A Tool, not a Toy: Using Virtual Reality to Evaluate the Communication Between Autonomous Vehicles and Pedestrians

Sebastian Stadler, Henriette Cornet, Tatiana Novaes Theoto and Fritz Frenkler

Abstract Although the main market for Virtual Reality (VR) is currently the gaming industry, advantages of using virtual environments in research and development have been already demonstrated e.g. for car industry or urban planning. Especially when no prototype is feasible or available, VR constitutes an advantageous alternative since it allows tests in laboratory conditions with high flexibility and ensured safety for test participants. In the presented study, it is investigated how VR can be used as a tool for Usability Tests to evaluate Human Machine Interfaces (HMI) for communication between autonomous vehicles and pedestrians. Singapore with its regulations and requirements has been selected as reference. Beyond the findings that explicit HMI concepts improve the communication between autonomous vehicles and pedestrians, VR was validated as suitable tool to conduct Usability Tests. Further studies plan to integrate additional case studies as well as improved immersion of test participants within the virtual environment.

Keywords Virtual reality · Usability tests · Human machine interfaces · Autonomous mobility

S. Stadler (✉) · H. Cornet · T. Novaes Theoto
TUMCREATE Ltd., Singapore, Singapore
e-mail: sebastian.stadler@tum-create.edu.sg

H. Cornet
e-mail: henriette.cornet@tum-create.edu.sg

T. Novaes Theoto
e-mail: tatiana.theoto@tum-create.edu.sg

F. Frenkler
Technical University of Munich, Munich, Germany
e-mail: fritz.frenkler@tum.de

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1 Introduction

Due to the lack of a driver in level 5 autonomous vehicles[1] (AV), communication between AVs and human road users, like pedestrians, has to be replaced. Human Machine Interfaces (HMI)—for instance, on-vehicle screens with real-time information—are a possible solution (Matthews & Chowdary, 2017). The critical nature of the task (i.e. crossing the street when an AV is approaching) demands visible and comprehensible information in order to ensure pedestrians' safety. Especially in a multicultural environment like Singapore,[2] universal comprehensibility of written information and/or symbols, which constitute the HMI concepts, is a prerequisite. Therefore, the usability of HMI concepts must be tested, as the implementation of such communication without appropriate verification could lead to misinterpretation and thus safety hazards.

However, the autonomous mobility context brings significant obstacles to reliable validation of HMI concepts mainly regarding complexity, effort, and safety. Indeed, in order to create an authentic traffic condition, a physical test bed has to be set up, including e.g. roads, junctions, sidewalks, traffic lights, zebra crossings, and traffic signs. Additionally, both manually driven cars and AVs have to be integrated into the test bed. Test participants, which include drivers, pedestrians, and passengers, also have to be present to create the environment. To ensure a reliable data collection, all these aspects have to work together perfectly—which results in a complex endeavour and leads to great effort regarding time and money spent. Furthermore, AVs raise concerns about the technology's safety (Eng, 2017). Misinterpretation can lead to accidents, as it became visible at the fatal crash caused by a Tesla in self-driving mode (The New York Times, 2016). Therefore, testing the usability of communication between AVs and pedestrians in real-life conditions remains potentially dangerous.

The hypothesis of the presented study is that Virtual Reality (VR) is a suitable tool to test the usability of HMI concepts between AVs and pedestrians as a replacement for tests in real-life conditions. Therefore, the objective is to develop a suitable methodology for Usability Tests within VR in the context of autonomous mobility.

[1]In contrast to level 0 automation, which means the human driver has to perform all aspects of the driving task, level 5 automation means that humans do not overtake or influence any task in any driving situation, but act solely as passengers (SAE International, 2016).

[2]For the investigation of communication between AVs and human road users, a geographical context is required. Singapore has been selected for this study. Its local regulations and cultural environment will be considered as requirements.

2 Literature Review

2.1 Context: Existing HMI for Communication Between AV and Pedestrians

The focus of this paper lies on communication between AVs and pedestrians, in an ambiguous situation at a one-way street without traffic lights and/or zebra crossing and a potential intention of crossing the road by the pedestrian while an AV is approaching. For this type of communication, a distinction can be made between explicit and implicit communication. While explicit communication implies direct messages exchanged between the road users (e.g. light signals, horn, gestures), implicit communication is linked to indirect messages in which the content is not directly addressed (e.g. a car reduces its speed to encourage pedestrians to cross) (Fuest, Sorokin, Bellem, & Bengler, 2017). Explicit communication occurs between pedestrians and drivers mainly via gaze and/or gestures (Šucha, 2014). Without driver in an AV, this communication has to be provided alternatively in the future.

