SMARTPHONE-BASED HUMAN-MACHINE-INTERFACE FOR BICYCLES: A STUDY ON BEHAVIORAL CHANGE AND LEARNING EFFECTS

Johannes Lindner, Corresponding Author
Chair of Traffic Engineering and Control Technical University of Munich (TUM)
Arcisstrasse 21, 80333 Munich, Germany
johannes.lindner@tum.de
ORCiD: 0000-0001-9385-2453

Georgios Grigoropoulos
Chair of Traffic Engineering and Control Technical University of Munich (TUM)
Arcisstrasse 21, 80333 Munich, Germany
george.grigoropoulos@tum.de
ORCiD: 0000-0002-0846-6441

Andreas Keler
Chair of Traffic Engineering and Control Technical University of Munich (TUM)
Arcisstrasse 21, 80333 Munich, Germany
andreas.keler@tum.de
ORCiD: 0000-0002-2326-1612

Klaus Bogenberger
Chair of Traffic Engineering and Control Technical University of Munich (TUM)
Arcisstrasse 21, 80333 Munich, Germany
klaus.bogenberger@tum.de
ORCiD: 0000-0003-3868-9571

Word Count: 7492 words + 0 table(s) × 250 = 7492 words

Submission Date: July 31, 2023

ABSTRACT

In future urban mobility, safe and efficient interaction between vulnerable road users and autonomous vehicles (AVs) will play a crucial role. In order to enable communication between human road users and AVs, different human-machine interfaces (HMI) are developed. Usually, these HMIs and onboard communication units are part of AVs, but some concepts exist that give cyclists communication capabilities and possibilities to interact with the human rider. This paper further investigates one of these on-bicycle HMIs that uses a smartphone mounted on the bicycle's handlebar. On the device, an application is running that augments routing apps with information about upcoming traffic scenarios and gives instructions on how to behave in certain situations. When interacting with AVs, knowing whether an HMI system influences the cyclist's behavior is crucial. Therefore, an AV can anticipate the cyclist's movement in the upcoming scenario reliably. In this paper, we focus on the research questions of whether there is a behavioral change, how it looks like, and whether learning effects with the application can be observed. We studied the behavior in a coupled Bicycle-AV-Simulator and focused on speed variations in the analysis, because of driving simulator validity. The results indicate a speed decrease after receiving app information about the upcoming scenario. However, a learning effect can be found. With an increasing number of study scenarios, the speed reduction decreases. Moreover, after receiving instructions on priority decisions, the cyclist reduces the speed if the AV takes priority and maintains or increases speed if the cyclist is prioritized.

Keywords: On-Bicycle Warning System; AV-VRU-Interaction; Human-Machine-Interface; Coupled Driving Simulator; Cycling Behavior; Vulnerable Road Users

INTRODUCTION

In urban mobility planning, efforts are made to increase traffic safety and more sustainable. Besides others, one can recognize these two trends: autonomous driving and the promotion of cycling in urban areas. In today's urban traffic, the interaction between motor vehicles and cyclists is associated with statistics about high fatality rates of cyclists in interaction with motorized traffic (*1, 2*). In the future, this interaction could be improved by excluding human errors through automation and communication technology. Automated vehicles are equipped with onboard units to enable communication with other road users and infrastructure, but how is the situation with cyclists? Traditional cycling is considered inexpensive, space-effective, and simple, and bicycle designs are not expected to change significantly in the future. However, few safety add-ons will likely be included in bicycle designs when market penetration of autonomous vehicles and V2X-communication (Vehicle-to-Everything communication, including infrastructure and other vehicles) coverage is high. Simple onboard units for better perception of cyclists and human-machine interfaces (HMI) to communicate to the human bicycle rider other vehicles' intentions or warning of safety-critical situations are discussed in the literature, besides other concepts (*3–5*). Even today, cyclists often use smartphone-based map services for routing while fixing the smartphone to the handlebar. This motivated Lindner et al. (3) to study whether extending those routing applications with additional safety-related information and behavior instructions in specific scenarios is possible. So far, whether an on-bicycle HMI influences cycling behavior has yet to be analyzed. For interaction with AVs and training the involved prediction algorithms, a behavioral change is highly relevant. This paper further analyzes the coupled driving simulator study in Lindner et al. (3) of an automated vehicle (AV) and a bicycle while the cyclist uses a smartphone as a communication device on the operational level of the bicycle ride. The research questions addressed in this paper are: (1) does cycling behavior differ with and without an on-bicycle HMI system in use, (2) if yes, how does the behavioral change look like, and (3) can learning effects be observed when using the HMI system? We first provide an overview of the state of the art of on-bicycle HMIs and bicycle simulators for road user interaction studies, followed by a description of the experimental setup and the simulator study. We then present the results of the bicycle behavior analysis, including the influence of HMI messages on cycling behavior and learning effects. Finally, we discuss the results regarding driving simulator validity, summarize our findings, and provide an outlook for future work.

STATE OF THE ART

On-Bicycle Human-Machine-Interfaces

Traditionally human-machine interface (HMI) research comes from the automotive domain to ensure and emend appropriate interaction between conventional vehicles and their drivers (*6*). With the development of advanced driver assistant systems (ADAS) toward a higher level of automation, new possibilities to communicate with the driver and other human road users have emerged. In recent years, a particular type of HMI was discussed intensively in research, the external HMI (eHMI) (*6–13*). Examples of HMIs are text messages displayed on the outside of the vehicle, light strips mounted on the windshield changing color depending on the vehicle's state, or concepts that imitate human behavior, such as eyes installed at the vehicle front looking at other road users. For external HMIs, many studies exist on which type of eHMI might be the best for communicating the AV's driving intention. So far, there is no clear recommendation for HMI design (*3, 7*). Also, there is criticism about the concepts because many are only investigated in 1-to-1 interaction, which is not necessarily the case in reality. It could especially lead to issues addressing information to one specific road user, ensuring that no other person misinterprets the eHMI's message. Moreover, there is criticism in the literature that the interaction for some road users, mainly AV to pedestrian, is much more investigated than for others. For example, AV-to-bicycle interaction is rarely investigated, although this mode of transport plays a vital role in urban traffic (*3, 7*). Moreover, Dietrich et al. (14) states that in today's traffic, such encounters are mostly resolved implicitly in urban traffic, i.e., through the kinematic motion of an approaching vehicle (*14*). For example, the driver decelerates to communicate the driver's intention to let a pedestrian cross. For safe interaction between vulnerable road users (VRUs) and AVs, both communication methods, implicit and explicit, should be integrated into the communication framework of an automated vehicle. For bicycles, there is little research in HMI development or investigation of AV-to-bicycle interaction (*15, 16*). Nevertheless, some visions and experimental designs of on-bicycle HMIs exist (*3, 5, 17, 18*). These concepts range from haptic interfaces (vibration motors at the handlebar) over auditory interfaces, like helmet audio, to visual interfaces using laser projections, a head-up display (HUD), or smartphones for cyclists. In contrast to HMI research for AVs, so far, these concepts should only be considered as safety add-ons. All these concepts are currently in the conceptual phase. The studies found focus on user acceptance, comparison of reaction times, and identification of the best communication modality of such a novel HMI system for bicycles (*3, 5, 17, 18*). The impact on cycling behavior has not been researched. Especially when interacting with AVs, it is essential to study the driving behavior of cyclists using such an HMI system. The AV's prediction algorithms need to be trained to determine whether there is a change in driving behavior and how it influences cyclists' behavior to correctly interpret cyclists' movements. In this paper, we address this research gap to identify the influence of one specific on-bicycle HMI on the driving behavior of a cyclist.

