Taming the eHMI jungle: A classification taxonomy to guide, compare, and assess the design principles of automated vehicles' external human-machine interfaces

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ARTICLE INFO	ABSTRACT
	There is a growing body of research in the field of interaction between automated vehicles and other road users in their vicinity. To facilitate such interactions, researchers and designers have explored designs, and this line of work has yielded several concepts of external Human-Machine Interfaces (eHMI) for vehicles. Literature and media review reveals that the description of interfaces is often lacking in fidelity or details of their functionalities in specific situations, which makes it challenging to understand the originating concepts. There is also a lack of a universal understanding of the various dimensions of a communication interface, which has impeded a consistent and coherent addressal of the different aspects of the functionalities of such interface concepts. In this paper, we present a unified taxonomy that allows a systematic comparison of the eHMI across 18 dimensions, covering their physical characteristics and communication aspects from the perspective of human factors and human-machine interaction. We analyzed and coded 70 eHMI concepts according to this taxonomy to portray the state of the art and highlight the relative maturity of different contributions. The results point to a number of unexplored research areas that could inspire future work. Additionally, we believe that our proposed taxonomy can serve as a checklist for user interface designers and researchers when developing their interfaces.

1. Introduction

Automated vehicles (AVs) are expected to help reaching "Vision Zero" in traffic (zero fatalities, proposed as major goal by the European Commission). However, to fulfill the promise of increased safety, the question arises, how AVs can communicate and interact with other road users (ORU) in the vicinity? These include Vulnerable Road Users (VRUs) such as pedestrians, cyclists, and wheelchair users, as well as manually operated vehicles. In AVs, depending on the level of automation (On-Road Automated Driving (ORAD) committee - SAE International, 2014), the driver (passenger) will no longer be responsible or available for communication with the outside environment. For example, drivers may be engaged in activities other than driving, and with higher automation levels, there may not even be a human on board. Such scenarios paved the way for new communication approaches between AVs and ORUs, that can replace long-established forms of communications. As a result, a variety of potential approaches have been introduced in recent years by vehicle manufacturers, suppliers, and research institutions.

The number of search results for the term "autonomous vehicle pedestrian communication" rose from 3250 in 2011 to more than 10,000 in 2020 in Google Scholar showing the increasing interest in this research field. Broadly speaking, the aspect of pedestrian communication can be approached from two different angles: (1) technical (such as network, communication, and integration with infrastructure using V2X technology) and (2) human factors (focusing solely on the ergonomics and interaction aspect of the interface between automated vehicles and pedestrians from a user-centered design perspective). It is the latter that is the focus of this paper. Solutions to human factors challenges in pedestrian communication, or communication with other road users in general have been explored with external human-machine interfaces (eHMIs) in scientific publications, media, patents, and industry concepts. Potential implementations of eHMIs are manifold, reaching from displaying text messages on external

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displays, over laser projections on the street, to personalized messages for smart and wearable devices (Fig. 1). Often, these concepts are limited to demonstrations for promotion purposes, proof-of-concept prototypes, or purely virtual solutions, which leads to different levels of fidelity or explained details of scenarios, use cases, and capabilities of the systems. Furthermore, it is hard to compare the individual approaches because evaluations of eHMIs were not conducted, not published, or differ significantly in their methods. Challenges in comparison also rise from employing different scales to measure eHMI efficacy, such as how likely VRUs would cross (Li et al., n.d.), understanding of the interface in terms of safety and comfort (Böckle et al., 2017), trust (Holländer et al., 2019a), use of qualitative evaluation methods such as interviews (Rothenbücher et al., 2016), objective performance parameters of pedestrian behavior such as the moment of stepping on the road (Holländer et al., 2019a), or time until crossing decisions (Löcken et al., 2019) which make it difficult to validate their efficacy. Recent works have begun to compare prominent concepts in single environments directly and with the same set of data collection methods to deal with this problem (Löcken et al., 2019; Ackermann et al., 2019; Bazilinskyy et al., 2019; Chang et al., 2018; Deb et al., 2018; de Clercq et al., n.d.; Fridman et al., 2019; Holländer et al., 2019b; Hudson et al., 2019; Lee et al., 2019; Verma et al., n.d.). These evaluations conclude that the presence of eHMIs generally tend to work towards mitigating pedestrians' ambiguities and increasing their understanding of an AV's intent. However, the performance and subjective preference of different eHMI significantly differ, and there is no consensus regarding the type, modality, or the nature of communication in an eHMI that can achieve optimal effectiveness.

In addition to direct comparisons among subsets of concepts, some efforts have recently been made to create an overview of the existing body of knowledge on AV-ORU interaction. In their 2016 report, Vissers et al. (2016) identified the studies conducted in the field to investigate AV-VRU interaction and summarized their findings from the perspective of answered research questions. Rasouli and Tsotsos (2019) extended upon this work by identifying and categorizing research work in the domain of AV-VRU interaction with a focus on research methodology, evaluation strategy, and the factors that influence pedestrian behavior. Schieben et al. (2018) categorized several existing eHMI concepts based on messages conveyed, and furnished an overview of the advantages and disadvantages of certain recurring form factors and design patterns used in eHMI design. As a part of a more extensive study, Bazilinskyy et al. (2019) categorized 22 eHMI concepts proposed by the industry according to their general characteristics. A recent work by Rouchitsas and Alm (n.d.) reviewed and structured the empirical work done in the area of eHMI development and evaluation. Colley et al. (2019) created another categorization for eHMI concepts, particularly from the perspective of design suitability for

visually-impaired pedestrians. Their recent works also attempted to formalize a design space for eHMIs based on communication theory (Colley and Rukzio, 2020) and highlighted the challenges in terms of scalability when it comes to communication between AVs and multiple road users (Colley et al., 2020). Each of these works attempt to impose a structure on the diversity of the plethora of the existing concepts.

However, there is a need to not only categorize concepts with respect to their physical attributes, but also from a user perception point of view in the context of traffic interaction. Most existing concepts address the use case of a single pedestrian crossing in front of a single AV. However, reality will be much more complex, and future communication systems will have to deal with larger numbers of VRUs, mixed traffic, including AVs at different automation levels, but also arbitrary configurations of intersections and crossing scenarios. Thus, there is a need to develop and evaluate concepts that account for various use cases in a standardized manner. To do so, recent works have proposed the use of design frameworks. Owensby et al. (2018) proposed an 8-point framework for mapping interactions between automated vehicles and pedestrians that attempts to structure the design of an interface from three perspectives (physical attributes, nature of the interaction, and user needs). Recently, Bengler et al. (2020) proposed a holistic HMI framework for automated vehicles encompassing interactions both inside and outside the vehicle. Mirnig et al. (2018) proposed to – instead of generating additional concepts – move towards standardization, and listed six relevant requirements for adequate implementation in future traffic. Among these is the consideration that communication systems ought to be validated (prove their capabilities in standardized tests such as Euro NCAP). Besides, communication systems ought to be sensitive to cultural differences (thus either adapt to different cultural preconditions; or be clearly designed for certain cultures), and individual differences (account for disabilities). Furthermore, an effective concept should be adaptive to the environment such as road and traffic configuration, changing weather conditions, non-obstructive to have the least negative impact on traffic flow, and scalable to be able to safely operate with any numbers of road users.

No existing categorization effort offers a unified framework or taxonomy which can serve the dual role of: (1) Classifying the existing concepts – not only based on their physical attributes, but also from the perspectives of usability and realism in the traffic context, and (2) Serving as a backbone for development and description of future concepts. Taxonomies to impose a structural order on a relatively new and unorganized field within the domain of HCI has seen benefits in the past. For instance, Pousman and Stasko (2006) introduced a taxonomy to systematically structure the design space of ambient displays and information systems across design dimensions. Closer to the field of automated driving, Mirnig et al. (2017) created a categorization framework to address control transition interfaces in Level 3

Fig. 1. Examples of several eHMI concepts showcasing the different ways they accomplish the communication task. Clockwise from top-left: Mercedes-Benz F015 Concept (Daimler, 2015), Nissan IDS Concept (Nissan Motor Corporation, 2015), Semcon Smiling Car Concept (Semcon, 2016), Volvo Concept 360 (Volvo Cars, 2018), Smart EQ ForTwo Concept (Daimler, 2017), Drive.ai Concept (Drive.ai (2), 2018), and Jaguar/Land Rover Virtual Eyes Concept (Jaguar Land Rover, 2018).

automated vehicles that deal with handover and takeover requests, and in turn revealed industry trends and research gaps. The National Highway Traffic Safety Administration (NHTSA) proposed several frameworks to act as design guidelines in line with ergonomics and human factors best practices (Campbell et al., 2016; Campbell et al., 2018). Similarly, while research on AV-ORU communication systems in the past explored a wide variety of possible solutions, a more systematic approach to the topic is required. Hence, we created a taxonomy to isolate and categorize key aspects of the problem domain, and reviewed 70 different concepts proposed by industry or academia. In this taxonomy, we extend the corpus of existing work by proposing a classification framework that identifies not only the physical attributes of eHMI concept interfaces but also considerations for their functional aspects and their potential efficacy in the real world. The contribution of our taxonomy is threefold. Firstly, it summarizes the state of the art. Secondly, it highlights gaps that have not yet been addressed in the domain. Thirdly, it contributes both to a clearer understanding of the problem and to a more systematic design approach for future research. Besides, such a taxonomy can help policymakers in allowing (at least in parts) to identify the points that need to be considered in the standardization and approval of concepts in the future.

2. Method

The method applied here consists of five steps (Fig. 2): 1) Concept selection (literature search for relevant eHMI concepts), 2) Taxonomy development (identification of relevant design dimensions), 3) Concept coding (application of the taxonomy), 4) Cross-validation (ensuring inter-coder reliability to rule out ambiguities in the taxonomy), and 5) Frequency analysis (deriving common design patterns based on the coding data and identifying research gaps). Each of these steps is described in more detail in the following sections.

2.1. Concept selection

To identify relevant eHMI concepts, we searched for concepts of AV-ORU interaction within four categories: academic publications, industry patents, industry concepts, and informal concepts. For academic publications, we used Google Scholar, ACM library, IEEE spectrum, and ScienceDirect, and for the other three kinds of work, we used the Google search engine. We performed a keyword search (within the title, abstract, or keywords for academic publications) using AND/OR operators across four categories:

- Autonomous, Automated, Self-driving, Driverless.
- Car, Vehicle.
- Pedestrian, Cyclist, Traffic, Other Road User, Vulnerable Road User, VRU.
- Interface, Interaction, Communication.

For patents, industry concepts, and other informal concepts, a Google search with the above keywords yielded several hundreds of thousands of

results. However, after looking at the links, we found that there were not many new concepts or patents in the results, and most results were repetitions of previous results from different sources. After three consecutive pages of finding no new concepts, we concluded our search on Google. Due to this selection strategy, we cannot claim that this classification work is exhaustive. Thus, we do not claim completeness in our attempt to classify "all existing concepts out there". However, we do show our process so that this can be reproduced in the future.

The search for concepts was focused on a Human-Factors point of view. Our keyword search also yielded numerous results which catered to AV-ORU communication from a technical frame of reference, and these were ignored in our coding. Once all the concepts were identified, a preliminary validity check was conducted by reading the abstracts of the papers and patents, and they were ignored if they did not fit the scope of our coding goal. In the end, we identified a total of 29 relevant candidates in publications in a downloadable paper, patent, or report form (Li et al., n.d.; Böckle et al., 2017; Benderius et al., 2018; Chang et al., 2017; Clamann, 2017; Dey et al., 2018; Florentine et al., 2016; Grimm et al., 2009; Habibovic et al., 2017a; Habibovic et al., n.d.; Habibovic et al., 2019; Hillis et al., 2016; James and Prokhorov, 2016; Lagström and Lundgren, 2015; Matthiesen et al., 2018; Mahadevan et al., 2018a; Matthews and Chowdhary, 2015; Matthews et al., 2017; Mitsubishi Electric Corporation, 2015; Mitsubishi Electric Corporation, 2017; Mitsubishi Electric Corporation, 2018; Pennycooke, 2010; Ross and Liu, 2017; Rothmüller et al., 2018; Song et al., 2018; Strickland et al., 2016; Tamatsu et al., 2014; Urmson et al., 2015; Vegt and Sorokin, 2016; Zhang et al., 2018), and a further 22 candidates as online links of industry visions or informal designs (Daimler, 2015; Nissan Motor Corporation, 2015; Semcon, 2016; Volvo Cars, 2018; Daimler, 2017; Drive.ai (2), 2018; Jaguar Land Rover, 2018; Bernstein et al., 2017; BMW, n.d.; Faas, 2018; Cohda Wireless, 2017; Ford Motor Corporation, 2017; Graziano, 2014; Habibovic and Klingegård, 2016; Haiyin, n.d.; Jaguar Land Rover, 2019; Drive.ai (1), 2016; Rinspeed, 2017; Sjoerdsma and Bohnen, 2016; Strauss, 2018; Teague Labs, 2017; Tomitsch and Ellison, 2016; Toyota Motor Corporation, 2018; Umbrellium, 2017). Some publications contained multiple proposals of concepts, which led to the total number of 70 identified and coded concepts. The majority of these originate from the US (22), Germany (12), Sweden (11), the Netherlands (7), Japan (6), and Canada (5). Among the other countries represented in the origin of the context were the UK (3), Australia, Italy and Switzerland (one each), and one concept which did not specify a country of origin. The search was conducted for the time period prior to June 2019, and the oldest concept we classified was by Pennycooke (2010) which was proposed in 2012. As the field matures and new concepts are put forward, this research will need to be extended and complemented to account for this growth.

To get a holistic picture of the research landscape our goal was to include as many unique eHMI concepts as possible in our analysis. Hence, we included everything we could find in academic publications, industry patents, and also informal prototypes. Some of these concepts have never
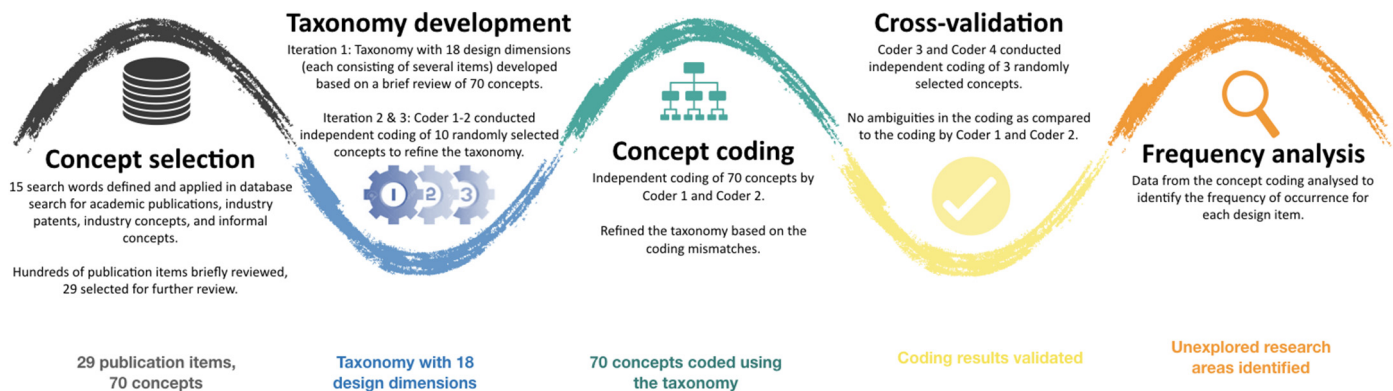

Concept selection
15 search words defined and applied in database search for academic publications, industry patents, industry concepts, and informal concepts.

Hundreds of publication items briefly reviewed, 29 selected for further review.

Taxonomy development
Iteration 1: Taxonomy with 18 design dimensions (each consisting of several items) developed based on a brief review of 70 concepts.

Iteration 2 & 3: Coder 1-2 conducted independent coding of 10 randomly selected concepts to refine the taxonomy.

Concept coding
Independent coding of 70 concepts by Coder 1 and Coder 2.

Refined the taxonomy based on the coding mismatches.

Cross-validation
Coder 3 and Coder 4 conducted independent coding of 3 randomly selected concepts.

No ambiguities in the coding as compared to the coding by Coder 1 and Coder 2.

Frequency analysis
Data from the concept coding analysed to identify the frequency of occurrence for each design item.

| 29 publication items, 70 concepts | Taxonomy with 18 design dimensions | 70 concepts coded using the taxonomy | Coding results validated | Unexplored research areas identified |

Fig. 2. Schematic overview of different steps in taxonomy development and coding.

made it to a prototype stage that would allow evaluation (or, in case of industry showcases, results might be hidden from the public) and existed only as design vision. On the positive side, this allowed us to have a potentially large database. However, this resulted also in a relatively high discrepancy regarding the depth and detail of information provided. Such issues were often dependent on the type of publication. For example, academic publications sometimes focused on specific research questions or hypotheses, where the implemented eHMI solution was mainly a tool needed for answering them. In such cases, the publication sometimes did not contain all the information necessary to be fully represented in all dimensions of the elaborated taxonomy. In contrast, for patents, sweeping and very broad implementation suggestions were a recurring theme. Contrary to specific, fully working implementations, patent authors tend to cover a lot of potential implementation possibilities to secure a competitive advantage for their assignee. This leads to a lot of unspecified or unclear elements in the description of the concepts and impedes comprehension. On the other hand, industry and informal concepts that are used to call attention to innovation and progress tend to highlight the visually appealing aspects of a concept without going into the details of functionality and typically fail to address every scenario and use case adequately. Despite the difficulties associated with each medium, all identified concepts were included in the coding to have a broad overview of the proposals in the design space.

