AR4CAD: Creation and Exploration of a Taxonomy of Augmented Reality Visualization for Connected Automated Driving

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Infrastructure-mounted sensors that monitor roads can provide essential information for manual drivers and automated vehicles, e.g., positions of other vehicles occluded by buildings. However, human drivers and passengers have to trust and accept their use. This raises the question of how trust can be increased in such a scenario. One important factor for this is understanding the available information, including its quality and, for passengers of automated vehicles, the actions planned based on it. For this, augmented reality is a promising visualization technology because it can present the relevant information integrated into the physical world. Thus, this work develops a taxonomy of augmented reality visualizations for connected automated and manual driving. It is intended to classify and compare existing visualizations, identify novel visualizations, and provide a common language for discussions. The use case infrastructure-supported automated driving is explored by suggesting augmented reality visualizations to inform passengers of automated vehicles and are intended to increase trust. They present information available from infrastructure and onboard sensors as well as the driving decisions based on it. Finally, we evaluated the visualizations' influence on trust in an automated vehicle by conducting a driving simulator study (N=18). Results indicate a high dependency of trust on presenting driving decisions and information on road users but less on location-specific information.

CCS Concepts: • **Human-centered computing → HCI theory, concepts and models**; **Empirical studies in HCI**.

Additional Key Words and Phrases: Connected Driving; Automated vehicles; Augmented Reality; interface design.

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1 INTRODUCTION

Connected Automated Driving (CAD), i.e., supporting an automated vehicle (AV) with information received from external sources such as infrastructure mounted cameras, road side units or close by vehicles, allows for automated maneuvers not possible before, like merging into a street without deceleration or platooning with reduced distance to preceding vehicles [79]. However, as the AV

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relies on data the human passenger is unaware of, the passenger can not understand the AV's movements (e.g., not slowing down despite blocked sight). This could lead to undertrust and, therefore, scarce usage of this potent technology. Prior work evaluated highlighting other vehicles under bad weather conditions [83] or pedestrian intention [11] to address such concerns.
Additionally, in manual driving, a human driver of such a technologically enhanced vehicle could also include this information in their decision process, for example, to estimate whether it is safe to merge in a gap between vehicles or to turn at a complex intersection.

However, the specific human factors related challenges and opportunities with integrating (unperceivable by the AV's sensors and the passenger) information about the scenery received by external sensors are unexplored. Additionally, the information which infrastructure support is available constitutes a completely novel information type not present in self-relying AVs. In the MEC-View project [23], for example, an AV is supported via sensors installed in the infrastructure, allowing it to merge into gaps at an intersection that are occluded for the AV's sensors. Thus, it is necessary to present easily understandable information about the vehicle's augmented perception and maneuver planning. Augmented Reality (AR), either via Head-Mounted Displays (HMDs) or via integrated AR windshields, seems like a suitable technology to visualize this information in a way that supports humans in understanding the decision process better and, therefore, increase trust. In particular, its ability to integrate virtual information into the physical environment is relevant in this context (see also [11, 12, 15, 83]).

To design and evaluate such visualizations, we first defined a taxonomy that supports the classification and comparison of existing visualizations. It aids in identifying previously not considered display variants and refines the vocabulary used to discuss such systems. Afterwards, we applied the taxonomy in a literature review. For our dimension *Information Type*, we found that *Action* elements, showing what the AV does or plans to do, and *Dynamic Environment* elements, showing which dynamic actors the AV perceives, were mostly used in related work. *Location-Specific* elements, showing which parts of the static environment are known to the AV including where infrastructure support via external sensors is available, were rarely used.

Subsequently, we employed the results and the taxonomy to design exemplary visualizations for different elements that present information to a passenger in an AV, like, e.g., a trajectory or a detected vehicle. Where possible, we based our designs on existing research to achieve adequate presentations, especially considering the right categorisation in each class.

Following this, we conducted a fixed-base simulator study (N=18) with two videos of test drives taken in the real world, with the augmented information overlaid on top via a HoloLens 1. Our focus was on the dimension *Information Type* to study its relevance for trust. We presented participants either with elements from all classes in this dimension, i.e., *Action*, *Dynamic Environment*, or *Location-Specific* elements, or omitted one by not visualizing its elements. For measuring, we used the three subfactors Reliability, Trust in Automation, and Understanding from the trust questionnaire by Körber [42].

Showing elements from all classes consistently led to the highest trust. Additionally, we found that omitting elements from the *Action* or the *Dynamic Environment* class led to significant reduction. Omitting *Location-Specific* elements, however, showed no significant differences in trust for any of the subfactors compared with visualizing all three classes.

Contribution Statement: This work provides a novel taxonomy regarding the AR visualization of information in the context of CAD. Additionally, it categorizes prior work based on a literature review. Furthermore, it defines possible visualization elements for each of the proposed information types. It presents the results of a fixed-base simulator study (N=18) in which the visualizations were shown in AR using a HoloLens 1. Our work helps to safely introduce CAD and calibrate trust in the vehicles equipped with this technology and provide a taxonomy to facilitate discussion and classification of such works.

2 APPROACH

As the first step, we defined a taxonomy for the analysis, classification, and comparison of existing visualizations, identification of relevant novel variants, and to provide a common language for further discussions. Subject of the taxonomy are *visual elements*, which each are visualizations of a specific information which shall be presented. As will be shown in the course of this work, previous approaches prove to be unsuitable for the CAD use case. The reason for this is that these do not account for the use and type of information, for example, whether a visualization is for informative purposes or if an action is expected.

In the following step, we collected and classified previously published work on AR visualizations to test our taxonomy and gain knowledge about previous work. Afterwards, novel *visual elements* relevant for CAD were conceptualized. These are based on identified necessary information, previous work, or when no appropriate element existed, were created. We then integrated these elements into a combined information display for CAD, realized in a fixed-base simulator using a HoloLens 1.

To verify that our approach of visualizing the additional information is use- and helpful, we then conducted a user study (N=18). Here, we aimed to show the relevance/validity of the created elements by showing that removing elements decreases trust.

3 RELATED WORK

This work builds upon three main (research) areas in autonomous or automated driving: Trust in automated driving (AD), increasing or calibrating trust in AD, for example, via AR displays, and previous design spaces and classification of AR design elements.

3.1 Trust in Automated Driving

In general, trust in AD is a subset of the work on trust in automation. Trust or distrust directly influences passenger's attitudes towards and usage of automation [54] and is an influential factor concerning the acceptance of automation by humans. Therefore, it is directly relevant for CAD [28, 58, 66, 81].

The definition of trust varies between proposed models. Lee and See define trust "as the attitude that an agent will help achieve an individual's goals in a situation characterized by uncertainty and vulnerability" [45, p. 51]. They model trust as a feedback loop with various steps between automation and a user, which is, in our case, the passenger. In their model, automation has a display that makes it perceptible for a user. The level of detail about the automation may vary. The trustor, i.e., the passenger, then assimilates the information, and a formation of belief occurs. A trust evolution follows this. If sufficient trust is achieved, the intention to rely on the trustee is formed and then executed. Otherwise, the model proposes to loop back in the *Information assimilation and Belief formation* phase. A trustee has, as adapted from Lee and Moray [44], three bases: (1) *Performance*, which corresponds to how well the automated system performs as a trustee, (2) *process* refers to how the automated system executes a task and how convenient the approaches it takes is, and (3) *purpose* corresponds to whether the automated system is used according to its respective design purpose. In the context of CAD, the most relevant recommendations of Lee and See [45] are, therefore, to "show the process and algorithms of the automation by revealing intermediate results" [45, p. 74], making the automation understandable, and present the classification of situations relative to the automation's capabilities.

Hoff and Bashier define trust as “a variable that often determines the willingness of human operators to rely on automation” [25, p. 407]. They developed a three-layered trust model (dispositional trust, situational trust, and learned trust), based on Marsh and Dibben [51]. *Dispositional trust* refers to the personal background described by the culture, age, gender, and personality traits of the trustor. *Situational trust* is described with internal and external variability. External variability refers to the increase or decrease in trust which changes according to the complexity of the automation. In contrast, internal variability corresponds to the person’s mental capacity and psychological state in a certain situation. *Learned trust* is appraised in two layers: initially learned trust, which refers to the pre-existing knowledge of the person about the automation, and dynamically learned trust, which is influenced during the interaction with the automated system. Trust in a situation is modeled as a loop with three elements. The *Dynamic Learned Trust* influences relying on the system, which influences the perception of system performance, which influences the *Dynamic Learned Trust*. The system’s design features also influence the perception of system performance. Furthermore, a human starts with an initial reliance strategy in a situation.