Bicycle Simulators for Road User Interaction Studies

In order to study novel interaction concepts, driving simulators can be used to research in a safe and reproducible environment. The most experience in the driving simulation domain has been gained with car driving simulators. Car driving simulators can differ greatly in their hardware setups, from simple keyboard-screen setups to highly elaborate systems using moving platforms, LED-Screens, and real vehicle mock-ups (*15, 19–21*). Also, bicycle simulators are increasingly used to study road user interaction and new infrastructure designs (*15, 16, 22–25*). As visualization methods, usually screens or virtual reality headsets are used. There are major differences in the sensory equipment and the force feedback loops of the simulators. Very elaborate setups exist, including steering force feedback, a motion platform (roll and pitch angels), brake force sensors, and a headwind simulator, only to name a few properties (*25*). On the other hand, simpler hardware setups measure only the main driving parameters, steering angle (without force feedback), and speed using a bicycle in a fixed frame (*15*). Despite the differences in the hardware setup of bicycle simulators, it still needs to be conclusively clarified which components lead to higher absolute validity of the study results. The requirements for bicycle simulators are also very different compared to car driving simulators. The physics of a bicycle ride is complex to reproduce in a simulator, for example, due to missing centrifugal forces in fixed-base simulators. So far, no moving-base bicycle simulator exists. The reasons for this are manifold, but two major ones are financial resources and the possibility of falling off the bike in the simulator and harming the user if vehicle dynamics a not modeled correctly. Also, the communication patterns of cyclists must be detectable in a bicycle simulator for proper examination of road-user interaction (*26*). The communication patterns include explicit cues, like hand gestures, and implicit cues, like head movement, body posture, and pedaling pace (*15, 27*). For simulator studies that research road user interaction, the usage of *Coupled Driving Simulators* can be beneficial (*15, 28–32*). In this simulation approach, multiple humans can interact in the same virtual environment using separate simulators. In the study discussed in this paper, a cyclist can interact with an AV passenger (*15*). Coupled driving simulator studies come with the drawbacks of higher implementation effort for study and software but promise higher validity concerning the interaction of road users. Driving simulator studies must always be critically examined regarding validity because elaborate setups or study methods do not necessarily increase validity (*33–35*). For behavioral validity in driving simulator studies, two terms must be distinguished: *absolute* and *relative* validity (*35*). Absolute validity compares the exact driving and interaction parameters (e.g., absolute speed) of a simulator experiment to the ones of a real-world experiment. Relative validity compares the tendency towards a driving action (e.g., braking or accelerating) to the real world. Most driving simulators, also the coupled Bicycle-AV simulator used for the study discussed in this paper, fulfill the criteria for relative validity but insufficiently for absolute validity (*36, 37*).

METHODOLOGY

Experimental Setup

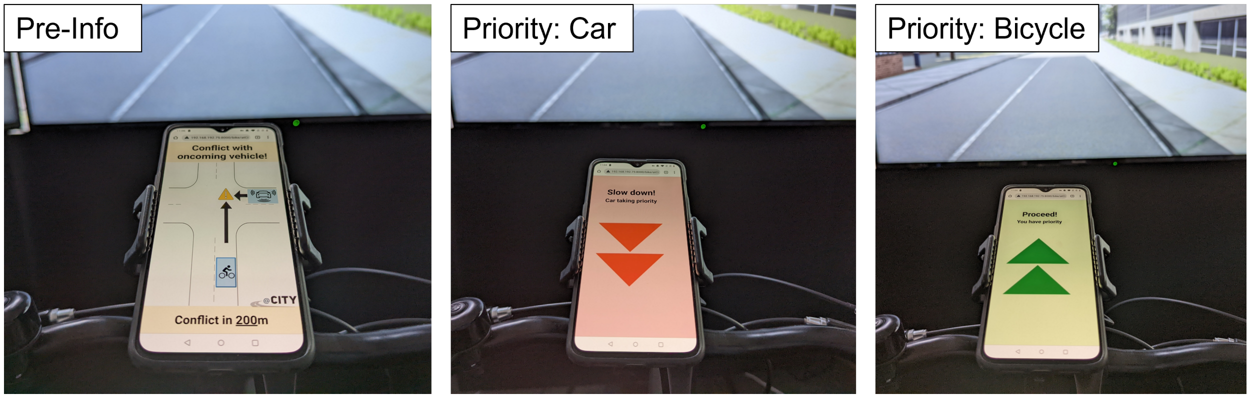

FIGURE 1: **Bicycle Simulator with Smartphone mounted on the Bicycle's Handlebar. Application showing the Pre-Info Screen in a Occlusion Scenario and both Variants of Screens after Priority Decision**

The study analyzed in this paper was conducted in a coupled driving simulator consisting of a separate bicycle and automated vehicle (AV) simulator. The coupling of the simulators in a multi-user simulator enables investigation of the interaction between those two road users. A more detailed description of the simulator setup and the software solution is described in Lindner et al. (15). The bicycle simulator consists of a training stand to fix the bicycle's position. The speed can be detected using an infrared sensor measuring the number of rotations of a metal cylinder driven by the bicycle's rear wheel. The steering angle is extracted by a magnetic rotary encoder measuring the rotation of a metal plate connected to the front wheel. Besides the speed and steering angle parameter, it could be measured whether cyclists give hand signals. For measuring the hand signals, a depth camera was used to obtain the skeleton points of the study participant. A pre-trained convolutional neural network can then detect whether or not a hand signal was given. More information about the used method to detect hand signals can be found in Malcolm et al. (38). The visualization and sound system for the bicycle simulator was covered by one 56 inch monitor with integrated speakers. The natural field of view of the monitor is 50°, but was increased by the virtual camera to 90°. What is unique about this study is a smartphone mounted on the handlebar that could show different screens connected to audio signals (information signals and warning signals), which are linked to the simulation (see, Figure 1). The cyclist receives routing information and notifications about upcoming scenarios and priority decisions via this mobile application.

