madigan, R.; Louw, T.; Merat, N. Designing the interaction of automated vehicles with other traffic participants: Design considerations based on human needs and expectations. *Cogn. Tech. Work* **2019**, *21*, 69–85. [CrossRef]
47. Fuest, T.; Michalowski, L.; Traris, L.; Bellem, H.; Bengler, K. Using the Driving Behavior of an Automated Vehicle to Communicate Intentions—A Wizard of Oz Study. In Proceedings of the 2018 21st International Conference on Intelligent Transportation Systems (ITSC), Maui, HI, USA, 4–7 November 2018; IEEE: New York, NY, USA, 2018; pp. 3596–3601.
48. Dou, J.; Chen, S.; Tang, Z.; Xu, C.; Xue, C. Evaluation of Multimodal External Human–Machine Interface for Driverless Vehicles in Virtual Reality. *Symmetry* **2021**, *13*, 687. [CrossRef]
49. Joisten, P.; Theobald, N.; Schwindt, S.; Walter, J.; Abendroth, B. Designing the Communication with Automated Vehicles: The Case of Elderly Pedestrians. In Proceedings of theWorkshop on Inclusive Communication between Automated Vehicles and Vulnerable Road Users. In conjunction with MobileHCI 2020, Darmstadt, Germany, 5–9 October 2022.
50. Colley, M.; Walch, M.; Gugenheimer, J.; Rukzio, E. Including people with impairments from the start. In Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, Utrecht, The Netherlands, 21–25 September 2019; Janssen, C.P., Donker, S.F., Chuang, L.L., Ju, W., Eds.; ACM: New York, NY, USA, 2019; pp. 307–314.
51. Colley, M.; Walch, M.; Gugenheimer, J.; Askari, A.; Rukzio, E. Towards Inclusive External Communication of Autonomous Vehicles for Pedestrians with Vision Impairments. In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, Honolulu, HI, USA, 25–30 April 2020; Bernhaupt, R., Mueller, F., Verweij, D., Andres, J., McGrenere, J., Cockburn, A., Avellino, I., Goguey, A., Bjørn, P., Zhao, S., et al., Eds.; ACM: New York, NY, USA, 2020; pp. 1–14.
52. Löcken, A.; Golling, C.; Riener, A. How Should Automated Vehicles Interact with Pedestrians? In Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, Utrecht, The Netherlands, 21–25 September 2019; ACM: New York, NY, USA, 2019; pp. 262–274.
53. Eisele, D.; Petzoldt, T. Effects of traffic context on eHMI icon comprehension. *Transp. Res. Part F Traffic Psychol. Behav.* **2022**, *85*, 1–12. [CrossRef]
54. Faas, S.M.; Baumann, M. Light-Based External Human Machine Interface: Color Evaluation for Self-Driving Vehicle and Pedestrian Interaction. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* **2019**, *63*, 1232–1236. [CrossRef]
55. Rettenmaier, M.; Schulze, J.; Bengler, K. How Much Space Is Required? Effect of Distance, Content, and Color on External Human–Machine Interface Size. *Information* **2020**, *11*, 346. [CrossRef]
56. Hümmer, M. Automatisiertes Fahren in der Stadt: Auswirkungen eines iHMIs auf Vertrauen, Akzeptanz und Sicherheitsgefühl. Master's Thesis, Hochschule Fresenius, Frankfurt, Germany, 2022.
57. Weber, F.; Sorokin, L.; Schmidt, E.; Schieben, A.; Wilbrink, M.; Kettwich, C.; Dodiya, J.; Oehl, M.; Kaup, M.; Willrodt, J.; et al. Final Human-Vehicle Interaction Strategies for the interACT Automated Vehicles: interACT D4.2, Project Deliverable. Available online: https://www.interact-roadautomation.eu/wp-content/uploads/interACT_WP4_D4.2_Final_Human_Vehicle_Interaction_Strategies_v1.1_uploadWebsiteApproved.pdf (accessed on 28 June 2023).
58. Wilbrink, M.; Schieben, A.; Oehl, M. Reflecting the automated vehicle's perception and intention. In Proceedings of the 25th International Conference on Intelligent User Interfaces Companion, Cagliari, Italy, 17–20 March 2020; ACM: New York, NY, USA, 2020; pp. 105–107.
