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A coupled driving simulator to investigate the interaction between bicycles and automated vehicles*

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Abstract— **In order to investigate the interaction between automated vehicles (AVs) and bicyclists, we present a coupled driving simulator that enables these two traffic participants to interact in a virtual environment. To avoid potentially dangerous situations in road traffic, human perception can be extended by communication between vehicles and their environment. In order to assist the communication process between traffic participants, mobile devices are applied as human-machine interfaces (HMIs). The simulator links the simulation and visualization software with a web application to control the HMIs. The passenger of the AV can change priority rules at conflict situation in the simulation with that application and therefore influence the vehicles behavior via the communication application. To test the coupled simulator, a proof of concept study with 16 simulation runs and two participants each is conducted. The subjects rated the overall simulation impressions tending positive. Based on the evaluation of the study participants, the simulator setup will be further developed.**

I. INTRODUCTION

Driving simulators are a valuable tool in traffic research [1]. They are applied in a wide range of applications in transportation planning and traffic engineering, in particular in testing new vehicle systems for automated cars [2]. A key issue related to automated driving is the communication between automated vehicles (AVs) and vulnerable road users (VRUs), because, as reviewed in [3], VRU accidents are often associated with possible occlusion, unexpected trajectories or difficulties of the VRU in threat perception. Communication as an enhancement to human perception in road traffic offers a possibility to improve safety in the VRU-to-AV interaction. Several studies present human-machine interfaces (HMI) as a communication method [4], [5], however, the majority of HMI studies mainly focus on pedestrian-to-AV interaction. The investigation with other user groups such as bicyclists is also required for a valid HMI-concept evaluation [6]. For complex traffic scenarios including multiple interacting traffic participants, conventional single-seat driving simulators (SSDS) reach their limits [7]. The behavior and interaction of several human road users can be investigated with higher validity when test subjects interact directly with each other in a virtual environment. Individual simulators must therefore be linked to form multiple-seat driving simulators (MSDS). In this paper, a concept of a coupled driving simulator is presented to study the interaction between (automated) vehicles and bicyclists. First, an overview of the state of the art in coupled driving simulation is given (II), followed by the explanation of the AV and bicycle simulator components and their interactions (III). The simulator is tested in a proof-of-concept study with 16 simulation runs. The results of a survey, regarding the overall impressions of the simulation and the interaction with the simulators, are presented in IV. The main innovation of this setup is the investigation of bicycle-to-AV interaction including mobile devices as HMI components for both traffic participants. They serve on the one hand as an information source, and on the other as devices for influencing the driving behavior of the simulated automated vehicle.

II. STATE OF THE ART OF COUPLED DRIVING SIMULATIONS

Coupled simulations have been used for different applications in the past. One application field is driver training [8]. Coupled simulators can provide a great advantage in driver training compared to SSDS. The drivers being trained drive not only in defined scenarios, but also have to react to the driving behavior of other road users. Also, the driving instructor can deliberately create critical and dangerous driving situations to better prepare the student for a real test drive. Another application field, in which coupled simulation is used, is engineering research and development [8]. In this field, coupled simulators are applied to test new vehicle systems, such as advanced driver-assistance systems (ADAS) [9], [10]. Another example is the evaluation of HMI-concepts that investigate the communication of automated vehicles and pedestrians [1]. Besides the thematic categorization of coupled driving simulator studies, they can be classified by simulated traffic participants as well as hard- and software components.

A. Simulated traffic participants in coupled driving simulator studies

In numerous studies [10]–[18], among others, car-car interaction was investigated. The number of interacting vehicles varies from a minimum two up to five or even more cars. Since the year 2015, work can be found in which VRUs are taken into account [1], [19]–[22]. The vehicle composition always consists of an (automated) passenger car and a VRU

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(motorcycle, bicycle or pedestrian), with pedestrian-to-car interaction predominating. Bicycles are presented in two papers with the focus on traffic safety [21], [23]. The bicycle-to-AV interaction is underrepresented in transportation research compared to pedestrian-to-AV interaction, although bicycle traffic is an important transportation mode of urban traffic.