Multiple car manufacturers proposed HMI solutions for their Level 4 and Level 5 AV concepts, like for instance the Mercedes F 015 (Mercedes, 2015) or the Nissan IDS concept (Nissan, 2015). In order to deal with the missing communication between drivers and pedestrians, on-vehicle displays and/or projection technology are possible solutions to signalize for instance instructions to the pedestrians.

However, comprehensive testing and validation of the results are not published. Some researchers—as Clamann, Aubert, and Cummings (2017) and Benderius, Berger, and Lundgren (2017)—have proposed and tested concepts by using regular cars disguised as autonomous vehicles, with mixed results regarding the interfaces' effectiveness.

With these insights, a method, which is safe and easy to set up, for evaluating the usability of communication concepts between AVs and pedestrians is still lacking.

2.2 Testing Usability

Usability is defined as 'the degree to which something is able or fit to be used' (Oxford Dictionary, 2018). Rubin and Chisnell (2008) define a product or service as truly usable when the user 'can do what he or she wants to do the way he or she expects to be able to do it, without hindrance, hesitation, or questions' and speak of 'absence of frustration in using something'. van der Bijl-Brouwer (2012) studied the link between varying use situations and usability. In the presented context of AV to pedestrian communication, it means that the designed HMI should provide information (e.g., intention and/or instructions) that the user needs in order to successfully complete a task—in this case, crossing a street—and that he/she understands without hesitation or question.

Table 1 Attributes of usability and implications for the study

Attribute	General definition	Context of the study: HMI for AV to pedestrian communication at a one-way street
Usefulness	To which extend a product or service supports the user to reach his/her goal with regard to the willingness from the user's side to use the product or service in the first place	How should be the HMI designed so that the user is supported in his/her intention to cross the road? Is an HMI even needed?
Efficiency	Time, accuracy and degree of completion to reach the user's goal	Is the HMI supporting a faster decision-making for crossing the road?
Effectiveness	To which extent a product behaves as expected	Is the HMI adapted to the situation and the environment e.g. regarding traffic conditions and safety? To which extent can the HMI prevent wrong behaviour from pedestrians?
Learnability	Ability from user's side to operate a product or system considering a certain level of competence to operate the system after a predefined period of time	Are any competences from the user side required to understand the HMI correctly? Is a phase of education necessary to understand the message provided?
Satisfaction	Subjective feelings, perceptions and opinions from user's side to reveal users' satisfaction levels	How does the user perceive the HMI for crossing the road?
Accessibility	Access to the products or services that are needed to reach the goal especially for users with disabilities (e.g. temporary or permanent limited mobility)	Is the HMI understandable for people with disabilities e.g. cognitive disabilities?

Source Based on Rubin and Chisnell (2008)

According to Rubin and Chisnell's definition (2008), to be useful, a product or service should enable usefulness, efficiency, effectiveness, learnability, satisfaction, and accessibility. Table 1 presents the definition of these attributes according to Rubin and Chisnell as well as their implications for the study.

For answering the questions raised in Table 1, several methods and techniques can be used and combined to evaluate the usability of a product or service such as observation of users in real-life environment, surveys, expert interview or classical experiments with large sample sizes and control groups. Considering the advantages and drawbacks of the methods for evaluating usability based on the work of Rubin and Chisnell (2008) as well as van der Bijl-Brouwer (2012), Usability Testing is selected for the presented study.

This method provides empirical data from the observation of representative users while using a product or system. Compared to classical experiments, Usability Tests are more informal, iterative and give qualitative insights of a product's or service's usability. Basic elements that are included in the method are:

(a) The articulation of research questions or test objectives
(b) A representative amount of users (randomly or not randomly chosen)
(c) Representation of actual environment
(d) Observations and Interviews
(e) Quantitative and qualitative data.

However, the representation of actual environment for Usability Tests raises issues in the presented study of AV to pedestrian communication since the conduct of Usability Tests in real-life conditions with AVs and pedestrians is potentially dangerous for the test participants. Moreover, building up a testbed in real-life conditions to test the AV to pedestrian communication would lead to great effort, as well as time and money to be spent.

To tackle safety issues, costs, and time spent, VR is investigated as alternative to Usability Tests in real-life conditions.

