A Design Space for External Communication of Autonomous Vehicles

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ABSTRACT

Autonomous vehicles are on the verge of entering the mass market. Communication between these vehicles with vulnerable road users could increase safety and ease their introduction by helping to understand the vehicle's intention. Numerous communication modalities and messages were proposed and evaluated. However, these explorations do not account for the factors described in communication theory. Therefore, we propose a two-part design space consisting of a **concept part** with **3** dimensions and a **situation part** with **6** dimensions based on a literature review on communication theory and a focus group with experts (*N*=4) on communication. We found that most work until now does not address situation-specific aspects of such communication.

CCS CONCEPTS

• **Human-centered computing → Interaction design theory, concepts and paradigms**.

KEYWORDS

Autonomous vehicles; self-driving vehicles; external communication; design space.

ACM Reference Format:

Mark Colley and Enrico Rukzio. 2020. A Design Space for External Communication of Autonomous Vehicles. In *12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '20), September 21–22, 2020, Virtual Event, DC, USA.* ACM, New York, NY, USA, 11 pages. https://doi.org/10.1145/3409120.3410646

1 INTRODUCTION

Interaction between pedestrians and vehicles will change with the introduction of autonomous vehicles (AVs) [44]. With no human driver present, interpersonal communication for situations, in which people use gestures or eye-contact [93] could, therefore, be challenging. Technologies such as displays [47], LED strips [47], or projections [5] were evaluated to overcome these communication challenges to vulnerable road users (VRUs). Various aspects of external concepts of AVs have been investigated and used for classification: Colley et al. [31] focused on the used modality in the concepts finding that visual concepts were most prevalent. Concepts from industry were analyzed by Bazilinskyy et al. [11] with a focus on visual features such as color and perspective. Such technology could also be used for a variety of other use cases such as displaying advertisement [27].

Researchers struggle with whether or when such communication is necessary [85] and which modality and technology to use given the numerous aforementioned opportunities. Therefore, various taxonomies were introduced, each focusing on specific aspect(s) [28, 73, 77]. Due to their limited scope, they do not consider important aspects of communication theory such as noise [38].

To fill this gap, we present a design space for such external communication of AVs based on research on communication theories of Berlo [15] and DeVito [38] as well as a focus group with experts on psychological aspects of autonomous driving (*N*=4) to inspire and outline research directions. The two-part design space consists of **9** dimensions split into *concept* (*Message Type*, *Modality*, and *Locus*) and *situation* (*Communication Relationship*, *Communication Partner*, *Number of Lanes*, *Acoustic Noise Level*, *Traffic Autonomy*, and *Weather*; see Section Design Space). Current work was classified and research gaps are named. We found that current external communication concepts mainly are of instructional or advisory nature, answers, e.g., for inquiries of pedestrians such as "Can I cross?" are unexplored.

The specific contributions of our work are: (1) Defining relevant dimensions of communication theory for a design space on external communication of AVs. (2) Conducting a focus group on such a design space. (3) Classifying prior work into the proposed design space and (4) presenting research gaps.

2 METHOD

This work builds on and enhances Colley and Rukzio's design space on external communication of AVs [29].

In this work, a literature survey on communication theory was performed, an expert focus group (*N*=4) on a design space on external communication of AVs was conducted, and a holistic view of this communication is proposed. This includes a construct common in psychology: the separation between a person (or in this case *concept*) and the situation (also called the "person—situation debate" [60, p. 249]). Relevant dimensions of the design space are named and parameters for each dimension are defined. According to the morphological analysis, the relevant parameters are combined in multiple multidimensional matrices, also called "Zwicky Box" [114]. This is an established tool for ideation and design space creation (e.g., [9, 59]). This matrix then contains all possible combinations of parameters relevant to the given problem. By classifying

AutomotiveUI '20, September 21–22, 2020, Virtual Event, DC, USA

ACM ISBN 978-1-4503-8065-2/20/09…$15.00
https://doi.org/10.1145/3409120.3410646

related work, promising approaches and lack of solutions can be identified.

Finally, relevant publications in the field of external communication of AVs were collected and categorized by the first author based on the modality and the message type. Unexplored setups and concepts are discussed, highlighting future research topics.

3 BACKGROUND

This work builds on research in *Design Spaces in HCI*, *Communication Theory*, *Traffic Scenarios*, and *External Communication of AVs*.

3.1 Design Spaces in (Automotive) HCI

In Human-Computer Interaction (HCI) research, taxonomies [48] and design spaces [59] enable the exploration of interaction possibilities. Current and upcoming technologies such as external communication of AVs [77] can be understood and knowledge can be systematized [48]. Card et al. [20] showed the possibility to use morphological analysis [114] to systematically create design spaces in HCI. In the automotive domain in general, design spaces and taxonomies have been widely used for a range of technologies, interactions, and applications. These design spaces vary in their associated user (e.g., driver [68]), technology (e.g., Augmented Reality [110]), area of interest (e.g., windshield [55] or entire vehicle [28]) or application (e.g., in-vehicle information systems [18]). Therefore, creating a design space about external communication of AVs can be the first step to understand current trends and to uncover unknown potential.