Körber [42] bases his definition of trust on the postulated dimensions by Mayer et al. [52] and Lee and See [45]. According to Körber, trust is influenced by Competence / Reliability (see Ability [52] or Performance [45]), Understandability / Predictability (see Integrity [52] or Process [45]), and Intention of Developers (see Benevolence [52] or Purpose [45]). The other included factors are Familiarity (with similar systems) and Propensity to Trust (i.e., how a trustor trusts automation in general).

Ekman et al. [18] used Lee and See’s [45] model as a basis to create a framework specifically intended for creating human-machine interactions (HMIs) that create trust in AD. This framework contains events during mixed manual/automated driving. For this work, the event *Automated Mode* is especially relevant. They give specific hints on what an HMI should fulfill: Present continuous information about upcoming events and how common goals are met to allow the passenger insight into the system process. Additionally, Ekman et al. [18] state that only the reason should be presented to reduce mental workload. However, the passenger has freed cognitive resources in an automated mode as no intervention or control over the vehicle is necessary.

Regarding trust measurement, there are several proposed questionnaires. Jian et al. [33] showed that trust and distrust complement each other and can be measured with a common scale. They empirically identified 12 items correlated to trust/distrust concerning trust in machines and on which they based their 12 questions with seven-point Likert scales.

Körber [42] measure each category with two or more questions with a five-point Likert scale. As Körber firmly grounds these questions in the models of Lee and See [45] and Mayer et al. [52], we chose to use this questionnaire for our evaluation.

3.2 Augmented Reality to Support Trust in Automated Driving

AR was used in a few studies either in Virtual Reality (VR) or in overlaid videos intended to increase/calibrate trust in AD. Kunze et al. [43] used AR to show the uncertainty of an AV. They compared 11 variables (position, size, shape, value, orientation, hue, grain, arrangement, saturation, crispness, transparency, and resolution) that can show uncertainty (equals urgency) for AD when the need for takeovers occurs. They found that especially hue was suitable to convey an order of urgency.

Colley et al. [12] used AR to present the result of a semantic segmentation task, which enables AV to detect relevant objects. This information directly includes the uncertainty information about the detection of relevant objects. They found neither a positive nor a negative effect on trust.

Von Sawitzky et al. [78] suggested five user interface concepts for windshield- or head-mounted displays with and without AR to support displaying information on driving decisions with a special focus on route indication. They tested these with different driving scenarios in a driving simulator based on a VR headset. Overall, they found that showing future maneuvers (ego-vehicle and other road passengers) helps to support trust in AVs. Our work builds upon and extends these findings as there was no structured examination of design parameters. We include additional information (e.g., infrastructure support) and propose a different methodology by investigating which information decreases trust.

Wintersberger et al. [83] conducted two studies in a simulator with a moving platform that both showed that AR visualization of detected objects helps to increase trust in AVs. In their work, parts of the environment were invisible (e.g., because of fog).

Colley et al. [11] evaluated different methods of visualizing pedestrian intent as an important factor in trajectory planning. They found that AR was clearly preferred over no and visualization on a tablet positioned at the center. Also, participants preferred higher granularity of information (i.e., more predicted states).

3.3 Design Spaces and Classification of Augmented Reality Elements

Häuslschmid et al. [30] defined a design space for AR applications on windshields with five categories, each containing one or more dimensions: User, Context, Visualization, Interaction, Technology. Their goal was to find a comprehensive and generic description of the possibilities one has when designing such user interfaces. For CAD, this design space, however, is too broad and strongly oriented towards design and other related properties.

This design space was extended by Wiegand et al. [80]. They presented a design space on 3D AR applications within the vehicle with the same categories but more dimensions and/or more options per dimension. Therefore, the same limitations as mentioned above apply to the CAD use case.

Tönnis et al. [75] defined six classes of principles for information presentation with AR: Continuity (Continuous vs. Discrete), Information Presentation Representation (2D Symbolic vs. 3D Information Presentation), Registration in Space (Contact-analog vs. Unregistered Presentation), Frame of Reference (Presentation in Different Frames of Reference), Type of Referencing (Direct vs. Indirect Referencing of Objects or Situations), and Location of Presentation in Relation to Glance Direction. While these capture important aspects to be included in our taxonomy, they miss the element *function* and *intention* and focus more on behavior and relation to the physical world.

4 A TAXONOMY FOR AUGMENTED REALITY VISUALIZATION

We propose a taxonomy for AR visualizations for the collection, classification, and comparison of existing AR visualizations for (C)AD with a special focus on trust support. This taxonomy is further intended to help identify previously not considered variants and provide a common language for discussion in the context of (C)AD. Especially relevant in this context are the type of information visualized and the function of this information. In the further course of the work, we applied this taxonomy for designing new visual elements and for investigating them in terms of supporting trust in connected automated driving.

The taxonomy is used to classify single visual elements of which an application might have arbitrarily many. Even though we are especially considering AR to increase trust in connected automated driving, we do not limit our taxonomy to AR elements specifically created for this. Instead, we include AR visualizations that inform drivers or passengers about the current driving context. While designing the taxonomy, we have integrated the trust aspects at relevant points. This is explained in more detail for the individual dimensions.

4.1 Method

We developed the included dimensions in two steps. Based on the presented design spaces and classifications, we first identified common dimensions. These were assessed based on their generalizability for the use case of CAD and incorporated with adaptations where appropriate. Dimensions that focus on other use cases (or use cases in general) and dimensions that focus on technologies (e.g., combiner technology) or visualizations (e.g., size or color) were discarded due to their limited relevance to the use case of connected automated driving. Secondly, we analyzed existing systems for relevant differences in the presentation of information that were not purely graphical in nature. Special focus was given to the CAD use case and AR as a visualization paradigm. Consequently, the dimensions from the first step were expanded, which resulted in the taxonomy presented here.

4.2 Dimensions

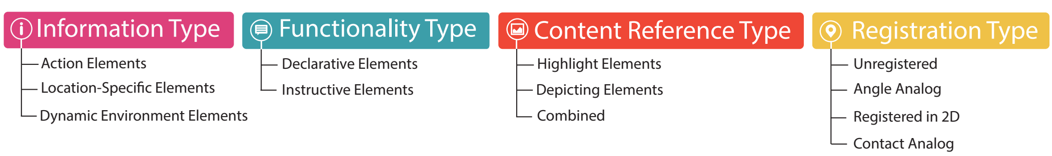


Fig. 1. Proposed taxonomy with the four dimensions and classes.

In the following, we report the derived dimensions for our taxonomy (see Figure 1).

4.2.1 Information Type. This type classifies the conveyed information. It is especially related to trust as it represents the AV's perception, intended maneuvers (see "how" and "why" information [41]), and the relevant context. The classes are:

- *Dynamic Environment elements*: These show which dynamic objects the vehicle is aware of, e.g., other vehicles. For CAD, this may also include what is received from infrastructure sensors, other connected vehicles, etc. Examples are highlights for cars in foggy weather by Wintersberger et al. [83] or marked pedestrians by Narzt et al. [57].
- *Location-Specific elements*: Location-Specific elements contain immovable information on a location such as properties of the road surface or traffic signs (e.g., Schall Jr et al. [70]).
- *Action elements*: These elements visualize information on the AV's (planned) actions or advice for a potential driver (depending on the dimension *Functionality Type*; see Section 4.2.2). Examples are navigation instructions (Narzt et al. [56]; Sato et al. [68]; Kim and Dey [39]) or indicators of the expected stopping distance (Tönnis et al. [77]).

Each of the classes in this dimension can have subclasses. For example, trajectory or stop position are subclasses of *Action* while detected vehicles or pedestrians are subclasses of *Dynamic Environment* elements.