2.3 Virtual Reality

VR's major scope of application is the gaming industry. One reason for this is the improved immersion into virtual environments and therefore enhanced experiences. However, it is also used as a tool in industry fields like automotive, construction and military (Berg & Vance, 2017). Deb, Carruth, Sween, Strawdermann, and Garrison (2017) used VR to conduct research in the field of pedestrian safety since it constitutes a safe alternative for test participants. Furthermore, VR is used as a research tool to conduct psychological studies thanks to its capabilities to create laboratory conditions for the experiments and its high flexibility to create immersive environments (Loomis & Blascovich, 1999). Mihelj, Novak, and Beguš (2014) state that VR is used for designing and testing machines and objects, especially when they are very expensive (e.g. power plants) or when they are produced in large quantities (e.g. cars).

Consequently, running Usability Tests in Virtual Reality (VR) environments is proposed as an alternative to real-life tests with the hypothesis that the attributes of usability can be evaluated similarly or even with advantages in regard to real-life tests, for instance, due to the possibility to neglect unintentional factors like the implicit communication of deceleration.

Therefore, the hypothesis is: Virtual Reality is a suitable tool to conduct Usability Tests with a multicultural selection of participants in order to evaluate the most *usable* HMI concept for the communication between AVs and pedestrians in ambiguous situations.

3 Method

3.1 Case Study

The purpose of the presented case study is to measure the usability of HMI display content for the AV to pedestrian scenario: A test person stands on the sidewalk of a one-way street with one lane and without traffic light and zebra crossing. The task is to cross the road as soon as the test person assesses the traffic situation to be safe. In each scenario, an AV that is equipped with an HMI concept approaches the test person. The HMI concepts indicate if it is safe for the test person to cross the road or not. To achieve this, each HMI concept consists of one "Cross" symbol and one "Don't Cross" symbol. The HMI concepts include the commonly understandable red and green colour combination, used at Singapore's traffic lights, in which green is used for indicating that the pedestrian has the right of way (Fig. 1):

- Walking man (a)
- Arrow (b)
- Check (c)
- LED strip (d)
- Traffic light (e)

A control test is made without any HMI concept in order to compare the HMI concepts with the absence of AV to pedestrian communication.

Since the goal is to evaluate the usability of used HMI concepts when applied in the AV to pedestrian scenario and not the display technology itself, a simple screen-like surface is positioned in front of the vehicle, where the content is shown (Fig. 2). Factors like reflections and brightness are neglected. A further controlled variable is the vehicle's deceleration: to avoid that pedestrians decide to cross based on the AV's kinematic cues, the AV's deceleration was disregarded.

In light of Singapore's speed limit regulations for one lane roads, a speed of 50 km/h (v = 13.9 m/s) was selected for the approaching vehicle (Land Transport Authority, 2017).

Initially, an appropriate distance from which the AV starts displaying the information to the user has been calculated (Distance to Zebra, DTZ), which is the product of the factors speed (v) and Time To Collision (TTC) (Eq. 1). TTC

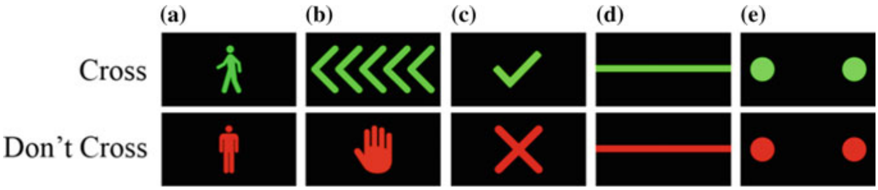
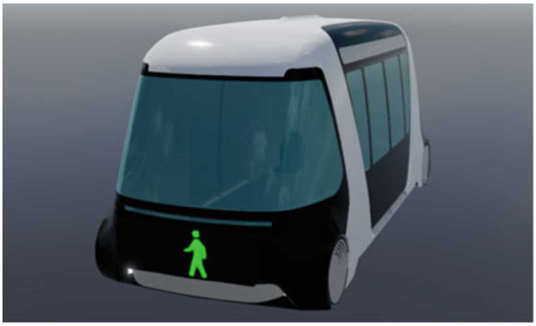


Fig. 1 Concepts tested for HMI content [The HMI concepts to be tested have been developed based on internal workshop sessions and surveys (Theoto, 2018)]

Fig. 2 Basic interface



describes the time it would take for the AV to reach the pedestrian's path if the chosen vehicle speed (v) is kept constant (Schneemann & Gohl, 2016).

$$DTZ = v \cdot TTC \tag{1}$$

TTC is the sum of the minimum perceptual reaction time of 2.5 s, and the average time required to cross a single lane of traffic of 2.7 s (based on Clamann et al., 2017) (2.5 s + 2.7 s = 5.2 s). The TTC of 5.2 s is within the critical gap acceptance interval as observed by Schmidt and Farber (2009): under 3 s, no pedestrian crosses the street, whereas everybody walks with a TTC above 7 s.