B. Hardware and Software of coupled driving simulators

Hardware and software components play a major role in driving simulations. Little commercial software exists that enable MSDS. In several studies only "SILAB" is mentioned as commercial software [13], [18]–[20]. For the majority of studies, custom software solutions are applied. These are often based on the Unity game engine, either standalone or in combination with other frameworks [1], [14]–[16], [23]. The hardware used for the simulators varies greatly across studies from high-fidelity simulators to simple setups with computer screens, steering wheel and pedals to simulate a passenger car. With the increasing number of involved traffic participants, the complexity of the individual simulators decreases. The fixed base bicycle simulator in [23] detects steering angle and speed while riding a real bicycle. Besides the driving simulators themselves, additional hardware to monitor the test subjects, for example eye tracking solutions, are installed in some cases [7], [21]. A coupled driving simulation contains many different hardware and software solutions. They all must work together efficiently to produce a high quality driving simulation. The combination of all these components is a major challenge in implementing coupled driving simulators [7]. In order to evaluate coupled simulator systems and guarantee system resilience, four requirements are defined in [8]: systematic approach, open system interface, configurability principle and modularity principle. These requirements represent an evaluation and implementation basis for coupled driving simulator systems.

The literature review indicates that there is a lack of coupled simulators that enable the investigation of HMI concepts between AVs and bicyclists. Also little work exists regarding HMI concepts for bicyclists, as described in [24]. Due to the trends of vehicle automation [25] and the promotion of sustainable modes of transport [26], [27], enabling safe encounter between AVs and bicycles will be a crucial point in future urban traffic.

III. METHODOLOGY

A. Simulator Study Design

In order to test the simulator setup, a proof-of-concept study with 16 simulation runs and two participants (13 female, 19 male - Age group *18-24*: 12, *25-39*: 19, *40-59*: 1) each is conducted. During the study, an AV and its passenger, and the bicyclist interact in a virtual environment. The AV drives on a predefined path, while the bicyclist can move freely in the virtual city model. The communication application includes a navigation mode, which on the one hand informs the AV-passenger about upcoming maneuvers of the AV, and on the other hand guides the bicyclist through the city network. At the intersection points of the vehicles' routes, the road users have to interact (see Fig. 1). These conflict points are chosen specifically to investigate certain traffic scenarios. When approaching a conflict point, we define three interaction types, depending on the priority rules at the conflict point and the information displayed on the HMI: (1) the default type, where conventional traffic rules apply, (2) the AV deciding autonomously about the traffic rules, and (3) the AV-passenger deciding about the traffic rules. If a non-default scenario is imminent, the application gives the HMI user a pre-information about the upcoming scenario. If the priority decision is up to the AV-passenger (option 3), the test subject can decide about priority rules and is then informed about the AV's driving behavior during the conflict scenario (see Fig. 2). If the AV decides autonomously about priority rules in a traffic scenario (option 2), only information about the vehicle's behavior during the scenario is displayed. The bicyclist also gets the pre-information followed by an instruction on how to behave in the scenario (priority given or taken). After leaving the traffic scenario, the application switches back in navigation mode. The decisions of the AV or its passenger are synchronised with the simulation. Depend-

Fig. 1: Conflict situation including bicyclist and AV

Fig. 2: Trigger points for the AV within an investigation scenario: Pre-information (PE), Decision phase, virtual stop line and the exit scenario trigger