The AV simulator is a low-fidelity driving simulator with a desktop screen setup, consisting of three 24 inch monitors and a separate speaker. Unique in this study was a tablet as HMI device that can, just like for the cyclist, display different screens and give audio signals. In specific scenarios, the AV passenger could control the behavior of the AV via priority decisions in the upcoming scenario, meaning prioritizing the cyclist or their vehicle. In future traffic, including AVs, a change of prioritization rules may have several advantages. It can improve traffic performance, enhance AVs' acceptability, or reduce interaction scenario complexity. Especially the last point is highly relevant for the widespread adoption of AVs. In complex interaction scenarios the AV cannot resolve, vehicle control must be handed over to a human driver or a remote control center operator (*3*). Reducing the probability of the emergence of this complex scenario type and providing tools to resolve these situations can facilitate AV operation greatly.

The software solution to conduct the coupled simulator study has two main components: the *simulation engine* and the *mobile application*. As a simulation engine, the game engine Unity3D was used. A benefit of using game engines is that a solution for multiplayer games usually exists, significantly reducing the implementation effort. Besides the networking and rendering tasks, the vehicle controls are the most important task of the simulation engine. In order to control the bicycle, the inputs must be processed and applied to the bicycle model. The parameters speed and steering angle are fed to a physics model (using Unity's physics engine) to control the bicycle. In other bicycle simulators, the Single-Track Model is used to control the bicycle in the simulation. For this simulation framework, we chose the approach of physics models because a broader range of 3D maps, including slopes and different road surfaces, can be simulated more easily. In contrast, the Single-Track Model represents vehicle movements in two-dimensional space (*39*). The AV control in the simulation depends on the cyclist's movement. Both road users follow a fixed route but should enter study scenarios at the same time. Thus, the AV follows a predefined path while the speed adopts the cyclist's speed. Also integrated into the simulation framework is the link to the web-based mobile application. The mobile application screens can be updated via an API (application programming interface) from the simulation engine. It conveys information about the current phase in the scenario and enables the AV passenger to decide about the priority in an upcoming scenario. The application usually receives state information from the simulation engine via the API. In the case of a priority decision, the mobile application provides the current scenario state to the simulation engine.

Simulator Study

Participants followed a predefined route during the driving simulation, including 5 different study scenarios out of the three scenario types *Static Bottleneck*, *Left Turn* and *Occlusion* (Figure 2). The mobile application routes the cyclist through the virtual city between the scenarios with dedecated navigation screens. The AV was controlled in a way that it adopts it's speed to the cyclist's position on the route in order to arrive at the next scenario at the same time. The scenarios differ in

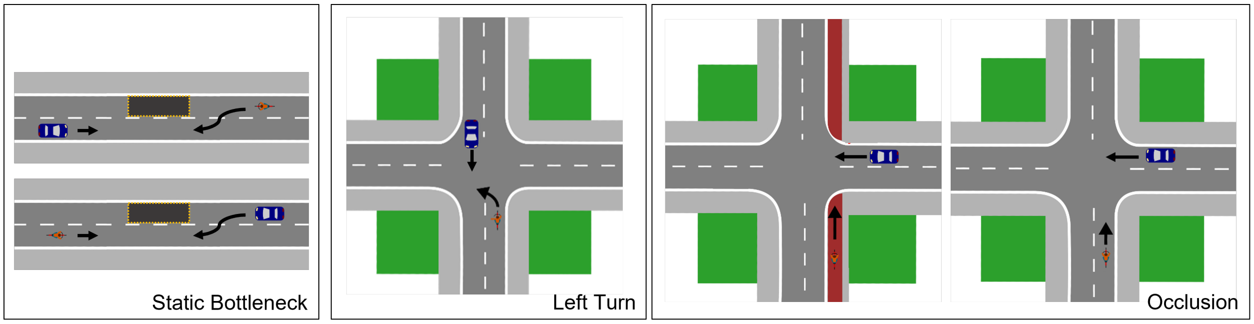

FIGURE 2: **Study Scenarios**

infrastructure and turning relations of the study participants. The scenario types are described in the following:

- **Static Bottleneck**
  There are two scenarios with a static bottleneck (truck and construction site) on a urban road with one line in each driving direction. In one of the scenarios, the bottleneck blocks the cyclist's lane (obstacle: truck). On the other one, it blocks the AV's lane (obstacle: construction site). No bicycle path exists, so the cyclist rides on the road. No other road users are present in the scenario.
- **Left Turn**
  The study includes two Left Turn scenarios. The scenarios are embed in to a road network with one lane in each driving direction. Both scenarios are the same from the infrastructure point of view and turning relations. The cyclist wants to turn left, while AV goes straight on the opposite lane. There was only a variation when deciding about prioritizing the AV passenger received additional screen information on whether the passenger's decision would improve traffic flow. For the cyclist, the displayed information does not change. The only difference for the cyclist is receiving the priority decision message later with additional traffic information because the AV passenger's decision duration is significantly longer than without additional information, as Lindner et al. (3) found. No other road users are present in the scenario.
- **Occlusion**
  There are two scenarios where buildings act as visual obstructions impeding the cyclist's line of sight. The cyclist goes straight, either on a bicycle path or the road(one lane per driving direction), while the AV crosses from the right. Without communication devices, the AV could be seen only briefly before the conflict point to increase the criticality of the situation. No other road users are present in this scenario.

Each scenario could have several variations regarding communication; see Figure3. Scenarios could be carried out as **Baseline Scenario**, which are referred to as *Default*. This means there is no additional communication, and the right-of-way is regulated like in normal conditions in today's road traffic. In scenarios where communication is investigated (**Communication Scenario**), there are two further variations of the priority decision instance. This can be the *AV*, simulating a case where the traffic control center communicates the AV an optimized traffic control strategy, or the *AV passenger*, who is free in the decision. In this simulation, there were only the options to prioritize the own vehicle or the cyclist, because no other road users were present in the simula-