59. Feierle, A.; Rettenmaier, M.; Zeitlmeir, F.; Bengler, K. Multi-Vehicle Simulation in Urban Automated Driving: Technical Implementation and Added Benefit. *Information* **2020**, *11*, 272. [CrossRef]
60. Rettenmaier, M.; Albers, D.; Bengler, K. After you?!—Use of external human-machine interfaces in road bottleneck scenarios. *Transp. Res. Part F Traffic Psychol. Behav.* **2020**, *70*, 175–190. [CrossRef]

61. Faas, S.M.; Stange, V.; Baumann, M. Self-Driving Vehicles and Pedestrian Interaction: Does an External Human-Machine Interface Mitigate the Threat of a Tinted Windshield or a Distracted Driver? *Int. J. Hum.–Comput. Interact.* **2021**, *37*, 1364–1374. [CrossRef]
62. Lagström, T.; Lundgren, V.M. AVIP—Autonomous Vehicles' Interaction with Pedestrians—An Investigation of Pedestrian-Driver Communication and Development of a Vehicle External Interface. Master's Thesis, Chalmers University of Technology, Gothenburg, Sweden, 2016.
63. Hudson, C.R.; Deb, S.; Carruth, D.W.; McGinley, J.; Frey, D. Pedestrian Perception of Autonomous Vehicles with External Interacting Features. In *Advances in Human Factors and Systems Interaction*; Nunes, I.L., Ed.; Springer International Publishing: Cham, Switzerland, 2019; pp. 33–39, ISBN 978-3-319-94333-6.
64. Hensch, A.-C.; Neumann, I.; Beggiato, M.; Halama, J.; Krems, J.F. Effects of a light-based communication approach as an external HMI for Automated Vehicles—A Wizard-of-Oz Study. *ToTS* **2020**, *10*, 18–32. [CrossRef]
65. Faas, S.M.; Mattes, S.; Kao, A.C.; Baumann, M. Efficient Paradigm to Measure Street-Crossing Onset Time of Pedestrians in Video-Based Interactions with Vehicles. *Information* **2020**, *11*, 360. [CrossRef]
66. Faas, S.M.; Mathis, L.-A.; Baumann, M. External HMI for self-driving vehicles: Which information shall be displayed? *Transp. Res. Part F Traffic Psychol. Behav.* **2020**, *68*, 171–186. [CrossRef]
67. de Clercq, K.; Dietrich, A.; Núñez Velasco, J.P.; de Winter, J.; Happee, R. External Human-Machine Interfaces on Automated Vehicles: Effects on Pedestrian Crossing Decisions. *Hum. Factors* **2019**, *61*, 1353–1370. [CrossRef]
68. Fuest, T.; Feierle, A.; Schmidt, E.; Bengler, K. Effects of Marking Automated Vehicles on Human Drivers on Highways. *Information* **2020**, *11*, 286. [CrossRef]
69. Kaß, C.; Schoch, S.; Naujoks, F.; Hergeth, S.; Keinath, A.; Neukum, A.A. Methodological Approach to Determine the Benefits of External HMI During Interactions Between Cyclists and Automated Vehicles: A Bicycle Simulator Study. In *HCI in Mobility, Transport, and Automotive Systems. Driving Behavior, Urban and Smart Mobility*; Krömker, H., Ed.; Springer International Publishing: Cham, Switzerland, 2020; pp. 211–227, ISBN 978-3-030-50536-3.
70. Joisten, P.; Schwindt, S.S.; Theobald, N.; Abendroth, B. Pedestrians' Mental Model Development after Initial Encounters with Automated Driving Systems. In Proceedings of the 33rd European Conference on Cognitive Ergonomics, Kaiserslautern, Germany, 4–7 October 2022; Ebert, A., Lachmann, T., Dreßler, K., Lindblom, J., Reinhard, R., Eds.; ACM: New York, NY, USA, 2022; pp. 1–4.
71. Weiß, S.L.; Eisele, D.; Petzoldt, T. External Human-Machine-Interfaces on Automated Vehicles: Which message and perspective do pedestrians in crossing situations understand best? In *Intelligent Human Systems Integration (IHSI 2022): Integrating People and Intelligent Systems*; Ahram, T., Karwowski, W., Di Bucchianico, P., Taiar, R., Casarotto, L., Costa, P., Eds.; AHFE International: Venice, Italy, 2022. [CrossRef]
72. Rettenmaier, M.; Pietsch, M.; Schmidtler, J.; Bengler, K. Passing through the Bottleneck—The Potential of External Human-Machine Interfaces. In Proceedings of the 2019 IEEE Intelligent Vehicles Symposium (IV), Paris, France, 9–12 June 2019; IEEE: New York, NY, USA, 2019; pp. 1687–1692.
73. Wilbrink, M.; Nuttelmann, M.; Oehl, M. Scaling up Automated Vehicles' eHMI Communication Designs to Interactions with Multiple Pedestrians—Putting eHMIs to the Test. In Proceedings of the 13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, Leeds, UK, 9–14 September 2021; ACM: New York, NY, USA, 2021; pp. 119–122.