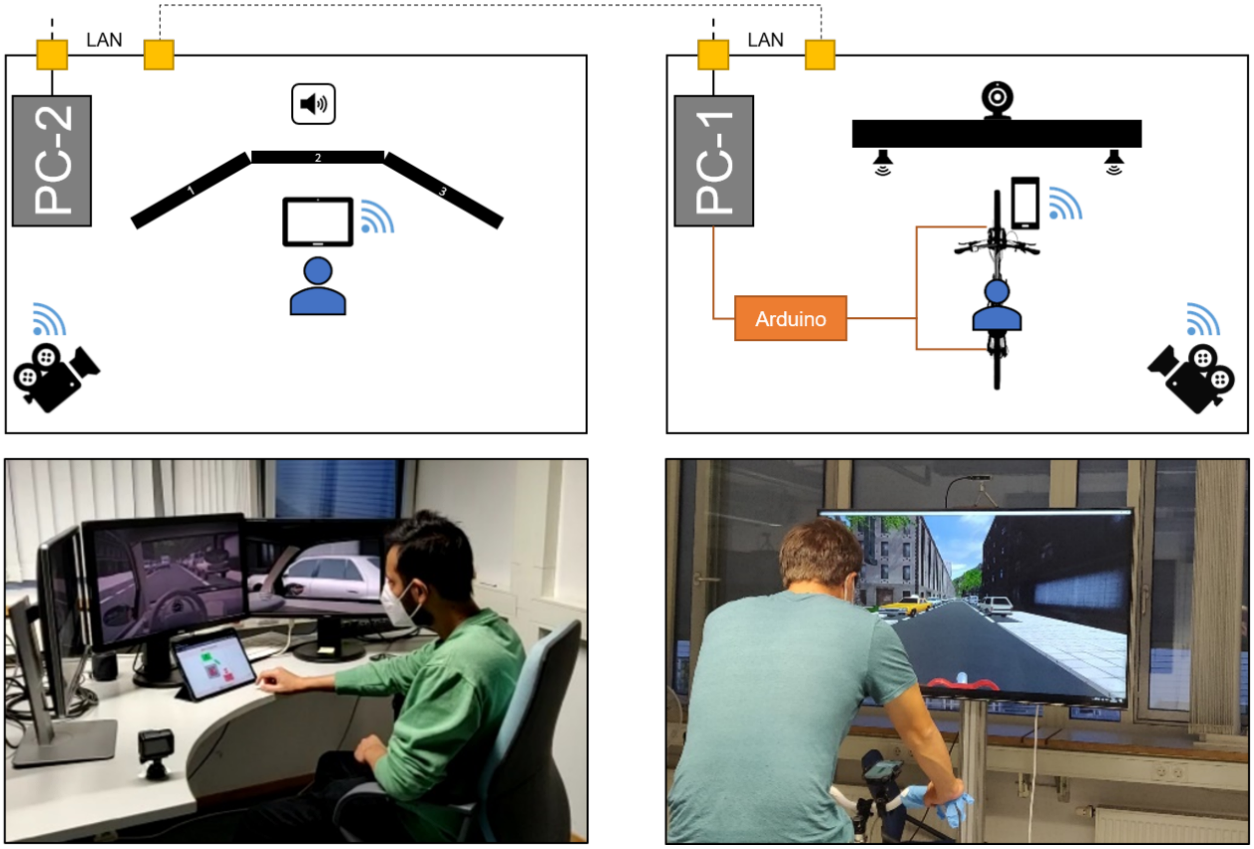

Fig. 3: Coupled simulator setup (Left: AV simulator. Right: Bicycle simulator)

ing on the current decision, the AV behaves differently and, for example, reduces the speed when the bicyclist is given priority. After each simulation run, the study participants had to fill out a survey. The results regarding the behaviour of the vehicles in the virtual environment and the interaction with the simulator are presented in IV.

B. Hardware

The coupled driving simulator consists of two parts: the AV simulator and the bicycle simulator (see Fig. 3). The AV simulator is composed of a PC with 3 monitors, a speaker and a tablet as a communication device. Optional are a steering wheel and pedals if the study includes a non-automated car. The bicycle simulator requires a more elaborate setup. For this purpose, the bicycle simulator of the Chair of Traffic Engineering and Control at the Technical University of Munich was used [28], [29]. This simulator is implemented with a real bicycle that is located in front of a television including a sound system. The steering movements of the bicycle are measured by a magnetic rotary encoder, mounted on a rotating plate on which the front wheel is placed. The speed of the bicycle is calculated by an infrared sensor which counts the rotations of a metal cylinder driven by the bicycle's rear wheel. Since only the rotation of the rear wheel is measured, only the rear brake is functional in this simulator setup. The sensor data is processed via an Arduino Uno microcontroller which sends the data to a communication port of a PC. The hand signals of the bicyclist are detected via a depth camera. Moreover, a smartphone as communication device is mounted on the bicycle handlebar. The two driving simulators are located in different rooms and connected via internet cable. For the communication application, PC-1 acts as server for both client devices, the tablet and the smartphone. During the entire communication, the PCs and the mobile devices are connected to a virtual private network (VPN). It is also possible to link the PCs via a direct LAN connection. Both test subjects are monitored with cameras during the simulation in order to intervene when problems occur.