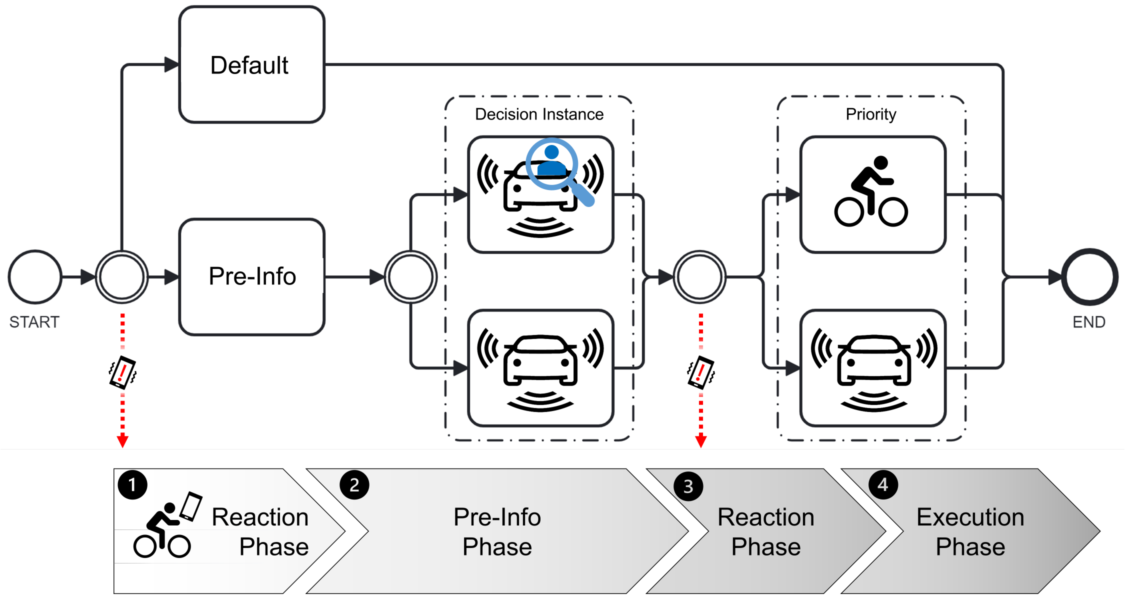

FIGURE 3: **Variation of Communication and Priority Decisions in Study Scenarios**

tion. Each communication scenario starts with the **Pre-Info Phase** and screen information about the upcoming scenario for AV passenger and cyclist (and an audio signal). This app screen depicts the infrastructure, the involved road users and their driving intention (see Figure 1). Also there is the distance to the conflict point is shown on the screen and updated in real-time. This phase is followed by the **Decision Phase**. The decision can be manually executed by the passenger or automatically by the AV. There is one special case for the scenario decision, as already mentioned in the description of the Left Turn scenario. At certain scenarios the AV passengers receive additional information on the planned decision. A feedback is displayed on whether the decision has a positive or negative impact on traffic flow. From the bicycles point of view this information is not relevant. After the Priority Decision phase, both study participants (AV passenger and cyclist) get notified about the priority decision and execute the instruction (**Execution Phase**). Not all of these phases are recognizable for the cyclist, and there are some differences in handling the app information compared to the AV. While the AV can instantly react to the decision or other instructions and adopt it's driving behavior, the cyclist requires a **Reaction Phase**. Every time the cyclist receives a message, some reaction time is involved. Also, the priority decision is not present for the cyclist and, therefore, the Decision Phase. The cyclist only receives the Pre-Info and the priority decision message, which is depicted at the bottom of Figure 3. The study included 16 simulation runs and two participants (13 female, 19 male - Age group 18-24: 12, 25-39: 19, 40-59: 1) each. If the simulation run is completed, every participant goes through 18 scenarios, including 3 Baseline and 15 Communication Scenarios. More details about the study, the participants, the procedure, and the app screens can be found in Lindner et al. (3).

RESULTS

This section analysis the bicycle trajectories of the coupled driving simulator study. The segments in which the cyclist received a notification via the mobile application are particularly interesting. The notification is visual information in the form of a new screen and an audio warning signal.

We separately analyze the **Pre-Info** message and the **Priority Decision** message. The focus of the behavior analysis is the speed variation. We are aware that there might be other interesting parameters like lateral position to study, but with the given experimental setup, the speed variation (compared to baseline scenario) can be analyzed with the highest validity. The Discussion and Limitations section will address the topic of driving simulator validity in more detail. Note also that in the following analysis, the scenarios are no more separated by decision instance. The reason is that from the cyclist's point of view, the notifications and screens do not differ for the decision instance. The cyclist only receives the Pre-Info and Priority Decision Messages in Communication Scenarios.

Cyclist Behavior after Pre-Info Message

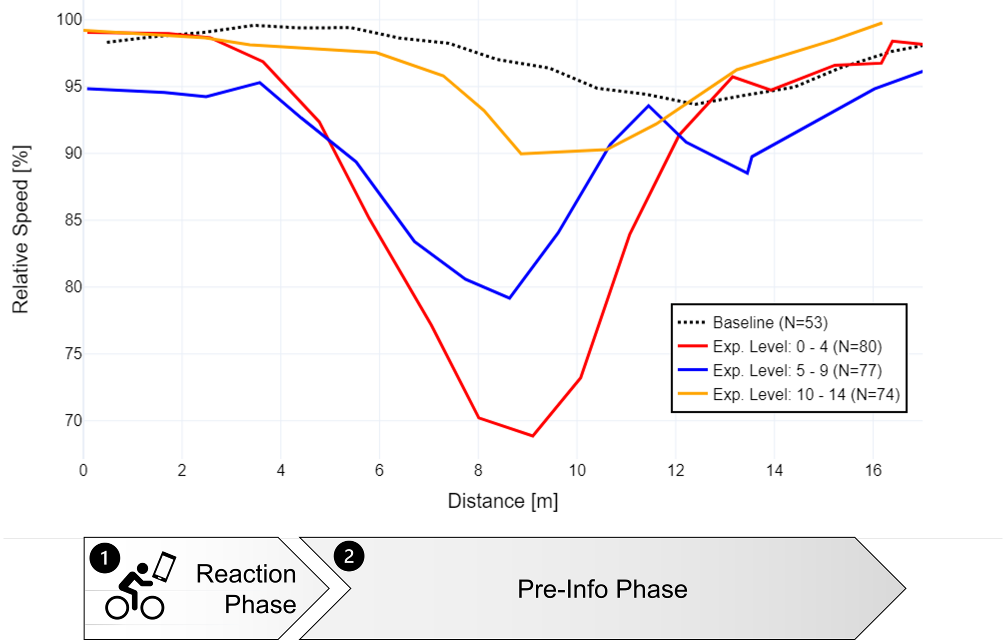

FIGURE 4: **Speed Reduction after Pre-Info Message: Comparison of Baseline with different Experience Levels of the Cyclists with the Mobile Application**