2.2. Taxonomy development

The taxonomy was developed in three major iterations. In Iteration 1, we developed the dimensions and definitions partly based on previous works (Schieben et al., 2018; Owensby et al., 2018; Bengler et al., 2020), and partly based on physical and functional core elements of eHMIs that we identified through a brief review of 70 concepts selected in the previous step. We created a preliminary framework of the coding scheme with 18 dimensions covering key attributes of eHMIs from two distinct perspectives:

1. Physical characteristics describe the observable and tangible features of the concept, such as position, location, color, or content.
2. Usability and realism describe the interpreted usability of the concept, based on its context of deployment in traffic, including elements like scalability, resolution, or complexity.

For each of the resulting 18 dimensions (see Fig. 3), we defined different manifestations, to which we further added the items "unclear" (when the description of the concept provided was not sufficient enough for categorization), and "unspecified" (in case the necessary information was not provided).

We then refined the taxonomy in two succeeding iterations, Iteration 2 and 3, to clarify subtle distinctions and small nuances of definitions in the
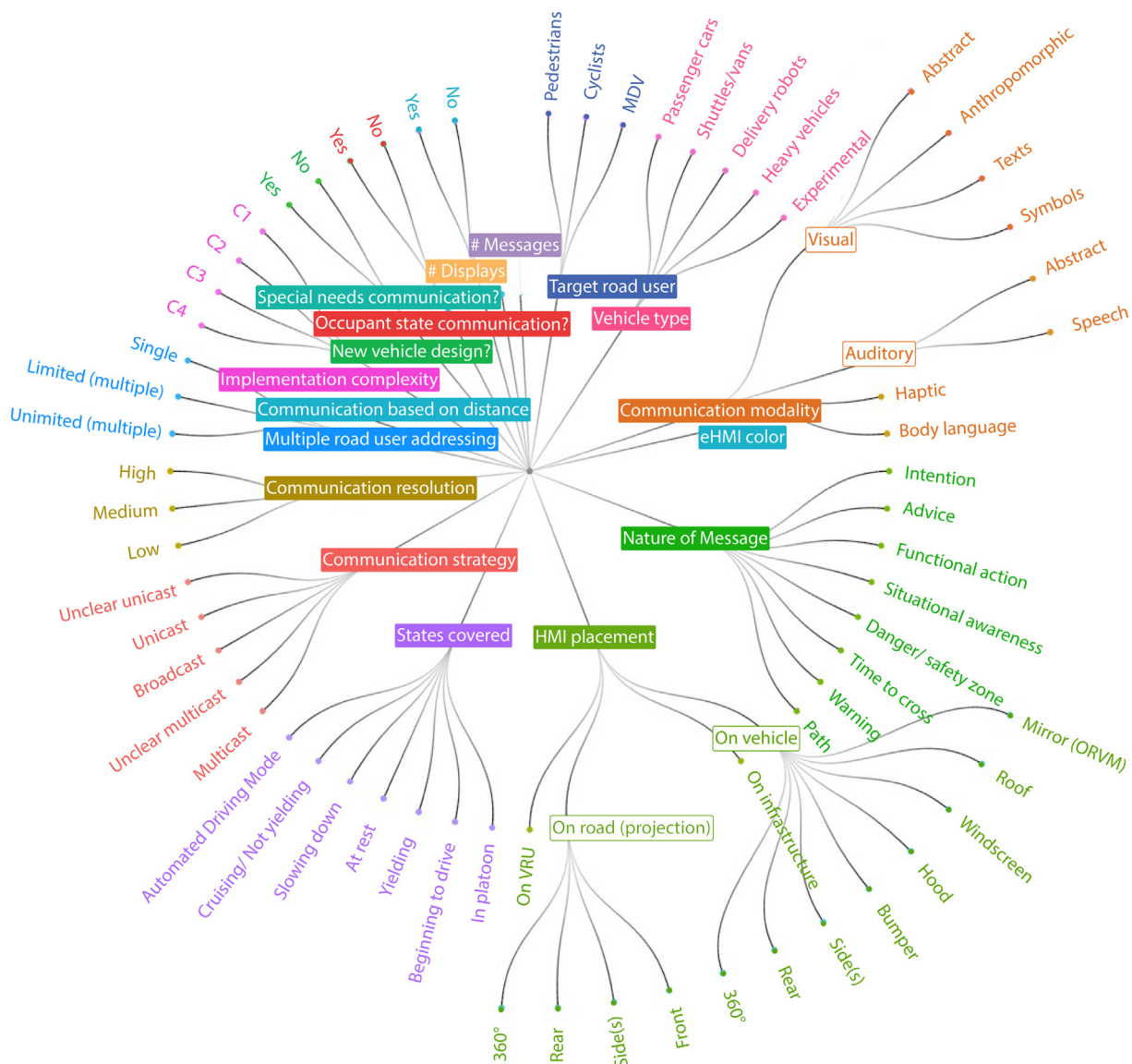

Fig. 3. This circular dendrogram visualizes the taxonomy used to code the existing eHMI concepts.

respective dimensions. In each iteration, 10 concepts were randomly selected and independently coded by Coder 1 and 2 (first two authors) using the taxonomy. After finishing the coding, the coders compared their results, resolved mismatches and updated the taxonomy accordingly. Each concept was analyzed to determine its fit within any of the existing categories. If a precise fit could not reasonably be obtained for the existing categories, we resolved the issue by creating new categories or modifying already existing ones and re-executing the coding process. Each author involved in this work in the capacity of developing the taxonomy and coding the concepts is a researcher and/or expert in the fields of either Human-Computer Interaction or Engineering/Traffic Psychology working in the domain of user-centered design and the user experience of interactions between automated vehicles and other road users. Therefore, the taxonomy was developed from the perspectives that pose challenges in the development of an efficient eHMI based on user-centered design principles. Furthermore, several authors are members of international committees such as UNECE[1] and ISO[2] that are involved in policy-making and standardization of regulations for AV-ORU interaction. Their involvement in iteratively refining the focus of the taxonomy ensured that the taxonomy brought the international and multi-stakeholder perspective of the challenge at hand.

2.3. Concept coding

Each of the 70 identified concepts was subjected to the full classification schema of the taxonomy. The entire process was carried out first as a consensus coding activity between two coders (Coder 1 and 2). The coders independently coded each concept, and in case of disagreement, the rationale was discussed to re-evaluate the classification until agreement was reached.

The physical characteristics and aspects of the concepts were coded as reported in the descriptions or demonstrations available to avoid inaccuracies as a consequence of erroneous assumptions. For instance, in the dimension of 'Target Road user', we coded only the kind of road user that was explicitly used to describe the functionality of the concept. Even if the concept might be extendable to other kinds of road users, we did not extrapolate this information. Other dimensions – particularly the ones concerning usability and realism (such as scalability, or communication resolution) – by nature delved deeper into the functionality of the concepts within the context of deployment in real-world traffic. Therefore, these aspects of the coding process required some coder interpretations. This also applied to some physical attributes such as the color of lights used in light-based concepts and subsequent conformity with current law. Since the exact color was not explicitly mentioned in many concepts, we used our best interpretation to code these designs from the image or video media included with the concepts. These interpretations were made jointly by the coders. Consequently, while making these interpretations, the definitions of these dimensions in the taxonomy were further refined and scoped to maintain consistency in the coding process across different concepts.

Many of the concepts did not have all content pertaining to the design in one place. Some academic concepts had the same design described over multiple publications (e.g. (Mahadevan et al., 2018a; Mahadevan et al., 2018b), (Matthews and Chowdhary, 2015; Matthews et al., 2017), (Habibovic et al., 2017a; Habibovic et al., n.d.; Lagström and Lundgren, 2015)). Many others – particularly industry concepts – showcased their design across many different video clips, articles, and documents. In such cases, we referred to all related sources to get a complete picture of the application and functionality of the concept in practice and coded these concepts as detailed as possible.

Some eHMI concepts were composites of multiple elements (e.g., the system proposed in an Uber patent (Ross and Liu, 2017) communicates through a combination of abstract, light-based messages, symbols, text displays, anthropomorphic gestures, and projection onto the street). In such cases, each sub-element of the composite eHMI solution was recorded in

the coding of the entire concept. If different sub-elements resulted in different levels of realism and usability scores (e.g. resolution, scalability), the results for each sub-element of the composite was recorded as comma-separated values for the coding of the entire concept. For instance, if a concept consisted of a composite of 'eyes' and a 'light bar', the coded results for each of these two components were recorded as a part of the result of the entire concept.

2.4. Cross-validation

To eliminate bias, two authors (in this case Coders 1 and 2) carried out the first round of coding for all 70 concepts in a consensus coding approach. To further validate the accuracy of the coding, a cross-validation was carried out. Three out of 70 concepts were randomly selected and independently coded by further two authors (Coders 3 and 4) using the taxonomy. A comparison of their results showed no discrepancies. Similarly, a comparison of their results with the coding results by Coders 1 and 2 revealed no discrepancies. This indicates that the taxonomy could potentially be used by other coders and still reveal similar results. However, it is difficult to say with certainty that this would be the case in practice without a broader validation across different user groups. This taxonomy is intended as a framework or initial basis for discussion, and will need to evolve and be refined as more knowledge is gained in the area.

2.5. Frequency analysis

The data from the coding of 70 concepts were analyzed to identify the frequency of occurrence for each design item. Based on this, we derived the current eHMI design trends and identified current gaps and implications for future research. After coding each concept according to the dimensions of the taxonomy, we clustered them according to the eHMI trends or 'design pattern' they followed. These design patterns were defined with a higher level of abstraction than the dimensions explored in the taxonomy and were identified based on recurring elements in the design of the concepts. The elements of the identified design patterns were combinations of multiple dimensions of the taxonomy relating to the concept's physical characteristics. They were chosen to give a broad overview of the plethora of eHMI concepts from the perspective of recurring themes.

3. Taxonomy and coding results

In this section, we present 18 taxonomy dimensions (see Fig. 3) along with the corresponding results of our analysis and implications for future research (in bold) resulting from the classification of the 70 eHMI concepts included in this review. A detailed overview of the results is given in Appendix A.

3.1. Target road user

This dimension defines the type of road user addressed in a concept. Research shows that pedestrians and cyclists have different behavioral patterns in traffic, resulting from different speeds, glancing behaviors, or movement forms (Trefzger et al., 2018; Hagenzieker et al., 2019). Other road users such as drivers of ordinary vehicles and motorcyclists exhibit different behavioral patterns when interacting with other vehicles on the road compared to cyclists and pedestrians (Fruhen et al., 2019; Habibovic et al., 2013). Compared to cyclists, drivers face different sets of circumstances that cause them distraction (Pettitt et al., 2009; Useche et al., 2018), which further suggests the possibility that the way drivers of vehicles operate in traffic are different from vulnerable road users such as cyclists, and by extension, pedestrians. Thus, vehicular interactions are different for different road users, and should be accounted for in a holistic eHMI design.

3.1.1. Results and implications

Analysis shows that *pedestrians* are the most targeted road user type: 42 concepts (60%) target pedestrians only, while 22 (31%) target pedestrians

and at least one other type of road user. Overall, pedestrians are addressed by 64 concepts (91%). *Cyclists* are targeted by 16 concepts (23%), each of which address at least one other type of road user. Interactions with *manually operated vehicles* are addressed by 10 concepts (14%), while 7 (10%) target '*other road users*' without further specification. Given that pedestrians constitute a high fraction of fatalities in traffic accidents (European Commission, 2018a; European Commission, 2018b), it is no surprise that as a group of target road users, pedestrians have received a high priority and importance in this research. However, the role of eHMIs in interactions between AVs and other road users apart from pedestrians – such as cyclists, motorcyclists, and other drivers – should receive more attention, particularly as they are currently unexplored in the current context.

3.2. Vehicle type

This dimension describes the type of vehicle on which the concept was demonstrated. Although many interfaces could be adapted or extended to multiple kinds of vehicles, we posit this category to be relevant for interpreting the results of existing experiments. For example, a heavy vehicle like a bus will likely influence ORUs' decisions to cross the road due to subjectively perceived risks of potentially more severe outcome as a result of a crash, or other factors such as significantly longer braking distance, and size differential acting as a confound for time-to-arrival such that larger vehicles are perceived to be closer than they actually are (DeLucia, 1991; DeLucia, 2013; Levulis et al., 2015; Smith et al., 2001) – attention need to be paid to these aspects of eHMI concepts for such vehicles must be considered with extra caution. In the coding scheme, we thus distinguish between *passenger cars*, *shuttles buses or vans*, *heavy vehicles* (*trucks and full-size buses*), *delivery robots*, *experimental vehicles*, and *other*.

3.2.1. Results and implications

The results show that eHMI concepts are predominantly installed or envisioned to be installed on *passenger cars*. 56 concepts (80%) address such vehicles, 9 (13%) *shuttles or buses*, 3 (4%) *heavy vehicles*, and 4 (6%) other vehicles types. It should be noted that the vast majority of the concepts have only been demonstrated for one vehicle type (67, or 96%). Passenger vehicles constitute the vast majority of vehicular traffic (ACEA, 2018), and it is therefore justified that it has received the biggest attention in this research. However, eHMIs for other vehicle types demand more attention, especially considering that interactions differ depending on vehicle type and size (DeLucia, 2013; Levulis et al., 2015). There may be some vehicle types that have not yet been used as platforms for the demonstration of eHMI concepts (such as delivery robots). As automated driving technology permeates our society, eHMI solutions may need to be tested or implemented on other kinds of vehicles that have not yet been explored. To reduce the potential risk of developing different concepts for different types of vehicle, it is also necessary to investigate the same concept for several different vehicle types. The results of the analysis in terms of vehicle type and target road users are summarized in Fig. 4.
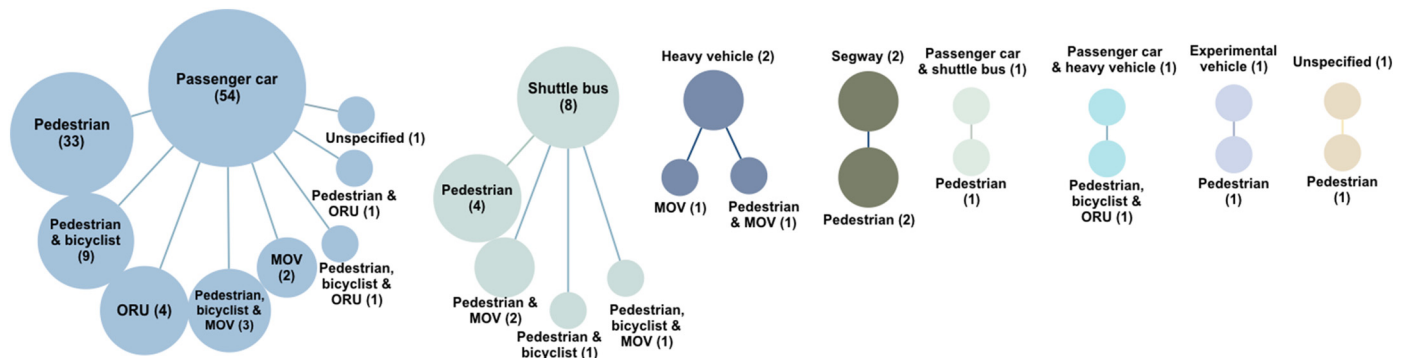
3.3. Modality of communication

This dimension refers to the way communication is achieved in the concept. If a concept offers multimodal communication, all existing forms are categorized. Sub-categories have been elaborated to account for potentially different ways in which communication is achieved within certain modalities. The categories in this dimension are described below.

Visual:

- *Anthropomorphic*: The concept uses human-like or anthropomorphic elements for communication, such as facial expressions (eyes, smiling), or gestures.
- *Text*: Explicit use of text, like "Stopping", "Driving", "Please cross", or any other variation that uses text to communicate vehicle state or instructions to VRUs.
- *Symbols*: Use of recognizable traffic symbols such as stop signs, pedestrian crossing (zebra crossing) lines, walking pedestrian symbol, arrows, or other forms of symbols used to communicate.
- *Abstract*: Abstract visual shapes or other forms of light-based or non-light-based communication devices that use metaphors, or signals that aim at communicating intuitively via a non-concrete, open-to-interpretation interface that is neither anthropomorphic, textual, or symbolic.
- *Unspecified*: The interaction or communication is visual, but the exact nature is not explained.

Auditory:

- *Speech*: Any form of spoken word (such as "stopping", "driving", or "please cross") used to communicate from the AV to the VRU.
- *Abstract*: Use of non-speech related audio signals that can be abstract or metaphorical.
- *Unspecified*: The communication uses sound, but the exact nature of the audio signals is unexplained.

Haptic: Any haptics-based signal used for communication. This will usually be the case for communication devices that are attached to VRUs, such as wearables, phones, or tablets.