C. Software

To realize the coupled real-time simulator study, efficient software solutions are required. The core components of the simulation are the virtual environment, the visualisation and control of the road users, the networking solution and the communication via the web application. The information flow between the components is displayed in a layer structure in Fig. 4. Based on the study design above, the single layers are explained in the following.

- *Unity game engine*
  The Unity game engine is the main part of the software concept [30]. All information streams flow together or distribute here. The virtual environment is built up and the vehicle models can be controlled within the game

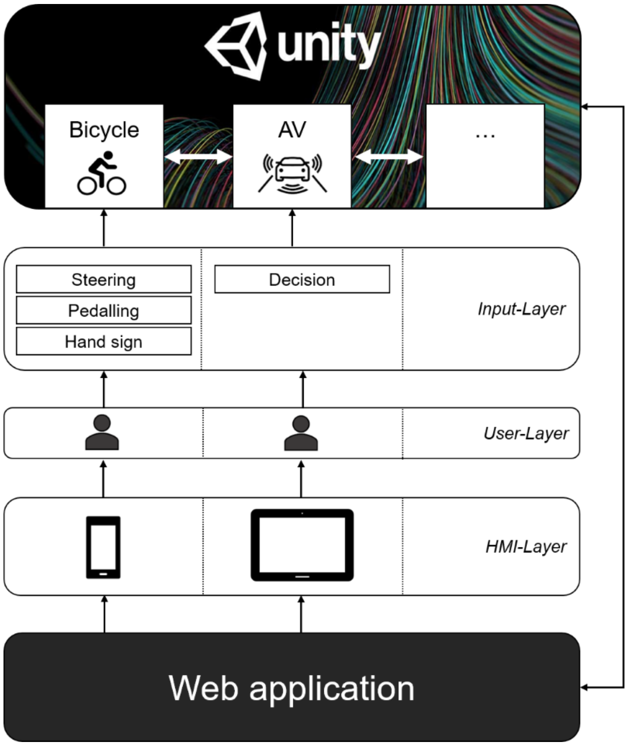

Fig. 4: Software layer structure of the coupled simulator

engine. This includes for the bicyclist the movement of the vehicle as well as the character animation with hand signals. The simulator input parameters (steering angle and speed) are processed to control the virtual bicycle model. The movement of the AV is controlled by an algorithm that adjusts the speed of the car in such a way that both road users enter the conflict situations at the same time. When the AV is in an investigation scenario, the communication application controls the speed input. Thus, a two-way communication between game engine and web application is realized.

A benefit of game engines used for coupled driving simulation is the know-how of the gaming industry in multiplayer games [1]. For this coupled driving simulator, the built-in networking solution is applied. It handles low level networking tasks and enables the traffic researcher to work on the networking at a higher abstraction level.

- *Web application*
  The web application provides the mobile device user information about navigation, traffic situations or vehicle behavior. It also enables the AV-passenger to interact with the vehicle and decide at certain situations about priority rules at a conflict point. In between investigation scenarios, the application is in navigation mode. It provides the AV-passenger information about the AV's behavior or guides the bicyclist through the virtual city network. Upon entering an investigation scenario, the application conveys basic information about the traffic situation and the upcoming conflict with another vehicle. Also, real-time information about the distance to the conflict point is displayed. After the priority decision to resolve the conflict situation, corresponding information is provided to the users. The web application also communicates this decision to the Unity game engine component, in order to adjust the AV's driving behavior. The communication between the web application and other software components is realized using the internet protocol HTTP. Access to the application is provided via a representational state transfer (REST) programming interface [31]. Thus, the application only has certain states, which can be triggered from an external software. During the development phase, it was a benefit to run the application with web technology, because it is platform- and device-independent. A version for native Android support is under development.
- *HMI-Layer*
  The human-machine interface layer is represented by the from the web application provided information to the mobile device user. Not only visual information in text or image form is displayed, but also audio signals are used to encode the message information by type. For example, warning messages have a unique signal tone.
  For simulation purpose, a mobile phone for the bicyclist and a tablet for the AV-passenger are used as hardware components. In reality, this concept is applicable for the bicyclist, because it is already common to use a mobile phone as a navigation device. Such a navigation application can then be extended with conflict information functionalities. In an automated vehicle it is conceivable that the automation HMI (aHMI) in the future is represented by a tablet. Nowadays it is practice that aHMIs are integrated in the instrument cluster in the windshield, a monitor on the center console or head-up displays [32]. A more detailed description of the communication application can be found in [24].
- *User-Layer*
  The test subject must be able to process the received information correct in content in adequate time. It has to evaluate the input from different information channels: the simulation world and the HMI device. Based on the bicyclist subject's perception, it adjusts the driving behavior and decisions. The AV-passenger is not required to perform driving actions. Rather, the focus is on user acceptance and trust in the automated system, and for this study design, on the priority decisions of the AV-passenger.
- *Input-Layer*
  The input layer represents the input from the physical driving simulators. The bicycle simulator provides the simulation with information about the steering angle and rear wheel's rotation. The raw values are adjusted to calibrate the sensitivity of the system input. The hand signs are detected by a depth camera with an underlying machine learning algorithm [33]. It detects whether a hand signal is being given based on skeleton points of