In the following, we analyze the cyclist's speed after receiving the Pre-Info notification. The screen on the smartphone gives an overview of the upcoming scenario, showing a map, all involved road users, and their driving intention. For this analysis, all five scenarios are used. The scenarios can be compared because all study scenarios' boundary conditions during the Pre-Info Phase are very similar. It is on a straight road (in one scenario on a bicycle path), including no other road users approaching a four-way intersection or a bottleneck. Also, the analysis only considers only relative speeds. For the level of detail in this analysis, the assumption of scenario comparability is thus sufficient. In Figure 4 we can see the speed variation in percent (100 percent is the highest speed in that interval) as a function of the distance in meters after the Point of Message Receiving (PMR). We could identify the reaction phase in the interval of 0 - 4m. This corresponds to approximately 1 second, considering the cyclist's average speed. We identified the reaction phase but do not analyze the reaction time in detail in this paper. After the reaction phase, the action of the cyclist starts. It is a temporary speed reduction with its maximum between 8 and 10 meters after the PMR. Moreover, the plot shows that a learning effect of using the application is recognizable. The data is split into the cyclist's experience level with the application compared to the baseline, corresponding to the Default scenarios without app intervention. In one simulation run, the cyclist drives through 15 scenarios, including app notifications. From this study design, we derive three experience levels (0 - 4, 5 - 9, and 10- 14 scenarios experience). After receiving the app notification, the speed reduction increases with a lower experience level. With a higher experience level, the speed reduction decreases. At the highest experience level, the speed curve is close to but not yet equal to the baseline case, and still, a speed reduction can be recognized in comparison to the baseline.

Cyclist Behavior after Priority Decision Message

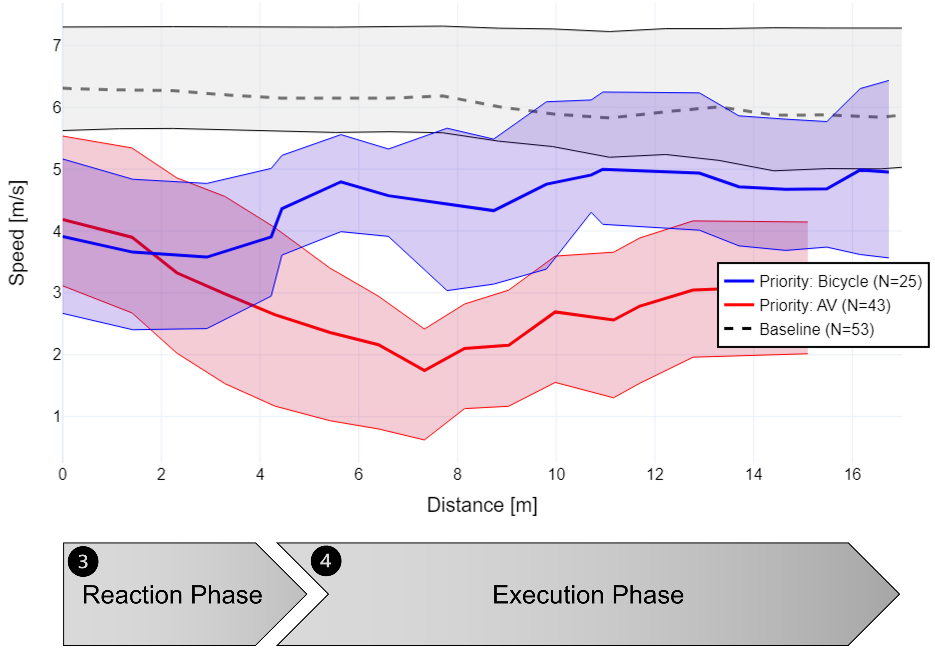

FIGURE 5: Speed profile of the Cyclist after Priority Decision Message compared to the Baseline

This section analyses the influence of the Priority Decision message, which corresponds to the Execution-Phase. Figure 5 shows the speed after the instruction to give way to the AV (Priority: AV, red) or to get priority (Priority: Bicycle, blue) compared to a baseline scenario (grey). The baseline scenarios in this plot only include scenarios in which the AV has priority according to today's traffic rules. For reasons of clarity in the plot, the opposite case, baseline scenarios with priority for cyclist, is not visualized, but the cyclist's speed choice looks very similar and can be considered equal for this comparison. The speed is visualized with the mean value and the 25 (bottom) and 75 (top) quartiles. The app message is received at the PMR (Distance = 0m). For this analysis, all study scenarios are considered, because we focus on the action, which is an increase/decrease in speed, not the absolute speed value. For different research questions, the scenarios should be evaluated separately. The reaction phase is less clearly visible in this plot compared to the previous one. Based on the previous Pre-Info plot, we assume a similar reaction time of approximately 1 second. One can also argue that reaction time is reduced, because after the Pre-Info message the cyclist also awaits the next screen. However, this is a research question for another analysis. After the reaction phase, we could observe the following.

- Priority Bicycle: In these scenarios, the cyclist received the message to have priority. Compared to the initial average speed, the speed after receiving the message leads to maintaining or increasing speed of the cyclist's velocity, starting about 4m after the message was received.
- Priority AV: The cyclist has to give way to the AV at an intersection or a bottleneck. The analysis shows that the cyclist reduces speed to give way to the AV. The minimum speed is reached 6 - 10m after the PMR.
- Baseline: The baseline corresponds to the data of Default scenarios. Since the initial app notification's position varies, the Default scenarios' trajectories start at the PMR of the non-default scenarios. The baseline plot shows that the speed in default scenarios remains relatively constant.

When comparing the absolute speeds in the plot, one can see that the average speed in the Default scenario (Baseline) is higher than in both Communication Scenarios (Priority: AV and Priority: Bike). Also the difference between the quartiles of the speed distribution remain in a similar range compared to the baseline scenario.