Body Language: Any movement-related "gestures" used by the vehicle to convey a message (e.g., acceleration, kneeling or braking, shape-changing interfaces, or changing body panels).

Other: Forms of communication that cannot be classified using the categories described above.

Fig. 4. Coding results for vehicle type and target road user (ORU = other road user; MOV = manually operated vehicle).

3.3.1. Results and implications

When it comes to the modality by which information is conveyed to other road users, the visual modality is the most frequently used. It is used in 68 concepts (97%). More specifically, 48 (69%) concepts use only the visual modality, while 20 (29%) apply a combination of visual and some other modality (e.g., auditory and haptic). *Abstract* visual information presented through lights and displays is the most commonly used solution (48 concepts, 69%), followed by *symbols* (20 concepts, 29%), *text* (16 concepts, 23%), and *anthropomorphic* features (10 concepts, 14%). There were also two concepts using some other type of visual modality. A total of 20 coded concepts (29%) used audio as a communication modality in some form. Auditory information is relayed either in the form of speech (6 out of 20) or non-speech audio signals that can be abstract and metaphorical (9 out of 20), while the rest of the concepts did not specify which kind of audio message was used. Haptics-based information such as vibrations was used in 3 (4%) concepts. Body language of the vehicle, such as acceleration or deceleration, was used in 3 (4%) concepts. In total, 50 of the coded concepts (71%) used only one modality. Dual modality was used in 16 (23%) concepts, while three modalities were used in 4 concepts (6%) only. This is summarized in Fig. 5.

Based on this, we argue that the vast majority of the concepts in their current form would not be able to provide sufficient information to a wider population for whom accessibility is critical. Only 20 of the concepts reviewed (29%) would be able to support people with special needs such as those with vision or hearing impairments. This requires more attention to multimodal designs and accessibility issues to be taken into account when proposing new concepts. However, it is also important to carefully chose the type and number of modalities to avoid information overload and misinterpretation. It is also notable that visual and auditory modalities are used predominantly over body language of the vehicle. Given that a large portion of current interactions among road users is based on body language (Dey and Terken, 2017; Moore et al., 2019), we conclude that the role of vehicle body language as a communication modality needs further investigation.

3.4. Colors (only for visual eHMIs)

This dimension applies exclusively to visual concepts (e.g., light strips, projection, or abstract animation), and defines the colors used for communication. If a concept consists of visual elements that communicate with different colors, all of them are recorded.

An extension of this element is the legal compliance of the colors used. Colors of an eHMI used for communication should not interfere with colors already implemented or reserved for other purposes in vehicles according to the specifications of SAE J578 Standard (SAE Lighting Standard Practices Committee, 2016) and UNECE Regulation R-65 (UNECE (United Nations Economic Commission for Europe), 2011). This limitation prohibits the use of red, yellow, amber, selective yellow, green, restricted blue, signal blue, and white (Tiesler-Wittig, 2019; Werner, 2018). This dimension defines whether the colors used in the concept conforms with current regulations (*yes*, *no*). Although non-compliance with current regulations does not inherently mean that the concept is poor, the value of novel design solutions that do not concur with regulations needs to be evaluated based on user-centered design principles. If the benefits of a regulation-defying design are found to be credible, regulations may be changed to accommodate a good design. This dimension can also be used to raise a flag to determine if a concept cannot be implemented "as-is" in current traffic scenarios and whether more evaluations are required.

3.4.1. Results and implications

The color could be classified for 59 of 70 concepts. About half of those use one color, while the other half utilizes multiple colors. Notably, 15 concepts (25%) use three or more colors. Among the 59 concepts which could be analyzed, the most frequently used colors are white (37%), green (30%), cyan or turquoise (29%), red (27%), blue (25%), and yellow (17%). In five of the non-classified cases, classifying the color was deemed to be not applicable (concepts that did not use light-based communication, e.g., (Vegt and Sorokin, 2016)). In the rest of non-classified cases, the color was not specified (e.g., patents). This is summarized in Fig. 6. This variety indicates that there is yet no clear consensus regarding color preference, although recent research has shown a trend towards adopting cyan or turquoise as a color of choice for AV communication (Tiesler-Wittig, 2019; Werner, 2018; Dey et al., 2020).

Our analysis also shows that only 25 concepts (36%) are in compliance with the current regulations specified by SAE J578 Standard (SAE Lighting Standard Practices Committee, 2016) and the UNECE Regulation R-65 (UNECE (United Nations Economic Commission for Europe), 2011). The remaining concepts were classified as non-complying (25 concepts, 36%), unclear (16 concepts, 23%) or not applicable (4 concepts, 6%, where no
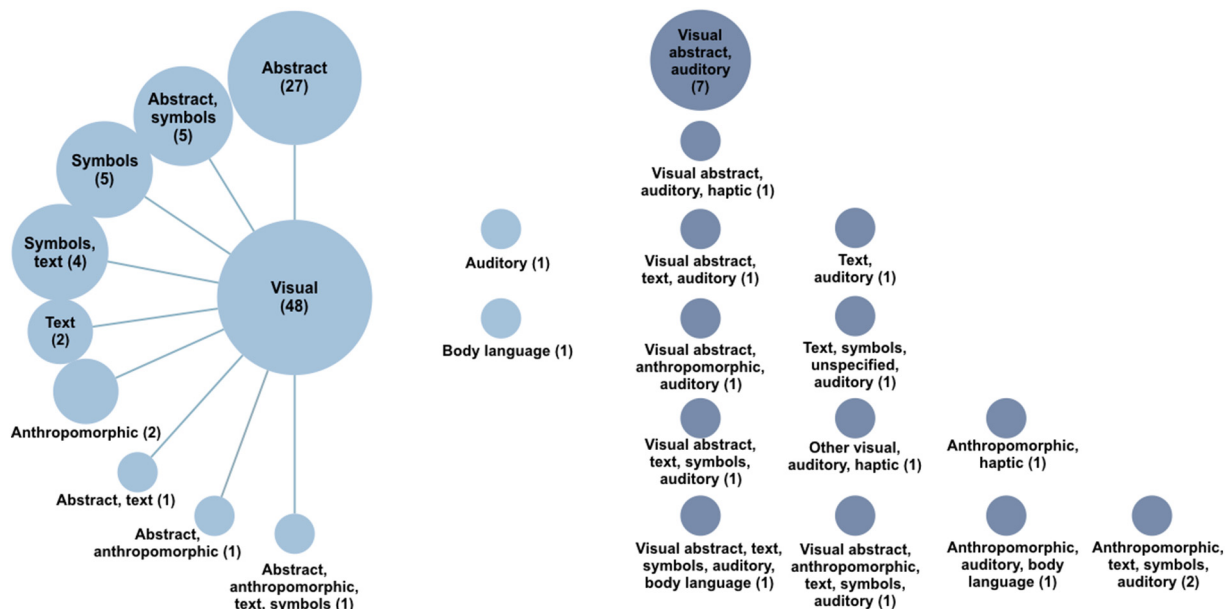

Fig. 5. Coding results for modality used to convey information to other road users (light blue denotes single modality, while dark blue denotes a combination of different modalities). Over 70% of the concepts apply one modality only.

Fig. 6. Coding results for color distribution (left) and the number of colors used simultaneously (right). Only about 25% the concepts are in compliance with the current regulations.

colored lights are used for communication). The high number of unclear cases also shows that the descriptions of the concepts in terms of color and compliance are often insufficient.

3.5. Covered states

This dimension identifies the specific states or operations the interface communicates, where we choose to include *driving mode* (*automated/manual*), *cruising, not yielding, slowing down, at rest, yielding, beginning to driver*, or *other*. However, several considerations regarding this dimension have to be taken into account. If a concept is designed to show that the vehicle is cruising in automated mode by default, and no separate indication is provided for driving mode, this is coded as "cruising". In terms of vehicle action or intent, there is a distinction between "cruising" and "not yielding". If a concept communicates that a road user has been recognized, but the vehicle is not intending to yield, it is coded as "not yielding". If the vehicle only shows that it is cruising (and that it does not intend to yield or stop for a road user), this is marked as "cruising", even though "cruising" can indicate in extension that a car is "not yielding". In case there are no distinct "states" described for a concept, and the vehicle can show one (possibly dynamic) message (such as its current speed) as an always-on display, this is also coded as "cruising".

We distinguish between the driving mode (e.g., the car is operating in automated mode) and driving action (e.g., "cruising" or "yielding") because the fact that the automation is activated is distinct from the automation's actions. For example, if the car stops and there are no VRUs to yield to, a status message may still show that the automation is active. However, this is not related to the car's driving action. Some concepts explicitly recognize "yielding" as a vehicle's action. For other concepts, different components of a yielding behavior are conveyed separately, e.g., stopping and resting.

If a concept describes negotiation of the right-of-way with a VRU without explicitly mentioning the distinction between actions like slowing, stopping, or resting, its state is marked as "yielding".

3.5.1. Results and implications

In total, we have identified 8 distinct states used in the 70 reviewed concepts. More specifically, 45 concepts (64%) convey information about the vehicle's yielding intent, compared to 23 concepts (33%) that communicate that the vehicle is cruising (in automated mode), or not yielding. In addition, unique communication of the automation state (i.e., "automation is

active") is incorporated in 16 concepts (23%). Other information on vehicle states includes *beginning to drive* (20 concepts, 29%), *resting* (9 concepts, 13%), *slowing down* (7 concepts, 10%), and *in platoon* (1 concept, 1%). Furthermore, 37 concepts (53%) convey information about multiple vehicle states in various levels of detail, from binary information ("not yielding", "yielding") up to multiple states (e.g., "automated driving mode", "yielding", "cruising"/"not yielding", "slowing down", "resting", "beginning to drive"). We also noted that 19 concepts (27%) convey information about one vehicle state only: *yielding* (13 concepts, 19%), *automated driving* mode (3 concepts, 4%), *cruising* in automated mode (1 concept, 1%), *slowing down* (1 concept, 1%) and *in platoon* (1 concept, 1%). This is summarized in Fig. 7.

The results imply that conveying the yielding intent of the vehicle (or negotiation of the right-of-way) is currently considered as the essential information, followed by the vehicle's intent to begin driving. Informing other road users about the automation state is also commonly suggested, however, it is not necessarily displayed as a unique message. The Information on the operating state is often embedded in other signals such as cruising or not yielding. This variety in the number of states shows an inconsistency in the research community when it comes to the question of which states are essential to be communicated. This open question highlights the need for more research to identify the key candidates for explicit communication in AV-ORU interactions. A wide variety in the communication of operating states can be confusing, and is not advisable. A recent technical report by ISO identifies the operating states that are candidates for explicit communication (International Organization for Standardization (ISO)/TR 23049, 2018), and can be treated as a starting point in developing a standardized communication paradigm.

3.6. Message of communication in right-of-way negotiation

This element defines the content of the communication when negotiating right-of-way – ideally answering "what does the vehicle say"? This dimension applies specifically to the message when negotiating the right-of-way, in contrast to the covered states in the above dimension.

- *Intention of vehicle's state*: The car communicates its intention in terms of its operating state, such as driving, yielding, at rest, or beginning to drive (see also the states described in Section 3.5).
- *Current functional action*: The car explicitly communicates its current state in terms of driving action, such as "speeding up", or "engaging brakes",
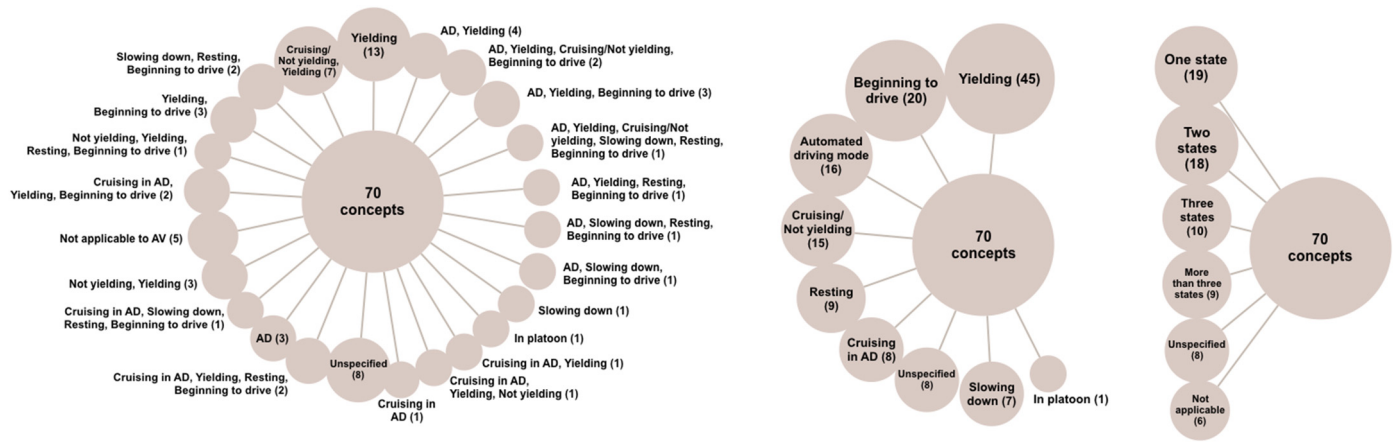
Fig. 7. Coding results for states covered by the concepts: different state combinations (left), frequency of states (middle), and number of states used per concept (right).

without explicitly mentioning its intention or action in the immediate future. This item specifically refers to communication regarding vehicle dynamics. Thus, direct intent communication is not coded under this category.

- *Advice*: The vehicle issues an advice, instruction, or other command and call to action to the road users, issues warnings, or shows messages that indicate that its action is contingent upon the ORU's actions. Examples of these messages are "please cross", "safe to cross", "do not cross", "unsafe to cross", and "waiting for you".
- *Time-to-cross*: The car communicates a form of countdown timer (either numerically, textually, or in an abstract way, e.g., as a progress bar) which allows the surrounding VRUs to determine how much time they have left to cross.
- *Situational Awareness*: The car communicates its awareness of elements or entities in its environment.
- *Path*: The car communicates its trajectory or intended path, or intended stopping point.
- *Danger/safety zone*: The car demarcates an area around it that is a danger or safety zone for an ORU.
- *Warning*: The car communicates with a general warning that does not apply to the other codes.

It is important to distinguish between intention and advice in this dimension. Road users may interpret the communication as either vehicle intention or advice to them, depending on the frame of reference. For example, a pedestrian can perceive a message that declares the vehicle's yielding intent as "the car is asking me to cross". This difference is particularly relevant for abstract communication that does not explicitly spell out the message but leaves room for interpretation. In such cases, we coded the message as "advice" only when there is an apparent instructive element in the message, and as "intention" otherwise.

3.6.1. Results and implications

Concerning right-of-way negotiations, 39 concepts (56%) convey the *intent* of the vehicle. In 17 of these cases (24%), the intent is the only message conveyed. For the remaining concepts, intent is supplemented with messages that communicate *situational awareness* (11 concepts, 16%) and/or *advice*, (8 concepts, 11%), *warnings* (6 concepts, 9%), *vehicle path/trajectory* (3 concepts, 4%), *time-to-cross* (2 concepts, 3%), and *danger zone indication* (1 concept, 1%). Only 7 concepts (10%) provide *advice* or *instruction* only. In a few cases, this message is conveyed along with *situational awareness* (2 concepts, 3%), and vehicle's path prediction (1 concept, 1%). Furthermore, 4 concepts (6%) convey situational awareness only. Similarly, 3 concepts (4%) convey a vehicle's path only, while 2 concepts (3%) convey this message along with a warning message. Warnings alone are conveyed by 4

concepts (6%). Only two concepts (3%) convey the current action (behavioral dynamic) of a vehicle. This is summarized in Fig. 8.

Overall, conveying intent alone or along with other messages is the current trend.

However, 29% of the concepts reviewed give advice or instructions to other road users. This raises some potential ethical and liability concerns, which we address in the Discussion section.

3.7. HMI placement

This dimension defines the locus of communication and identifies the place where the messages are conveyed, including the following categories:

- *On the vehicle*: The communication device is mounted on the body, including the *windscreen*, *hood*, *roof*, *bumper* (including *grills* and *headlights*), *sides*, *rear*, and *all around*.
- *Projection on the road*: The communication is achieved by projecting messages, trajectories, stopping point, intention, directions, or symbols on the road (*front, side, rear, all around*).
- *On the infrastructure*: The HMI is located on the traffic infrastructure (e.g., traffic lights or smart roads).
- *On the VRU*: The communication device is attached to the VRU (e.g., wearable, phone, or tablet) and uses proximal communication.