3.2 Communication Theory & Models

Communication has been widely studied and its research can be broadly distinguished into intercultural [24], international [107], interpersonal [38], intrapersonal [62], non-verbal [81], mass [80], and organizational [83] communication. Communication theory is a multidisciplinary research field. Three common models are *Linear*, *Interactional*, and *Transactional*. The first linear model was introduced in 1949 [99] with no feedback or response mechanisms. In interactional models, positions as sender and receiver [98] are switched, e.g., in the Sender-Message-Channel-Receiver (SMCR) Model of Communication [15]. This model describes communication with four components: sender, message, channel, and receiver. Additional factors such as social or cultural context can be included [10]. DeVito's interactive model [38] includes the factors context, feedback, and noise. Noise can be divided into four categories: (1) physical or external noise such as startling sounds or background music, (2) physiological noise such as fatigue, hunger, or pain, (3) psychological noise meaning your preconception, bias, assumptions, or stereotypes alter the conversation, and (4) semantic noise caused by using confusing language [97]. Lanham [70] described the constructionist view on communication which assumes that the meaning of a message is not solely dependent on the sender (encoder) but also on the receiver (decoder). This can even be seen as an effect of culture: "communication is a process whereby people in groups, using the tools provided by their culture, create collective representations of reality" [109, p. 32]. For a design space on external communication of AVs, relevant factors of the described theories have to be weighed for their relevance in communication between AVs and VRUs. This was done in the focus group and via discussions amongst the authors.

3.3 Traffic Scenario Definition

The traffic scenario is relevant as we divide the design space into a concept and a situation part. Hogan, however, states that "after 40 years, there is little agreement about how to define situations" [60, p. 249]. Hogan goes on to claim that situations are per definition unique [60]. Despite this uniqueness, there is work suggesting how situations should be defined. Reis [96] proposed to extend Mischel and Shodas Cognitive-Affective Personality System [84] by incorporating an *Encoding Process* as an objective situation is likely to be perceived differently by individuals [96]. Reis highlights the need to define situations with *objective* factors [96].

Several approaches to define traffic scenarios were given in the literature. Especially in categorizing accidents, statisticians define various parameters of crashes such as distance to the vehicle ahead, attention status, alcohol-induced impairment, age, light condition, road type, whether it was holiday season, etc. [6, 17, 45, 46, 54, 100]. These parameters are also adjustable at the Fatality and Injury Reporting System Tool (FIRST) [7].

Füst et al. [51] proposed a taxonomy targeted towards the definition of traffic situations for communication between one AV and one VRU. This taxonomy focuses on the attributes *Right of way, AV's intention regarding the right of way, HRU's (Human road user) intention regarding the right of way, Longitudinal distance (Headway), Lateral distance, Attention HRU, Impairment of the HRU's perception, Speed AV, Speed HRU, Driving direction AV, Perspective* (from the perspective of the AV). This taxonomy is targeted towards "the interaction between **one** AV and **one** HRU" [51, p. 718] omitting issues related to scalability [33, 73], environmental factors such as weather or traffic characteristics such as traffic density or autonomy of vehicles [106].

Kaß et al. [67] propose a standardized procedure for external communication concepts for AVs. While not going into the definition of concepts, their work provides guidance to develop relevant use cases for the evaluation of concepts as well as usability requirements that should be met. For the definition of use cases, they defined relevant and generic situations with the according possible driving maneuvers of AVs. These are intended for VRUs. The VRU approaches the AV frontally, orthogonally, or merges in front of the AV [67]. For the specific situation, Kaß et al. [67] employ the factors and levels of Füst et al. [51].

3.4 Design Spaces and Taxonomies of External Communication of Autonomous Vehicles

Bengler et al. [13] described a high-level view on Human-Machine Interfaces (HMIs) in the automotive domain in which external HMIs are only a subgroup. Another group is, for example, the infotainment HMI. Design spaces for aspects of external communication of AVs have been proposed. Colley et al. [28] show attachment locations for external displays on a vehicle distinguished into dimensions *display areas*, *interaction methods*, and *contextual factors*.

Löcken et al. [73] classified the interaction concepts under investigation into four categories: *visual only*, *visual plus acoustic*, *anthropomorphic*, and concepts including *infrastructure*. They further distinguished each category based on the complexity of the information presented. Mahadevan et al. [77] employed a method called PICTIVE [87] to elicit possibilities for external communication of AVs. They propose a design space with the dimensions *Cue category* (Visual, Auditory, and Physical) and (not explicitly stated) *Locus* of the communication (Vehicle-only, Vehicle and Street, Vehicle and Pedestrian, Mixed). Colley and Rukzio presented the first approach towards a concise design space of external communication of AVs [29]. They distinguish 4 dimensions: *Message Type* (instruction, command, advisory, answer, predictive, historical), *Modality* (auditory, visual, tactile), *Locus* (device, vehicle, infrastructure), and *Communication Participants* (one-to-one, one-to-many, many-to-one, many-to-many). Their preliminary work is based on a literature review on interpersonal communication frameworks.