Comparison of Scenarios separated by Priority Decision Message

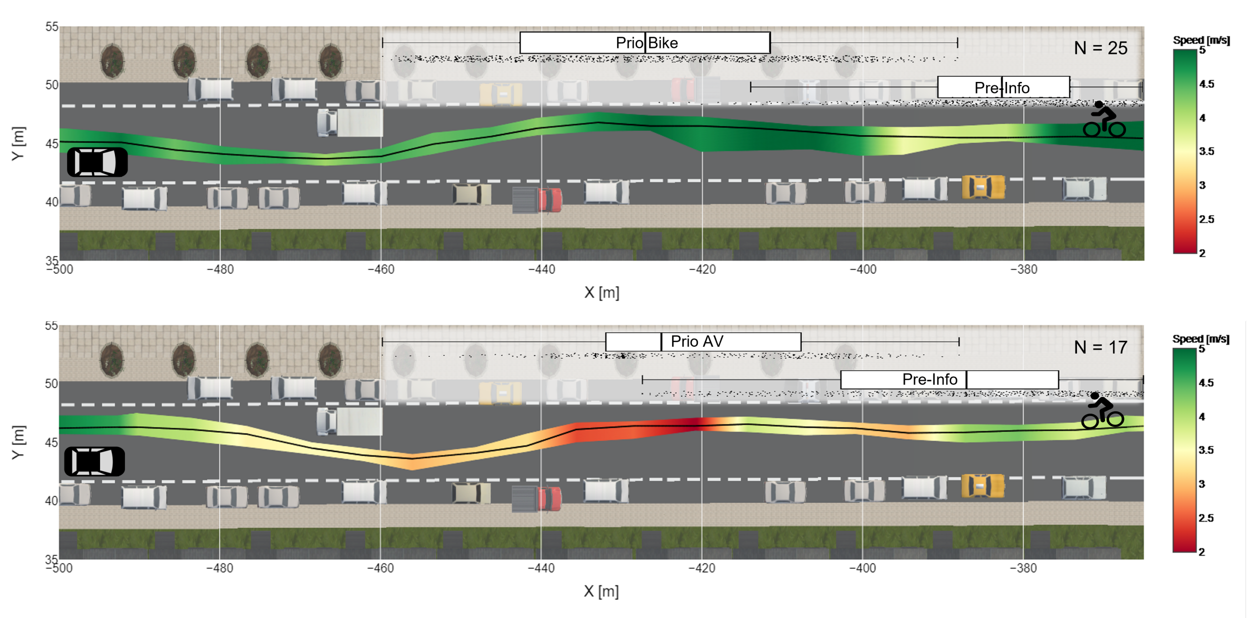

FIGURE 6: **Analysis of a Bottleneck Scenario including lateral Position Distribution, Speed and App Notifications (Priority Bicycle, top and Priority AV, bottom)**

This section analyzes the trajectories of the cyclist of all study participants and simulation runs. It visualizes some of the results from the sections above, additionally with positional information by the example of one Bottleneck Scenario. The top subplot in Figure 6 shows a bottleneck scenario with the obstacle on the cyclist's lane and priority given to the cyclist. The bottom subplot visualizes the same scenario with priority for the AV. Again, the analysis will be performed based on actions because only relative validity could be assumed for the simulator results (*36, 37*). This means the maneuver intention can be interpreted as valid (e.g., braking intention, lane change intention) but not the absolute trajectory (e.g., exact position, speed). All figures include an aggregated visualization of the trajectories of all simulation runs and participants. The trajectories are depicted as area, while the color indicates the speed. The top and bottom border of the area is the 25 (bottom) and 75 (top) quartiles of the y-position of a 6 m discrete element in the x-direction. The black middle line represents an x-discrete element's median. The top two box plots in each subplot indicate the position of the Pre-Info and Execution phases. In this plot, not the PMR but the whole time the cyclist received the respective screen information. Thus, the app information's position can be directly compared with the bicyclist's speed and position. The variation of the notification position has several explanations. In scenarios with the AV passenger as the priority decision instance, the timing depends on the decision duration of the passenger. Other influencing factors are the speed of the cyclist and latency effects. Moreover, it was possible in the simulator to give and detect hand signals. A general observation of that simulator study is that participants rarely use hand gestures, too little to include them in this plot meaningfully. In the top subplot, the cyclist approaches the scenario from the right side of the figure. After the Pre-Info, the app informs the cyclist to have priority against today's existing traffic rules. The plot clearly shows that after receiving the Pre-Info, the cyclist slows down. The cyclist increases or maintains the speed after receiving the second message about the priority decision. The bottom subplot shows a scenario in the same environment. Only the priority decision has changed, and now the AV has priority. Like in the first case, a deceleration could be observed after the Pre-Info screen. The cyclist gives way to the AV and decelerates as a consequence of the priority decision.

DISCUSSION

This study's main objective is to identify the cyclist's behavioral changes and learning effects. On-bicycle HMIs are developed as an add-on for cycling safety using V2X communication. As we could identify in the literature review, these HMI concepts should also improve the encounter with automated vehicles. Prediction of other road users is an essential aspect of AV research. Especially critical is the prediction of VRU behavior, but also complex at the same time. An additional system like on-bicycle HMIs could further increase the complexity of the prediction task. If the bicycle HMI affects behavior, the behavior should be analyzed and used as input for prediction algorithms. In this paper, we focus on speed variations because the relative validity of the bicycle simulator can be assumed. Other parameters like lateral position or eye movement to study attentiveness may also have an influence, but could not be studied validly given the available simulator setup. Considering this background, we can answer the first and second research questions of whether and how the behavioral change of cyclists changes. After the Pre-Info notification, we can observe a speed reduction after the PMR. Given the average cyclist's speed, the deceleration process starts after approximately one second of reaction time, corresponding to 4m. The results indicate a behavioral change in speed adaption. One aspect must be highlighted here, which also answers the third research question. The study participants have a learning effect when using the application, as shown in Figure 4. The speed reduction decreases with an increasing number of Communication

Scenarios, including app notifications. One can state the hypothesis that a new task increases the cyclist's cognitive workload and directs the visual attention from the road to the mobile phone, resulting in a speed reduction, as found in previous simulator studies (*40*). This result indicates that this on-bicycle HMI influences speed adaption. However, not only a behavioral change but also a learning effect could be observed. Whether the speed reduction can be neglected after a certain training period has yet to be answered. Besides the speed reduction after the Pre-Info Message, the behavior after receiving the Priority Decision message was analyzed. This behavior is even more interesting for interaction with AVs. After the priority decision in favor of the AV, one can expect a speed reduction of the cyclist to let the AV pass. The other way around, the cyclist maintains speed or slightly accelerates. Figure 5 also contains the baseline scenario. Compared to the communication scenarios, the average speed is higher, excluding the effect of speed reduction after the AV gets priority. An explanation could be that due to the Pre-Info message before, the study participants are waiting for new messages and therefore reduce their speed to react quickly to the instructions. Since we used all scenarios in this analysis and since absolute speed values might not be represented validly in the simulator, this finding needs to be reviewed using another study method before making a definitive statement. For the behavior after the Priority Decision message, no learning effect could be observed, except for a trend that the initial speed was higher for scenarios with the highest experience level. When conducting further studies on the learning effect, the absolute speed in the scenarios separated by priority decision type should be included. What could also influence the study results, in general, is the fact that the study was conducted on a bicycle simulator. In this simulator setup, the bicycle is held in a fixed frame that does not allow any movement. The participant does not have the usual cycling task, including balancing out the own and the bicycle's weight. Moreover, the benefit of driving simulators is that scenarios can be investigated safely, which negatively impacts behavioral simulator validity at the same time (*41*). Study participants will not behave like in an actual safety-critical situation because the presence in the simulation may be insufficient and, therefore, subjective safety might not be represented validly in a driving simulator. The scenario design could also impact the results because, except for one AV, no other road users were involved. More road users could lead to a more cautious driving style. For future investigations, we recommend using controlled field test experiments to include not only the parameter speed but also get insights into the variation of the lateral position. Also included should be eye tracker measurements to study attentiveness in the scenarios. The field test experiment also has the benefits that the vehicle dynamics can be included, and the possibility of falling or crashing because of inattentiveness is present. The learning effects must also be studied in long-term experiments or experiments with many more repetitions to evaluate whether the speed variation effect can be neglected after a familiarization phase.

