Context-Based Interface Prototyping and Evaluation for (Shared) Autonomous Vehicles Using a Lightweight Immersive Video-Based Simulator

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ABSTRACT

Autonomous vehicles (AVs; SAE levels 4 and 5) develop rapidly, whereas appropriate methods for interface design and development for such driverless vehicles are still in their infancy. This paper presents a simple approach for context-based prototyping and evaluation of human-machine interfaces for (shared) AVs in public transportation. It demonstrates how to set up a lightweight immersive video-based AV simulator using real-world video and audio footage captured in urban traffic. In two user studies ($n_1 = 9$; $n_2 = 31$) we investigate presence perception and simulator sickness to provide initial evidence for the suitability of this cost-effective method. Furthermore, with the intent to increase presence perception and technology acceptance, we combine the AV simulator with a human actor imitating a passenger that gets on and off a shared AV ride.

Author Keywords

Shared Autonomous Vehicles; Public Transport; Prototyping; Simulation; Immersive Video; Evaluation; Human-Machine Interfaces; User Experience Design.

CSS Concepts

•Human-centered computing~Human computer interaction (HCI)~HCI design and evaluation methods •Human-centered computing~Ubiquitous and mobile computing~Ubiquitous and mobile computing design and evaluation methods

INTRODUCTION

Over the past three decades, much effort has been put into the development of driver-assistance systems and automated driving systems [3]. The Society of Automotive Engineers (SAE) [36] describes six levels to classify automotive systems according to their degree of automation: (0) No Driving Automation, (1) Driver Assistance, (2) Partial Driving Automation, (3) Conditional Driving Automation, (4) High Driving Automation and (5) Full Driving Automation.

Figure 1. Immersive video-based autonomous vehicle simulator with a 26-inch passenger information display.

In SAE levels 0 to 3, a driver is still required – either to perform (parts of) the driving task or to take back control when the system reaches its limitations (or fails), whereas in levels 4 and 5 a (remote) driver is optional. To avoid misconceptions, this paper uses the term "autonomous" vehicles (AVs) to describe SAE levels 4 and 5 as also proposed by [43].

When a human driver is no longer required, two things need to be considered. First, all occupants are passengers who do not have to pay attention to the driving task. Thus, they can perform non-driving related activities while traveling. Similar to train or bus travels, passengers might use the attained flexibility for communication, productivity or relaxation [15]. Second, when using AVs in public transport, human-machine interfaces (HMIs) need to provide the passengers with all the information they need along their travel journey. Such HMIs compensate for the absence of a human driver and are a key source of passengers' trust in the system. This is also very important for shared autonomous vehicles (SAVs).

SAVs have great potential for solving common challenges of today's public transport systems, e.g. regarding congestion, accessibility or first and last mile problems [7, 22, 34, 41]. They promise to provide low-cost traveling and, as vehicle stops can be spatially and temporally flexible (i.e. there is no necessity for fixed timetables or fixed stops), SAVs can potentially substitute the demand for personal cars [30, 34]. In addition to technical hurdles that need to be overcome, a lack of public trust is considered as the central barrier for adaption

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of SAVs [24]. To defy these hurdles, a precise understanding of the interrelation between people, system, and environment is needed [29] while human factors and user requirements need to be considered from early development phases on [4]. Suitable analysis, design and evaluation methods, as well as appropriate prototyping approaches, are required to inform and enable both, researchers and designers. Contributing to the development of such approaches, this paper explores prototyping and evaluation methods as well as human factor challenges with a focus on contextual simulation and HMIs for (S)AVs, e.g. concerning passenger information systems in a public autonomous mobility-on-demand (AMOD) system.

The contribution of this paper is twofold. First, we introduce and evaluate a simple method for creating a low-budget (S)AV simulator. In contrast to common driving simulators, our approach does neither have any controls related to the driving-task nor rely on a 'pure' virtual environment in terms of computer-generated imagery (CGI). Instead, real-world video and audio footage is used to create an audiovisual simulation. Second, we investigate the influence of an actor – imitating an entering and leaving passenger – has on presence perception, simulator sickness and on participants' assessment of prototypes and systems.

BACKGROUND

In the past years, a sizeable body of literature on AVs, especially regarding their technological and socio-economic aspects was published. See [34] and [30] for traffic simulations and case studies on the implementation of AMOD in New York City, Singapore, and Austin. Furthermore, more and more AVs are now being tested publicly in many cities around the world, e.g. in Phoenix (USA) [21], Greenwich (UK) [19] or Berlin (Germany) [32]. Some literature focusses on human factors challenges on a rather theoretical level, but only few investigate practical implications of these aspects. The same applies for design methods and processes for designing and developing (shared) AVs and AMOD systems. However, practicable methods are needed to align human factor challenges and user requirements with the technological possibilities.

Human factor challenges

Key hurdles for the acceptance and adoption of SAVs are users' expectations, the technology's reliability, performance and security as well as privacy concerns and trust issues [24]. The main barrier for the success of AVs is the latter aspect, public trust [24], which can be described as "a belief that something is expected to be reliable, good and effective" and as a mental state people have based on their expectations and perceptions [29]. Easy-to-understand human-AV interactions are crucial to counteract public trust and acceptance issues [12]. To develop such interactions, it is essential to gather a clear understanding of the interrelation between people, system, and environment [29]. Therefore, straightforward context-based methods for design, prototyping and evaluation are needed.