While the aspects of Colley et al.'s [28] design space are also relevant for external communication of AVs, the focus was narrowed down compared to for example Mahadevan et al.'s [77] or Colley and Rukzio's [29] work. Mahadevan et al.'s work [77] misses a classification of the message type and only includes intent and awareness. Löcken et al. [73] include the dimension complexity but provide no concise design space as their focus was on classifying prior work. Colley and Rukzio [29] do not account for situation relevant dimensions for the external communication of AVs.

4 FOCUS GROUP

To (1) gain a psychological view on external communication of AVs and (2) to discuss prior design spaces of this communication, a *focus group* with experts (*N*=4) of the *psychological* department of Ulm University was conducted by the first author.

4.1 Participants

Participants were on average *M*=26.75 (*SD*=3.59; range: 24 to 32) years old. Three identified as female and one as male. All participants are currently working as research associates or PhD students in the intersecting fields of AVs and psychology for *M*=2.63 years (*SD*=2.29; range: 1 to 6 years). On 7-point Likert scales (*1=strongly disagree*, *7=strongly agree*), participants reported their work to be highly concerned with AVs (*M*=7.00, *SD*=.00) and communication (theory; *M*=5.75, *SD*=1.50) and concerned with taxonomies and classifications (*M*=4.25, *SD*=1.50). On a 5-point Likert scale (*1=strongly disagree*, *5=strongly agree*), participants reported a high interest in AVs (*M*=5.00, *SD*=.00), believed such a system to ease their lives (*M*=4.50, *SD*=.58), and did not believe AVs to become reality by 2030 (10 years from today; *M*=2.50, *SD*=1.00).

4.2 Procedure

At first, participants signed informed consent. The focus group was split into *introduction* and an open *discussion*. During the entire session, audio was recorded. After introducing the organizer, current external communication concepts [14, 26, 75] were presented. Afterwards, the to date proposed design space of Mahadevan et al. [77], the classification of Löcken et al. [73], and the proposed design space of Colley and Rukzio were explained [29], followed by an open *discussion* on a design space for external communication of AVs. Benefits and drawbacks of the current design spaces were discussed. The focus group lasted about 1.0 h, 10 min for the *introduction*, 50 min for the *discussion*. Demographic data was gathered afterwards via an online questionnaire.

4.3 Results

In the following, the results of the focus group are reported. The topics emerged during the open discussion.

Design Space as an Ideation Tool: [P2] explicitly stated that for the ideation of communication situations, such a design space could be useful. [P1], who is working on cooperation in urban situations, also highlighted the common ground for discussing ideas.

Deductive vs. Inductive Approach: The participants argued that both deductive and inductive approaches for creating a design space are valid in their methodology. As most work in the field of external communication of AVs currently takes place in an exploratory manner (e.g., [5, 39, 40, 76, 77]), a different approach was also argued to be beneficial as a different view is taken. [P3], however, was concerned with the deductive approach taken and suggested to employ a *Bottom Up* (Inductive) approach, therefore, identifying relevant scenarios in which to employ external communication of AVs and to individually assess these situations. Despite the discussion about a *Bottom Up* approach, the chosen theories and dimensions were all rated as appropriate.

Communication and Situation: [P4] argued that in communication theory, a common distinction is made between the characteristics of the person (e.g., social context [38]) and the situation (e.g., noise [15, 38]). Therefore, it was argued that a concise design space for external communication of AVs must consist of the actual concept and the situation it is applied to. This falls in line with the discussion about *scalability* of these concepts, as the situation is different when multiple vehicles or pedestrians are present [33, 39, 73, 76, 77, 105]. The dimension *Communication Participants* [29] was argued to be actually a dimension of the situation. The discussion then turned towards relevant dimensions of the situation. While no final set of dimensions was derived, the following dimensions were regarded as relevant: the communication partner (e.g., pedestrian, police officer, (motor-)cyclist, and their social context), the number of communication partners (see *Communication Participants* [29]), traffic characteristics (e.g., purely AVs or mixed traffic; traffic flow; number of lanes; see [94]), and weather characteristics. The distinction between personality and situation is common [41] and is viewed "nearly a truism" [66, p. 1149] in psychology with controversy only in specific applications [74]. Therefore, we decided to distinguish the design space into a *concept* and a *situation* part.

5 DESIGN SPACE

After the (1) literature review and the (2) discussion with experts in the field, we present the two-part design space consisting of the (1) external communication concept and the (2) situation.