Limitations

One major drawback of the study results is the limited sample size, as discussed in Lindner et al. (3). More trials must be carried out in order to obtain more reliable results. Also, the composition of the sample collective is not representative because mainly students within younger age groups took part. Another limitation is that only two road users were involved in the studied scenarios, the AV and bicycle. The concept's applicability must be studied further for scenarios involving multiple interacting road users. For comparability of the scenarios and the different study participants, the study design with a 1-to-1 interaction was chosen. Already often described in this paper is the topic of driving simulator validity. Studies with a driving or bicycle simulator always have the limitation that, to a certain extent, reality cannot be reproduced entirely. In this study, the main restriction from the simulator was the missing vehicle dynamics and limited field of for the cyclist. We thus do not expect a high value of absolute validity for distance and speed perception. When receiving an app notification, there are likely other effects than speed variation. Possible effects can be higher variance in lateral position because of a more unstable bicycle ride due to the shifted attention to the smartphone screen. Moreover, the absolute speed value may vary during study scenarios compared to a regular bicycle ride because the cyclists keep attention and wait for new instructions. These two effects cannot be studied validly with this simulator setup.

CONCLUSION

This paper investigates the variation of a cyclist's behavior in scenarios with an on-bicycle HMI. We focus on relative speed variation for reasons of driving simulator validity. We could observe a speed reduction of the cyclist after receiving a Pre-Info message. More interestingly, study participants have a learning effect when using the application. With an increasing number of communication scenarios, the speed reduction decreases. After notifications of priority decisions, the cycling speed differs depending on priority. If the cyclist has the right-of-way, the average speed remains constant or increases. If the cyclists must give way to the AV, the speed temporarily decreases. These results show that the on-bicycle HMI in use influences the cyclist's behavior, specifically on the speed variation, as long as the cyclist is in the early learning stage of the system. Future studies must investigate whether a behavioral change can still be observed after a more extended training period. The results also show that when designing an on-bicycle HMI of this or a different type, evaluating the behavioral changes induced by this bicycle safety add-on is necessary. Especially in the interaction with autonomous vehicles, predicting road user behavior is an essential part that must be addressed.

ACKNOWLEDGMENTS

This work is part of the research project @CITY – Automated Cars and Intelligent Traffic in the City. The project is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi), based on a decision taken by the German Bundestag, grant number 19A17015B. The authors are solely responsible for the content of this publication.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows. Study conception: JL, GG, AK, KB; literature review: JL; methodology: JL, GG, AK; data collection, data preparation, and implementation: JL; analysis and interpretation of results: JL, GG, AK, KB; draft manuscript preparation: JL, GG, AK. All authors reviewed the results and approved the final version of the manuscript.

References

1. European Commission, *Facts and Figures: Roads Inside Urban Areas*, 2022.
2. European Commission, *Facts and Figures: Cyclists*, 2023.
3. Lindner, J., G. Grigoropoulos, A. Keler, P. Malcolm, F. Denk, P. Brunner, and K. Bogenberger, A mobile application for resolving bicyclist and automated vehicle interactions at intersections. In *2022 IEEE Intelligent Vehicles Symposium (IV)*, 2022, pp. 785–791.
4. Kapousizis, G., M. B. Ulak, K. Geurs, and P. J. Havinga, A review of state-of-the-art

bicycle technologies affecting cycling safety: level of smartness and technology readiness. *Transport Reviews*, Vol. 43, No. 3, 2023, pp. 430–452.

5. Hou, M., K. Mahadevan, S. Somanath, E. Sharlin, and L. Oehlberg, *Autonomous Vehicle-Cyclist Interaction: Peril and Promise*, Association for Computing Machinery, New York, NY, USA, p. 1–12, 2020.
6. Bengler, K., M. Rettenmaier, N. Fritz, and A. Feierle, From HMI to HMIs: Towards an HMI Framework for Automated Driving. *Information*, Vol. 11, No. 2, 2020.
7. Dey, D., A. Habibovic, A. Löcken, P. Wintersberger, B. Pfleging, A. Riener, M. Martens, and J. Terken, Taming the eHMI jungle: A classification taxonomy to guide, compare, and assess the design principles of automated vehicles' external human-machine interfaces. *Transportation Research Interdisciplinary Perspectives*, Vol. 7, 2020, p. 100174.
8. Rouchitsas, A. and H. Alm, External Human–Machine Interfaces for Autonomous Vehicle-to-Pedestrian Communication: A Review of Empirical Work. *Frontiers in Psychology*, Vol. 10, 2019.
9. Merat, N., T. Louw, R. Madigan, M. Wilbrink, and A. Schieben, What externally presented information do VRUs require when interacting with fully Automated Road Transport Systems in shared space? *Accident Analysis & Prevention*, Vol. 118, 2018, pp. 244–252.
10. Chang, C.-M., K. Toda, T. Igarashi, M. Miyata, and Y. Kobayashi, A Video-Based Study Comparing Communication Modalities between an Autonomous Car and a Pedestrian. In *Adjunct Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, Association for Computing Machinery, New York, NY, USA, 2018, AutomotiveUI '18, p. 104–109.
11. Forster, Y., F. Naujoks, and A. Neukum, Your Turn or My Turn?: Design of a Human-Machine Interface for Conditional Automation. *Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 2016.
12. Bazilinskyy, P., D. Dodou, and J. de Winter, Survey on eHMI concepts: The effect of text, color, and perspective. *Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 67, 2019, pp. 175–194.
13. Li, Y., H. Cheng, Z. Zeng, H. Liu, and M. Sester, Autonomous Vehicles Drive into Shared Spaces: eHMI Design Concept Focusing on Vulnerable Road Users. In *2021 IEEE International Intelligent Transportation Systems Conference (ITSC)*, 2021, pp. 1729–1736.
14. Dietrich, A., P. Maruhn, L. Schwarze, and K. Bengler, Implicit Communication of Automated Vehicles in Urban Scenarios: Effects of Pitch and Deceleration on Pedestrian Crossing Behavior. In *Human Systems Engineering and Design II* (T. Ahram, W. Karwowski, S. Pickl, and R. Taiar, eds.), Springer International Publishing, Cham, 2020, pp. 176–181.
15. Lindner, J., A. Keler, G. Grigoropoulos, P. Malcolm, F. Denk, P. Brunner, and K. Bogenberger, A coupled driving simulator to investigate the interaction between bicycles and automated vehicles. In *2022 IEEE 25th International Conference on Intelligent Transportation Systems (ITSC)*, 2022, pp. 1335–1341.
16. Kaß, C., S. Schoch, F. Naujoks, S. Hergeth, A. Keinath, and A. Neukum, A Methodological Approach to Determine the Benefits of External HMI During Interactions Between Cyclists and Automated Vehicles: A Bicycle Simulator Study. In *HCI in Mobility, Transport, and Automotive Systems. Driving Behavior, Urban and Smart Mobility* (H. Krömker, ed.), Springer International Publishing, Cham, 2020, pp. 211–227.