Considering a constant speed of the vehicle and a TTC of 5.2 s, the DTZ has been set to 72.2 m (Eq. 2).

$$DTZ = v \cdot TTC = 13.9 \frac{\text{m}}{\text{s}} \cdot 5.2\ \text{s} = 72.2\ \text{m} \tag{2}$$

Figure 3 showcases the configuration of the virtual environment. The participant position is delimited with a cross on the virtual sidewalk, and as soon as he/she faces to the right-hand side, the vehicle appears. Other traffic and road users were neglected. This guarantees that all participants face the AV at the same initial spot and under the exact same conditions.

Fig. 3 Configuration of virtual environment

3.2 Test Participants

As one aspect of the scenario lies on a multicultural environment, the chosen quota sample for the recruitment of test participants reflects Singapore's ethnic distribution. Since there is no ethnic data for the large non-resident population (which account for 29.4% of the country's population, i.e. 1.65 million people), the sample is based on the citizens and permanent resident (PR) data (Singapore Statistics, 2017). Therefore, the ethnic composition of the sample is 53.8% Chinese, 10.6% Malay, 5.2% Indian, and 30.4% PRs with other ethnicities.

3.3 Virtual Reality Hardware Setup

The Virtual Reality Laboratory consists of an empty space of up to 4.5 m × 4.5 m. Tracking devices allow investigating position changes as well as head movement. Test persons get immersed in the virtual scenario with help of a Head Mounted Display (HMD) (i.e. HTC Vive). Input devices allow the test person to interact with the virtual scenario if needed. To deepen the immersion, the test person wears noise-cancelling headphones. Additional hardware is located outside the tracked area.

3.4 Adaptation of Usability Tests Within VR

The Usability Tests within VR focus on the following attributes of usability listed in Table 1: *efficiency*, *effectiveness*, and *satisfaction*. The attributes are chosen due to the fact that the quantitative measures of *efficiency* and *effectiveness* (i.e. reaction time and error rate) can be collected very accurately with the help of VR. *Satisfaction* is chosen in order to get qualitative insights about the test participants feelings and perceptions regarding the HMI concepts.

For the assessment of *efficiency* of selected HMI concepts, reaction times are measured and compared afterwards with the control group. The reaction time is defined as the time it takes from the moment when the test participant sees the AV until he/she starts to cross the road. *Effectiveness* can be derived from an error analysis, in which the amount and type or errors (e.g., the pedestrian crosses when he/she must not) are collected and analysed. The level of *satisfaction* is assessed with qualitative data, collected with questionnaires before and after the Usability Tests.

The procedure for the tests is shown in Table 2.

One test person is tested at a time. Prior to the tests, a first questionnaire is conducted. Then, the participants are introduced to the VR setup with help of a tutorial in order to get familiarized with the technology. After the tutorial, the

Table 2 Procedure of the tests within VR

Procedure	1	2	3	4
Activity	First questionnaire	Tutorial	Usability tests	Final questionnaire
Duration (min)	5	2	10	3

Usability Tests are conducted. Here, the test participant gets the task to cross the street while an AV is approaching. Since there are five HMI concepts that include one symbol for "Cross" and one symbol for "Don't Cross", as well as one control group, the test is conducted eleven times per test participant. First of all, the control group without HMI concept is conducted, followed by the five HMI concepts. The sequence of procedure for the HMI concepts is randomized to rule out distorted results caused by the testing order. After the tests, a final questionnaire is conducted in order to get insight into the feelings and perceptions of the test participants.

4 Findings

Overall 18 people participated in the Usability Tests. The ethnic distribution of test participants was: 10 Chinese participants, 2 Malay participants, 1 Indian participant and 5 Participants with other ethnicities.

Figure 4 presents results of the test, i.e. the average decision times for each HMI concept.

The result showed that the decision times differed significantly between the control group and any HMI concept. While the average reaction time for the control group is 4.8 s, the average reaction times for the HMI concepts lie between 2.0 and 3.0 s.