5.1 Dimensions and Values for Part 1 — Concept

Relevant dimensions of communication theory were defined for the definition of part 1 of this design space. *Message* and *Channel* are relevant variables for the external communication of AVs [29].

The first concept dimension (CD) **CD1** *Message Type* is based on the *message*. According to Colley and Rukzio [29] and according to the discussion of whether **explicit** communication of AVs is actually needed [85], we distinguish **CD1** *Message Type* into implicit and explicit messages.

Colley and Rukzio [29] built their design space on the message types proposed by Buck [19]. However, we propose to enhance Buck's [19] levels of message type (*Instruction*, *Command*, *Advisory*, *Answer*, *Historical*, and *Predictive*). *Answer*, as the most common message type when using displays [19], provide information to a *Question* such as what speed something is traveling with. Therefore, we argue *Question* to also be a relevant message type. The lack of this message type in [19] can be explained by the focus of Buck on simple displays with no possibility to receive an answer after posing a question. His definition of display was, therefore, quite limited: "Displays are devices, no matter how simple, which are used by the information sender to communicate with human **receiver**" [19, p. 196]. The distinction between *Instruction*, *Command*, and *Advisory* is as follows: instructions guide behaviour, commands are straightforward statements referring to high priority items. Advisory messages are toned down compared to the other two message types, an example is to provide information to be able to plan one's next steps. *Historical* displays provide information on the state of a variable over a period of time. *Predictive* messages allow for the examination of a current value and the likely future value based on assumptions (e.g., projected future accidents) [19].

In marketing research, there is the distinction between conative, affective, and cognitive messages [8]. Affective messages have also been studied especially in the context of babies [102]. These messages do not necessarily carry meaning but are highly important for human communication. This is also resembled by another categorization of message types: Nominal, Expressive ("Emotional") and Predicative, ("Propositional")[1]. Therefore, we argue *affective* messages, i.e., messages related to emotions, to be an important message type.

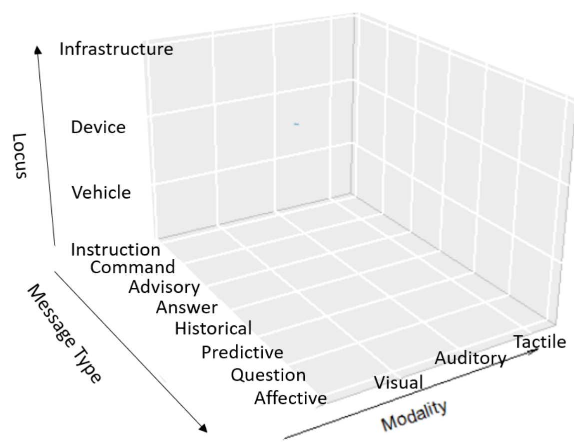
Therefore, **CD1** *Message Type* consists of the levels *Instruction*, *Command*, *Advisory*, *Answer*, *Historical*, *Predictive*, *Question*, and *Affective*.

The second dimension, based on the *channel*, is **CD2** *Modality* with the levels *Auditory*, *Visual*, and *Tactile* (see [29]). The combination of these two dimensions is shown in Figure 1a.

The third dimension **D3** *Locus* is based on the work of Mahadevan et al. [77]: *Vehicle*, *Personal Device*, and *Infrastructure*. All three dimensions combined are shown in Figure 1b. We also refrain from including *technology* as a dimension to avoid excluding future technological advances [29].

			Modality		
			Auditory	Visual	Tactile
Message type	Implicit	Instruction			
		Command			
		Advisory			
		Answer			
		Historical			
		Predictive			
		Question			
		Affective			
	Explicit	Instruction			
		Command			
		Advisory			
		Answer			
		Historical			
		Predictive			
		Question			
		Affective			

(a) All parameter combinations of CD1 and CD2.



(b) Concept design space containing all parameter combinations of CD1 (not split into implicit and explicit), CD2, and CD3.

Figure 1: A Zwicky Box and the design space for the *concept*.

5.2 Dimensions and Values for Part 2 — Situation

Colley and Rukzio [29] proposed a fourth dimension *Communication Participants* based on Löcken et al. [73] and propose the levels *one-to-one*, *one-to-many*, *many-to-one* and *many-to-many* [65, 71]. While we agree that this an important aspect, we argue that the communication participants are actually a property of the situation

[1] https://www.csun.edu/~vcoao0el/de361/de361s41_folder/tsld004.htm, Accessed: 17-FEBRUARY-2020

instead of the communication concept (see Section Focus Group). Rasouli and Tsotsos report **38** factors that influence crossing decisions [94]. Colley et al. [32] already recommended to consider these in external communication research. Including all 38 factors in the design space seems undesirable as the usage would be very difficult. After multiple discussions, we propose the following objective dimensions including factors reported by Rasouli and Tsotsos [94] as well as Füst et al. [51].