3.7.1. Results and implications

In 52 concepts (73%), the eHMI is placed only on the vehicle. However, there are additional 10 concepts that use devices on the vehicle in combination with other devices located elsewhere. Within the 62 concepts that showcase eHMIs on the vehicle (89%), the eHMI is attached to the vehicle: mostly on the *windshield* (20 concepts, 29%), followed by *bumper* (12 concepts, 17%), *roof* (11 concepts, 16%), *grill* (11 concepts, 16%), *hood* (8 concepts, 11%), *sides* (8 concepts, 11%), *headlights* (5 concepts, 7%), and *rear* (5 concepts, 7%), while 3 concepts (4%) were not further specified. It should be noted that several concepts convey messages via two or more of these locations. The projection of messages onto the road is used in 12 concepts (17%), out of which 5 concepts (7%) use it as the only means of communication. Ten of these concepts (14%) project in front of the vehicle, while two of them project on the side of the vehicle, one in the rear, and one is unspecified. In addition, we identified 5 concepts (7%) where messages are displayed via devices on the VRU (e.g., wearables, smartphones). In three of these cases, they are the only used communication means. Furthermore, in three concepts (4%) messages are conveyed using devices in the infrastructure (traffic lights or roads). In one of these cases, it is the only means of communication. Fig. 9 summarizes these results and highlights the degree of inconsistency and the lack of coherence in current eHMI concepts.
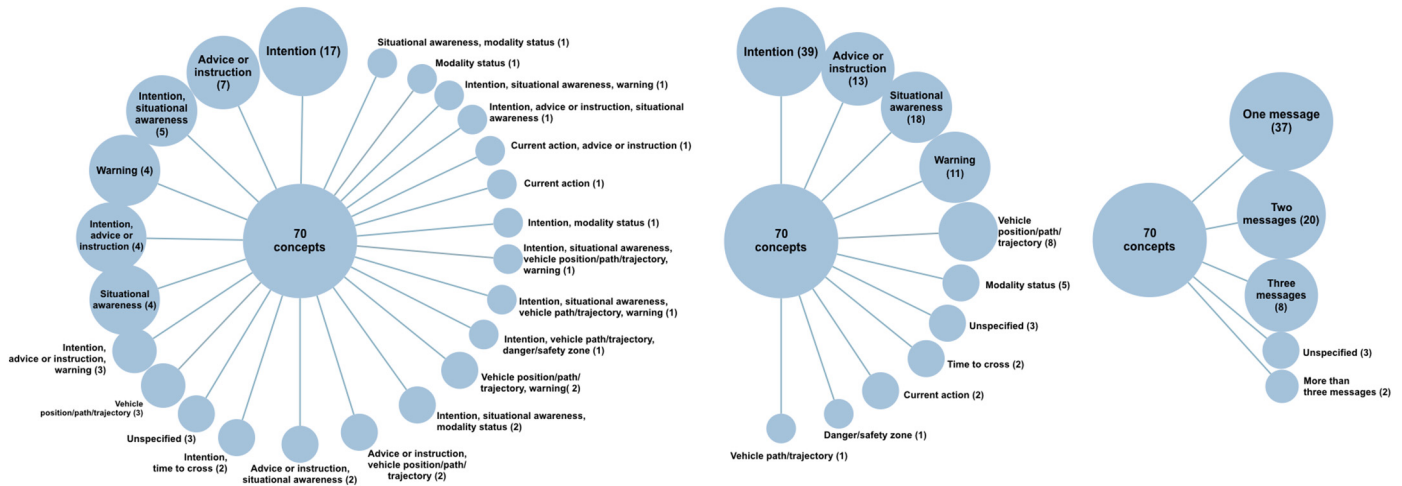
Fig. 8. Coding results for different combinations of messages in right-of-way negotiation (left), message type (middle), and number of messages utilized per concept.

Our findings imply that there is currently no consensus regarding the optimal locus of the communication source, although, using the windshield seems to be a trend. However, this trend may be problematic as it can obstruct both the view from inside the vehicle for the occupants (and driver when the vehicle is manually operated) and the camera sensors that are commonly placed on the windshield behind the rear-view mirror. Thus, it is important to address the issue more holistically, also taking the information needs of vehicle occupants into account.

3.8. Number of displays

For our analysis, we defined a "display" as any communication device, which is capable of communicating an atomic piece of information or message at a time to one recipient road user. The modality is thereby not limited to vision (light bar/matrix, text display) and also includes auditory (speaker), haptic (wearable device), etc. A continuous display hardware

such as a light band around the vehicle, may be able to address multiple pedestrians; however, at any given time it functions as a single display for one pedestrian (and is thus considered one display). A display is not defined by its hardware constraints, but by the distinct nature of information it can communicate. Within this dimension, we record the number of displays, what can partly be seen as a form of "efficiency": a high number of displays does not necessarily have a specific connotation but it could point towards redundancy (potentially increasing clarity when it comes to interpreting messages), or complexity (potentially causing information overload).

3.8.1. Results and implications

33 concepts (47%) use only one display for conveying one message to one recipient at a time. However, there are several concepts that use multiple displays to convey a message: two (19 concepts, 27%), three (9 concepts, 13%), or four displays (3 concepts, 4%). In six cases (9%), it was either unclear or not specified how many displays are envisioned.
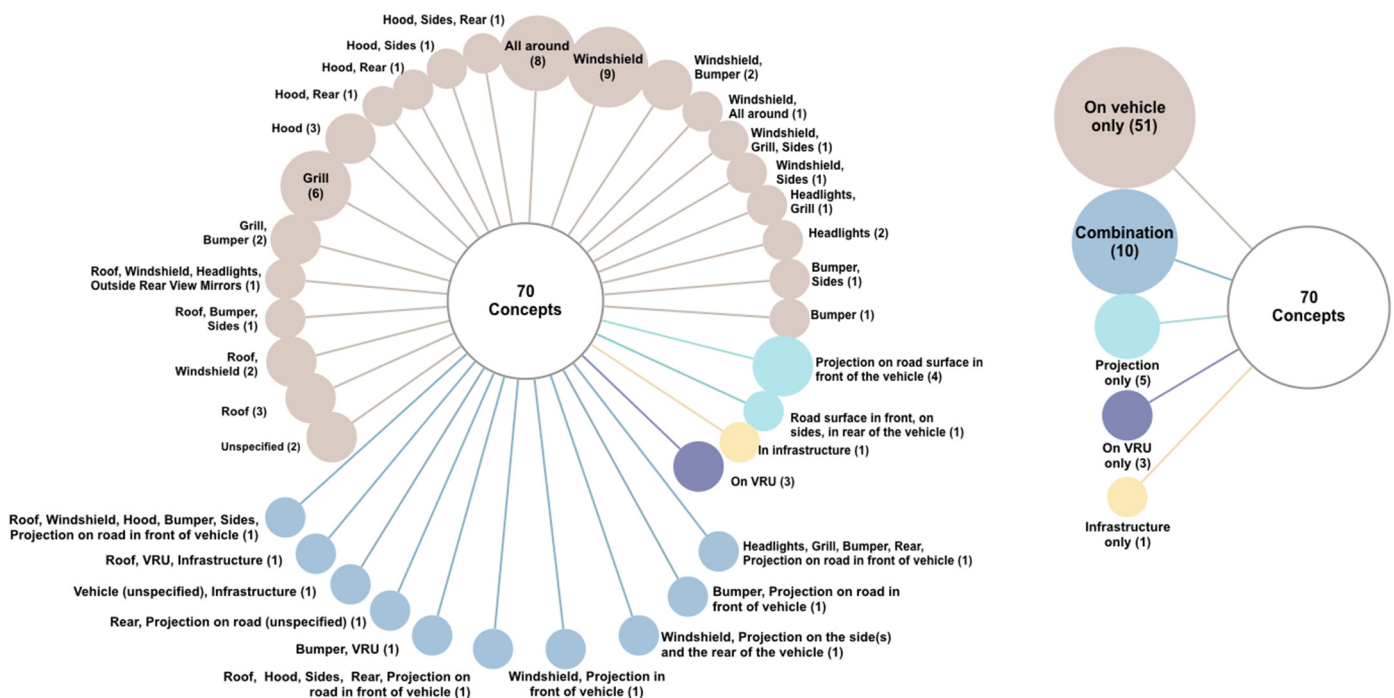

Fig. 9. Coding results for eHMI placement show that majority of concepts are placed on vehicle only (pink), but there is also a significant portion of concepts combining different placements (blue).

Our results suggest that it is equally common to use either one or multiple displays to convey a message. While it can be useful to obtain information from multiple displays, it can also be a distracting factor that requires extra resources from the recipient, especially in complex, dynamic, and time-sensitive situations. Thus, in the absence of a consensus on how to best communicate messages in traffic, further research is required to identify a good degree of redundancy in communicating messages explicitly in traffic.

3.9. Number of messages

This defines the number of distinct messages that can be communicated by a concept. A distinct message is defined as an atomic message communicated by a single display. A display can show multiple messages, but only one message at a time. The following rules are considered to code this dimension:

- Each unique message shown at a given time is identified for each display (i.e., repeated for every display in the concept).
- If the same message is shown on multiple displays, it is still considered as one message.
- If a continuous process is displayed (e.g., the frequency of the light represents the distance to the pedestrian, or a light segment moves continuously by tracking a pedestrian as a situation awareness display), it is counted as one message.

3.9.1. Results and implications

The number of distinct messages varies from 1 to 7, depending on the concept. Eight concepts (11%) are able to display only one message, 14 concepts (20%) display two messages, 19 concepts (27%) display three messages, 4 concepts (6%) display four messages, 5 concepts (7%) display five messages and one concept (1%) displays 7 messages. We also identified one concept with 20 unique messages (Drive.ai (2), 2018), however, it is unclear how these messages are envisioned to be used. Furthermore, the number of messages was unclear for 11 concepts (16%), and unspecified for 7 concepts (10%).

Overall, the analysis shows that a great majority of the concepts communicate multiple messages. This communication could be both an advantage and a disadvantage because such concepts can be flexible and adapt to many situations, but could also lead to confusion or information overload, especially in scenarios where multiple vehicles with eHMIs are present.

3.10. Communication strategy

This dimension defines how an eHMI addresses road users in a negotiation, and whether the communication happens on an individual or group level, and in a targeted or non-targeted manner. It aims to identify how well a concept is able to communicate with road users about the intention of the vehicle in the context of a dynamic, urban scenario with multiple road users around the vehicle having different intentions. We adopted the terminology "casting" from the model of transmitting data over a network in computer science, and adapted it to the nuances of communication as applied to AV-VRU interaction. This element is coded as a combination of three sub-elements:

- Communication subject (determined from a system [vehicle] point-of-view): Identifies whether the system is capable of addressing one or more individuals simultaneously (one person, multiple people).
- Messages (determined from a system [vehicle] point-of-view): Identifies whether the system is capable of showing only one or more than one message at a time (one message, multiple messages).
- Clarity of recipient (determined from a human [road user] point-of-view): Identifies whether it is clear whom the system is addressing from a road user's point of view. This element is coded by imagining an interaction with the vehicle on a busy road with many other road users. Subsequently, we ask the question: "Is it clear to me/am I absolutely sure that

the message addresses me"? Examples of a clear communication would be concepts of eHMIs that can highlight or precisely address the subject of its communication, such as personal addressing (name or picture), projecting a pedestrian crossing precisely in front of the subject, messaging on a smartphone or nomadic device, or other forms of highlighting and clarifying a road user as the addressee. The coded values are either *clear* or *unclear*.

Based on the results of these three sub-elements, coders can follow the flowchart in Fig. 10 to determine the addressing capability of the eHMI concept, distinguishing the following categories:

- *Unclear Unicast*: The concept is capable of addressing only one road user at a time and is not able to show clearly which road user among a group of (proximate) road users it addresses.
- *Clear Unicast*: The concept is capable of addressing only one road user at a time but can clearly show which one among a group of proximate road users the recipient is.
- *Broadcast*: The concept is capable of addressing multiple road users but does not distinguish between different road users, and communicates its message for everyone in the environment to see. This is the only non-targeted form of communication, as the other four methods of communication attempt to target and address specific users.
- *Unclear Multicast*: The concept is capable of addressing multiple specific road users at a time but is not able to show clearly which road user among a group of proximate road users it addresses.
- *Clear Multicast*: The concept is capable of addressing multiple specific road users at a time and is also able to clearly specify which road user among a group of proximate road users it addresses.

3.10.1. Results and implications

The most widely used communication strategy turned out to be a non-targeted broadcast, where the vehicle simply announces its messages to the environment for anyone in the vicinity to intercept and interpret in their way. There were 8 concepts (11%) that consisted of composite eHMI solutions with multiple communication strategies (i.e., a combination of broadcast, unicast, and multicast). However, among the concepts that used only one kind of strategy, 47 concepts (67%) used broadcast, while the rest used other targeted forms of communication (2 unclear unicast, 2 clear unicast, 5 unclear multicast, and 4 clear multicast). Furthermore, 2 concepts (3%) could not be classified due to insufficient description.

The analysis indicates that overall, a non-targeted communication is the preferred strategy, probably due to the challenges of targeted communication in very large, dynamic, or complex environments.

3.11. Communication resolution

This question should be considered from the point of view of a road user who is among other road users sharing the same space, but not necessarily the same intentions, and/or not having the same right-of-way. This element defines the clarity of whom the message of an eHMI is intended. From a road user's safety point-of-view, we ask the question: "is it safe to proceed"? Example scenarios, which can be used to determine the answer to this question, are shown in Fig. 11. Although not every road user in these scenarios has right-of-way, we ask whether the eHMI concept enables the road user to identify with a certain level of detail or clarity for whom the message is meant. The coded categories are:

- *Low*: Knowing whether it is safe for the road user to cross is fully left to interpretation and deduction based on the car's communication. This item usually applies to vehicles that use abstract and unspecific indications to communicate "intention" or "situation awareness" without further information.
- *Medium*: Whether it is safe for the road user to cross is left to interpretation. However, the car does provide additional information that aims to make its specific intentions easier to understand, rather than, for example, just communicating that the car is going to yield. Examples are
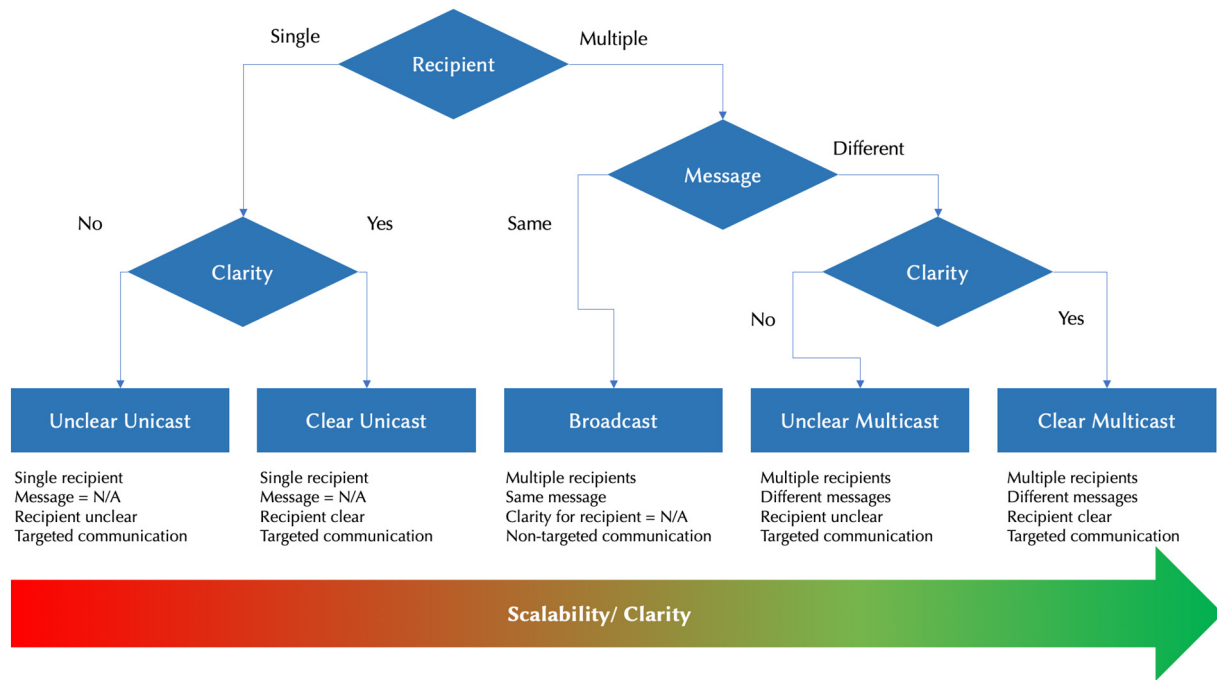
Fig. 10. The flowchart used in coding the communication strategy for a specific eHMI concept. Note: For a single recipient, multiple messages are unnecessary and irrelevant. Hence, we do not check for multiple messages for eHMIs capable of only addressing a single road user. Contrarily, for eHMIs catering to multiple users but showing the same message (Broadcast), we do not inquire for Clarity for the recipient; if the message is the same, it does not matter who the recipient is.

information on the time or place where the car will stop, or feedback about the car's situation awareness.

- *High*: The car communicates clearly and unambiguously if it is safe for a certain road user to proceed.

When explicitly addressing co-located road users, who may not all have the same right-of-way, it is unclear if an eHMI should communicate to road users who do not have the right-of-way at all and only communicate with the specific road users whom the AV has to yield to legally. However, this may have implications in situations when traffic rules need to be broken to ease a complex traffic situation. Ethnographic studies of pedestrian and vehicle behavior in traffic have shown that in many ambiguous situations,

implicit and explicit communication takes place, and the ambiguity is resolved by temporarily and safely breaking the traffic rule (Risto et al., 2017; Vinkhuyzen and Cefkin, 2016; Müller et al., 2016). Thus, it is essential to take into consideration a design for such nuanced and ambiguous situations.