Prototypes and simulation

Field studies with real AVs, e.g. [32], are currently only feasible under very limited conditions. These limitations restrict use cases that can possibly be evaluated and might bias the results. As it will still take a few years until (S)AVs can be used and tested in natural everyday situations, it is essential to explore appropriate methods for simulation and prototyping of realistic scenarios to overcome adoption hurdles. Such methods can be applied in lab environments featuring large experimental control and high replicability.

On the nature of prototyping

Prototypes are an integral part of most design and development life cycles. Typically, there are two major use cases of prototypes: generating ideas about the design of interfaces and evaluating the quality of (design) solutions, especially in early development phases [2]. Often, prototypes are just regarded as an instrument for the latter. However, they can be a tool for "traversing a design space" to create and gain knowledge about the (final) design and also as "manifestations of design ideas" [31]. By considering both perspectives, prototypes become a key component in all phases of the design process. Creating prototypes enables the experience of (not available or not yet created) products, spaces, and systems [6]. They empower designers, users and other stakeholders (1) to understand context and already existing user experiences, (2) to explore and evaluate new concepts as well as (3) to communicate ideas [6].

Need for context-based design and evaluation

Especially in driving scenarios, contexts are often highly dynamic and complex and are thus very important to be considered in human-machine interaction [26]. A context comprises not only audio-visual impressions and the surrounding environment, but might also include the presence of other people and the user's relationship with them [26]. This aspect becomes especially important in shared rides, as other passengers might influence a person's interaction with a system. For example, the presence of others might induce stress on people [13]. Since "autonomous ridesharing is still a theoretical subject […] and users still lack the hands-on experience" [35], high-fidelity prototypes are needed to simulate this context. In-line with that, Krome et al. [27] highlight the importance of considering environmental factors when designing automated driving systems. Their approach encompasses the lab-based simulation of specific contextual attributes. To achieve this, they played back video footage from real traffic situations on a monitor display to evaluate their prototype with a basic ride simulation, which appeared to be a promising approach.

Driving simulation and immersive video

Simulators enable the safe assessment of new systems and interfaces in early development phases. They allow high controllability, reproducibility, and standardization of test parameters and feature high flexibility and simplicity in data collection [37, 42]. A major challenge regarding the use of driving simulators is the creation of a participant's experience of presence in the simulated environment [5]. To achieve high presence perception, high fidelity reproduction of visual, acoustic, haptic and spatial stimuli is essential [5]. As limitations regarding the realistic representation of these stimuli persist even in modern simulators, the validity of (automated) driving simulators studies remains an important research topic [23]. Furthermore, 'simulator sickness' symptoms – e.g. nausea, vertigo, sweating or headache [23] – might occur while being in the virtual environment. Hock et al. [23] provide a checklist to overcome typical challenges when conducting driving simulator studies.

Most modern driving simulators display computer-generated virtual environments for sight simulation, e.g. [17]. They often use either CAVE-like [9] virtual environments, head-mounted displays or a compilation of three monitors. Such setups are mostly applied to simulate non-driverless vehicles, i.e. SAE levels 0 – 3, or – in combination with live-video streaming – for vehicle teleoperation (e.g. [10]).

Instead of computer-generated environments, it is also possible to use (real-world) videos for the simulation. For example, Krome et al. [27] use a video from real-world traffic to provide a basic ride simulation for their HMI studies. Taking this approach one step further, multiple real-world videos can also be used to create a 'CAVE'-like [9] environment [see 26, 33]. Kray et al. [26] call this approach 'immersive video'. It features realistic audio-visual representation of real-world contexts as well as a high degree of control. Gerber, Schroeter & Vehns [16] combine a pre-existing advanced driving simulator with the immersive video approach and with virtual reality to increase the driving simulator's immersion.

VIDEO-BASED (SHARED) AV SIMULATOR

We consider – similar to Krome et al. [27] – investigating the future context of driving in a (S)AV as a 'prototyping challenge'. To solve this challenge, we created an immersive video-based AV simulator (Figure 1). The simulator consists of a CAVE-like environment that was created by setting up three video projectors, a stereo sound system and a 3×2 seating group in an office room. The video footage was recorded using three action cameras while driving through urban traffic and postprocessed to create a synchronized immersive video. Using immersive video holds two major advantages: it provides a high-fidelity representation of the real world and the creation of the simulation does not require programming skills.

Basically, our setup makes riding in a driverless pod-like AV experienceable and provides the basis for context-based user research, interface prototyping and usability testing. Interfaces – e.g. passenger information displays – can be evaluated in a controlled environment including high-level contextual information. In contrast to the setup by Gerber, Schroeter, & Vehns [16], our approach focuses explicitly on simulating a (shared) AV (SAE levels 4 and 5). However, it can be regarded as a modified adaption of their 'IVAD' simulator [16]. By using relatively low-budget consumer equipment only, we place particular emphasis on simplicity, reproducibility and cost efficiency.

Setting up the simulator

As AVs are driverless, it is not necessary to have control elements like a steering wheel or a gas pedal. Thus, the simulator interior can be rather simple and abstract. We – for example – use a standard office room as a basis to make the setup easy to reproduce in any kind of typical (office) building.