74. Joisten, P.; Theobald, N.; Abendroth, B. Pedestrians' Crossing Decisions While Interacting with Automated Vehicles—Insights from a Longitudinal Study. In *Human Factors in Transportation, Proceedings of the 13th International Conference on Applied Human Factors and Ergonomics (AHFE 2022), New York, NY, USA, 24–28 July 2022*; AHFE International: New York, NY, USA; p. 2022.
75. Colley, M.; Bajrovic, E.; Rukzio, E. Effects of Pedestrian Behavior, Time Pressure, and Repeated Exposure on Crossing Decisions in Front of Automated Vehicles Equipped with External Communication. In Proceedings of the CHI Conference on Human Factors in Computing Systems, New Orleans, LA, USA, 29 April–5 May 2022; Barbosa, S., Lampe, C., Appert, C., Shamma, D.A., Drucker, S., Williamson, J., Yatani, K., Eds.; ACM: New York, NY, USA, 2022; pp. 1–11.
76. Schieben, A.M.; Wilbrink, M.; Kettwich, C.; Dodiya, J.; Oehl, M.; Weber, F.; Sorokin, L.; Lee, Y.M.; Madigan, R.; Markula, G.; et al. *Testing External HMI Designs for Automated Vehicles—An Overview on User Study Results from the EU Project interACT*; 19. Tagung Automatisiertes Fahren: Munich, Germany, 2019. Available online: https://mediatum.ub.tum.de/doc/1535145/1535145.pdf (accessed on 28 June 2023).
77. Parkin, J.; Clark, B.; Clayton, W.; Ricci, M.; Parkhurst, G. Autonomous vehicle interactions in the urban street environment: A research agenda. *Proc. Inst. Civ. Eng.—Munic. Eng.* **2018**, *171*, 15–25. [CrossRef]
78. Björklund, G.M.; Åberg, L. Driver behaviour in intersections: Formal and informal traffic rules. *Transp. Res. Part F Traffic Psychol. Behav.* **2005**, *8*, 239–253. [CrossRef]
79. Imbsweiler, J.; Ruesch, M.; Weinreuter, H.; Puente León, F.; Deml, B. Cooperation behaviour of road users in t-intersections during deadlock situations. *Transp. Res. Part F Traffic Psychol. Behav.* **2018**, *58*, 665–677. [CrossRef]
80. Risser, R. Behavior in traffic conflict situations. *Accid. Anal. Prev.* **1985**, *17*, 179–197. [CrossRef]
81. Xing, Y.; Lv, C.; Cao, D.; Hang, P. Toward human-vehicle collaboration: Review and perspectives on human-centered collaborative automated driving. *Transp. Res. Part C Emerg. Technol.* **2021**, *128*, 103199. [CrossRef]
82. Stoll, T.; Lanzer, M.; Baumann, M. Situational influencing factors on understanding cooperative actions in automated driving. *Transp. Res. Part F Traffic Psychol. Behav.* **2020**, *70*, 223–234. [CrossRef]

83. Li, Y.; Cheng, H.; Zeng, Z.; Liu, H.; Sester, M. Autonomous Vehicles Drive into Shared Spaces: eHMI Design Concept Focusing on Vulnerable Road Users. In Proceedings of the IEEE International Intelligent Transportation Systems Conference (ITSC), Indianapolis, IN, USA, 19–22 September 2021. [CrossRef]
84. Mertens, J.C.; Knies, C.; Diermeyer, F.; Escherle, S.; Kraus, S. The Need for Cooperative Automated Driving. *Electronics* **2020**, *9*, 754. [CrossRef]
85. Matsunaga, N.; Daimon, T.; Yokota, N.; Kitazaki, S. Effect of External Human Machine Interface (eHMI) of Automated Vehicle on Pedestrian's Recognition. *Proc. Int. Disp. Work.* **2019**, *26*. [CrossRef]
86. SAE. *Ground Vehicle Standard: Taxonomy and Definitions for Terms Related to Driving Automation Systems for on-Road Motor Vehicles*; SAE International: Warrendale, PA, USA, 2021; (J3016_202104). Available online: https://saemobilus.sae.org/content/j3016_202104 (accessed on 30 March 2023).
87. Schindler, J.; Herbig, D.L.; Lau, M.; Oehl, M. Communicating Issues in Automated Driving to Surrounding Traffic—How should an Automated Vehicle Communicate a Minimum Risk Maneuver via eHMI and/or dHMI? In *HCI International 2020—Late Breaking Posters*; Stephanidis, C., Antona, M., Ntoa, S., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 619–626, ISBN 978-3-030-60702-9.