17. Oczko, M.-C. H., L. Stratmann, M. Franke, J. Heinovski, D. S. Buse, F. Klingler, and F. Dressler, Integrating Haptic Signals with V2X-based Safety Systems for Vulnerable Road Users. In *2020 International Conference on Computing, Networking and Communications (ICNC)*, 2020, pp. 692–697.
18. Berge, S. H., M. Hagenzieker, H. Farah, and J. de Winter, Do cyclists need HMIs in future automated traffic? An interview study. *Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 84, 2022, pp. 33–52.
19. Kummetha, V. C., A. Kondyli, and S. D. Schrock, Analysis of the effects of adaptive cruise control on driver behavior and awareness using a driving simulator. *Journal of Transportation Safety & Security*, Vol. 12, No. 5, 2020, pp. 587–610.
20. Himmels, C., J. Venrooij, M. Gmünder, and A. Riener, The influence of simulator and driving scenario on simulator sickness. In *Proceedings of the Driving Simulation Conference 2022 Europe VR* (A. Kemeny, J.-R. Chardonnet, and F. Colombet, eds.), Driving Simulation Association, Strasbourg, France, 2022, pp. 29–36.
21. Himmels, C., V. Andreev, A. A. Syed, J. Lindner, F. Denk, and A. Riener, Are Head-mounted Displays Really Not Suitable for Driving Simulation? A Comparison with a Screen-Based Simulator. In *2023 IEEE Intelligent Vehicles Symposium (IV)*, 2023, pp. 1–6.
22. Keler, A., J. Kaths, F. Chucholowski, M. Chucholowski, G. Grigoropoulos, M. Spangler, H. Kaths, and F. Busch, A bicycle simulator for experiencing microscopic traffic flow simulation in urban environments. In *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*, 2018, pp. 3020–3023.
23. Bogacz, M., S. Hess, C. Calastri, C. F. Choudhury, A. Erath, M. A. B. van Eggermond, F. Mushtaq, M. Nazemi, and M. Awais, Comparison of Cycling Behavior between Keyboard-Controlled and Instrumented Bicycle Experiments in Virtual Reality. *Transportation Research Record*, Vol. 2674, No. 7, 2020, pp. 244–257.
24. Brown, H., C. Sun, and Z. Qing, Investigation of Alternative Bicycle Pavement Markings with the Use of a Bicycle Simulator. *Transportation Research Record*, Vol. 2662, No. 1, 2017, pp. 143–151.
25. Fischer, M., G. Temme, K. Gröne, D. M. Garcia, G. Grolms, and J. Rehm, A VRU-simulator for the evaluation of pedestrian-and cyclist-vehicle interaction –Design criteria and implementation. In *Proceedings of the Driving Simulation Conference 2022 Europe VR* (A. Kemeny, J.-R. Chardonnet, and F. Colombet, eds.), Driving Simulation Association, Strasbourg, France, 2022, pp. 153–160.
26. Färber, B., *Communication and Communication Problems Between Autonomous Vehicles and Human Drivers", bookTitle="Autonomous Driving: Technical, Legal and Social Aspects*, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 125–144, 2016.
27. Grigoropoulos, G., P. Malcolm, A. Keler, F. Busch, and K. Bogenberger, Predicting Bicyclist Maneuvers using Explicit and Implicit Communication, 2022.
28. Bazilinskyy, P., L. Kooijman, D. Dodou, and J. de Winter, Coupled simulator for research on the interaction between pedestrians and (automated) vehicles, 2020.
29. Noyce, D., J. Kearney, S. Chakraborty, Y. Jiang, and K. Santiago-Chaparro, Multi-Modal Distributed Simulation Combining Cars, Bicyclists, and Pedestrians, 2018.
30. Song, Y. E., C. Lehsing, T. Fuest, and K. Bengler, External HMIs and Their Effect on the Interaction Between Pedestrians and Automated Vehicles. In *Intelligent Human Systems*

Integration (W. Karwowski and T. Ahram, eds.), Springer International Publishing, Cham, 2018, pp. 13–18.

31. Lehsing, C., A. Kracke, and K. Bengler, Urban perception - A cross-correlation approach to quantify the social interaction in a multiple simulator setting. In *2015 IEEE 18th International Conference on Intelligent Transportation Systems*, 2015, pp. 1014–1021.
32. Sawyer, B. D. and P. Hancock, Development of a Linked Simulation Network to Evaluate Intelligent Transportation System Vehicle to Vehicle Solutions. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Vol. 56, No. 1, 2012, pp. 2316–2320.
33. Blaauw, G. J., Driving Experience and Task Demands in Simulator and Instrumented Car: A Validation Study. *Human Factors*, Vol. 24, No. 4, 1982, pp. 473–486.
34. Milleville-Pennel, I. and C. Charron, Driving for Real or on a Fixed-Base Simulator: Is It so Different? An Explorative Study. *Presence*, Vol. 24, No. 1, 2015, pp. 74–91.
35. Zöller, I. M., *Analyse des Einflusses ausgewählter Gestaltungsparameter einer Fahrsimulation auf die Fahrerverhaltensvalidität*. Ph.D. thesis, Technische Universität, Darmstadt, 2015.
36. Törnros, J., Driving behaviour in a real and a simulated road tunnel—a validation study. *Accident Analysis & Prevention*, Vol. 30, No. 4, 1998, pp. 497–503.
37. Godley, S. T., T. J. Triggs, and B. N. Fildes, Driving simulator validation for speed research. *Accident Analysis & Prevention*, Vol. 34, No. 5, 2002, pp. 589–600.
38. Malcolm, P., G. Grigoropoulos, A. Keler, H. Kaths, and K. Bogenberger, *Analysis of Bicyclist Communication in a Simulator Environment*, 2021.
39. Schramm, D., M. Hiller, and R. Bardini, *Single Track Models*, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 225–257, 2018.
40. Engström, J., E. Johansson, and J. Östlund, Effects of visual and cognitive load in real and simulated motorway driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 8, No. 2, 2005, pp. 97–120, the relationship between distraction and driving performance: towards a test regime for in-vehicle information systems.
41. de Winter, J. and R. Happee, Advantages and Disadvantages of Driving Simulators: A Discussion, 2012.