4.2.2 Functionality Type. This type distinguishes whether an element is intended to potentially influence a driver's actions or solely inform them about the AV's knowledge or plans. With the increased automation of a vehicle, the elements should change from being instructive to being declarative as there is less information that is shown for a passenger/driver to react to. *Functionality Type* stands for the context in which information is displayed and can, for example, help to explain why a piece of information is displayed differently. The classes are:

- *Instructive Elements*: These instruct drivers about relevant actions or information to be considered in their driving decisions. Examples range from detected vehicles [83] over emphasizing road signs [70] to proposed trajectories [56, 63, 64].

- *Declarative Elements*: These display knowledge of the vehicle or imminent actions to a driver/passenger They are used by von Sawitzky et al. [78] (route indications) or Wintersberger et al. [83] (sensor data and route indications).

4.2.3 Content Reference Type. This dimension differentiates whether an AR element shows actual (additional) information to a passenger or if it highlights something in the physical world. For example, combined with the *Functionality Type* class *Declarative Element*, the AV can highlight that it has perceived a visible for the passenger, object (as done by Colley et al. [12]). Also, elements referenced can be visible and inside the field of view (FoV), occluded and inside the FoV, or outside the FoV. The classes are:

- *Highlight Elements*: These elements highlight existing information in the physical world and add none or only minor information to it. One information is always conveyed by it: the vehicle is aware of the marked object/area. Used visualization may be frames, pointers, etc. Example: highlights of traffic signs by Schall Jr et al. [70].
- *Depicting Elements*: These Elements depict information that is not present in the physical world. This may be related to physical objects, e.g., by attaching further information to other vehicles, but also independent of objects, e.g., for a trajectory [63].
- *Combined*: These elements highlight **and** depict information not present in the physical world.

4.2.4 Registration Type. Registration type describes in which way the information is registered in the physical environment. It is included because, in AR, the relation of virtual information and the physical world is highly relevant and probably influences how the combination is seen, experienced, and understood [55]. The classes are:

- *Contact Analog*: These elements are registered in the physical world both in orientation and position. For head-up displays, the phrase contact analog is used [65]). Häuslschmid et al. [30] use the term 3D registered.
- *Registered in 2D*: These elements are placed close to the line of sight of the viewer to the related object/area/position but do not share the same depth or are integrated into the physical environment (see [30]).
- *Angle Analog*: These elements point to objects in the car's environment while they themselves are registered in the car's reference system. The difference to registered in 2D is that these objects are not specifically placed close to the line of sight. (see [14])
- *Unregistered*: These are elements without any spatial relation to the vehicle's environment. This includes elements that are positioned inside the vehicle, i.e., are technically AR, but where the position does not have any specific meaning relevant to the driving situation. Further, elements that are not AR according to Azuma's definition [5] and, e.g., positioned on the display plane are part of this class (see also [30, 75]).

4.3 Comparison to Previous Design Spaces and Classifications

In this section, we compare our proposed taxonomy with previously introduced design spaces and classification schemes.

Compared to Häuslschmid et al. [30], our taxonomy is more condensed. As we focus on visualizing information, the User Mode (single or multi-user) is irrelevant. The observer we defined the taxonomy for is always the user of the AV, which can either be a supported driver or a passenger. The intended usage for either is defined via the dimension *Functionality Type* (Instructive for drivers, declarative for passengers). As the driver or passengers do not interact with the visualizations, the dimension Actor is unnecessary. As our taxonomy focuses on the element level (not complete applications), we omitted the *Context* category with the dimensions Application Purpose, Information Context, Driving Mode, Level of Automation, and Privacy. Regarding the category *Visualization*, the *Level of Augmentation* is irrelevant as we specifically focus on AR. *Registration* is included in our taxonomy. Gaze-dependent content would be categorized as Unregistered in our taxonomy, as it is not spatially registered. We also included Angle Analog to express pointing elements without direct spatial assignment. The *Field of View Position* is implicitly included as AR content is especially registered in the world. Therefore, elements will naturally shift between the three classes Foveal, Central, and Peripheral/Ambient. Nonetheless, Unregistered content has to keep the limitations of peripheral content in mind. The dimensions of *Presentation* and *Graphic Design Factors* are relevant; however, as we do not focus on graphical representation but function, we omitted these. The categories *Interaction* and *Technology* were omitted as we focus on information presentation and do not want to restrict this to a specific technology.

InCarAR by Wiegand et al. [80] is in the nature of the work by Häuslschmid et al. [30]. Therefore, we only focus on the relevant additional dimensions. As we want to classify elements regarding trust, the *Context* aspect *Travel Time* (short, medium, long duration) is not applicable. While the necessity of visualizations to improve trust might decrease over time when the trust was sufficiently built, this is out of the scope of this taxonomy. The *Visualization* aspect *Placement Strategy* describes changes in the registration type or the position of visualizations [80]. While interesting, there is no apparent relevance to trust; hence, we omitted this dimension.

Tönnis et al. [75] provide a taxonomy intended for windshield AR and HUDs. Their dimension of *Continuity* is divided into Continuous (permanent) and Discrete (depending on an event). This dimension is implicitly included in our dimension *Information Type*.
As we omitted concrete *Representation*-related attributes, there is no comparable dimension in our taxonomy.
The dimension *Registration in Space* was divided into *Contact-Analog* and *Unregistered*. We included these in our dimension *Registration Type* in higher granularity (i.e., added *Angle Analog*). The dimension *Frame of Reference* classifies information presentation on a continuum between egocentric and exocentric. As our goal is to present information specifically for the passenger of an AV with AR, our visualizations are always *egocentric*. The dimension *Type of Referencing* describes "if an object or a situation is directly visible, if it is occluded in the field of view or if it lies outside the driver's field of view" [75, p. 4]. This aspect is included via the *Content Reference Type* and the *Registration Type*. The last dimension, *Location of Presentation in Relation to Glance Direction*, was omitted as Tönnis et al. especially envision this to matter for quick information uptake in dangerous situations, which is a special case for non-regular situations that is not considered here.

4.4 Classification of Augmented Reality Applications in the Automated Driving Context

We provide a classification of prior work to (1) test the applicability of the taxonomy, (2) determine frequently used classes of visualizations, and (3) to provide some examples for our taxonomy. We classified the work on AR visualization in the driving context (both manual and automated) as defined by Colley et al. [14]: Starting with known publications relevant to the topic (called "query articles" [32]). We analyzed backward and forward citations [27]. For relevant work, we repeated the process. In total, we repeated the process three times. Additionally, we only included work with a clear depiction and explanation of the AR visual elements (e.g., excluding work by Alves et al. [2]). If works describe multiple elements, these have been categorized in separate rows (e.g., [56]).

Table 1. Classification of previous work according to our taxonomy. Dyn. Env. stands for Dynamic Environment.