We propose to group the dimensions as follows: Situation dimension (SD) **SD1** and **SD2** make up the *communication relevant* part. A further distinction could be drawn with relation to the *age* (e.g., communication towards children [35]) of the human communication participants, but this is omitted to avoid making the design space unusable. However, we included *person with impairment* to provide consideration of the specific needs. **SD3** and **SD4** revolve around *traffic related attributes* and **SD5** and **SD6** are a *vis major*, something the designer cannot or hardly influence. *Time of day* as a factor influencing the crossing decision [94] was excluded. It is hypothesized that audibility or visibility of visual, for example, display communication is, to a higher degree, influenced by fog or rain than by daytime (e.g., day or night).

These grouped dimensions are shown in the matrices obtained by the morphological approach [114] in Figure 2. Highlighted in gray are the combinations that make no sense or are irrelevant (see Section Rationale for Irrelevant Combinations).

- **SD1** *Communication Relationship*: *one-to-one*, *one-to-many*, *many-to-one*, and *many-to-many* (see *Communication Participants* in [29])
- **SD2** *Communication Partner*: *vehicle driver*, *pedestrian*, *person with impairment* (e.g., [30]), *cyclist* [51], *motorcyclist*, *official* (e.g., police officer), *(automated) vehicle* (for communication from VRU towards AV as recommended by Ngueyen et al. [88]),
- **SD3** *Number of Lanes*: *single*, *two-lane*, *three-lane*, *four-lane*, *five-plus-lane*
- **SD4** *Acoustic Noise Level* [33]: < 40 dB(A) (rural area [89]), > 40 and < 70 dB(A), > 70 dB(A) (often louder in big cities [95])
- **SD5** *Traffic Autonomy*: *totally manual*, *mixed* or *totally autonomous*
- **SD6** *Weather*: *air*, *haze*, *fog*, ~~*cloud*~~, *rain*, *snow* (adopted from [79], cloud was removed as it has the same qualities as fog for our use case)

		Communication Partner						
		Vehicle driver	Pedestrian	Cyclist	Motorcyclist	Official	Person with impairment	(automated) vehicle
Communication Relationship	One-to-one							
	One-to-many							
	Many-to-one							
	Many-to-many							

(a) All parameter combinations of SD1 and SD2.

		Communication Partner (from)						
		Vehicle driver	Pedestrian	Cyclist	Motorcyclist	Official	Person with impairment	(automated) vehicle
Communication Partner (towards)	Vehicle driver							
	Pedestrian							
	Cyclist							
	Motorcyclist							
	Official							
	Person with impairment							
	(automated) vehicle							V2X

(b) All parameter combinations of SD2 and itself showing the possibility of communication from and towards AVs.

		Number of Lanes				
		Single	Two-lane	Three-lane	Four-lane	Five-plus-lanes
Noise Level	< 40 dB(A)					
	>40 and <70 dB(A)					
	>70 dB(A)					

(c) All parameter combinations of SD3 and SD4.

		Weather				
		Air	Haze	Fog	Rain	Snow
Traffic Autonomy	Totally manual					
	Mixed					
	Totally Autonomous					

(d) All parameter combinations of SD5 and SD6.

Figure 2: Parameter combinations for some of the combined dimensions.

5.2.1 Rationale for Irrelevant Combinations. Figure 2c shows the matrix resulting of the morphological approach for **SD3** *Number of Lanes* and **SD4** *Acoustic Noise Level*. In a single lane, it is unlikely to have noise levels above 70 dB(A) as this is a noise level in big cities [95]. Accordingly, noise levels below 40 dB(A) are unrealistic on four or more lane roads. Even with electric vehicles, the minimum sound is likely to be above this level as the European Union, for example, requires an Acoustic Vehicle Alerting System (AVAS) [2] with at least 56 dB(A).

AVs will communicate with other AVs and even with infrastructure via wireless technologies [25, 56]. Therefore, no visible, audible, or tactile communication is needed between AVs [67]. As we are interested in a design space for communication with an AV, we excluded all communication combinations between human communication partners.

5.3 Limitations

These dimensions are not exhaustive neither for the concept nor for the situation part. As this design space is intended for ideation, numerous factors of the 38 factors influencing crossing decisions [94] such as *time of day* were excluded. Depending on the research question, these can be included. The taxonomy of Füst et al. [51] could also be applicable. The authors state that "the taxonomy can be used by choosing attributes and value facets that are relevant for a specific research question" [51, p. 708]. While we acknowledge the importance of these factors, all of our proposed dimensions are not accounted for (e.g., scalability attributes such as *number of lanes* and *noise* [33]) as the authors themselves state that the taxonomy is targeted towards "the interaction between **one** AV and **one** HRU" [51, p. 718].

6 CLASSIFICATION

In this section, the design space is used to classify existing work to (1) show promising concepts and (2) reveal opportunities for future research. Very little work has gone into communication with devices and infrastructure (see work by Sieß et al. [101]), therefore, we restrict to classifying related work into the matrix shown in Table 1 for the **CD3** *Locus Vehicle* part of the *concept* design space. If multiple variations were evaluated (e.g., [77]), this publication was categorized into multiple cells. The communication of awareness [77] is seen as a form of answer, as it provides information to the question "Does the vehicle recognize me?"