Our sight simulation encompasses a viewing area of about 270° (Figure 1) and is displayed by three video projections (Vivitek DH833 with 1080p resolution). The projections resemble the view out of the front window (projection size: 96.5 inch × 41.34 inch) and the side windows (projection size: 72.8 inch × 41.34 inch) of a "pod"-like people mover, e.g. [11]. We also considered using large monitor displays instead of video projectors for the wall-size simulation but decided to go with the latter because they are both, less obtrusive while not in use and less expensive.

A stereo sound system (Fostex PM0.3d) displaying the acoustic simulation and sound signals accompanies the visual simulation. For testing purposes, the setup can be extended by HMI displays and controls as well as by seating groups and other components resembling the interior of the respective vehicle. In our case, we want the simulator to look like the interior of a people mover used for public transport with a 3×2 seating group in the front area. Figure 2 schematically illustrates our final setup.

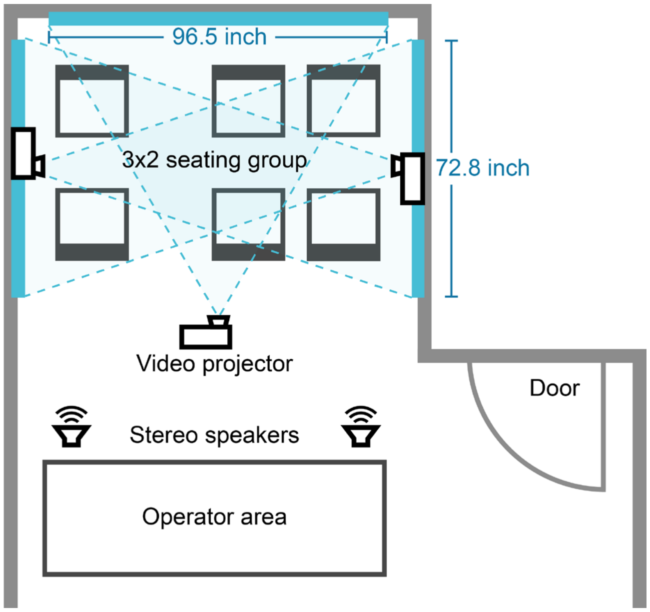


Figure 2. Schematic illustration of the AV simulator setup consisting of three 1080p video projectors, stereo speakers, and a 3×2 seating group.

Recording video and audio

The video and audio footage necessary for the basic simulation can be recorded anywhere by driving a common camera-equipped car through traffic. There is no need for special or expensive equipment. However, the route (and potential stops) should be carefully planned in advance to meet the requirements of the intended (prototyping or evaluation) activities. In case of simulating a shared ride, the AV needs to stop sometimes to enable other (simulated) passengers to enter or leave the vehicle. It is recommended to devise a plan for adequate spots for such breaks in advance and to determine parameters like stopping time before starting the ride. To mimic the behavior of an AV, the driving style should be very conservative, highly anticipatory and conform with the traffic rules [16]. Additional recordings of GNSS data, e.g. with a smartphone navigation app, help to synchronize HMI information afterwards.

For the video recordings, three identical low-budget action cameras (Crosstour CT8500, 4K resolution, 170° wide-angle fisheye lens) were used. The cameras were mounted with suction cups on the car's windscreen, left window and right window (Figure 3). To later create an immersive video out of the recordings, the cameras need to be aligned to each other regarding position, height, orientation and color configuration. No special equipment, e.g. a video rig [16], was used, in order to keep the setup effort as minimal as possible. In our case it worked best to simply position the cameras on about the same height and at the center of the three windows (Figure 3). Then, they were manually fine-calibrated in terms of alignment and orientation with a small overlap area at the edge of the videos, while monitoring their streams on a 10.1-inch tablet.

Figure 3. Recording footage of urban traffic for the visual simulation using low-budget action cameras.

Certain challenges arise when placing the cameras behind the car's windows, e.g. reflections, occlusions and rain drops or dirt on the windows might impair video quality. To minimize disturbing artifacts, some preparations are necessary. Reflective interior elements should be covered with non-reflective materials, e.g. dark tape. Drivers should wear long dark clothes to diminish reflections of body parts. Windows and camera lenses should be kept clean at all times. To avoid extreme lighting, raindrops or other adverse effects, the recording time should be carefully chosen with regard to the weather conditions. In support of [16], recording in bright, but cloudy weather is recommended. If possible, the cameras' white balance levels as well as their apertures and shutter speeds should be consistent and therefore configured manually – especially when a mostly bright route contains some dark areas like tunnels or forests.

For the sound simulation, we recommend using the audio track recorded by the center camera or by an additional microphone mounted inside the car during the video recordings as a basis. Additional sounds – e.g. the sound of closing doors, noises of other passenger or signal sounds – can be digitally created or recorded separately and merged afterwards. For example, for the second experiment some extra sounds from busses and trams were recorded to simulate the context of a public transport environment. Voice prompts – e.g. announcing upcoming stops – can be recorded with sufficient quality by using built-in microphones of smartphones or laptops.