Paper	Visualization	Information	Functionality	Content Reference	Registration
Plavšic et al. [64]	Warnings	Dyn. Env.	Instructive	Highlight	Contact Analog
Plavšic et al. [64]	Warnings	Dyn. Env.	Instructive	Highlight	Unregistered
Pfannmüller et al. [63]	Navigation - Chevrons or Arrows	Action	Instructive	Depicting	Contact Analog
Jansen [31]	Navigation - Virtual Cable	Action	Instructive	Depicting	Contact Analog
Narzt et al. [56]	Navigation - Augmented Road	Action	Instructive	Depicting	Contact Analog
Narzt et al. [56]	Navigation - Car to follow	Action	Instructive	Depicting	Contact Analog
Sato et al. [68]	Navigation - signs and driving directions projected onto the windshield	Action	Instructive	Depicting	Registered in 2D
Assmann [3]	Possible braking position	Action	Declarative	Depicting	Contact Analog
Tönnis et al. [77]	driving corridor	Action	Instructive	Depicting	Contact Analog
Tönnis et al. [77]	braking position	Action	Instructive	Depicting	Contact Analog
Sauerbrey [69]	Warning: Blind-spot assistance	Dyn. Env.	Instructive	Depicting	Unregistered
Kojima et al. [40]	Virtual mirror for blind intersections	Dyn. Env.	Instructive	Highlight	Contact Analog
Wintersberger et al. [83]	detected vehicles and information on crossing possibility	Dyn. Env.	Declarative	Highlight	Contact Analog
Schall Jr et al. [70]	emphasizing warning signs	Location-specific	Instructive	Highlight	Contact Analog
Taya et al. [74]	Virtual mirror for blind intersections using slope	Dyn. Env.	Instructive	Highlight	Contact Analog
Tönnis and Klinker [76]	3D arrow	Dyn. Env.	Instructive	Highlight	Angle Analog
Narzt et al. [57]	Highlight other road users	Dyn. Env.	Instructive	Highlight	Contact Analog
Colley et al. [11]	Visualizing pedestrian intention	Dyn. Env.	Instructive	Combined	Contact Analog
Colley et al. [12]	Visualize detected objects (humans and vehicles)	Dyn. Env.	Instructive	Highlight	Contact Analog
Colley et al. [12]	Visualize detected objects (signposts)	Location-specific	Instructive	Highlight	Contact Analog
Poitschke et al. [65]	Navigation - Arrow	Action	Instructive	Depicting	Contact Analog
Kim and Dey [39]	Navigation - mapping aid	Action	Instructive	Combined	Contact Analog
Bergmeier and Lange [9]	Warnings - Night Vision Systems	Dyn. Env.	Instructive	Highlight	Contact Analog
George et al. [22]	Obstacle detection assistance	Dyn. Env.	Instructive	Highlight	Angle Analog
Park et al. [61]	Visualize detected vehicles and pedestrians	Dyn. Env.	Instructive	Highlight	Contact Analog
Yoon et al. [84]	Visualize detected vehicles and pedestrians	Dyn. Env.	Instructive	Highlight	Contact Analog
Hosseini et al. [26]	Warnings - Night Vision Systems	Dyn. Env.	Instructive	Highlight	Contact Analog
Yoon and Kim [85]	Visualize detected pedestrians and vehicles	Dyn. Env.	Instructive	Highlight	Contact Analog
Yoon and Kim [85]	Lane change guidance and lane departure warnings	Action	Instructive	Depicting	Contact Analog
Gabbard et al. [21]	Conformal Navigation Arrow	Action	Instructive	Depicting	Contact Analog
Gabbard et al. [21]	Screen-fixed Navigation Arrow	Action	Instructive	Depicting	Unregistered
Bauerfeind et al. [8]	Navigation Arrow	Action	Instructive	Depicting	Contact Analog
Kunze et al. [43]	Ego trajectory	Action	Declarative	Depicting	Contact Analog
Medenica et al. [53]	Navigation Line and Arrow	Action	Instructive	Depicting	Contact Analog
Chu et al. [10]	Highlighting signpost and adding information (duration, accident)	Location-specific	Instructive	Combined	Contact Analog
Ng-Thow-Hing et al. [59]	Street information	Action	Instructive	Highlight	Contact Analog
Ng-Thow-Hing et al. [59]	Safety Grids	Dyn. Env.	Instructive	Highlight	Angle Analog
Ng-Thow-Hing et al. [59]	Projected Paths	Dyn. Env.	Instructive	Depicting	Contact Analog
Damböck et al. [16]	Own trajectory	Action	Instructive	Depicting	Contact Analog
Damböck et al. [16]	Other vehicles	Dyn. Env.	Instructive	Highlight	Contact Analog
Damböck et al. [16]	Highlight signposts	Location-specific	Instructive	Highlight	Contact Analog
Soro et al. [71]	Badges on vehicles	Dyn. Env.	Instructive	Combined	Contact Analog
Kim et al. [38]	Takeover - show relevant vehicles	Dyn. Env.	Instructive	Highlight	Contact Analog
Lorenz et al. [48]	Visualize safe and restricted driving corridor	Location-specific	Instructive	Depicting	Contact Analog
Hwang et al. [29]	Highlight pedestrians and vehicles	Dyn. Env.	Instructive	Highlight	Contact Analog
Abdi and Meddeb [1]	Visualization of pedestrians and vehicles	Dyn. Env.	Instructive	Highlight	Contact Analog
Abdi and Meddeb [1]	Collision Warning	Action	Instructive	Depicting	Contact Analog
Abdi and Meddeb [1]	Navigation Chevrons	Action	Instructive	Depicting	Contact Analog
Tangmanee and Teeravarunyou [73]	Navigation Arrows	Action	Instructive	Depicting	Contact Analog

Tangmanee and Teeravarunyou [73]	Navigation Arrows in HUD	Action	Instructive	Depicting	Unregistered
Park et al. [60]	Detected pedestrians	Dyn. Env.	Instructive	Highlight	Contact Analog
Lindemann et al. [47]	Navigation corridor	Action	Instructive	Depicting	Contact Analog
Lindemann et al. [46]	Threat and Warning markers	Dyn. Env.	Instructive	Highlight	Contact Analog
Lindemann et al. [46]	Oncoming traffic indicators	Dyn. Env.	Instructive	Highlight	Angle Analog
Lindemann et al. [46]	Brake and stopping bar	Action	Declarative	Depicting	Contact Analog
Lindemann et al. [46]	Moving object markers	Dyn. Env.	Instructive	Highlight	Contact Analog
Lindemann et al. [46]	Road sign overlay	Location-specific	Instructive	Highlight	Contact Analog
Detjen et al. [17]	Accident warning	Dyn. Env.	Declarative	Highlight	Contact Analog
Detjen et al. [17]	Accident warning	Dyn. Env.	Declarative	Highlight	Unregistered
Kawamata et al. [36]	Floating Road Map	Location-specific	Instructive	Highlight	Contact Analog
Bark et al. [7]	Navigation arrows and distance and maneuver	Action	Instructive	Combined	Contact Analog
Wiesner et al. [82]	Future road course	Action	Instructive	Highlight	Angle Analog
Jose et al. [35]	Navigation Arrows	Action	Instructive	Depicting	Unregistered
Kazazi et al. [37]	Warning in HUD	Dyn. Env.	Instructive	Depicting	Unregistered

In total, we classified 26 publications with 65 visualizations. Regarding the *Information Type*, *Action* (46.15%) and *Dynamic Environment* (44.62%) elements were mostly used. Only six visualizations (9.23%) provided *Location-Specific* information. The great majority (90.77%) of visualizations provided *Instructive* information. This was mostly registered *Contact Analog* (78.46%), followed by *Unregistered* (12.31%), *Angle Analog* (7.69%), and *Registered in 2D* (1.54%). Most visualizations *Highlight* information (50.77%). Nonetheless, 43.08% *Depict* additional and 6.15% combine both *Content Reference Types*. *Location-specific* visualizations were mostly highlighted signposts. This indicates that especially the use case of CAD is underrepresented in current research. For the *Registration Type*, *Contact Analog* and *Unregistered* combined represent more than 90% of the visualizations. This shows that most works either want to provide information continuously (using *Unregistered*) or spatially directly located at the relevant object. Using *Registered in 2D* or *Angle Analog* potentially is scarce due to the additional mapping necessary by a passenger to understand which object is relevant for the visualization. The high prevalence of *Instructive* information can probably be explained by the focus on manual driving. AutoUI, the International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications, for example, started addressing automated driving mostly from 2016 onward [4]. The *Content Reference Type* was almost on par. Most works focused on highlighting other road users or signposts. *Depicting* work mostly showed the trajectory or navigational aspects. This can also be explained by the focus on manual driving. Overall, this classification shows that numerous works explored AR in the context of driving, however, the specific aspects of CAD, such as presenting the passenger with declarative or location-specific information, is lacking.

In general, we found that our taxonomy is capable of classifying all found prior work, indicating that no major classes were missed. In the next step, we aimed to determine the effects of visualizations especially relevant to the use case of CAD.

5 AUGMENTED REALITY VISUALIZATIONS TO SUPPORT TRUST IN THE AUTOMATED DRIVING CONTEXT

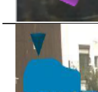
After defining and comparing our taxonomy to previous work, we suggest a set of visual AR elements to visualize CAD information. We started with the collected and classified visualizations, in particular, with the different types of information represented by them. This set of visualizations contributes to the development of user interfaces for the representation of AD functions. Each element visualizes specific information, such as the position of hidden vehicles reported via infrastructure-based sensors or the planned trajectory of the ego vehicle. Further, each element belongs to a specific class in the dimension *Information Type*, for example, the hidden vehicle is a *Dynamic Environment* element while the trajectory is an *Action* element. In the following, we describe the elements in terms of (1) information content, (2) rationale, (3) prior publications using such elements, (4) the concrete visualization, and (5) the classification of this element in our proposed taxonomy.