For the *situation* part of the concept, we refrain from classifying work as this was recently done for **SD1** *Communication Relationship*, **SD3** *Number of Lanes*, and **SD4** *Acoustic Noise Level* in [33]. For *mixed traffic*, we only found work by Mahadevan et al. [76]. Regarding weather conditions, all research projects seemed to have been performed under good (simulated) weather conditions (e.g., [30, 76]). No work was found that explicitly distinguishes between communication partners.

The publications classified by Colley et al. [33] excluding overviews such as [73] were classified.

7 DISCUSSION

We presented a design space on the external communication of AVs. In this section, we discuss limitations of the proposed design space, highlight unexplored concepts, and discuss usage scenarios.

7.1 Towards the Big Picture of External Communication of Autonomous Vehicles

The bigger picture of external communication of AVs is shown in Figure 3. Not all levels of every dimension are shown for clarity. The yellow part stands for the two parts of our design space: concept and situation. The green rectangles define the dimensions. Grey shows levels of the defined design space, while dashed lines show dimensions omitted or defined by other design spaces [29, 33, 51, 67, 76]. The defined design space for the concept excludes the dimension *technology* and does not go into specifics for example for the **CD3** *Locus Vehicle* as there already is work on such design spaces (e.g., [27]). While most dimensions for the situation except **SD4** *Acoustic Noise Level* are described in other work, our work differs in broadness and elaborateness in specific dimensions. In **CD1** *Message Type*, we define all possible combinations for the communication relationship compared to [51], who only include the *one-to-one* relationship. For **SD2** *Communication Partner*, we propose specific partners compared to [51], who are broader with their categorization between being motorized or not. We defined a more precise definition to allow designer to tailor their design to populations with special capabilities and needs [111]. The **SD3** *Number of Lanes* defines a number of roads but does not go into details about their location ([51] provides values for urban, rural, and highway). We omitted this as details for these scenarios are different per country and, therefore, not generalizable. **SD5** *Traffic Autonomy* defines the autonomy of the *entire traffic* compared to defining the communicating vehicle [51]. This is relevant, and, therefore, shown beneath **SD5** *Traffic Autonomy*. As this is a design space for external communication, we excluded this as the definition of the actual communicating vehicle is obviously needed. For **SD6** *Weather*, we defined clear conditions compared to the broad distinction between normal and bad sight [51]. Fog, for example, has different properties than rain regarding noise, however, both provide bad sight.

7.2 Usage of Design Space

The design space is used twofold: (1) as a taxonomy tool to see where one's own external communication concept can be grouped and (2) as an ideation tool for the generation of novel concepts in suited situations. Especially the second use case poses the possibility to look into situations in which external communication could provide benefits. We propose to ideate as follows: (1) Define the **big picture**: **SD6** *Weather* and **SD5** *Traffic Autonomy*. (2) Define the parameters of the traffic: **SD3** *Number of Lanes* and the directly related **SD4** *Acoustic Noise Level*. (3) Define the **SD2** *Communication Partner* and the **SD1** *Communication Relationship*. After setting the situation, (4) define the purpose of the concept: "What is the goal of the communication?" Communicating awareness or intent [77] are possible purposes, but defining relationships could also be done, for example, towards the owner or a person saying "thank you" for letting them pass (see Alexa using emotions [52]). (5) Appropriate to this purpose, one should define the parameters of the concept: **CD1** *Message Type*, **CD2** *Modality*, and **CD3** *Locus*.

7.3 Need for Situation Aware Communication

This design space is built upon the "nearly truism" [66, p. 1149] in psychology that the behavior of a person is influenced by the personality and the situation. While this is true for interpersonal communication, it is not clear that this holds true for external communication of AVs. The current ISO technical report [1] fosters the information type *intention* which equals *Advisory* in this design space. This message type seems independent of the situation. However, using only this type of message limits the potential of external communication concepts severely. For example, an explicit question towards an AV such as "Can I cross?" cannot be answered appropriately via intention-based messages. This is also supported by the work of Kaß et al. [67], who define generic and specific situations for the evaluation of such concepts and by Sorokin et al. who state that "[the AV's] behavior depends on the traffic situation and only makes sense within this context" [103, p. 5].

7.4 Need for Message Types

8 message types have been described based on a literature analysis. These are divided into implicit and explicit messages. It is not clear that all message types can be used implicitly (e.g., *Historical* data) and whether this is actually useful. We argue to keep these values in the design space to evoke potential new ideas for such communication. Previous work has indicated that *mode signals* could be beneficial for AVs [49] and for external communication [43, 58]. This can be seen as an explicit answer to the question "in which mode are you?" and, therefore, is no separate message type.