Postprocessing video and audio

To create the immersive video, we postprocessed the three videos with Adobe After Effects (AE) CC 2019. The videos were placed in a virtual three-dimensional room within AE resembling the dimensions of the office room (Figure 1, Figure 2) to adjust their overlapping areas, perspective, scaling, distortion (to remove the fish eye effect) and position. This enabled us to precisely synchronize and calibrate the footage and to correct minor flaws of the recording process. As the footage was recorded in 2K (and the projectors were only capable of displaying 1080p), it provided sufficient video quality to make the adjustments.

The sounds were normalized using Adobe Audition CC 2019 and distorting noises were removed. Furthermore, some extra environmental sounds, signal sounds and voice prompts for our second study were added.

Synchronized playback

All components, i.e. three video files, one sound file and (optional) HMI displays needed to start synchronously. The best operational setup we tested consisted of a single Macbook Pro (2015) controlling both, sight and sound simulation. Therefore, all video and audio files were opened in QuickTime Player (v. 10.5) and an Apple Script was used to trigger the play event for all opened files.

STUDY 1

To explore the proposed setup, its strengths and weaknesses, HCI professionals were invited. Similar to conducting expert-based usability evaluations of in-vehicle systems [20], we wanted the experts to share their unbiased opinions on the simulation and to provide insights on how to improve the setup. The main purpose of study 1 was to investigate the quality of the simulation, to eliminate potential issues with the setup and to derive optimizations.

Participants

9 participants (4 female, 5 male, 0 n/a) with an average age of *M* = 29.56 years (*SD* = 4.22; [23; 38]) took part in the study. They were recruited internally from design and development teams (but were external to the project) and had a professional background in HCI.

Experimental design and procedure

After a short introduction from the experimenter, the participants filled out a demographic questionnaire. Then, they took a 20 minutes ride in the AV simulator while thinking-aloud, i.e. they verbalized any thoughts they had during the ride. Directly after the ride, participants filled out a questionnaire to evaluate the quality of the simulation and the experienced level of realism. We chose the Igroup Presence Questionnaire (IPQ) [38, 39] for a standardized assessment of presence as it provides "the highest reliability within a reasonable timeframe" [40] among presence questionnaires. In the last phase, the experimenter conducted a semi-structured interview with the participant to learn about their experiences in the simulator setup and to uncover issues and optimization potential.

Results

Results of the IPQ show positive ratings in the four subscales (Table 1). In terms of the scale Experienced Realism the results are, however, slightly on the lower side of the scale. The results of the IPQ are backed by ratings for the single item *"I found the ride in the simulator realistic."* with $M = 3.56$ *(SD = 0.53)* [from *0 = not at all* to *5 = fully]*.

Subscale	M *(SD)*
Spatial Presence	4.00 *(0.51)*
Involvement	3.36 *(1.05)*
Experienced Realism	2.93 *(0.58)*
General	3.56 *(1.33)*

Table 1. Means *(SD)* of the IPQ [38, 39] subscales [from *0 = low* to *6 = high*] from study 1 (*n* = 9).

Qualitative feedback from the participants of the exploratory study supports the findings regarding presence perception and the general suitability and potential of the AV simulator. All nine experts commented positively on the context-based prototyping approach. Potential for optimization was in particular revealed regarding the sound simulation. Participants suggested to add sounds of opening and closing doors, noises from other passengers and signal sounds for announcing the next stop. Furthermore, three participants emphasized the idea of increasing presence perception by adding actors to simulate passengers getting on and off during shared rides.

STUDY 2

In study 2 we intended to evaluate the setup with a larger sample and to find out whether AV simulator studies would actually benefit from involving an actor mimicking the behavior of other passengers in terms of participants' subjective presence perception, technology acceptance and motion sickness. Furthermore, the simulator was extended by including the proposed additional sounds.

As other passengers are omnipresent in public transportation (and shared rides) and therefore an important part of the context, study 2 aimed to investigate their effects on both, the simulation and overall technology acceptance of shared AVs. However, the presence of others might induce stress resulting in adverse effects on passengers' wellbeing [13]. We expected the negative effects of involving an actor to be rather small and hoped to increase participants' presence perception within the simulation. Furthermore, we expected to discover positive changes in participants' acceptance regarding the use of a shared AV. Consequently, the following hypotheses for study 2 were derived:

H_1 The involvement of an actor has a positive effect on participants' presence perception in AV simulator rides.

H_2 The involvement of an actor has a negative effect on participants' wellbeing in AV simulator rides.

H_3 The involvement of an actor has a positive effect on participants' technology acceptance of shared AVs.

Participants

To achieve sufficient power (> .80) with an alpha error of $\alpha \leq .05$, a required sample size of $n_{a\text{-priori}} = 27$ was calculated using G*Power for Mac (v. 3.1.9.4). Medium effects according to [8] were assumed due to practical considerations, e.g. economic viability, as smaller effects might not warrant the increase in setup effort by enlisting an actor. 31 participants (15 female, 16 male, 0 n/a) with an average age of $M = 31.97$ years ($SD = 10.46$; [18; 54]) took part in study 2. Thus, an actual power of .859 was achieved. All participants were recruited via online postings and received financial compensation. 58 % of participants were holding a university degree and an additional 26 % had a higher secondary school leaving certificate. The Affinity for Technology Interaction (ATI) score [14] of $M_{ATI} = 4.41$ ($SD_{ATI} = 0.76$; 0 = low; 6 = high) indicates high technology affinity among the sample.