The designs have been discussed with *N*=10 experts in AR visualizations for driver assistance systems and - where necessary - updated according to their remarks. We only report on the updated designs, but occasionally refer to the previous drafts to explain specific design decisions. We refrain from proposing elements based on the (estimated) intention of other road users as done by Colley et al. [11] as the uncertainty of its detection limits this for the purpose of increasing trust.

5.1 Dynamic Environment Element: Vehicle Marker

These markers indicate the position of all other vehicles known by the ego vehicle, either because of on-board or of infrastructure sensors.
Vehicles have a major influence on the planning of the ego vehicle's trajectory. Visualizing vehicles not visible to the passengers allows forming an understanding of the AV's actions. Visualizing vehicles visible to the passengers allows them to match the displayed information with their own perception, quickly getting a sense of the possibilities of the AV (see [12]). Based on previous work [11, 12, 83], we assume such a visualization to increase trust. We propose a visualization dependent on the situation: If the vehicle/pedestrian is visible to the user, indicate the recognition with a cone above the vehicle/pedestrian (see Figure 4b) to not conceal the object. If the vehicle is inside the FoV but occluded, an icon is included below the cone that scales in size with the distance and via vanishing lines gives an impression of the direction (see Figure 4c). We argue that the other vehicle should be made visible to a passenger to provide information about its position and distance, but it should be sufficiently abstract to reflect the limited information. If the vehicle is outside the FoV, the cone is positioned at the side of the FoV and showing in the vehicle's direction to make the passenger aware of the recognized vehicle without posing visual clutter (see Figure 2). A highly visible purple tone was chosen as it does not have a pre-assigned significance like yellow or red. The classification of this visualization can be seen in Table 2. The *Content Reference Type* for the cone is *Highlight*, for the icon, it is *Depicting*. If the cone only shows the direction towards a known vehicle (see Figure 2), its *Registration Type* is Angle Analog.

Table 2. Classification of Vehicle Marker cone and icon.

Image	Information Type	Functionality Type	Content Reference Type	Registration Type
	Action Location-Specific **Dynamic Environment**	**Declarative** Instructive	**Highlight** Depicting Combined	Unregistered **Angle Analog** Registered in 2D **Contact Analog**
	Action Location-Specific **Dynamic Environment**	**Declarative** Instructive	Highlight **Depicting** Combined	Unregistered Angle Analog Registered in 2D **Contact Analog**

5.2 Location-Specific Elements

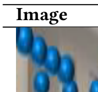
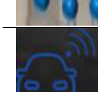
Location-Specific elements can inform the passenger about available infrastructure support and the covered area. This helps the passenger in understanding where the ego-vehicle has information beyond that given by ego sensors. For example, this answers the question "if no traffic is shown on a crossroad, is there really no traffic, or is there just no infrastructure support?" We expect this to positively impact trust because it provides system transparency [45, 78].

Fig. 2. Illustration of a superimposed video showing the Angle Analog Vehicle Marker (left), the trajectory (white chevrons), the Stop Indication with bar and pointer, and the speed indication and the dots representing location support. This scenario was not part of the study due to technical issues.

We propose a visualization combined of two parts to show infrastructure support. First, a well-known connection symbol (circular lines above a symbolized vehicle, see Figure 2) that is easily found above the glove compartment but does not obscure relevant parts of the scenery. Additionally, we propose to show which areas of one or more roads are covered by infrastructure support via dots (size ≈20 cm) floating high (≈4 m) above the respective parts (see Figure 2 and Figure 4). This allows the passenger to easily understand which roads are covered as dots reduce visual clutter compared to lines. The height was chosen to reduce the obscuring of relevant other information. A highly visible blue tone which does not have a pre-assigned significance like yellow or red was chosen.

We further considered two elements that are not included here. One is a map of the surroundings, including aspects like the road, planned trajectory, and other vehicles. However, while such a map could be helpful, map design itself is a very complex topic [50] and only has a limited relation to the topic of AR for CAD. The other element is a roadblock, indicating a closed road, e.g., due to construction work. This element was left out after discussions with the mentioned experts as most of them identified it as unnecessary. The classification of this visualization can be seen in Table 3. The *Registration Type* for the connection symbol is *Unregistered*, for the dots, it is *Contact Analog*.

Table 3. Classification of Location-Specific elements.

Image	Information Type	Functionality Type	Content Reference Type	Registration Type
	Action	**Declarative**	Highlight	Unregistered
	Location-Specific	Instructive	**Depicting**	Angle Analog
	Dynamic Environment		Combined	Registered in 2D
				Contact Analog
	Action	**Declarative**	Highlight	**Unregistered**
	Location-Specific	Instructive	**Depicting**	Angle Analog
	Dynamic Environment		Combined	Registered in 2D
				Contact Analog

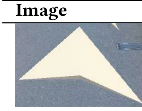
5.3 Action Elements

We propose four *Action Elements*: the (1) own trajectory, a (2) speed, and a (3) stop indication for the own AV, and the visualization of (4) detected gaps the AV can merge into. The own trajectory and speed indication should always be available, while the stop and gap indication is dependent on the available data and the traffic scenario.

5.3.1 Trajectory. This visualization shows the planned near-future vehicle movements. Thus, it allows the passenger to prepare for driving maneuvers. It is expected that this increases trust based on von Sawitzky et al. [78] as it shows intermediate results [45] and informs about upcoming events [18].

We propose to use chevrons based on the trajectory's length, as previously proposed by Pfannmüller et al. [63]. These are projected onto the road. White was chosen to create sufficient contrast to the underlying road (see Figure 2). The inclusion of individual chevrons was chosen because they also provide directional information locally. Therefore, it is not necessary for an observer to see the entire shape, unlike this is the case for, e.g., a continuous tube [63]. While we first considered including additional information such as acceleration/deceleration, this was later disregarded to not overload the element and, thus, the passenger with information. The classification of this visualization can be seen in Table 4.

Table 4. Classification of the Trajectory.

Image	Information Type	Functionality Type	Content Reference Type	Registration Type
	**Action**	**Declarative**	Highlight	Unregistered
	Location-Specific	Instructive	**Depicting**	Angle Analog
	Dynamic Environment		Combined	Registered in 2D
				Contact Analog

5.3.2 Speed Indication. This visualization shows the currently driven speed. As additional information, the maximum allowed speed is included. We expect that (at least) passengers new to AVs will regularly check the tachometer as this is currently necessary. Providing this information lets the passenger monitor system performance [18] and provides sufficient information to the passenger about the appropriateness of the current speed.

The speed limit is visualized like a road sign for the speed limit to allow high recognizability based on previous knowledge. The currently driven speed is displayed as a number followed by km/h next to the speed limit as already used in digital cluster instruments (see Figure 2). The classification of this visualization can be seen in Table 5.

Table 5. Classification of the Speed Indication.

Image	Information Type	Functionality Type	Content Reference Type	Registration Type
	**Action**	**Declarative**	Highlight	**Unregistered**
	Location-Specific	Instructive	**Depicting**	Angle Analog
	Dynamic Environment		Combined	Registered in 2D
				Contact Analog

5.3.3 Stop Indication. This visualization shows the planned stopping maneuvers with the corresponding position. This again shows intermediate results [45] and informs about upcoming events [18] and is, therefore, expected to increase trust.

We propose to display a stop position bar and a stop position pointer. The yellow stop position bar is placed on the ground at the vehicle's position is planning to stop. The bar shape was chosen to give it a solid impression without leading to too much occlusion. The color yellow was chosen to be salient for a passenger, but it still does not have the warning character of red. Nonetheless, a novel color was needed to improve delimitability to the other visualizations.

The stop position pointer is a yellow arrow placed above the stop position bar pointing towards it. The shape arrow was chosen to highlight the stop position even from a further distance. The classification of this visualization can be seen in Table 6. The *Content Reference Type* for the stop position bar is *Depicting*, for the stop position pointer, it is *Highlight*.

Table 6. Classification of the Stop Indication.