A good eHMI should be able to communicate clearly and effectively to other road users, particularly in a dynamic, busy traffic situation. According to Hall's 'Encoding/Decoding' model for communication (Hall, 1980; Shaw, 2017), both good encoding and decoding are necessary for successful communication. The dimensions in Sections 3.10 and 3.11 collectively attempt to capture the 'good encoding and decoding' as applied to the domain of AV-RU interaction. The clarity of both – the message and the subject of the communication – are crucial for success.
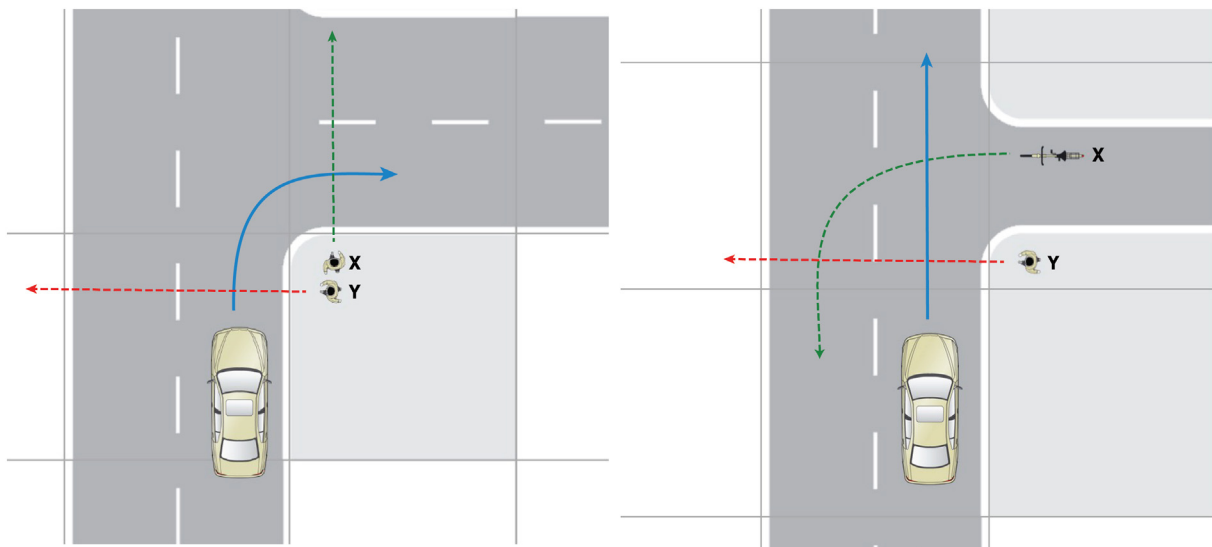
Fig. 11. Two examples of traffic situations that are used to aid the coding of the element "communication resolution" in Section 3.11. The figures describe scenarios in which two VRUs share the same approximate position in relation to the car, but have different priorities/right-of-way (in each case, X has the right-of-way before the car but Y does not).

3.11.1. Results and implications

The analysis shows that 26 of 70 concepts (37%) have low resolution meaning that the knowledge of whether it is safe for the other road user to proceed is entirely left to interpretation and deduction based on the vehicle's communication. Typically, these concepts use abstract and unspecific "intention" or "situation awareness" indication to communicate without any further information. Moreover, half of the concepts (35, 50%) have a medium resolution meaning that the concept, in addition to showing the message of intent, also shows some information regarding the time and the place when or where the vehicle will come to a stop, or the vehicle's situation awareness. However, the knowledge of whether it is safe for the road user to act (e.g., cross) is left for interpretation. Of all the coded concepts, only 9 (13%) provided high-resolution communication.

We conclude that the current design principles include information to other road users that support situation understanding and decision making without directly informing the other road user whether it is safe to cross or not.

3.12. Addressing road users: How does it apply to multiple road users?

This question clarifies whether the concept is applicable to a high number of other road users, thus the degree of scalability.

- *Unlimited* number of multiple road users (Highly scalable).
- *Limited* number of multiple road users (Partially scalable).
- *Single* road user (Not scalable).

This dimension is similar to Section 3.10, but it differs specifically in that it delves deeper in the level of potential scalability. Some eHMIs are capable of addressing multiple road users at a time, but only up to a certain limit. For example, an eHMI concept based on situational awareness – while able to cater to multiple road users at a time – cannot scale infinitely with respect to its form factor. This dimension captures whether from a design perspective, the eHMI can scale infinitely, or whether there are limits even when the eHMI is capable of addressing multiple road users.

3.12.1. Results and implications

For a great majority of the concepts (52 concepts, 74%), we determined that an unlimited number of road users could be addressed. We also found out that there are 13 concepts (19%) that might be able to address a limited number of road users, i.e., more than one but not an unlimited amount of road users. Examples of such concepts are ones that use light cues around the vehicle that follow the motion or relative position of a pedestrian with respect to the vehicle, e.g., (Nissan Motor Corporation, 2015; Dey et al., 2018). The remainder of the concepts (7%) can only address one road user at a time. These concepts typically use anthropomorphic features in the form of eyes, e.g., (Jaguar Land Rover, 2018; Pennycooke, 2010).

An insight from this coding is that the concepts of communication resolution and scalability are inversely related to each other – the more precisely a concept communicates with specific road users, the more it loses the ability to communicate with a large number of road users with the same precision and resolution. There are exceptions to this, and we discuss this further in the Discussion section.

3.13. Communication dependence on distance

The nature of communication may be based on the distance or time-to-arrival estimates between the vehicle and the addressed VRU. Properly utilized, this could be valuable as it has been shown that VRUs focus on different areas depending on the distance to a vehicle (Dey et al., 2019a), which this item takes into account.

- *Yes* (Y): The nature of the communication (e.g., modality, placement, or message) changes with the distance of the vehicle from the pedestrian or stopping point. This behavior needs to be clearly defined for the concept.

- *No* (N): Apart from the activation of a communication stimulus based on the car's intention to yield at a prescribed distance, the nature of the communication (e.g., modality, or message) does not change as the car comes closer to the pedestrian or stopping point.

There is a nuance to the aspect of vehicle distance in the interaction: the message's content may change as a consequence of the car approaching a stopping point, such as from "I am cruising" to "I am yielding". However, this direct effect of the vehicle's distance is not what is referred to in this coding. Instead, we look at whether the nature of the information presentation changes with the distance of the vehicle.

3.13.1. Results and implications

Our analysis shows that of the 70 concepts coded, only three concepts (Li et al., n.d.; Cohda Wireless, 2017), and Concept 6 of Dey et al. (2018) considers the element of distance in manipulating the nature or content of the communication message in interacting with pedestrians. For one of the concepts (Tomitsch and Ellison, 2016) a clear coding decision could not be made due to a lack of detailed description. However, for all other concepts, the aspect of the distance or the time-to-arrival of the vehicle was not instrumental in facilitating communication. This lack of concepts with distance encoding reveals another potential gap to explore in design consideration while developing and evaluating new eHMI concepts.

3.14. Complexity in implementation

This dimension classifies how complex the deployment of a concept in real traffic scenarios would be. It accounts for concepts that are highly aspirational and, while perhaps good in theory, are less realistic to put in practice given current technological and infrastructure setup. This classification is made based on the complexity of the interface technology used in the concept. This dimension does not account for complexity in sensing or processing technology, but specifically for the technology used in communicating to the end-user. As automated driving and the associated exploration of the solution to the communication gap via eHMI are in their nascent stages, this innovation trigger has the potential to cause inflated expectations that may not be commercially viable, as explained by the Gartner Hype Cycle (Gartner Inc, 2016). This dimension attempts to identify the viable drivers of this technology's commercial promise.

- *C1*: Able to use technology already in the car.
- *C2*: Needs new already-available technology, but does not depend on large-scale deployment or infrastructure changes to function.
- *C3*: Needs new already-available technology, but depends on large-scale deployment or infrastructure changes to function.
- *C4*: Uses technology that is not yet developed or not widely available on the market.

3.14.1. Results and implications

The analysis of the readiness of the concept interfaces shows that 45 of 70 concepts (64%) would be possible to implement using widely available technology (e.g., a light strip). Nineteen concepts (27%) would require new but already available technology on the market that does not depend on large-scale deployment or infrastructure changes (e.g., projection on the road, "eyes"). The results also show that 5 concepts (7%) would need new already available technology that depends on large-scale deployment or infrastructure changes. Only one of the concepts uses technology that is not yet widely available on the market (which requires the use of windshield displays). Consequently, most of the proposed systems could be implemented soon, and without the need for major technological advances.

3.15. Dependence on new vehicle design

Some eHMI concepts are easily implementable on current vehicles (e.g., a simple addition of an eHMI on the body panel of a car), while others require a completely new vehicle design to work (e.g., the Volvo Concept

360 (Volvo Cars, 2018)). Past research has shown that vastly futuristic and unusual designs of automated vehicles may cause hesitation in pedestrian interactions with vehicles – particularly in the early stages of their introduction in mixed traffic situations (Dey et al., 2019b). In this dimension, we capture whether the paper/patent/document utilizes a novel/different model of a car to explain the concept: *yes*, the concept is demonstrated with currently existing vehicle form factors; *no*, the concept is showcased on a yet unavailable vehicle design.

3.15.1. Results and implications

The analysis shows that 54 concepts (77%) are showcased using existing vehicle designs (i.e., vehicle models that are available on the market). The remaining 16 concepts are showcased on new vehicle designs (i.e., vehicle models that are currently not available on the market).

From this perspective, a great majority of the concepts explored in this study are designed to suit existing vehicle models. It is, however, important to note that only a few of the concepts have been showcased as physical prototypes, making it difficult to determine if the concepts showcased on existing vehicle models would be implementable in practice. Given that vehicle design may pose different requirements on eHMI and may have a significant effect in pedestrian interactions (Dey, 2019), this is an important element to investigate in detail.

3.16. Vehicle occupant state

This dimension pertains to shared guidance. Recent research has shown the importance of shared control of an automated vehicle from the perspective of a vehicle occupant (Baltzer and Lopez, 2016; Flemisch et al., 2012; Habibovic et al., 2017b). If the decision of the vehicle occupant (i.e., driver or passenger) has an impact on other road users, it may be important to communicate this explicitly. This dimension captures whether the eHMI enables the occupant to communicate their intention or state of mind to other road users (e.g., "in a hurry", "angst", "politeness", or "social gestures"), or is involved in the decision whether the vehicle should stop for another road user: *yes* the concept accounts for communication on behalf of the occupant, including polite/social gestures; *no*, the concept works solely automated.

3.16.1. Results and implications

Our coding shows that no analyzed concept so far accounts for the communication pertaining to the occupant of the vehicle. This observation reveals a gap in the research regarding the effects and communication of shared control or other aspects of occupant-influenced vehicle driving decisions.

3.17. Support for people with special needs

Does the concept take the special needs of impaired persons into account by means of multimodal communication (*yes*, *no*)?

3.17.1. Results and implications

Based on the coding results for the dimension "Modality of Communication" (Section 3.3), a large number of concepts do not use multiple modalities and redundancies to facilitate communication. From this, our interpretation is that a great majority of the concepts in their current form would fail in sufficiently conveying information to a broader population. Given the number of modalities used, our conclusion is that only 20 concepts (29%) would have the ability to support people with special needs such as vision or hearing impairment. This calls for more attention to multimodal designs while considering accessibility issues in proposing new concepts.

3.18. Evaluation of the concept

This dimension captures whether or not the concept has been evaluated (*yes*, *no*). If it is mentioned that an evaluation was conducted, but no results are presented, the item was still coded as "unknown". Only when the provided information allowed to code along the categories above, this field

was marked as yes. In case the answer is yes, this dimension identifies the conditions and setup of the evaluation. The following items are categorized:

- *Time of day*: Daylight conditions, evening conditions, nighttime conditions, unspecified, unclear.
- *Number of simultaneous road users per trial.*
- *Number of simultaneous vehicles per trial.*
- *Method of evaluation*: Naturalistic, controlled outdoor, Virtual Reality, video, unspecified, unclear.
- *Weather conditions*: Direct sunlight, indirect sunlight, rain, snow, unspecified, unclear.
- *Road condition*: Clean roads, water on road, snow on road, unspecified, unclear.
- *Sample size*: Number/Unknown
- *Sample age*: Number/Unknown
- *Method*: Subjective (qualitative) evaluation, Objective (Empirical/quantitative) Evaluation, Mixed methods

The analysis shows that a majority of 50 concept descriptions (71%) either did not include any information about an evaluation or stated that the concept had not been evaluated with potential users. Only 20 concepts (29%) were evaluated. In each of these cases, the evaluation involved only one automated vehicle and one other road user.

Except for one study, where the sample size exceeded 1800 participants (Ford Motor Corporation, 2017), 9–125 participants (average 42) were sampled for evaluation. In 11 of the 20 evaluations, the sample size was 9–34 participants, while it ranged between 50 and 125 participants in 6 of the 20 evaluations. The sample size was unspecified for two of the concepts. The analysis shows that the age of the participants was not specified for all evaluations, as only 13 of the 20 studies provided this information. Another finding is that the age was rather low in several cases: in 10 of the 13 evaluations, the mean age was in the range 18–37 years. Altogether, these findings indicate that evaluations tend to include a somewhat limited sample of participants within a certain age group. The most commonly used evaluation method was a controlled outdoor experiment (9 of 20 concepts), followed by virtual reality experiment (4 of 20 concepts), video (4 of 20 concepts), controlled indoor experiment (2 of 20 concepts) and naturalistic study (1 of 20 concepts). Furthermore, the analysis shows that the majority of the evaluations were of a rather limited scope as they commonly incorporated only one traffic scenario (15 of 20 evaluations). The most common traffic scenario was an uncontrolled zebra crossing (15 concepts), followed by road mid-block without a zebra crossing (6 concepts), parking lot (2 concepts), and controlled intersection (1 concept). One of the evaluations was decontextualized, and in two cases, the scenario was not described at all. A great majority of the evaluations incorporated good light, weather, and road conditions. More specifically, except for two evaluations that were carried out both in daylight and darkness, and two others that were carried out only in darkness, 15 evaluations were carried out in daylight only. Similarly, three evaluations were carried out both in good and rainy/stormy weather conditions, while 17 were carried out under good weather conditions only (one evaluation was decontextualized, one unspecified). Also, two evaluations included both clean and wet roads, while 16 evaluations involved clean roads only (one evaluation was decontextualized, one unspecified). This is summarized in Fig. 12. When it comes to the data collected in these 20 evaluations, the analysis shows that 9 of the evaluations focused on qualitative data only, 3 focused on quantitative data only, and 8 focused on both qualitative and quantitative data.

3.18.1. Results and implications

Overall, this shows a lack of focus on a thorough evaluation of the proposed concepts in different situations, under different lighting and environment conditions, and with a diverse set of demographics. While the pool of proposed concepts of eHMI is vast, it is largely not validated for most traffic situations. This observation calls for attention towards empirically determining the efficacy of various concepts in realistic implementation and making valid design choices based on actual user needs, preferences, and behaviors.

4. Discussion

In this paper, we proposed a taxonomy to create a systematic overview of the design space for the concepts of eHMI that attempt to facilitate effective communication and interaction between AV and other road users. Our taxonomy looked at 18 different physical and functional dimensions of eHMIs that contribute to effective communication in the dynamic and complex traffic situations. Subsequently, we coded 70 existing concepts of eHMI designs to categorize them under the taxonomy and identify existing solutions and recurring design patterns. In the previous section, we already looked at the implications of our coded results for the existing concepts. Here, we reflect on the problem space of AV-ORU communication from a higher level and discuss the research gaps, limitations, and future research.

4.1. Design patterns of eHMI

The recent advent of eHMI concept proposals has seen a recurrence of certain patterns of design choices for communication of right-of-way negotiation. These design patterns are not necessarily derived from specific individual elements of the taxonomy but are combinations or abstractions thereof. We clustered the concepts under 12 design patterns that we identified within the pool of the concepts we coded through which communication is achieved:

- Projection on the road.
- Symbols – commonly-understood traffic symbols.
- Text – message script in characters or numbers.
- Smile – anthropomorphic smile element to indicate friendly (yielding) behavior.
- Eyes – anthropomorphic eyes to show the AV's situational awareness.
- Other anthropomorphic designs – 'gestures', avatars, or other elements that are approximations of human communication behavior.
- Abstract lighting element: one-dimensional light bar or segment.
- Abstract lighting element: two-dimensional display.
- Abstract lighting element: tracker – to show the situational awareness of the car in its environment.
- Audio.
- Infrastructure elements.
- Mobile and/or wearable devices.
- An interesting point to note is that the design patterns of 'smile', 'eyes', or 'other anthropomorphic elements' may be implemented using two-dimensional light display. However, a concept is coded under 'Abstract lighting element: two-dimensional display' when the communication is not in a concrete, recognizable form, and cannot be decisively coded under the other elements.