Experimental design

The study used a counterbalanced within-subjects design with a within-subjects factor of riding with an actor or not. To avoid systematic carry-over effects, condition order was pseudo randomized, ensuring an equal number of orders. Dependent variables (presence perception, well-being, technology acceptance) and their respective operationalization are listed in Table 2.

Factor	Operationalization
Presence perception	Igroup Presence Questionnaire (IPQ) [38, 39] 'Feeling of reality' – single item *„I found the ride in the simulator realistic."*
Wellbeing	Motion Sickness Assessment Questionnaire (MSAQ) [18] (German translation) 'Feeling of comfort' – single item "*I felt comfortable during the ride."*
Technology acceptance	Acceptance Questionnaire of Van der Laan et al. [28] (German translation [25])

Table 2. Dependent variables and their corresponding operationalization for study 2.

Again, we used the IPQ in combination with the single item 'feeling of reality' (*„I found the ride in the simulator realistic."*) to assess presence perception. To evaluate participants' wellbeing and corresponding adverse effects (e.g. simulator sickness) a German translation of the Motion Sickness Assessment Questionnaire (MSAQ) [18] along with the single item 'feeling of comfort' (*"I felt comfortable during the ride."*) was used.

Regarding H_3, a German translation [25] of the Acceptance Questionnaire by Van der Laan et al. [28] was applied.

In addition to the quantitative measurements, the AV simulator and the prototype of a passenger information system were examined exploratively by observing the reactions and behavior of participants during simulator rides and interviewing them afterward to gather qualitative feedback.

Procedure

On arrival, participants received a short briefing on the study including general information on (shared) AVs, the general objective of the study, and information on simulator sickness. Furthermore, they signed a participation consent form.

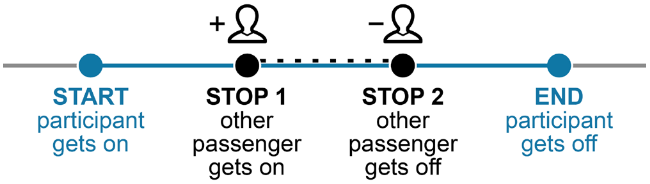


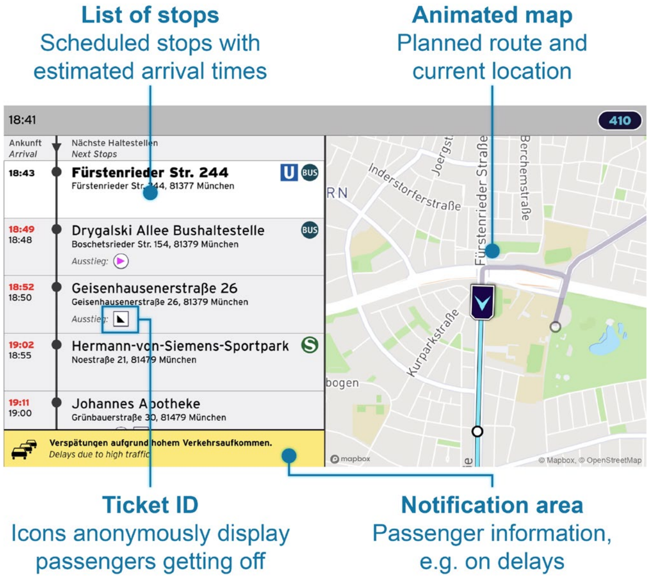
Figure 4. Schematic illustration of the ride sequence.

Participants took two rides in the AV simulator. Before each ride, the scenario (taking a shared AV to a park and back) was presented and a paper ticket was given to the participants. Each ride took about 14 minutes. In both rides, the simulated SAV stopped twice before the participants reached their destination (Figure 4). Another passenger joined the ride at the first stop and left at the second stop. An information display, as well as the sound simulation (step noises), provided information about another passenger getting on/off the vehicle. In one of the two rides (randomly permutated) an actor representing this passenger physically entered the AV simulator. Participants did not receive a briefing on this prior to the rides. In the condition without an actor, the other passenger entered only 'virtually' (i.e. he was only represented by the sounds being heard).

In both conditions, the other passenger's getting on/off was displayed on an information display (Figure 5). At the third 'end' stop participants reached their target destination. After each ride, participants filled out a digital questionnaire to assess the variables listed in Table 2. At the end of the session, they received a debriefing and their compensation.

HMI concept

During the ride, an audiovisual HMI (26-inch display and stereo sound system) communicated the SAV's current location (position in the map), upcoming stops, the planned route and traffic conditions (e.g. delays caused by congestion). For study 2, some parts of the visual information display (Figure 5) were personalized, e.g. respective passenger destinations were indicated via unique ticket IDs. The visual information was complemented with signal sounds and voice prompts announcing upcoming stops. The audiovisual HMI was integrated in the AV simulator as a video-based prototype (Figure 1).