Image	Information Type	Functionality Type	Content Reference Type	Registration Type
	**Action**	**Declarative**	**Highlight**	Unregistered
	Location-Specific	Instructive	Depicting	Angle Analog
	Dynamic Environment		Combined	Registered in 2D
				Contact Analog
	**Action**	**Declarative**	Highlight	Unregistered
	Location-Specific	Instructive	**Depicting**	Angle Analog
	Dynamic Environment		Combined	Registered in 2D
				Contact Analog

5.3.4 *Gap Indication.*

This visualization shows a (either hidden or visible) gap on the crossroad the AV plans to merge into when turning onto the road. In the considered use case of CAD, an AV may target driving into a gap when turning onto another road not visible to the passenger (e.g., through occlusion). By showing the gap, the passenger is informed about the AV's plan, thus, reducing surprise at the intersection. While the individual vehicles would be known via the vehicle indicator, the passenger could be unsure whether the gap is sufficient. This again shows intermediate results [45] and informs about upcoming events [18] and is, therefore, expected to increase trust.

The gap is shown as a green bar between the two vehicles in front or behind the gap (see Figure 2). The color green was chosen in the style of traffic lights to symbolize a free entrance. The width is about the width of one lane, and the shape follows the shape of the respective lane. It has a height of a few centimeters to give it a more massive impression as a flat lane would be difficult to perceive. If a gap is only limited by one vehicle (e.g., a leading vehicle but no second vehicle), it is shown with the approximately necessary merging size including safety margins. The classification of this visualization can be seen in Table 7.

Table 7. Classification of the Gap Indication.

Image	Information Type	Functionality Type	Content Reference Type	Registration Type
	**Action**	**Declarative**	Highlight	Unregistered
	Location-Specific	Instructive	**Depicting**	Angle Analog
	Dynamic Environment		Combined	Registered in 2D
				Contact Analog

6 EMPIRICAL EVALUATION

After the definition of the taxonomy and the proposal of AR visualizations to support trust in (C)AD, we designed and conducted a study on the effect of whether different types of information support building trust. At this point, we again built on the taxonomy by taking the dimension *Information Type* as the basis for the investigation.

Before the experiment, we computed the required sample size via an a-priori power analysis using G*Power [19]. To achieve a power of .80, with an alpha level of .05, 17 participants should result in medium effect size (0.3 [20]) in a within-factors repeated measures ANOVA.

We recruited N=18 participants (3 female, 15 male, 0 diverse). Participation was voluntary. On average, participants were M=27.72 (SD=10.11) years old. All participants were employees or interns at Robert Bosch GmbH and working in the Renningen site. Seven participants (38.8%) had experience with Head-Up Displays (HUDs) and automated driving systems. The results from one participant had to be removed due to problems with the understanding of the task.

6.1 Apparatus

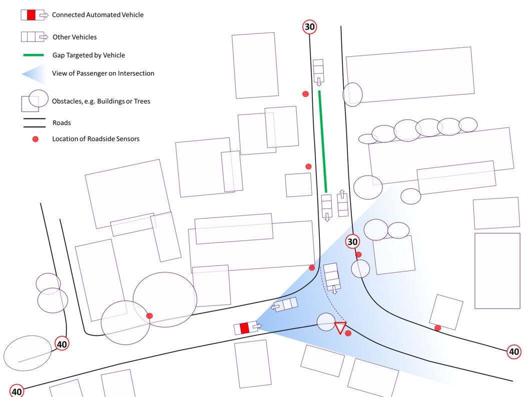
The experiment was conducted in a fixed-base driving simulator to increase reproducibility compared to driving in real vehicles (see Figure 3). The simulator consists of a seven meters wide and three meters high screen where the driving situation is displayed as a video and a vehicle mockup to increase immersion.

Fig. 3. The fixed-base simulator showing the screen with the video, and the vehicle mockup.

The videos were taken with an Apple iPhone 11 in Ulm, Germany, which was positioned behind the windshield, approximately in the middle between the driver and passenger seat. We chose two scenarios. In the scenario *Free Turn*, the AV receives information that the street is free; therefore, it can turn right without stopping (see Figure 4d). In scenario *Merge*, the vehicle knows about the distance between two vehicles at the intersection, and it merges in the gap between these two vehicles (see Figure 4c and Figure 4d). A third scenario, where the vehicle has to stop, was considered but could not be included into the final study due to technical reasons (see Figure 2).

An overview of the scenario with the approaching vehicle on the bottom is shown in Figure 4a. This intersection is, in reality, equipped with sensory to capture traffic in the MEC-View project [23].

For the visualization of the AR content, a Microsoft HoloLens Version 1 was used. This enables passengers to experience AR content as envisioned. We opted for using the HoloLens compared to other possible presentation modes because of several reasons. In contrast to a video that includes



(a) Overview of the merging scenario in Ulm, Germany.


(b) Scenario Free Turn.


(c) Scenario Merge showing invisible vehicles.

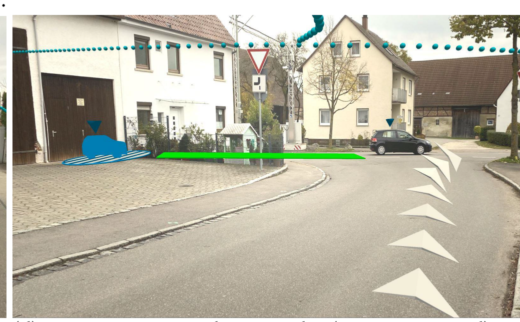

(d) Scenario Merge showing the (post-processed) gap indicator. The gap is too small for a merging maneuver but is shown to visualize the nature of the element.

Fig. 4. Scenario screenshots with superimposed AR visualizations. The screenshots were post-processed for better visibility, as neither photographs through the combiner glasses nor the screenshots from the built in HoloLens function came close to the actual impression.

virtual overlays, the HoloLens provides binocular depth cues which more realistically represent what users in a real vehicle would perceive. Furthermore, we expect that increasing the FoV until it is as large as a human's will remain a challenge for combiner hardware manufacturers in the near and medium future [86]. The resulting effect that only a fraction of the scene is augmented at any given time, but at the same time the user is in control of which one it is, is lost when overlaying the information in a video.

Another alternative display mode, an AR head-up windshield display that could be used to display CAD-relevant visualizations, is very difficult to employ in such a study due to technical reasons. Additionally, they limit the orientation of the FoV in such a way that most parts of the environment cannot be overlaid with information. This could also lead to future manufacturers including external devices in their interaction concepts despite being moderately heavy on the head. The synchronization of the video with the content displayed on the HoloLens was achieved as follows. First, the video was recorded. Then the vehicle's drive was mapped to a virtual map of the test area and the relevant virtual objects, including their movements, were added. For the trials, this virtual ride was then played back on the HoloLens as if it were connected to a real vehicle performing the driving in real time. To match, the video was played simultaneously, started by the same key press that also started the simulation. The software used in this experiment was developed for use in a vehicle and then adapted for the study. For the display the elements described in Section 5 were used.

6.2 Study Design

As previous work indicated that using AR supports trust in AD [11, 43, 78, 83], we were especially interested in the novel use case of CAD and the effect of *Information Type*. Therefore, we omitted a superficial baseline without any visualization. Instead, we chose to include all *Information Types* or omit one information class per condition. Therefore, the independent variable was the information types included and consisted of *all classes*, *no Action*, *no Dynamic Environment*, and *no Location Specific* as per our taxonomy. The conditions for each of the videos/situations are listed in Table 8.

Table 8. List of visual elements displayed in each study condition per video. Sit. stands for situation.

Condition	Action	Dynamic Environment	Location-Specific
1: all three classes	Trajectory, Speed, Gap (only Sit. 2)	Vehicle Marker (visible & invisible)	Infrastructure support
2: no Action	X	Vehicle Marker (visible & invisible)	Infrastructure support
3: no Dynamic Environment	Trajectory, Speed, Gap (only Sit. 2)	X	Infrastructure support
4: no Location Specific	Trajectory, Speed, Gap (only Sit. 2)	Vehicle Marker (visible & invisible)	X

Our hypotheses were:

H_1: Displaying elements from **all three classes** will result in higher trust than displaying elements only from **Dynamic Environment** class and **Action** (no Location-Specific) class for both scenes.

H_2: Displaying elements from **all three classes** will result in higher trust than displaying elements only from the **Dynamic Environment** class and **Location-Specific** (no Action) class in both scenes.