Instructions, *Commands*, and *Advisory* messages are very close in their content. However, according to Buck [19], a distinction has to be made. Examples for these three types can be found in the work by Deb et al. [36]: The word *Braking* is *Advisory* as it helps the pedestrian to assess the situation (see *Intention*). The smile

			Modality		
			Auditory	Visual	Tactile
Message **Type**	Implicit	Instruction			
		Command		[82, 113]	
		Advisory	[47, 63]	[3, 4, 12, 77, 85, 113]	
		Answers		[113]	
		Historical			
		Predictive			
		Question			
		Affective			
	Explicit	Instruction	[30, 36, 37, 63]	[5, 35, 36, 50, 58, 63, 72, 91]	
		Command	[76, 77, 82]	[26, 35, 50, 61, 63, 76–78, 104]	[26, 76, 77]
		Advisory(Intention)	[16, 30]	[5, 16, 21, 23, 26, 34, 36, 43, 50, 58, 82, 88, 92, 112]	
		Answer(Awareness)		[5, 22, 36, 43, 82, 88, 91]	
		Historical			
		Predictive			
		Question			
		Affective			

Table 1: Non-exhaustive classification of previous research based on the Dimensions CD1 *Message Type* and CD2 *Modality*.

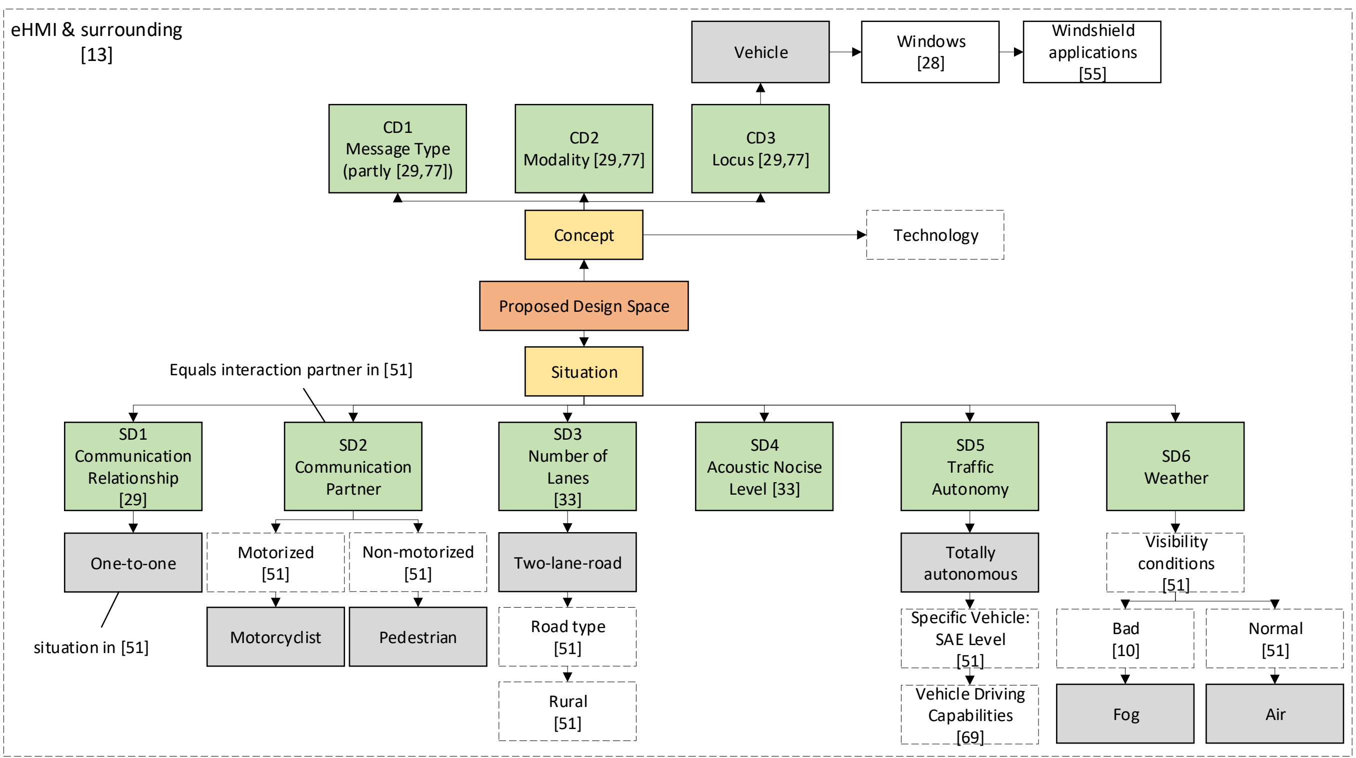


Figure 3: The proposed design space with reference to other relevant design spaces in the field of external communication.

is a *Visual Answer* as it provides information of "what has been detected?" This is described as follows: "when this car detects a pedestrian, a smile lights up on the front car display confirming the car's intention to stop" [36, p. 137]. The animated pedestrian silhouette is an *Instruction* as it shows what the pedestrian should do, however, not as a command. With the often mentioned distinction of *awareness* and *intent* messages in external communication concepts of AVs (e.g., [77]), the question arises whether these message types or their naming are still relevant in this context.