The coded results are shown in Fig. 13. Our coding shows that by far, the most popular design pattern chosen for an eHMI concept is the *One-*

dimensional, abstract light bar (used by 25 concepts). A possible reason for this is the general ease of designing and implementing such an interface within the existing form factor of the vehicle and the infrastructure. Subsequently, other popular design patterns were *Text* (14 concepts), *Symbols* (13 concepts), *Projection on road* (12 concepts), *Tracker* (12 concepts), and *Audio* (10 concepts). Less popular design patterns were the use of *Mobile/wearable devices* (5 concepts), anthropomorphic elements such as *Eyes* (4 concepts), *Smile* (1 concept), and *Other anthropomorphic designs* (3 concepts). There were only 3 concepts that used an *abstract 2D light-based display*, and 2 concepts that made use of the *Infrastructure* elements.

There were several eHMI concepts that were composite solutions that made use of multiple design patterns within the design, which explains why the summation of the number of concepts under each design pattern is larger than the number of eHMI concepts we coded. These composite concepts are highlighted in bold typeface in Fig. 13.

4.2. Common research gaps

The coding of the existing concepts shows a multitude of different approaches when it comes to facilitating communication between AV and other road users. Several different modalities, physical placements, and strategies have been explored to solve various interaction issues that may arise in complex traffic scenarios. However, despite the attention to a large number of use cases, one scenario that has received consistently little attention is the design for visually impaired road users (taxonomy item 3.17). Ignoring a subsection of the demographic in designing for an effective eHMI will hinder a successful deployment and integration of automated driving technology in traffic. The work of Colley et al. has been one of the first to lay the groundwork for including visually impaired pedestrians from the start of the design process for eHMI (Colley et al., 2019). However, mature, robust, and multimodal solutions that cater to visually impaired road users are clearly lacking and need attention in future research.

Another area that has seen little attention in this space is the design for shared control by the occupant of an AV, and a corresponding communication of the vehicle's occupant state or consequences of this for the interaction with other road users (taxonomy item 3.16). Previous research has clarified that driving is a highly social activity that often leads to a wide array of implicit and explicit communication for effective negotiation (Risto et al., 2017; Vinkhuyzen and Cefkin, 2016). Other research has also shown that communicating the intent and the emotional state of mind of a driver can aid empathy and cooperative behavior in traffic with other road users (Wang et al., 2014; Wang et al., 2017). In automated driving, when a human driver is out of the picture, there have been predictions that pedestrians will be able to take priority without impunity (Millard-Ball, 2016). For example, particularly at uncontrolled pedestrian crossings in areas with heavy pedestrian traffic, it is possible that AVs will have to
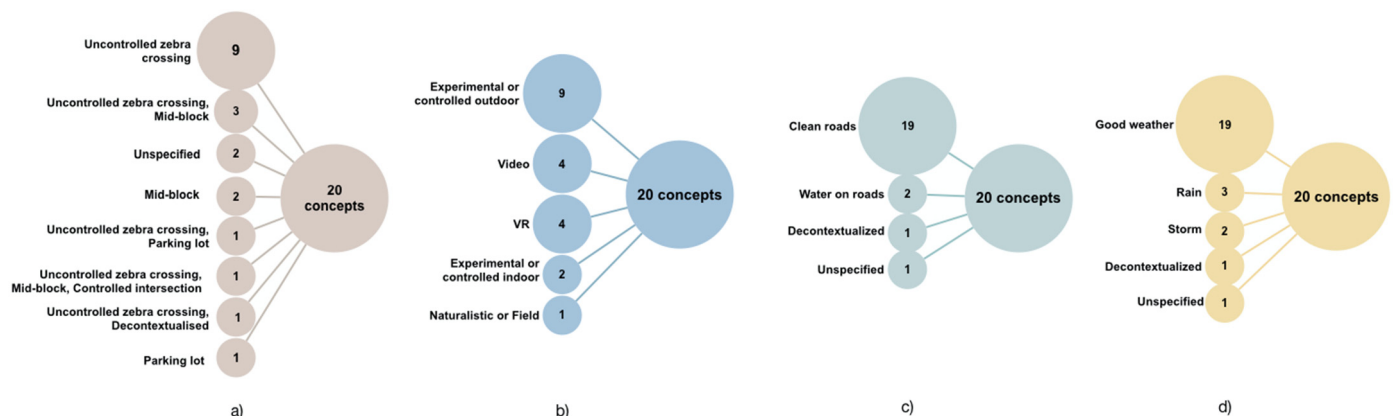
Fig. 12. The analysis shows that only 20 of 70 concepts reviewed were evaluated. Evaluation scenarios (upper left), road conditions (upper right), evaluation method (lower left) and weather conditions (lower right).
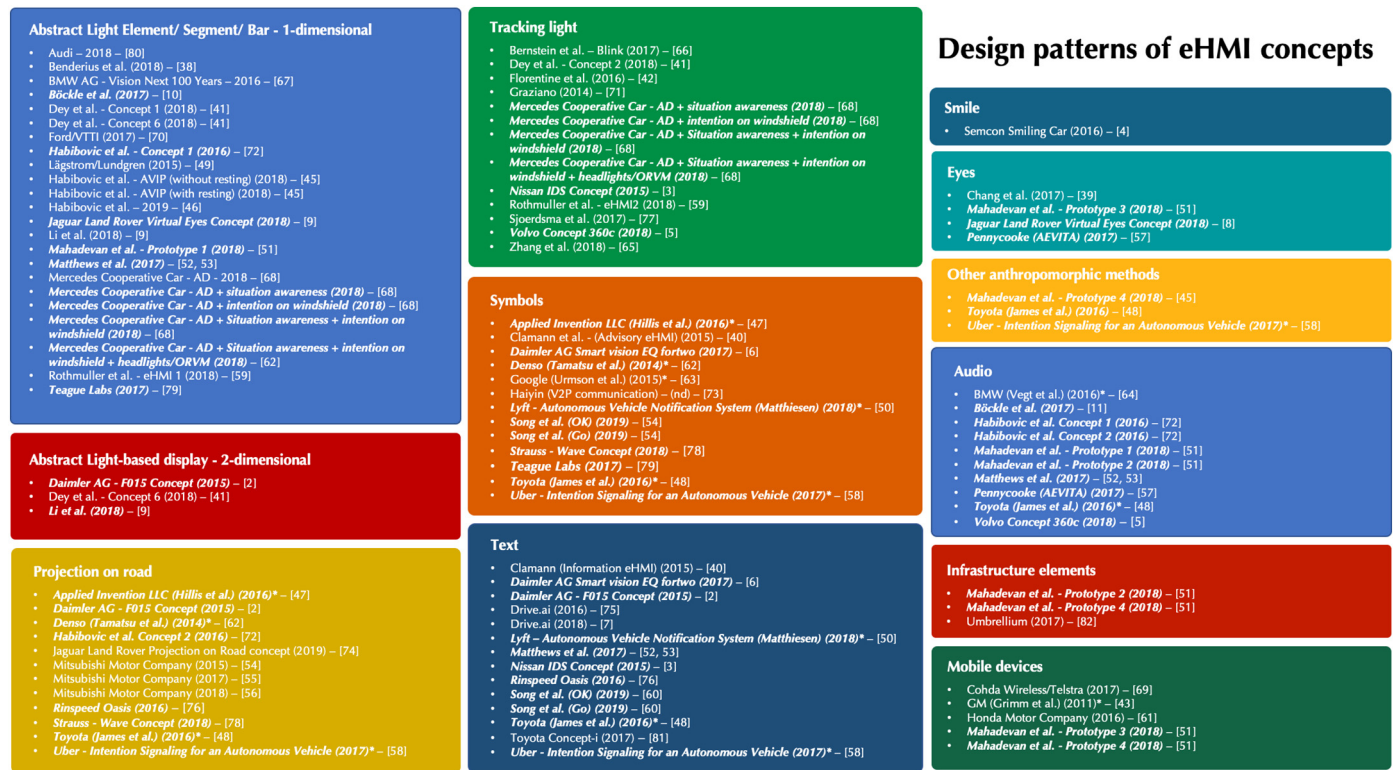
Abstract Light Element/ Segment/ Bar - 1-dimensional

- Audi – 2018 – [80]
- Benderius et al. (2018) – [38]
- BMW AG - Vision Next 100 Years – 2016 – [67]
- *Böckle et al. (2017)* – [10]
- Dey et al. - Concept 1 (2018) – [41]
- Dey et al. - Concept 6 (2018) – [41]
- Ford/VTTI (2017) – [70]
- *Habibovic et al. - Concept 1 (2016)* – [72]
- Lägström/Lundgren (2015) – [49]
- Habibovic et al. - AVIP (without resting) (2018) – [45]
- Habibovic et al. - AVIP (with resting) (2018) – [45]
- Habibovic et al. - 2019 – [46]
- *Jaguar Land Rover Virtual Eyes Concept (2018)* – [9]
- Li et al. (2018) – [9]
- *Mahadevan et al. - Prototype 1 (2018)* – [51]
- *Matthews et al. (2017)* – [52, 53]
- Mercedes Cooperative Car - AD - 2018 – [68]
- *Mercedes Cooperative Car - AD + situation awareness (2018)* – [68]
- *Mercedes Cooperative Car - AD + intention on windshield (2018)* – [68]
- *Mercedes Cooperative Car - AD + situation awareness + intention on windshield (2018)* – [68]
- *Mercedes Cooperative Car - AD + Situation awareness + intention on windshield + headlights/ORVM (2018)* – [62]
- Rothmuller et al. - eHMI 1 (2018) – [59]
- *Teague Labs (2017)* – [79]

Abstract Light-based display - 2-dimensional

- *Daimler AG - F015 Concept (2015)* – [2]
- Dey et al. - Concept 6 (2018) – [41]
- *Li et al. (2018)* – [9]

Projection on road

- *Applied Invention LLC (Hillis et al.) (2016)* * – [47]
- *Daimler AG - F015 Concept (2015)* – [2]
- *Denso (Tamatsu et al.) (2014)* * – [62]
- *Habibovic et al. Concept 2 (2016)* – [72]
- Jaguar Land Rover Projection on Road concept (2019) – [74]
- Mitsubishi Motor Company (2015) – [54]
- Mitsubishi Motor Company (2017) – [55]
- Mitsubishi Motor Company (2018) – [56]
- *Rinspeed Oasis (2016)* – [76]
- *Strauss - Wave Concept (2018)* – [78]
- *Toyota (James et al.) (2016)* * – [48]
- *Uber - Intention Signaling for an Autonomous Vehicle (2017)* * – [58]

Tracking light

- Bernstein et al. - Blink (2017) – [66]
- Dey et al. - Concept 2 (2018) – [41]
- Florentine et al. (2016) – [42]
- Graziano (2014) – [71]
- *Mercedes Cooperative Car - AD + situation awareness (2018)* – [68]
- *Mercedes Cooperative Car - AD + intention on windshield (2018)* – [68]
- *Mercedes Cooperative Car - AD + Situation awareness + intention on windshield (2018)* – [68]
- *Mercedes Cooperative Car - AD + Situation awareness + intention on windshield + headlights/ORVM (2018)* – [68]
- *Nissan IDS Concept (2015)* – [3]
- Rothmuller et al. - eHMI2 (2018) – [59]
- Sjoerdsma et al. (2017) – [77]
- *Volvo Concept 360c (2018)* – [5]
- Zhang et al. (2018) – [65]

Symbols

- *Applied Invention LLC (Hillis et al.) (2016)* * – [47]
- Clamann et al. - (Advisory eHMI) (2015) – [40]
- *Daimler AG Smart vision EQ fortwo (2017)* – [6]
- *Denso (Tamatsu et al.) (2014)* * – [62]
- *Google (Urmson et al.) (2015)* * – [63]
- Haiyin (V2P communication) – (nd) – [73]
- *Lyft - Autonomous Vehicle Notification System (Matthiesen) (2018)* * – [50]
- *Song et al. (OK) (2019)* – [54]
- *Song et al. (Go) (2019)* – [54]
- *Strauss - Wave Concept (2018)* – [78]
- *Teague Labs (2017)* – [79]
- *Toyota (James et al.) (2016)* * – [48]
- *Uber - Intention Signaling for an Autonomous Vehicle (2017)* * – [58]

Text

- Clamann (Information eHMI) (2015) – [40]
- *Daimler AG Smart vision EQ fortwo (2017)* – [6]
- *Daimler AG - F015 Concept (2015)* – [2]
- Drive.ai (2016) – [75]
- Drive.ai (2018) – [7]
- *Lyft – Autonomous Vehicle Notification System (Matthiesen) (2018)* * – [50]
- *Matthews et al. (2017)* – [52, 53]
- *Nissan IDS Concept (2015)* – [3]
- *Rinspeed Oasis (2016)* – [76]
- *Song et al. (OK) (2019)* – [60]
- *Song et al. (Go) (2019)* – [60]
- *Toyota (James et al.) (2016)* * – [48]
- Toyota Concept-i (2017) – [81]
- *Uber - Intention Signaling for an Autonomous Vehicle (2017)* * – [58]

Design patterns of eHMI concepts

Smile

- Semcon Smiling Car (2016) – [4]

Eyes

- Chang et al. (2017) – [39]
- *Mahadevan et al. - Prototype 3 (2018)* – [51]
- *Jaguar Land Rover Virtual Eyes Concept (2018)* – [8]
- *Pennycooke (AEVITA) (2017)* – [57]

Other anthropomorphic methods

- *Mahadevan et al. - Prototype 4 (2018)* – [45]
- *Toyota (James et al.) (2016)* – [48]
- *Uber - Intention Signaling for an Autonomous Vehicle (2017)* * – [58]

Audio

- BMW (Vegt et al.) (2016)* – [64]
- *Böckle et al. (2017)* – [11]
- *Habibovic et al. Concept 1 (2016)* – [72]
- *Habibovic et al. Concept 2 (2016)* – [72]
- *Mahadevan et al. - Prototype 1 (2018)* – [51]
- *Mahadevan et al. - Prototype 2 (2018)* – [51]
- *Matthews et al. (2017)* – [52, 53]
- *Pennycooke (AEVITA) (2017)* – [57]
- *Toyota (James et al.) (2016)* * – [48]
- *Volvo Concept 360c (2018)* – [5]

Infrastructure elements

- *Mahadevan et al. - Prototype 2 (2018)* – [51]
- *Mahadevan et al. - Prototype 4 (2018)* – [51]
- Umbrellium (2017) – [82]

Mobile devices

- Cohda Wireless/Telstra (2017) – [69]
- GM (Grimm et al.) (2011)* * – [43]
- Honda Motor Company (2016) – [61]
- *Mahadevan et al. - Prototype 3 (2018)* – [51]
- *Mahadevan et al. - Prototype 4 (2018)* – [51]

Fig. 13. A summary of the recurring design patterns used in the eHMI concepts we coded. The concepts in bold typeface are composite solutions that use multiple design patterns – they appear in two or more blocks. Patents are marked with an asterisk (*).

wait an undesirably long time to find a window to cross. One potential solution is to explore whether an eHMI that offers the possibility of showing the mental state (of urgency or acknowledgment) of the AV occupant may be better at negotiating traffic interactions that have a social component. However, this also has implications in terms of the privacy of the vehicle occupant, and questions arise how ethical and privacy concerns must be tackled if eHMIs are to handle this aspect of interaction.

We have also noted that the description of existing eHMI-concepts is mainly focused on physical interface elements (e.g., color, placement, number of messages). However, behavioral dynamics, or functional elements, of such interfaces are commonly unspecified and unexplored. For instance, no concept in our analysis specify what triggers transition from one eHMI-signal to another, or what is the timing of an eHMI-signal as compared to visible change in vehicle speed or traffic situation. A critical next step in eHMI design should be to derive and evaluate such characteristics. Related to this, we have also noted that designers of eHMI are commonly focusing on improving "safety" and "user experience". However, effects of eHMI on efficiency are not addressed yet. Given the fact that safety, efficiency and user experience often require a trade-off, this is an urgent future research topic.

Yet another area that has seen little attention is the design of eHMI that adapts its communication strategy based on its time-to-arrival or distance from a pedestrian and its own stopping point (taxonomy item 3.13). Recent research has shown that pedestrians tend to focus on different parts of an approaching vehicle, likely in an attempt to seek different kinds of information as its distance/time-to-arrival changes (Dey et al., 2019c). This may have implications in eHMI design from a user-centered design perspective: an effective eHMI should present the right information at the right place and time to reduce cognitive load on other road users. In our analysis, we found that only for 3 of 70 concepts, the nature of the communication changed with the distance or time gap (Concept 6 from Li et al. (n.d.); Dey et al. (2018); Cohda Wireless (2017)). This shows that this is a potential research and design direction that is currently rather unexplored, and needs more attention.

4.3. Taxonomy and coding challenges

One repeated observation was that while propositions of new concepts were relatively easy to come across, information on their efficacy and validity based on empirical studies were not available. Many concepts exist only as visualizations or low- to medium-fidelity prototypes without any further proof of their viability in actual road user interactions. This sometimes caused a difficulty in getting a holistic overview of the different functionalities and features of a concept being coded.

One of the major challenges in coding of the concepts according to the taxonomy is the fact that several dimensions of the eHMI according to the taxonomy had to be subjected to coder interpretation. Despite executing consensus coding, we cannot guarantee that the coded classifications were entirely in alignment with the vision of the developer(s) of the concept(s). For example, contrary to the physical attributes of the eHMI which are relatively simple to observe and report, many of the functional dimensions of the taxonomy such as communication strategy, resolution, and scalability (Sections 3.10, 3.11, and 3.12) require thought and interpretation as such details are commonly not specified by the designers and authors: these are interrelated dimensions for which strict boundaries between various coding levels are dependent on the context and interpretation. However, this brings into attention the need for proper descriptions of detailed functionalities and use cases catered by the concept, and highlights the current lack of well-furnished descriptions. An ideal concept is one which answers each dimension of the taxonomy with clarity and can be coded by this schema without any need for coder interpretation. Here, the taxonomy helps future researchers to describe their eHMI concepts in a standardized and comprehensive manner.