H_3: Displaying elements from **all three classes** will result in higher trust than displaying elements only from **Action** class and **Location-Specific** (no Dynamic Environment) class for both scenes.

6.3 Procedure

Participants were welcomed and asked to sign informed consent. Next, they were informed about the purpose of the study briefly. Afterward, they sat in the car mock-up in the passenger seat. The use case was explained to them before each scenario was shown, and they watched each scenario without the HoloLens first. They were then informed about the HoloLens 1, and they tried it on to get comfortable with it. They were able to adjust the seat and the HoloLens 1. Then they watched the four variations of each of the two scenarios with the HoloLens 1. Scenario *Free Turn* took 21s, scenario *Merge* 28s. Before each variation was shown, the FoV of the participants was calibrated to align with the video. Subsequently, the visual elements were explained, and it was ensured that they understand these. The participants first encountered scenario Free Turn in the counterbalanced four variations, then scenario Merge in the counterbalanced four variations. The duration of the user study was approximately 35min per participant.

6.4 Measurements

After each condition, participants filled out the *Trust in Automation* questionnaire [42]. For the trust measurement, we employed the dimensions *Reliability/Competence*, *Understandability/Predictability*, and *Trust in Automation* of the Trust in Automation questionnaire by Körber [42]. Finally, they answered a demographics questionnaire.

7 RESULTS

First, due to non-normally distributed data, we employed the factorial non-parametric analysis of variance (NPAV) provided by Lüpsen [49]. We included a random intercept for participants for each dependent variable because of the hierarchical data (measurements nested within participants). Effect sizes were calculated using Rosenthals's formula [67]. Results for both videos/situations were evaluated separately as the NPAV found no significant main effects of scenario nor interaction effects with scenario. Depending on the data's nature [72], we used Friedman's ANOVAs tests (non-parametric) or a repeated measures ANOVA (parametric) to compare the four conditions per scenario. For post-hoc tests, Bonferroni correction was used.

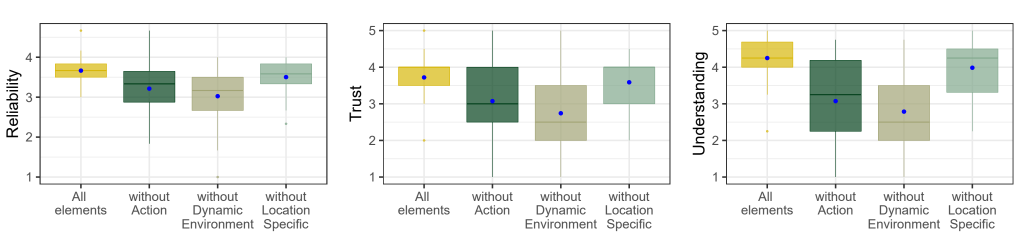
We used Version 4.1.3 of R and RStudio Version 2022.02.0 with all packages up-to-date as of April 2022. For the figures, we used *ggstatsplot* [62]. These include the mean or median (red dot), the density plots, the boxplots, and the data points. It also includes statistical details such as the used test and the effect size. Therefore, we refrain from rewriting these in text. Instead, we only report the significant differences relevant to our hypotheses.

7.1 Factorial Analysis

The NPAV found a significant effect of *visualizations* on reliability ($F(3, 48) = 18.90$, $p<.001$, r=-0.67, Z=-5.53, see Figure 5a). Post-hoc tests using Dunn's test revealed that *All elements* lead to higher reliability assessments compared to *without Action* and *without Dynamic Environment*. Also, *without Dynamic Environment* lead to significantly lower reliability assessment compared to *without Location Specific*.

The NPAV also found a significant effect of *visualizations* on trust ($F(3, 48) = 11.03$, $p<.001$, r=-0.53, Z=-4.37, see Figure 5b). Dunn's test revealed that *All elements* lead to higher trust compared to *without Action* and *without Dynamic Environment*. Additionally, *without Dynamic Environment* lead to significantly lower trust compared to *without Location Specific*.

Finally, the NPAV found a significant effect of *visualizations* on understanding ($F(3, 48) = 18.34$, $p<.001$, r=-0.66, Z=-5.47, see Figure 5c). Dunn's test showed that *All elements* lead to higher understanding compared to *without Action* and *without Dynamic Environment*. Also, *without Action* and *without Dynamic Environment* lead to significantly lower understanding scores compared to *without Location Specific*.

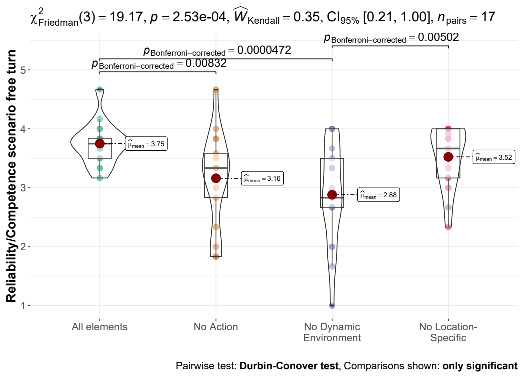


(a) Main effect on reliability. (b) Main effect on trust. (c) Main effect on understanding.

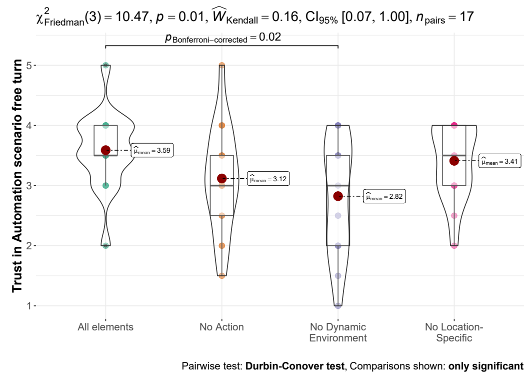
Fig. 5. Main effects of visualizations. The blue dot represents the mean value.

7.2 Scenario Free Turn

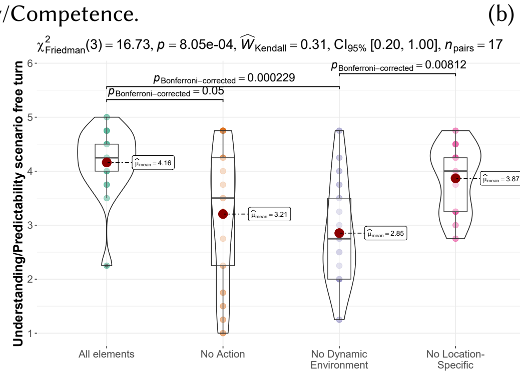
A Friedman's ANOVA with post-hoc tests showed a significant difference for Reliability (see Figure 6a), Trust (see Figure 6b), and Understanding (see Figure 6c). Perceived Reliability was rated significantly higher with all elements displayed than omitting Action or Dynamic Environment



(a) Reliability/Competence.



(b) Trust.



(c) Understanding/Predictability.

Fig. 6. Results for scenario *Free Turn*.

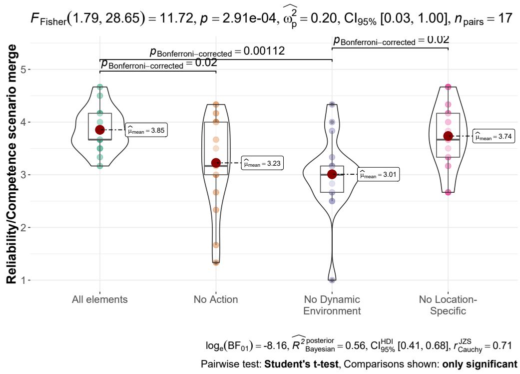
elements (see Figure 6a).
Trust was rated significantly higher with all elements displayed compared to omitting Dynamic Environment elements (see Figure 6b). Understanding was ratedrated significantly higher with all elements displayed than omitting Action or Dynamic Environment elements (see Figure 6c).