List of stops
Scheduled stops with estimated arrival times

Animated map
Planned route and current location

18:41

Ankunft *Arrival*	Nächste Haltestellen *Next Stops*
18:43	**Fürstenrieder Str. 244** Fürstenrieder Str. 244, 81377 München
18:49 18:48	Drygalski Allee Bushaltestelle Boschetsrieder Str. 154, 81379 München *Ausstieg:*
18:52 18:50	Geisenhausenerstraße 26 Geisenhausenerstraße 26, 81379 München *Ausstieg:*
19:02 18:55	Hermann-von-Siemens-Sportpark Noestraße 21, 81479 München
19:11 19:00	Johannes Apotheke Grünbauerstraße 30, 81479 München

Verspätungen aufgrund hohem Verkehrsaufkommen.
Delays due to high traffic

Ticket ID
Icons anonymously display passengers getting off

Notification area
Passenger information, e.g. on delays

Figure 5. HMI concept (© 2020 by Ergosign GmbH; map: © Mapbox, © OpenStreetMap) providing information on the current location of the SAV (position in map), the planned route, passengers getting on/off, and traffic conditions.

Results

Tests on normality (Shapiro-Wilk) were performed on the underlying distributions prior to the statistical analysis. In case they returned non-significant, parametric inferential statistics (paired-samples t-tests) were calculated. Otherwise, Wilcoxon signed-rank tests were computed. For the statistical analysis JASP for Mac (v. 0.10.2) was used. The reported participant statements were translated into English by the authors.

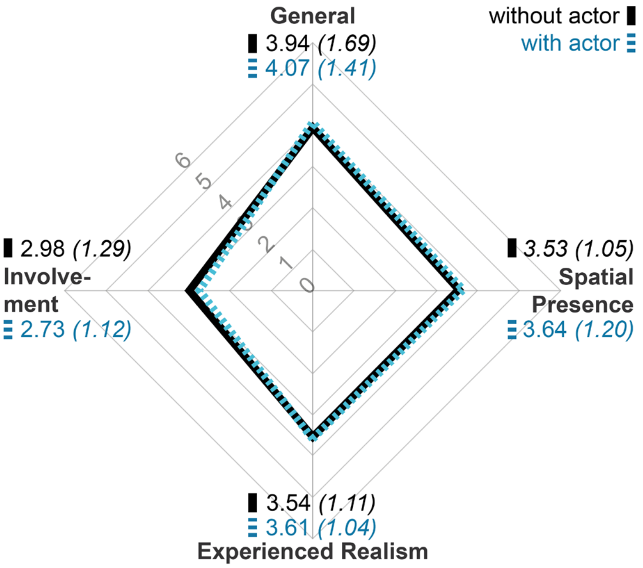


Figure 6. Means *(SD)* of the IPQ [38, 39] subscales [from *0* = *low* to *6* = *high*] for the two conditions (without actor – with actor; *n* = 31).

Presence perception

Descriptive statistics and plots of the IPQ scales (Figure 6) reveal similar results to study 1. A tendentially positive evaluation of presence perception within the AV simulation, especially in terms of spatial presence and experienced realism, is observable. Regarding the Involvement subscale, a slight trend in favor of the condition without actor is recognizable. Inferential statistics (paired samples t-tests) on the IPQ subscales corroborate these observations but do not return significant results (Table 3).

Subscale	t_{paired}	*df*	*p*	d_{paired}
Spatial Presence	-0.826	30	.208	-0.148
Involvement	1.598	30	.940	0.287
Experienced Realism	-0.356	30	.362	-0.064
General	-0.626	30	.268	-0.112

Table 3. Paired samples t-tests and Cohen's *d* on the IPQ [38, 39] subscales. Hypothesis is without actor rating decreases against with actor.

The ratings of the single item 'feeling of reality' are generally high in both conditions and higher than in study 1 (Table 4). This is also strongly supported by anecdotal evidence (i.e. by the reports of the participants in the questionnaire and in informal talks during and after the experiment).

Subscale	Without actor	With actor
Feeling of reality	3.81 *(1.01)*	4.23 *(0.85)*

Table 4. Means *(SD)* for the rated single item "feeling of reality" [from *1 = not at all* to *5 = fully*] for the two conditions (without actor – with actor; *n* = 31).

Eleven participants commented positively on the feeling of reality. For example: "incredibly real." (P8); "I had the feeling of actually sitting in a car" (P11); "[it feels] very real, although one sits on a chair in a room." (P15); "the ride reminds me of a normal car or bus journey. It was very real" (P17); "the ride was very realistic due to the environment and the people." (P17); "the immersion is extremely good due to the real pictures" (P19); "comparable to reality" (P23). Three participants (P9, P11, P12) actually reported that their body wanted to move in accordance with the visual simulation (e.g. when the car stopped or accelerated). Five participants (P11, P17, P23, P24, P26) explicitly appreciated the conservative and anticipatory driving style of the simulated AV.

Six participants, however, commented negatively regarding the feeling of reality: "movements of the chairs and the simulator itself are missing" (P13); "design of the simulator's interior feels more like a waiting room" (P13); "Although the situations were good represented, I noticed the equipment" (P15); "I always knew inside that it is fake" (P14); "the left image was much sharper than the other videos" (P21); "it doesn't feel so realistic when there is always a free parking slot available [for the AV] at just the right place" (P26); "color variances in the video projections had a negative effect on the ride experience" (P31).