We also highlight that the taxonomy proposed in this paper is not exhaustive. As the domain of AV-ORU interaction research matures and new considerations come into light, this taxonomy can be extended and adapted to meet the needs of the community. In its current form, our taxonomy may be treated as a tool and starting point for discussing eHMI design

alternatives and asking research and design questions in defining the requirements for an effective eHMI to facilitate AV-ORU interaction.

In coding the existing concepts of eHMI, our goal was to include as many unique concepts of eHMI that we can find. However, a challenge in meeting this goal was in being exhaustive, and also in making the decision of which concepts to include, and which to exclude, and how 'unique' was defined. In this nascent field, eHMI concepts are being proposed at a very high rate. As mentioned earlier, one of the difficulties is the incomplete nature of the descriptions of many of these concepts as highlighted earlier. The other difficulty lies in identifying whether a concept is a new one given the small, incremental modifications to eHMI concepts. Thus, we used our best judgment to exclude any concepts that were minor modifications of an existing concept. An example is the 'Smiling car' eHMI proposed by Semcon (2016). While this car concept proposed by Semcon was the first concept of this type, it was shown as a proof of concept without detailed description or evaluation. Subsequently, this concept was evaluated in two papers (Deb et al., 2018; de Clercq et al., n.d.) and although this concept appeared in multiple sources, they were not counted as multiple concepts. Similarly, concepts that were reused later than their original publication to be evaluated (sometimes by other authors) were not considered as independent, individual concepts. However, this leads to a nuanced challenge – eHMI concepts can change based on very subtle and specific elements. A light-bar eHMI on a bumper of the vehicle may be considered different from a light bar element on the windshield of a vehicle, even though both these eHMIs share the same general form factor. Continuing with the example of a light bar eHMI, a light bar mounted on the windshield of a truck may have completely different interaction effects than one on the windshield of a car due to the difference in the height of placement owing to the size difference of the vehicles. Thus, we cannot claim that we were able to exhaustively code all eHMI concepts that currently exist. However, this does not detract from the contribution of this work in terms of the taxonomy which may be used as a framework for defining requirements for future eHMI designs, and coding them as they are published or demonstrated.

4.4. Implications of eHMI design choices

In the course of coding the concepts, our analyses and examinations revealed some potentially significant implications of particular design choices and trends we observed in eHMIs. Several concepts that show attractive solutions such as projections of zebra crossings on the road need concrete evaluations whether such communications are effectively able to facilitate interactions in edge use cases such as inclement weather or broad daylight. It may be conjectured that such communication in a bright environment, or a road with mud, water, or snow may not be equivalent to communication with a clear projection on a pavement on low-light conditions in a clear day. Furthermore, most of the evaluations that have been done on a small subset of the concepts we analyzed pertained to mostly controlled, laboratory experiments. Such studies were conducted often via virtual reality or video, with a limited sample size and target demographic (e.g., specific age range, university students, etc.), specific road conditions (e.g., clear road, no mud or snow), specific traffic scenarios (mostly one person interacting with one vehicle at a time instead of complex traffic situations), and specific lighting and weather conditions (clear weather, typically either in daytime or dusk conditions). More information is needed if generalizable conclusions regarding the efficacy of the concepts with different kinds of road users and under different conditions are desired.

Another point of concern arises from the interrelated and interdependent dimensions of communication strategy, resolution, and scalability (Sections 3.10, 3.11, and 3.12). An on-vehicle eHMI that adopts a communication strategy of non-targeted broadcasting typically leads to a highly scalable design as it is able to communicate the same message to every road user in the environment without needing to personalize it for a specific recipient. Contrarily, while a targeted communication is able to achieve higher resolution of communication by clarifying its recipient, scalability suffers as such high resolution is not usually achievable for a large number of people. While an ideal eHMI is one which is able to offer a high-

resolution communication and scale infinitely, practical limits prohibit this for most concepts that are centered on the vehicle. In this context, it appears that concepts that rely on smart infrastructure and personal nomadic devices (wearables and phones) are able to achieve both high scalability and resolution of communication. However, given that solutions based on smart infrastructure are complex and require large scale deployment, it is interesting to explore whether communication resolution and scalability for on-vehicle eHMI solutions can be improved.

Similarly, the implications of the number of displays and number of messages handled by a concept (Sections 3.8 and 3.9) are unclear. There is no absolute number of displays or number of messages that can be determined as advantageous or harmful. While multiple displays showing the same message can offer an insight into the level of redundancy, and multiple messages indicate the flexibility of the eHMI concept to handle different situations, simply these figures cannot determine the effectiveness of an eHMI. A high number of displays and messages can also increase the complexity of the system and work against the primary goal of such a system by increasing cognitive load of the road users whom it attempts to address. Thus, more research is needed to determine the optimal level of communication and complexity for an effective eHMI solution.

Finally, attention is needed on the challenges with ethics and privacy in the design and development of eHMIs. This becomes particularly relevant in the context of the message of communication (Section 3.6) employed by an eHMI. An eHMI can communicate in many ways; however, communicating an advice or an instruction to a road user in terms of what a road user should do can have grave consequences in terms of liability. While an automated vehicle has control over its own actions in traffic, it cannot control the actions of other traffic entities in the environment. If a traffic accident is caused by a collision between a vehicle and vulnerable road user who stepped on to cross a road because they were instructed to do so by an automated vehicle, there may arise issues of ethical responsibility. As a result, research and industry best practices have begun to suggest avoiding the use of advice or instructions as a message for eHMIs (International Organization for Standardization (ISO)/TR 23049, 2018; Andersson et al., 2017). Privacy concerns also arise in the case of eHMIs that 'track' road users to identify their positions and give feedback about the vehicle's situational awareness, as well as in situations where an eHMI may show an occupant's state of mind in use cases demanding shared control, as explained earlier. Responsibilities regarding ethics and privacy are critical in a holistic deployment of automated driving technology, and need further research within the context of the design of eHMIs.

5. Conclusion

In this paper, we proposed a taxonomy that can serve as a framework for categorizing existing eHMI concepts. Apart from the physical elements of an eHMI, the taxonomy addressed several functional dimensions grounded in the context of effective communication between automated vehicles and human road users in complex traffic scenarios. We used the taxonomy to classify 70 unique existing eHMI concepts and thereby summarized the current design choices, recurring patterns, and research gaps in this area. We identified several research gaps that may be investigated in the future:

Unexplored interactions Interactions with road users besides pedestrians, and vehicle types besides passenger cars, are rather unexplored.
No clear eHMI placement There is no clear trend on where to place an eHMI, though most are located near the windshield.
Need for universal design Most eHMIs use a single modality and would thus not address road users with special needs, such as people with vision or hearing impairments.

Functional elements of an eHMI, such as encoding of distance and signal transitions, are largely unaddressed.

No communication of passenger context Concepts do not look into communicating the state or intent of the AV's passengers. Knowing

about a passenger's state, such as "relaxed" or "in a hurry", could have an impact on how other road users perceive, assess, or accept the actions of an AV.

Communication ambiguities Most concepts apply a communication strategy where information is communicated to everyone around and, therefore, risk misunderstandings if this communication is not limited to an AV's intention, and more than one other road user is around.

Which states to communicate? The communicated states of an AV vary largely between the concepts. It will be important to find a consensus on which states need to be communicated to have a common "language" instead of confusing road users with specific states per brand.

Strive for balanced information The diverging number of displays and messages between the concepts show that future research may investigate how to find a good balance between confusing or overloading road users with too much information and needed redundancy in modalities and messages to ensure their safety.

Technology readiness With regard to a potential realization of a concept, most eHMIs were designed for currently available technologies and vehicle designs.

Efficacy of colors & regulation The majority of light-based emissive eHMIs seem to not be in line with current regulations. Continued research is necessary to investigate the efficacy of specific colors and whether regulations need to be adjusted.

Investigate more diverse traffic scenarios Most concepts have not been tested for various traffic scenarios, with diverse user groups, under various ambient or weather conditions. It is thus crucial to conduct user studies with more holistic approach under more realistic conditions.

Cater for efficiency Designers of eHMIs are commonly focusing on improving "safety" and "user experience", while relationship to efficiency is largely unaddressed.

This taxonomy covers the design aspects of current eHMI concepts. It may need to be refined as the field evolves and new ideas are developed. The goal of our taxonomy is to introduce an inventory of critical design and functional questions regarding eHMI concepts. This allows researchers and designers to use the taxonomy as tool in the design process to explore and discuss design alternatives. In addition, it offers a standardized narrative in describing future eHMI solutions. Overall, this work benefits researchers and practitioners alike as it not only shows current research gaps but also provides a methodical guide to check if all aspects of an eHMI were considered in the development, evaluated in the studies, and reported in publications for others to replicate or build on.

Appendix A. Coded results

The results of the coding of the 70 concepts are shown in Tables A.1 through A.3. The results are displayed in abbreviations to save space. The legend of the abbreviations used are elaborated below:

#1 *Target Road User*: Pedestrians (P), Bicyclists (B), Manually-Operated Vehicles (MOV), or Other road users (O).

#2 *Vehicle Type*: Passenger cars (P), Shuttle buses or vans (S), Heavy vehicles: e.g. trucks and full-size buses (H), Delivery robots (R), Experimental vehicles (E), and Other (O).

#3 *Modality of communication*: Visual Anthropomorphic (VH), Visual Text (VT), Visual Symbols (VS), Visual Abstract (VA), Visual Unspecified (VU), Auditory Speech (AS), Auditory Abstract/Other (AO), Auditory Unspecified (AU), Haptic (H), Body Language (B), Other (O).

#4 *Colors for visual eHMIs*: Black (BK), Blue (BU), Cyan (CY), Green (GR), Red (RD), Purple/Violet (VT), White (WT), Yellow/Amber (YL), Unspecified (U).

#5 *Covered states*: Driving mode status (AD), Cruising/Not yielding (C), Yielding (Y), Slowing down (S), At rest (R), Beginning to Drive (B), In platoon (P), Other (O).

#6 *Message of Communication in Right-of-Way Negotiation*: Intention announcement (I), Current action – behavioral dynamic (C), Advice/Instruction (A), Time-to-cross (T), Situational awareness (S), Vehicle position/path/trajectory (P), Danger/safety zone (Z), Warning (W), Other (O).

#7 *HMI Placement*: On vehicle - windshield (VW), On vehicle - Grill (VG), On vehicle - Bumper (VB), On vehicle - sides (VS), On vehicle - rear (VR), On vehicle - all around (VA), On vehicle - Hood (VH), On vehicle - Top of roof (VT), On vehicle - unspecified (VU), On vehicle - outside rear view mirrors (VM), On VRU (VRU), Projection on road - in front of vehicle (PF), Projection on road - on the sides(s) of the vehicle (PS), Projection on road - on the rear of the vehicle (PR), Projection on road - exact location unspecified (PU), on Infrastructure (I).

#8 *Number of displays*: Numeral representing the number of displays, '?' for unclear.

#9 *Number of messages*: Numeral representing the number of displays, '?' for unclear.

#10 *Communication strategy*: Unclear Unicast (UU), Clear Unicast (CU), Broadcast (B), Unclear Multicast (UM), Clear Multicast (CM).

#11 *Communication resolution*: Low (L), Medium (M), High (H).

#12 *Multiple road user addressing capability*: Single (S), Limited multiple (L), Unlimited multiple (U).

#13 *Communication dependence on distance/time gap*: Yes (Y), No (N).

#14 *Complexity to implement*: C1, C2, C3, C4.

#15 *Dependence on new vehicle design*: Yes (Y), No (N).

#16 *Ability to communicate vehicle occupant state/shared control*: Yes (Y), No (N).

#17 *Support for people with special needs*: Yes (Y), No (N).

#18 *Evaluation of concept*: Yes (Y), Unspecified (U).

Table A.1
Coded concepts #1 - #27.

#	Concept	Pub type	Loc	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18
1	Applied invention LLC (Hillis et al., 2016)	Patent	US	P	P	VS	U	Y	I, P, Z	VW, PF	2	?	B	M	U	N	C2	N	N	Y	U
2	Audi (Tomitsch and Ellison, 2016)	Industry concept	US	P	P	VA	WT	Y	I	VW	1	?	B	L	U	?	C1	N	?	?	U
3	Benderius et al. (2018)	Paper	SE	P, B, O	P, H	VA	WT, YL, RD	S	I, S, P, W	VG, VB	1	?	B	M	U	N	C1	N	N	N	U
4	Bernstein et al. - Blink (2017)	Informal concept	UK	P	U	VA	GR, WT	?	S	VU	?	?	?	N/A	L	N	C1	N	?	?	U
5	BMW (Vegt et al., 2016)	Patent	US	O	P	AO	N/A	Y	?	VU	?	?	B	L	U	N	C1	N	N	N	U
6	BMW Vision Next 100 Years (2016) (BMW, n.d.)	Industry concept	DE	P	P	VA	WT, GR	AD, Y	I	VW	1	2	B	L	U	N	C1	Y	N	?	U
7	Böckle et al. (2017)	Paper	SE	P	S	VA, AO	BL, YL	C, R, Y, B	I	VA	2	5	B	M	U	N	C1	Y	N	P	Y
8	Chang et al. (2017)	Paper	JP	P	P	VH	BU	C, Y	I	VL	1	2	UU	L	S	N	C2	N	N	N	Y
9	Clamann - Advisory eHMI (2017) (Clamann, 2017)	Paper	US	P	S	VS	WT	C, Y	A	VG	1	2	B	L	U	N	C1	N	N	N	Y
10	Clamann - Information eHMI (2017) (Clamann, 2017)	Paper	US	P	S	VS	WT	C	C	VG	1	1	B	L	U	N	C1	N	N	N	Y
11	Cohda Wireless/Telstra (2017) (Cohda Wireless, 2017)	Industry concept	AU	P, B	P	VU, AU, H	N/A	N/A	W	VRU	3	1	CM	H	U	Y	C3	N	N	Y	U
12	Daimler AG - Smart Vision EQ fortwo (2017) (Daimler, 2017)	Industry concept	DE	P	P	VH, VT, VS	CY	C, Y, B	A	VL, VG	2	?	B	M	U	N	C2	Y	?	N	U
13	Daimler AG - Mercedes-Benz F015 Concept (2015) (Daimler, 2015)	Industry concept	DE	P, MOV	P	VT, VS, VA, AS	RD, BU, GR	C, Y	I, A, W	VL, VG, VB, VR, PF	4	3	B	H	L	N	C2	Y	N	P	U
14	Denso (Tamatsu et al., 2014)	Patent	US	P	P	VS	GR, RD, YL	N/A	I, A, W	PF	1	3	CU	H	L	N	C2	N	N	N	U
15	Dey et al. - Concept 1 (2018) (Dey et al., 2018)	Paper	NL	P, B	P	VA	CY	C, Y, B	I	VB	1	3	B	L	U	N	C1	N	N	N	U
16	Dey et al. - Concept 2 (2018) (Dey et al., 2018)	Paper	NL	P, B	P	VA	CY, GR, RD	C, Y	I, S	VA	1	3	UM	M	L	N	C1	N	N	N	U
17	Dey et al. - Concept 3 (2018) (Dey et al., 2018)	Paper	NL	P, B	P	VA	CY	C, R, Y, B	I	VH	1	4	B	L	U	N	C2	N	N	N	U
18	Dey et al. - Concept 4 (2018) (Dey et al., 2018)	Paper	NL	P, B	P	VA	CY	C, S, R, B	I, T	VH	1	4	B	L	U	N	C1	N	N	N	U
19	Dey et al. - Concept 5 (2018) (Dey et al., 2018)	Paper	NL	P, B	P	B	N/A	Y, B	I	VH	1	2	B	L	U	N	C2	N	N	N	U
20	Dey et al. - Concept 6 (2018) (Dey et al., 2018)	Paper	NL	P, B	P	VA	CY	C, R, Y, B	I, T	VW, VB	2	5	B	M	U	Y	C4	N	N	N	U
21	Drive.ai (2016)	Industry concept	US	P	P, S	VT, VS, VA, AO, B	BU	C, Y	A	VT	2	2	B	M	U	N	C1	N	N	?	U
22	Drive.ai (2018)	Industry concept	US	P, B, MOV	S	VT, VS	RD, YL, GR, BU	AD, C, S, R, Y, B	I, A	VH, VS, VR	4	20	B	M	U	N	C1	N	N	N	U
23	Florentine et al. (2016)	Paper	US	P	P	VA, AO	RD, BU	?	S	VA	2	?	UM	M	L	N	C1	N	N	P	U
24	Ford/VTTI (2017) (Ford Motor Corporation, 2017)	Industry concept	US	P, B	S	VA	WT	AD, C, Y, B	I	VW	1	3	B	L	U	N	C1	N	N	N	Y
25	GM (Grimm et al., 2009)	Patent	US	P, B	P	VA, AS, AO, H	U	N/A	P	VRU	3	1	CM	H	U	N	C3	N	N	Y	U
26	Google (Urmson et al., 2015)	Patent	US	P	P	VH, VT, VS, AU	U	C, Y	C, A	VH, VS	?	?	B	M	U	N	C1	N	N	P	U
27	Graziano (2014)	Informal concept	IT	P	P	VA	BU	?	S	VA	1	1	UM	M	L	N	C1	Y	N	N	U

Table A.2
Coded concepts #28 - #51.