7.3 Scenario Merge

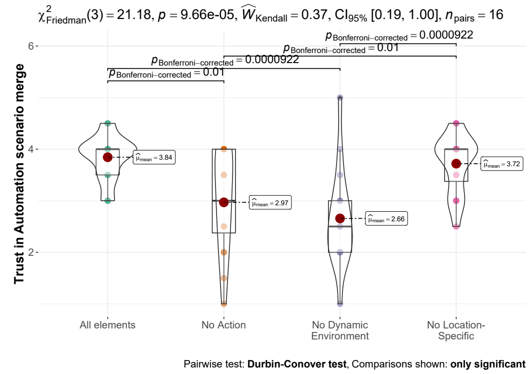
A Friedman's ANOVA with post-hoc tests showed a significant difference for Reliability (see Figure 7a), Trust (see Figure 7b), and Understanding (see Figure 7c). Perceived Reliability was rated significantly higher with all elements displayed than omitting Action or Dynamic Environment elements (see Figure 7a).
Trust was rated significantly higher with all elements displayed than omitting Action and Dynamic Environment elements (see Figure 7b). Understanding was rated significantly higher with all elements displayed than omitting Action or Dynamic Environment elements (see Figure 7c).

7.4 Evaluation of Hypotheses

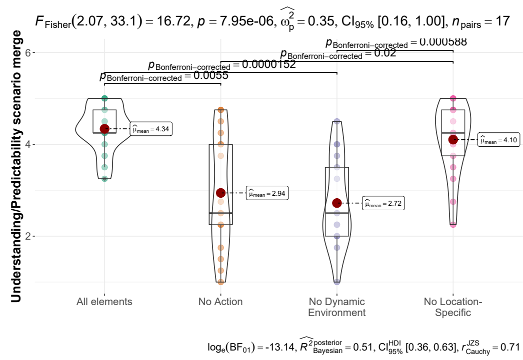
To accept a hypothesis, we define that at least two of the three dependent trust factors (*Reliability/Competence*, *Understandability/Predictability*, and *Trust in Automation*) must be significantly higher in one condition compared to the relevant other condition in **both** situations and **none** must be significantly higher in the other condition. We argue that this is the minimum necessary to show that one condition is better unambiguously.



(a) Reliability/Competence.



(b) Trust.



(c) Understanding/Predictability.

Fig. 7. Results for scenario *Merge*.

With the presented results, we can accept and reject our hypotheses as follows:

H_1: For the comparison between conditions *All Elements* / *No Location-Specific*, there is no significant difference for any of the three dependent trust factors. Therefore, we reject this hypothesis.

H_2: For the comparison between conditions *All Elements* / *No Action*, only the difference in *Trust in Automation* in scenario Free Turn is not significant (but still lower). Therefore, we accept this hypothesis.

H_3: For the comparison between conditions *All Elements* / *No Dynamic Environment*, all three dependent trust factors are significantly higher in the *All Elements condition* in both videos. Therefore, we accept this hypothesis.

8 DISCUSSION

This work presented a novel, technology-independent taxonomy for AR visualizations that inform human drivers and passengers of AVs and support trust in CAD. Based on this taxonomy, we collected and categorized previous work. Furthermore, we defined relevant visualizations for the CAD use case, including representations for information regarding the dynamic environment, location-specific information, and the vehicle's planned actions. In a user study (N=18) using a fixed-base driving simulator and a HoloLens 1, we showed that visualizing elements of all three classes increased trust significantly compared to removing *Dynamic Environment* and *Action* elements. However, we found no significant differences between visualizing all classes and removing *Location-Specific* elements. In the following, we discuss the classification of prior work, the chosen study design, the necessity and appropriateness of the visualizations to increase trust in CAD, and practical implications.

8.1 On the Study Design

In this work, we chose to compare **all three** visualization classes with three conditions in which one of these (Action, Dynamic Environment, or Location-Specific) were omitted. Classical studies include a baseline without any visualization; however, recent work has shown that this could lead to numerous concepts, each significantly higher rated compared to the baseline, but with few differences among each other [14]. Additionally, prior work has already shown the positive impact of visualization on trust in AD [11, 12, 43, 78, 83]. It was also shown that the human passenger desires granular information, at least in the introductory phase [11]. Therefore, we assumed that visualizing *more* information will lead to the highest ratings in trust, which our experiment confirmed (see Figure 6 and Figure 7). With the chosen study design, we are, therefore, able to assess the impact our implementation of each class has on the perceived trust. Significant differences when leaving out a visualization are, thus, interpreted such that this visualization is an important aspect towards building trust in the system. Furthermore, we can assess combinations of the classes, which would be difficult in a classical design as this would result in a multitude of conditions (baseline, conditions per class (3), dual combinations (6), 1 combining all three classes equals 11 conditions).

8.2 Necessity of Visualizations

Our hypotheses H_1, H_2, and H_3 stated that omitting one of the classes *Action*, *Dynamic Environment*, and *Location-Specific* would lead to significantly lower trust compared to the combination of all three. This was not the case for *Location-Specific* elements. Therefore, we argue that the *Location-Specific* elements contributed little to trust formation with the subfactors Reliability, Trust, and Understanding. This was the case in both scenarios. This could depend on several factors. First, participants were not required to drive themselves; therefore, the expectations towards the automated capabilities of the AV could already have been such that even without *Location-Specific* support, the AV should be capable of performing the driving task. Also, dynamic objects pose the highest risk in a driving scene [11], therefore, static support for a street could be viewed as less relevant. This focus on *Dynamic Environment* elements seems to be underpinned by the highest difference between visualizing all elements and omitting *Dynamic Environment* elements (e.g., see Figure 6b). The results seem to indicate that the most important visualizations show dynamic objects followed by the *Action* elements.

8.3 Practical Implications

This work is in line with previous work in showing the necessity to highlight dynamic objects [11, 12, 83]. Additionally, we showed that visualizing the trajectory of the AV is beneficial for increasing trust. These visualizations are only partially feasible today. First, the required sensor networks to detect and then convey the relevant information has to be installed. For this, especially occluded and dangerous intersections seem most relevant. Furthermore, the display technology has to be available. While current Head-Up Displays can display elements in 10m distance [34], showing content in continuous depth is not yet feasible. Nonetheless, Panasonic claims to be able to produce such windshield displays by 2024 [6].

Especially for (partial) manual driving, the effects and benefits of these visualizations including potential visual clutter have to be further evaluated. The reason for this is that a driver must not only understand what a vehicle perceives and plans, but also see all relevant parts of the environment and take decisions.

8.4 Limitations

A limited number of participants (*N*=18, one had to be removed from analysis) took part in the study. These were relatively young (*M*=27.72, *SD*=10.11) and employees of Robert Bosch GmbH, therefore, a high technological affinity could be assumed, and the results might not be generalizable. Furthermore, the generalizability is also affected by the usage of a fixed-base driving simulator. Still, a video taken at a real intersection with numerous sensors and a HoloLens 1 was used. Therefore, we argue that the study setup was more realistic than, for example, using a Virtual Reality simulator. Nonetheless, higher degrees of freedom could improve immersion and increase external validity (e.g., [13] or [24]). While we believe our designed visualizations are sound, there are numerous other visualization options to be investigated. The taxonomy focuses on four dimensions: *Information*, *Functionality*, *Content Reference*, and *Registration Type*. While many other dimensions seem possible and relevant, we focused on the, in our opinion, most important ones.

9 CONCLUSION

Overall, we present a novel taxonomy for AR visualizations to support trust in CAD. This taxonomy contains four dimensions: *Information*, *Functionality*, *Content Reference*, and *Registration Type*. We classified prior work in AR visualizations and named current trends. Furthermore, using the taxonomy, we defined exemplary visualizations to represent information supporting trust in CAD functions. In a subsequent study with *N*=18 participants, we found that visualizing elements from each of the three *Information Type* classes *Action*, *Dynamic Environment*, and *Location-Specific* lead to the highest trust. Omitting *Action* or *Dynamic Environment* elements lead to significantly lower trust. Our work is, to the best of our knowledge, among the first to specifically look at augmented reality to increase trust in CAD and further enhance the body of knowledge on factors for a successful introduction of AVs.

On the basis of the results presented here, various topics for future research arise. Certainly, the set of presented visual elements is not complete and there are many more that can be included. Pedestrians or cyclists are obvious possibilities here. This also raises the question, at which points further elements only create visual clutter and may even decrease trust. In addition, the location-specific elements were found to have no detectable effect on trust. This leads to the issue as to whether there really is no correlation or the presentation was chosen inappropriately. Further investigations are necessary here.

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