This data proved that the symbolic representations lead to a reduced pedestrians' reaction time. When HMI concepts were not present, the mean reaction time was significantly larger (4.8 s instead of 2.0–3.0 s), showing that display intention or instructions to pedestrians can help their decision process, at least when no other intention indicators (deceleration, engine sound) are present. However, no significant decision time variation among the different HMI concepts was observed.

Through the collection of error rates, the HMI concepts' *effectiveness* regarding usability has been evaluated. As Table 3 shows, the test revealed that in 72.2% of the tests the control group led to errors, as test participants crossed the street when the vehicle exercised its right of way and did not stop for the test participants. When the HMI concepts were present, errors occurred only in three out of 90 trials.

This outcome is an indicator of the HMI concepts' *effectiveness*, as the error rate declined steeply when HMI concepts were present. A comparison among the different HMI concepts was possible, as the "Check" and "LED Strip" were less effective than the other ones.

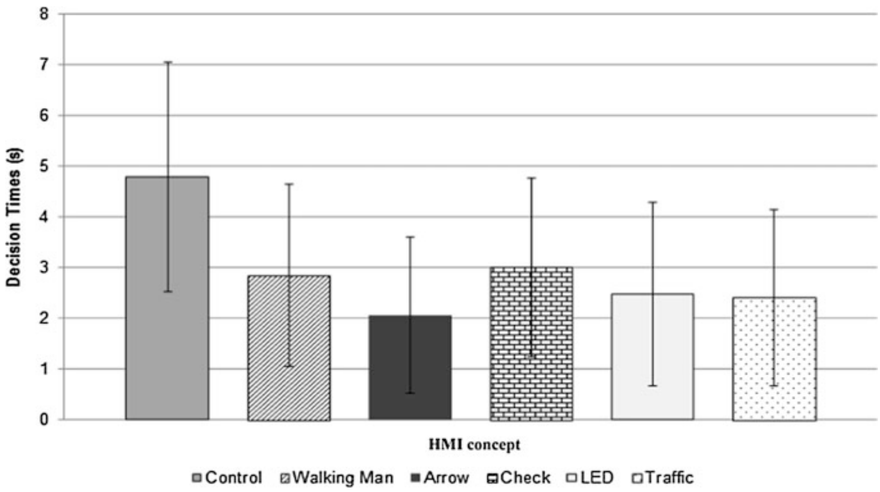


Fig. 4 Comparison between average decision times, in seconds, for the control group and different HMI concepts

Table 3 Error analysis for control group and different HMI concepts

HMI concept	Error frequency (%)
Control	72.2
Walking man	0
Arrow	0
Check	5.5
LED strip	11.1
Traffic	0

Finally, the *satisfaction* was analysed thanks to the questionnaire after the tests. The questions to be answered concerned the subjective cognitive effort for the test participant to complete the task. This question had to be answered for each HMI concept as well as for the control group. In order to get a homogenous outcome, the test participants were asked to indicate the effort on a scale which ranges from −60 (very low effort) to 60 (very high effort). Consequently, negative results indicate a low effort to complete the task. The answers revealed that only the control group's value was distinguishable from HMI concepts, whereas the values of the HMI concepts among one another did not lead to significant differences (Table 4).

Further questions were insightful regarding the perception if the test participant was able to detect the HMI concept (Detection), if the HMI concepts influenced the decision making for crossing the street or not (Influence on crossing), and if the HMI concepts were comprehensible for the test participants. "Yes or No" questions were asked to evaluate aforementioned perceptions. Figure 5 presents the answers

Table 4 Subjective effort to cross the road for the HMI concepts and control group

HMI concept	Indicator of effort
Control group	−22.8
Walking man	−42.5
Arrow	−46.8
Check	−35.4
LED strip	−43.0
Traffic	−42.9

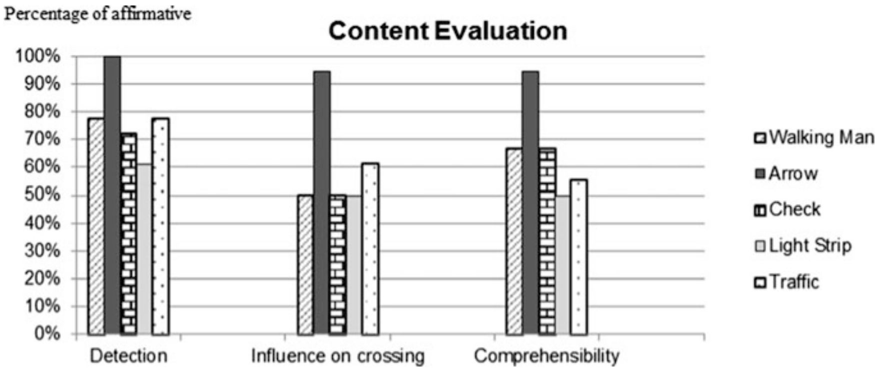


Fig. 5 Results of questions regarding detection, influence on crossing and comprehensibility of HMI concepts

for the questions regarding the possibility to detect the HMI concepts, if the HMI concepts influenced the decision making on crossing the street, and if the HMI concept was understandable for the test participant.