In contrast to the results of the IPQ's subscales, results of the single item 'feeling of reality' (Table 4) show a positive tendency towards using an actor. A paired samples t-test exposes a significant difference between the conditions (t_{paired} (30) = -2.64, *p* = .007) favoring using an actor with a medium effect of d_{paired} = -0.47. Seven participants explicitly support the measurements with their comments, e.g.: "It was kind of spooky when the guy came in." (P8); "it felt more real when someone entered the vehicle" (P10); "It felt really realistic. I was almost shocked when the person entered the vehicle." (P11); "the entrance [of another passenger] was very realistic" (P17); "the co-passenger made the ride more realistic" (P18).

Technology acceptance

Both subscales of the acceptance questionnaire [28] show a slight positive trend toward involving an actor (Table 5).

Subscale	Without actor	With actor
Usefulness	1.17 *(0.51)*	1.25 *(0.49)*
Satisfying	1.23 *(0.52)*	1.27 *(0.53)*

Table 5. Means *(SD)* of the acceptance questionnaires' [28] subscales [from *-2 = negative* to *2 = positive*] for the two conditions (without actor – with actor; *n* = 31).

Paired-samples t-tests do not reveal significant differences (Table 6). However, the tests indicate a non-significant trend with a small effect of d_{paired} = -0.28 regarding the usefulness (t_{paired} (30) = -1.56, *p = .065*) in favor of actor involvement.

Subscale	t_{paired}	*df*	*p*	d_{paired}
Usefulness	-1.56	30	.065	-0.28
Satisfying	-0.63	30	.265	-0.11

Table 6. Paired samples t-tests and Cohen's *d* for the Acceptance questionnaire [28] subscales. Hypothesis is without actor rating decreases against with actor.

Wellbeing

Whilst descriptive statistics of the MSAQ generally show low values in all subscales, slightly higher values are observable regarding the condition involving an actor (Table 7).

Subscale	Without actor	With actor
Gastrointestinal	17.12 *(9.73)*	22.04 *(16.67)*
Central	17.06 *(10.76)*	19.28 *(15.13)*
Peripheral	13.50 *(6.45)*	13.86 *(6.62)*
Sopite-related	20.61 *(11.89)*	22.04 *(13.07)*
Overall	17.29 *(6.94)*	19.65 *(9.81)*

Table 7. Means *(SD)* of the MSAQ [18] subscales [from *11 = low* to *100 = high*] for the two conditions (without actor – with actor; *n* = 31).

Subscale	W	p	r_{rb}
Gastrointestinal	50.50	.038*	-0.47
Central	30.00	.083	-0.43
Peripheral	2.50	.231	-0.50
Sopite-related	62.50	.163	-0.27
Overall	65.00	.024*	-0.49

Table 8. Wilcoxon signed-rank test and rank-biserial correlations for the MSAQ [18] subscales. Hypothesis is without actor rating decreases against with actor. *significant ($p < .05$)

Wilcoxon signed-rank tests reveal significant differences in the subscale Gastrointestinal ($W = 50.00$, $p = .038$, $n = 31$) with a medium effect of $r_{\text{rb}} = -0.47$, as well as in the Overall MSAQ scale ($W = 65.00$, $p = .024$, $n = 31$) also with a medium effect of $r_{\text{rb}} = -0.49$. The results indicate significantly higher values for motion sickness in SAV simulator rides involving an actor.

Subscale	Without actor	With actor
Feeling of comfort	4.07 *(0.89)*	4.03 *(0.98)*

Table 9. Means *(SD)* for the rated 'feeling of comfort' [from *0 = not at all* to *5 = fully*] for the two conditions (without actor – with actor; $n = 31$).

The subjective feeling of comfort *"I felt comfortable during the ride."* achieves high values in both conditions (Table 9) with no relevant difference ($W = 44.00$, $p = .672$, $n = 31$). Four participants explicitly mentioned symptoms related to simulator sickness: "I got a little woozy, but I'm fine" (P2); "when I turned around, my head was slightly spinning" (P8); "I felt uncomfortable driving over the cobblestone at the end of the second ride" (P13); "sometimes I got a little nauseous during the ride" (P15).

DISCUSSION

We evaluated the presented AV simulator in two user studies ($n_1 = 9$; $n_2 = 31$). Both studies investigated the suitability of the simulator for context-based prototyping and evaluation. The findings of the expert consultation in study 1 were primarily used to discover issues and optimization potential of the setup. In study 2, we focused on investigating the impact of involving an actor in AV simulator studies in terms of participants' presence perception, wellbeing and technology acceptance.

Immersive video-based AV simulation

The tested prototype received quite positive ratings in both studies regarding presence perception. Considering subjective quantitative and qualitative ratings in terms of participants' presence perception and feeling of reality, the results are encouraging. The improvements of the sound simulation based on the findings of study 1 (e.g. including sounds of open/closing doors, other passengers and signal sounds) seem to have a positive effect on the quality of the simulation and should therefore be further investigated. Extending the video-based setup with a motion simulation might increase presence perception. As a participant mentioned in study 2, rides might possibly feel more real when they are less smooth. For example, the AV might stop only close by to a certain scheduled stop, but not exactly at the given location.

In general, the results provide support for the suitability of the method to enable straightforward context-based design and evaluation.

Involving an actor in shared AV simulation

Anecdotal evidence and a significant medium effect in the single item 'feeling of reality' suggest a positive influence of actor involvement. However, in contrast to our expectations, this is not backed by the results of the standardized IPQ.