#	Concept	Pub type	Loc	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18
28	Habibovic et al. (2019)	Paper	SE	MOV	H	VA	WT	P	I	VA	1	2	B	L	U	N	C1	N	N	N	U
29	Habibovic et al. - AVIP (without resting - car) (2018) (Habibovic et al., n.d.)	Paper	SE	P	P	VA	WT	AD, Y, B	I	VW	1	3	B	L	U	N	C1	N	N	P	Y
30	Habibovic et al. - AVIP (with resting - car) (2018) (Habibovic et al., n.d.)	Paper	SE	P	P	VA	WT	AD, Y, B, R	I	VW	1	3	B	L	U	N	C1	N	N	N	Y
31	Habibovic et al. - AVIP (truck) (2017) (Habibovic et al., 2017a)	Paper	SE	P, MOV	H	VA	WT	AD, Y, B	I	VG	1	3	B	L	U	N	C1	N	N	N	Y
32	Habibovic et al. - Concept 1 (2016) (Habibovic and Klingegård, 2016)	Informal concept	SE	O	P	VA, AO	WT	S, R, B	I	VW	1	3	B	L	U	N	C1	N	N	P	U
33	Habibovic et al. - Concept 2 (2016) (Habibovic and Klingegård, 2016)	Informal concept	SE	O	P	VA, AO	WT	S, R, B	I	PF	1	3	B	L	U	N	C1	N	N	P	U

Table A.2 (continued)

#	Concept	Pub type	Loc	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18
34	Haiyin - V2P communication - (ND) (Haiyin, n.d.)	Informal concept	?	P	P	VT, VS	CY, RD	C, Y	A	VG, VB	2	2	B	M	U	N	C1	Y	N	?	U
35	Honda Motor Company (2016) (Strickland et al., 2016)	Patent	US	P	P	VT, AO	N/A	N/A	W	VRU	1	2	CM	H	U	N	C3	N	N	Y	U
36	Jaguar Land Rover - Virtual Eyes Concept (2018) (Jaguar Land Rover, 2018)	Industry concept	UK	P	P	VH, VA	GR, RD	C, Y	I, S	VW, VB	2	3	UU, B	M	U	N	C2	Y	N	N	U
37	Jaguar Land Rover - Projection on Road concept (2019) (Jaguar Land Rover, 2019)	Industry concept	UK	P	P	VA	WT, BU	C, Y	P	VB, PF	2	2	B	M	U	N	C2	Y	N	N	U
38	Lagstrom/Lundgren (2015) (Lagström and Lundgren, 2015)	Paper	SE	P	P	VA	WT	AD, R, Y, B	I	VW	1	4	B	L	U	N	C1	N	N	N	Y
39	Li et al. (2018) (Li et al., n.d.)	Paper	CA	P	P	VA	RD, GR, YL, WT	?	W	VW, VG, VS	3	3	CU	M	L	Y	C1	N	N	N	Y
40	Lyft - Autonomous Vehicle Notification System (Matthiesen et al.) (2018) (Matthiesen et al., 2018)	Patent	US	P, B, MOV	P	VT, VS, VU, AU	U	Y	I, A, W	VW, VS	3	?	B	M	L	N	C1	N	N	P	U
41	Mahadevan et al. - Prototype 1 (2018) (Mahadevan et al., 2018a)	Paper	CA	P	P	VA, AS	RD, GR, BU, YL	Y, B	I, S	VW	2	3	B	M	U	N	C1	N	N	P	Y
42	Mahadevan et al. - Prototype 2 (2018) (Mahadevan et al., 2018a)	Paper	CA	P	O	VA, AS	RD, YL, GR	Y	A, S	VU, I	2	5	B	M	U	N	C3	N	N	P	Y
43	Mahadevan et al. - Prototype 3 (2018) (Mahadevan et al., 2018a)	Paper	CA	P	O	VH, H	N/A	Y	I, S	VB, VRU	2	2	UU, CM	H	U	N	C2	N	N	P	Y
44	Mahadevan et al. - Prototype 4 (2018) (Mahadevan et al., 2018a)	Paper	CA	P	P	VH, VA, AS	RD, YL, GR	Y	A, S	VT, VRU, I	3	5	B, CM	H	U	N	C3	N	N	P	Y
45	Matthews et al. (2015, 2017) (Matthews and Chowdhary, 2015; Matthews et al., 2017)	Paper	US	P	P	VT, VA, AU	BU	Y	A	VT, VW	3	?	B	M	U	N	C1	N	N	?	Y
46	Mercedes Cooperative Car - AD (2018) (Faas, 2018)	Industry concept	DE	P	P	VA	CY	AD	None	VT	1	2	B	L	U	N	C1	N	N	N	U
47	Mercedes Cooperative Car - AD + intention on windshield (2018) (Faas, 2018)	Industry concept	DE	P	P	VA	CY	AD, Y	I	VT, VW	2	3	B	L	U	N	C1	N	N	?	U
48	Mercedes Cooperative Car - AD + situation awareness (2018) (Faas, 2018)	Industry concept	DE	P	P	VA	CY	AD	S	VT	1	3	B, UM	M	L	N	C1	N	N	?	U
49	Mercedes Cooperative Car - AD + Situation awareness + intention on windshield (2018) (Faas, 2018)	Industry concept	DE	P	P	VA	CY	AD, Y	I, S	VT, VW	2	4	B, UM	M	L	N	C1	N	N	?	U
50	Mercedes Cooperative Car - AD + Situation awareness + intention on windshield + headlights/ORVM (2018) (Faas, 2018)	Industry concept	DE	P	P	VA	CY	AD, Y	I, S	VT, VW, VL, VM	4	?	B, UM	M	L	N	C1	N	N	?	U
51	Mitsubishi Motor Company (2015) (Mitsubishi Electric Corporation, 2015)	Industry concept	JP	P, MOV	S	VA	WT, RD, GR	N/A	P	PF, PS, PR	3	1	B	L	U	N	C2	Y	N	?	U

Table A.3
Coded concepts #52 - #70.

#	Concept	Pub type	Loc	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18
52	Mitsubishi Motor Company (2017) (Mitsubishi Electric Corporation, 2017)	Industry concept	JP	P, MOV	S	VS, VA	WT, YL	N/A	P, W	VW, PS, PR	3	2	B	M	U	N	C2	N	N	?	U
53	Mitsubishi Motor Company (2018)	Industry concept	JP	P, MOV	P	VS, VA	WT	?	P, W	VR, PU	?	?	B	M	U	N	C2	N	N	?	U
54	Nissan IDS Concept (2015) (Nissan Motor Corporation, 2015)	Industry concept	JP	P, B	P	VT, VA	CY	Y	I, S	VW, VA	2	3	B, UM	M	L	N	C1	Y	N	?	U
55	Pennycooke - AEVITA (2012) (Pennycooke, 2010)	Paper	US	P	E	VH, AS, B	BU	C, Y	I, A, S	VL, VU	2	?	UU	H	S	N	C2	Y	N	P	U
56	Rinspeed Oasis (2016) (Rinspeed, 2017)	Industry concept	CH	P	P	VT	RD	Y	I, A	PF	1	?	B	M	U	N	C2	Y	N	?	U
57	Rothmuller et al. - eHMI 1 (2018) (Rothmüller et al., 2018)	Paper	DE	P	P	VS, VA	GR	?	A	VW	1	2	B	M	U	N	C1	N	N	N	Y
58	Rothmuller et al. - eHMI 2 (2018) (Rothmüller et al., 2018)	Paper	DE	P	P	VA	CY, GR	?	S	VA	1	1	UM	L	L	N	C1	N	N	N	Y
59	Semcon Smiling Car (2016) (Semcon, 2016)	Industry concept	SE	P	P	VH	WT	C, Y	I	VG	1	2	B	L	U	N	C1	N	N	N	U
60	Sjoerdsma et al. (2017)	Informal	NL	U	P	VA	GR, RD,	Y	I, S,	VA	1	3	UM	M	L	N	C1	N	N	?	U

Table A.3 (*continued*)

#	Concept	Pub type	Loc	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18
	(Sjoerdsma and Bohnen, 2016)	concept					BU		W												
61	Song et al. (Go) (2018) (Song et al., 2018)	Paper	DE	P	P	VT, VS	BU, WT, BK	Y	A	VG	1	1	B	M	U	N	C1	N	N	N	Y
62	Song et al. (OK) (2018) (Song et al., 2018)	Paper	DE	P	P	VT, VS	BU, WT, BK	Y	A	VG	1	1	B	L	U	N	C1	N	N	N	Y
63	Strauss - Wave Concept (2018) (Strauss, 2018)	Informal concept	US	P	P	VS, VA	D, GR	C, Y	A, P	PF	1	3	B	M	U	N	C2	N	N	N	U
64	Teague Labs (2017)	Industry concept	US	P	S	VS, VA	GR, YL, RD, CY	AD, C, Y, B	I, A	VT, VB, VS	3	7	B	M	U	N	C1	Y	N	N	U
65	Toyota (James and Prokhorov, 2016)	Patent	US	P, B, MOV	P	VH, VT, VS, AU	U	Y	A, P	VT, VH, VS, VR, PF	?	?	B	M	U	N	C2	N	N	?	U
66	Toyota Concept-i (2018) (Toyota Motor Corporation, 2018)	Industry concept	JP	P	P	VT	VT, CY	AD	I	VH, VR	2	?	B	L	U	N	C1	Y	N	?	U
67	Uber - Intention Signaling for an Autonomous Vehicle (Ross and Liu, 2017)	Patent	US	O	P	VH, VT, VS, VA, AU	U	Y, B	I, A	VT, VW, VH, VB, VS, PF	?	?	B	M	U	N	C2	N	N	P	U
68	Umbrellium (2017)	Informal concept	UK	P, B	N/A	VS	N/A	N/A	A	I	?	?	B	H	U	N	C3	N	N	N	U
69	Volvo Concept 360c (2018) (Volvo Cars, 2018)	Industry concept	SE	P, B, MOV	P	VA, AO	CY, YL	AD, S, B	I, S, P, W	VA	2	?	B, UM	M	L	N	C1	Y	N	P	U
70	Zhang et al., (2018)	Paper	US	P, O	P	VA	BU, GR, RD	AD, S, R, B	I	VB, VS	1	5	B	L	U	N	C1	N	N	N	Y

Appendix B. Coding example

In this section, we show with how we used the taxonomy to analyze and code two eHMI concepts. For this example, we use Concept 1 and Concept 2 of (Dey et al., 2018). This can be used as a guide or an example for how to use the taxonomy towards classifying future concepts.

#1 Target Road User: The paper explicitly mentions Pedestrians (P) and Bicyclists (B) as the target road users that the authors focused on while developing the concepts, hence this field is coded accordingly.

#2 Vehicle Type: Both concepts are demonstrated explicitly using a Passenger car (P), and are coded thus. Although the concepts may be extended to other vehicle typed, this extrapolation is not carried out by the coders. The efficacy of the concept on other vehicle forms are left to future design and evaluation.

#3 Modality of communication: Both concepts communicate using visual expressions using abstract communication using a light band. They are therefore both categorized under 'Visual abstract (VA)'.

#4 Colors for visual eHMIs: The paper explicitly talks about using the color cyan for the default eHMI colors. Concept 1 uses only cyan as the default color, and is therefore coded as such (CY). Concept 2, in addition to cyan, also used Green and Red, and is therefore coded as (CY, GR, and RD). Based on this, Concept 1 is in compliance with regulations, while Concept 2 is not.

#5 Covered states: Concept 1 describes 3 independent states explicitly, cruising in automated mode (C), yielding (Y), and beginning to drive (B). The paper mentions that the car continues to show its yielding intention when the car is at rest, and the message does not change when the car is at rest, thus 'at rest' is not coded as a separate state for this concept. For concept 2, the authors explicitly mention the eHMI's states when the car is cruising (C), and yielding (Y). No distinct communication is mentioned for any other states, and thus the coding stops here.

#6 Message of Communication in Right-of-Way Negotiation: In concept 1, the eHMI changes its state to show the vehicle's yielding intention (I), and no other forms of communication is executed. In concept 2, when the vehicle yields, the eHMI changes state to show the road users that the vehicle has detected in its environment. This is representative of a display of the vehicle's Situational Awareness (S). In addition, for each detected road user, the corresponding light element either in green or red contingent upon the vehicle's intention to yield to them or not. Thus, the vehicle also provides information regarding its intention (I).

#7 HMI Placement: For concept 1, the eHMI is a light band mounted on the bumper of the vehicle, only in the front. It is therefore categorized as 'On vehicle - Bumper' (VB). For concept 2, the eHMI is a light band that is on the vehicle, all around covering each side of the car. It is this coded as On vehicle - all around (VA).

#8 Number of displays: According to the definition of a 'display', the number of communication device the eHMI in concept 1 contains is the light band on the bumper; hence the number of displays is 1. Similarly, for concept 2, the eHMI is the light band all around the vehicle, and hence the number of displays for concept 2 is 1 as well. Although in concept 2, the expansive light band that wraps around the entire car can display multiple communication elements, each pertaining to a different road user, there is only one display that shows the relevant communication message to one road user.

#9 Number of messages: For concept 1, for each of the 3 states covered, the eHMI is able to show a unique message (the light band shows a different message depending on whether the vehicle is cruising, yielding, or beginning to drive again). As a result, the number of messages for concept 1 is 3. For concept 2, the eHMI is capable of showing whether the vehicle is cruising without recognizing any road user, and whether it has perceived the presence of road users around it. However, when it recognizes other road users, it is able to further show with different messages whether it intends to yield to them or not. Thus there are 3 messages that the eHMI is capable of showing ("I am cruising and I do not perceive anyone around me", "I perceive someone and I am yielding to them", and "I perceive someone and I am not yielding to them").

#10 Communication strategy: In concept 1, the eHMI simply shows its messages to the world and does not specifically address any particular road user. Following the flowchart: the message of the eHMI is meant for more than a single road user, but for multiple (co-located) road users, the message is not different (i.e. the eHMI does not distinguish its message for different road users). This, this communication is categorized as a 'Broadcast' (B). For concept 2, once again, the communication is meant for multiple road users. However, in this case, the message may be different for different road users (the eHMI is able

to distinguish its message for different road users). However, for co-located road users, who is specifically being addressed may not be clear. This is thus coded as 'Unclear Multicast' (UM).

#11 *Communication resolution*: For concept 1, the communication is broadcast for any road user in the vicinity to see. However, it is not clarified whom in particular the message is meant for, and the road user must interpret what the message means for them. Therefore, the resolution of this concept is coded as Low (L). In contrast, concept 2, the eHMI not only specifies the vehicle's situation awareness, but also furnishes further information regarding the vehicle's intention to yield (or not) for each of the detected road user. However, despite this additional information, the clarity of the information regarding whom the eHMI is addressing is still ambiguous (e.g. for multiple people sharing the same location who may have different intentions in traffic as in Fig. 3.10, it is not clear whom specifically the eHMI is attempting to address). This leads this aspect of this eHMI to be coded as Medium (M) instead of High.

#12 *Multiple road user addressing capability*: Concept 1 simply broadcasts it message for any road user in its vicinity to see, and does not attempt to individually address multiple road users. As a result, it is able to cater to an unlimited number of road users (U). In contrast, concept 2 specifically addresses multiple road users. However, due to limitations of the form factor of the eHMI (the light band around the vehicle), as the number of road users around the vehicle increases, a limit is reached beyond which the eHMI cannot effectively communicate by addressing specific road user and communicating to them. Thus, concept 2 is coded as eHMI having a Limited multiple (L) road user addressing capability.

#13 *Communication dependence on distance/time gap*: For both concepts 1 and 2, the aspect of distance or the time-to-arrival of the vehicle from the road users do not play a role in the communication process. Thus, this dimension is coded as a 'No' (N) for both concepts.

#14 *Complexity to implement*: For both concepts 1 and 2, the eHMI can be developed by adding already-available technology to the car. The interfaces of both concepts use light bands, which are commonly available, and both concepts are therefore coded as C1.

#15 *Dependence on new vehicle design*: Neither of the concepts were demonstrated on a special vehicle design and are able to be implemented on current vehicle form factors; hence this element is coded as 'No' (N) for both concepts.

#16 *Ability to communicate vehicle occupant state/shared control*: Neither concept accounts for expression of shared control or communication from the occupant(s) of the vehicle, and thus both concepts are coded as 'No' (N).

#17 *Support for people with special needs*: Neither concept implements a multimodal eHMI and only focus on visual, light-based communication. Thus, the concepts are not suitable for communication with visually-impaired pedestrians (N).

#18 *Evaluation of concept*: Information regarding whether these concepts have been evaluated is not available, and is thus coded as 'Unspecified' (U).

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