The bars represent the percentage of participants that answered the questions affirmatively. This means for instance that 100% of test participants could detect the HMI concept "Arrow" and 50% of test participant stated that the HMI concept "LED Strip" influenced their decision making on crossing the street. As it is visible in Fig. 5, the "Arrow" HMI concept had the highest rates in all three categories. On the other hand, the "LED Strip", "Check", and "Traffic" HMI concepts were the concepts that influenced least the decision making to cross the street. Furthermore the "LED Strip" and "Traffic" HMI concept were the least comprehensible concepts in the test participants' subjective sense. This qualitative data indicates a higher user *satisfaction* when interacting with the "Arrow" HMI concept than with the other concepts.

5 Discussion

The discussion merges the facts that have been brought to light by the case study regarding the HMI and the more general points about the Usability Tests within VR that have been found out during the development process of the methodology.

Within the presented study, it was possible to demonstrate the need for an explicit HMI for the communication between AVs and pedestrians in ambiguous situations. Indeed, even though the HMI concepts did not have significant differences in terms of *efficiency*, *effectiveness*, and *satisfaction* among one another, the results had significant differences compared to the control group without any explicit HMI concept. This could be highlighted within VR since it was possible to test the explicit HMI concepts in an isolated way without interfering factors like deceleration. In other studies, like the one from Clamann, Aubert, and Cummings (2017), who conducted research on explicit HMI for manually driven cars that were disguised as AVs, deceleration and gap distance were identified as the main indicators for pedestrians to assess traffic situations. We suppose that these indicators interfered with the accurate evaluation of explicit HMI concepts since they constituted unneglectable variables. However, the neglect of these variables was possible within VR and thus the presented method is validated as suitable tool for evaluating communication concepts without interferences.

Furthermore, Pillai (2017) conducted a study of implicit communication (i.e. deceleration behaviour) between AVs and pedestrians at zebra crossings within VR. Beyond the results that a “human-like” driving behaviour from AV’s side improves the interaction with pedestrians, the study revealed that explicit HMI concepts would have been useful for the test participants to further assess the situation correctly. This underlines the necessity for explicit HMI concepts.

In further studies, it is planned to investigate a combination of explicit and implicit communication for better usability for pedestrians. Supplementary development can also accommodate further scenarios in which for instance more than one pedestrian are willing to cross the road, or pedestrians come from different directions.

Regarding the methodology used within VR, the presented study has validated that VR is a suitable tool to conduct Usability Tests for the case study of explicit communication between AVs and pedestrians in ambiguous situations. There are drawbacks in using VR like limited immersion and absence of haptic feedback. However, VR enables high flexibility to create the environment and the scenarios and the tests could be conducted with ensured safety for the test participants. This is aligned with findings from Deb et al. (2017) and Pillai (2017).

As a next step, a benchmark test is planned to be conducted to prove the validity of collected data within VR. In order to do so, a scenario will be created in real-life conditions as well as in VR and afterwards compared regarding congruence of results.

Finally, it will be investigated if the presented methodology can be used for other case studies like for instance how information, related to AV technology (e.g. intention or detection) can prevent anxiety from passengers' side inside an AV for public transport.

6 Conclusion

The present work highlighted the suitability of Virtual Reality as a tool to test usability, particularly in the context of communication between AVs and pedestrians. On the one hand, when no functional AV prototype is available, the method worked as a quick, preliminary validation method for the presented case study. On the other hand, the case study showed that the absence of communication between driver and pedestrian needs to be compensated towards an explicit HMI. Even though there are no significant results about differences of *efficiency*, *effectiveness*, and *satisfaction* attributes among the tested concepts, the VR Usability Tests helped to evaluate and dismiss several alternatives. Regarding the case study, further tests are necessary to evaluate the influence of implicit communication for the decision making of pedestrians in the Av to pedestrian scenario. In order to further validate VR as a suitable tool for the conduct of Usability Tests in general, additional case studies will be selected and additional usability attributes will be focused on.

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