With current commands such as *Cross* [77, 104], it is not always clear whether to classify these into *command* or *instruction*. While it is a *visual* symbol, further breaking down these modalities could provide additional information. Potential classes are: *Text*, *emojis*, *animations*, and *other*.

7.5 Non-Evaluated Concepts

Various relevant dimensions of the design space have not yet been actively used for the evaluation of concepts for external communication. Especially implicit communication seems to be scarcely researched (7/39 paper classified). Moore et al. [85] claim that most situations can be handled **without** explicit but by simple implicit external communication. A first prototype was tested with variations of movement patterns to indicate specific messages [113]. Additional work on such patterns seems necessary. This also calls for more work on relevant situations which is already addressed by this two-part design space.

Several explicit concepts are unexplored. No awareness was signalized through auditory or tactile cues. With the advancement of directional audio beam loud speakers [90], such communication could be feasible. For tactile concepts, usage patterns and coordination between AVs are necessary. Tactile concepts, in general, seem hardly designed and evaluated. This, however, is necessary for people with visual **and** hearing impairments ($\approx$ 15 million people or 0.02% of the global population [64]).

Combined with the **CD1** *Message Type*, the **CD2** *Modality Tactile* seems unfeasible or at least difficult to perceive for the users for such message types as *Historical*, *Predictive*, or *Question* both for implicit and explicit communication.

7.6 Non-Evaluated Situations

Colley et al. [33] investigated scalability aspects of external communication evaluations and report that simulated traffic noise is not yet actively a part of the definition of communication concepts, which could be because most concepts are visual [30]. The typical simulated scenario seems to be that one pedestrian tries to cross a street with various number of lanes. Mahadevan et al. [76] did explore mixed traffic (see **SD5** *Traffic Autonomy*), however, most work seems to only address less realistic or only autonomous traffic (e.g., [30]). Regarding the communication partners, very little work has gone into the various possible partners.

7.7 Towards More Natural and Customized Communication?

Current external communication concepts of AVs are goal-oriented and brief. However, future communication patterns are hardly foreseeable. As people create an emotional bond to (personalized) objects such as cars [53, 57, 86], more natural communication could increase affection towards AVs and, therefore, increase trust [42] or, moving towards marketing, create a specific brand image [69].

SD2 *Communication Partner* defines different partners that could communicate with each other. This distinction between partners calls for customized communication. The communication towards a police officer has to meet different requirements (e.g., clearness, available time budget) than the communication towards a cyclist (e.g., time budget, available cognitive capabilities, one's own speed) or a person with impairments (e.g., cognitive resources, modalities available). To date, no studies compare the impact of external communication concepts of AVs with different road users [67].

7.8 Classification of Prior Work

Being an active and early research field, the relevant related work explores several communication concepts (e.g., [77]). These concepts vary widely in the used message types (e.g., [77]). In general, implicit communication seems to be less evaluated. Visual concepts were evaluated mostly [31]. This is understandable as the possibilities for this modality outnumber the others. It seems that especially communicating complex messages via tactile is difficult. As outlined, various aspects of the two-part design space seem to not have been accounted for in current research or prototypes.

8 FUTURE WORK & LIMITATIONS

This design space calls for usage as an ideation tool. Therefore, future work should consider especially the unaccounted aspects in this design space. We want to explore the design space and implement some of the potential communication possibilities, especially regarding questions and affective messages.

Only 4 experts were included in the focus group. While this not necessarily decreases validity [108], a more diverse focus group could have provided additional insights. *Technology* was excluded from the design space to avoid excluding future advances, however, this could decrease the usefulness for practitioners. In general, the proposed design space is not complete as numerous factors are relevant for crossing decisions [94], still, this design space attempts to uncover relevant dimensions. In the future, all relevant factors could be included in an attempt to provide a complete taxonomy regarding which factors were considered in research on external communication of AVs.

9 CONCLUSION

In this work, a design space on external communication of AVs with VRUs was defined with the parts *concept* and *situation*. This deductive approach was based on a literature review of communication theories and an expert focus group (*N*=4). Current work was classified, research gaps are named, and future approaches are outlined. Overall, our work highlights the various possibilities for external communication of AVs. We argue that both the situation and the actual concept have to be considered in the design process of external communication of AVs. In the future, we will design and evaluate novel concepts based on the gaps unveiled in this design space.

ACKNOWLEDGMENTS

We thank all workshop participants. This work was conducted within the project 'Interaction between automated vehicles and vulnerable road users' (Intuitiver) funded by the Ministry of Science, Research and Arts of the State of Baden-Württemberg.

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