Moreover, while the general feeling of comfort was rated high in both conditions with no relevant difference, negative effects of actor involvement on participants' well-being have been revealed by the MSAQ. Although, the overall occurrence of motion sickness symptoms measured by the MSAQ was very low, they were slightly, but significantly higher when an actor was involved in the simulation. This might have been caused by a disruption of participants' immersion when the actor entered/left the simulation. It might also reflect a general feeling of stress and discomfort when unknown people are present (see [13]).

Despite a non-significant trend with a small effect in the usefulness subscale (indicating slight differences favoring the involvement of an actor), we did not observe a statistically relevant effect regarding participants' acceptance ratings of (shared) AVs. On this basis, no conclusion can be drawn regarding neither a positive nor a negative effect of actor involvement on technology acceptance.

To sum up, Hypothesis H_1 (positive effect of actor involvement on participants' presence perception) is partly supported and Hypothesis H_2 (negative effect of actor involvement on participants' wellbeing) is supported by the results, whereas, Hypothesis H_3 (positive effect of actor involvement on participants' technology acceptance) is not supported.

Challenges and limitations

The proposed AV simulator provides a simple framework for creating high-fidelity prototypes of (S)AVs. Some challenges should, however, be considered when using the method. As cameras are mounted behind the windows to capture the footage, it is only possible to create visual simulations under appropriate weather conditions, as for example raindrops or reflections might restrict the visibility. In order to create suitable simulations, careful advance planning of scenarios is required because editing of existing footage is only possible within tight limits.

Since the simulation is based on videos created during driving in public, undesired artifacts (e.g. caused by the behavior of other road users, camera focus or orientation) may occur and have adverse effects on quality and precision of the simulation. Furthermore, controllability of the video-based simulation is limited, especially in comparison to computer-generated environments.

Regarding the reported studies, limitations are primarily induced by the sample composition and the questionnaires used. The ATI indicates high technology affinity among the well-educated participants of study 2, which is considered a common phenomenon in HCI research [14] and might impair external validity. The used IPQ was initially created to measure the subjective sense of presence in virtual environments [39]. Since the created AV simulator setup differs from 'classic' computer-generated virtual environments, it cannot be directly compared to provided benchmarks, restricting the interpretability of results.

Future work

The immersive video-based AV simulator provides a suitable basis for context-based prototyping and evaluation of interfaces for (shared) AVs. Further studies might, for example, use the setup for usability testing of in-vehicle HMIs or mobile apps, but also for user research (e.g. regarding technology acceptance and trust). In addition, the simulator might be used by designers and researchers to support research-through-design approaches, e.g. for ideation techniques like body-storming (or 'car-storming' as described by [27]). Furthermore, the video-based approach could be transferred to other domains and used to investigate experiences in other future modes of transport (e.g. autonomous air taxis).

Regarding the investigation of the potential effects of actor involvement, further studies can build upon the findings of study 2 and extend the operationalization of the independent variable, e.g. by adding a third condition where there is no other passenger present at all – neither physically (as an actor) nor virtually (in terms of sound or imagery).

Since the described approach is limited regarding the controllability of the video-based simulation (i.e. the immersive video), further work should put special attention toward refining and potentially standardizing the way of manual data collection, while maintaining the approach's simplicity. Quality and precision of the video recordings might, for example, benefit from video rigs (like e.g. used by [16]), fixed camera mounts or by using a single 360° camera instead of multiple cameras. However, using special equipment would also make the setup less simple and more expensive. The immersive video might also be extended by CGI (e.g. [16]) or combined with real-world data-based generation of virtual environments (e.g. [1]) to simulate specific situations. Researchers and designers might also share and exchange audio and video files in order to minimize qualitative differences and to conduct comparable studies.

To further investigate the AV simulator's validity and cost-efficiency, experiments should be compared to both, real-world experiments and laboratory experiments. To conduct studies in the real world, vehicles with 'real' autonomous driving functionalities might be used. But, as mentioned above, such studies are often only feasible within tight limits. Thus, utilizing 'common' vehicles in combination with wizard-of-oz techniques might be – depending on scenario and study objective – a better fit. Regarding the comparison to laboratory studies, 'standard' setups without contextual simulation should be taken into consideration as well as setups with CGI-based simulation. Altogether, this would allow for a profound evaluation of the simulator's external validity. It would also support a better understanding of the type of prototyping fidelity needed for cost-effective design and evaluation of AV interfaces and, consequently, enable the creation of a methodological framework.

CONCLUSION

In this paper, we presented a simple immersive video-based AV simulator as a prototyping and evaluation method for (S)AVs and AMOD systems. The cost-effective setup consisting of real-world videos and a CAVE-like environment is comparatively easy to (re-)create and can be likewise used by designers, engineers and researchers as a prototyping framework for design and evaluation activities. It can be used to study user behavior and to counteract human factor challenges related to (S)AVs from early development phases on.

Presented results of two user studies can be taken as initial evidence for the simulators' suitability for context-based prototyping of HMIs for AVs. However, due to the simple approach, the method is limited in terms of precision and controllability of the simulation.

Although, we found some support for the idea of using an actor as a part of the simulation of a shared ride, it seems not to have a significant positive impact on participants' presence perception. Moreover, it might also have adverse effects on their wellbeing (e.g. regarding simulator sickness). Thus, we do not recommend using an actor in AV simulator studies.

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