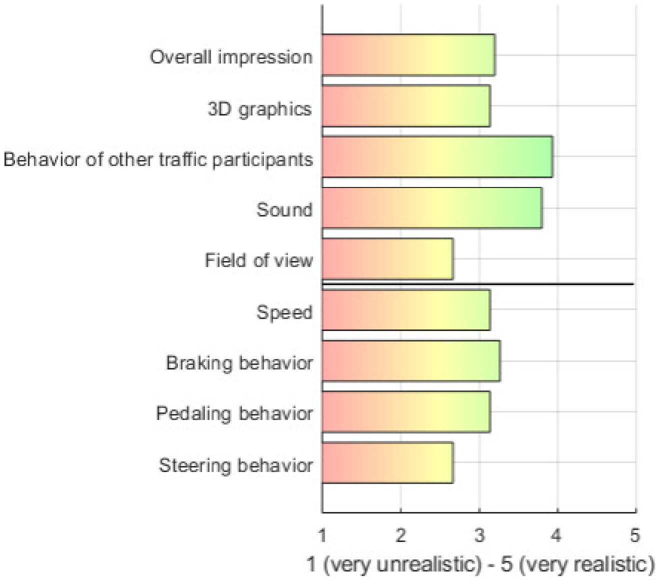

Fig. 5: Bicyclist evaluation of the simulation impressions and interaction with the simulator

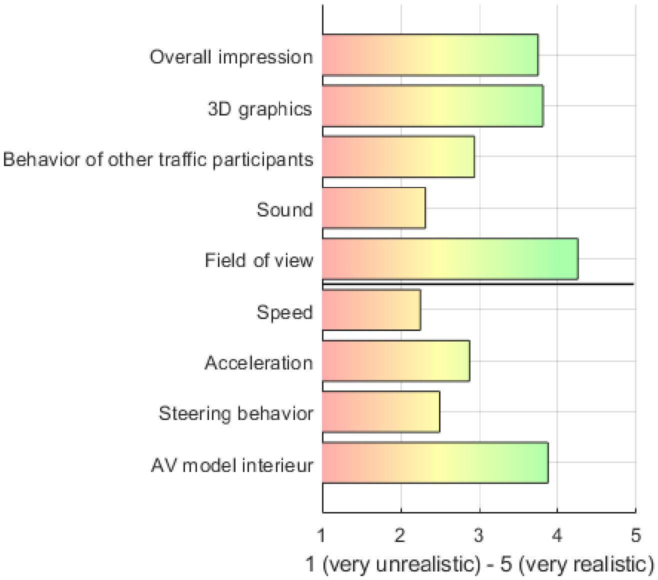

Fig. 6: AV-passenger evaluation of the simulation impressions and interaction with the simulator

the bicyclist. This information is synchronized to the animations in the game engine.

The input from the AV-passenger is handled by the web application. The application transfers the decision about priority rules to the game engine.

During the simulation data is collected from the study participants and saved in two CSV files. The game engine writes one file with information about position, rotation and the use of blinkers and hand signs. The web application saves time and type of when a HMI screen is triggered. Moreover, the test subjects had to fill in one short survey about the performance of the web application and the safety perception right after each investigation scenario. They also answered an extensive survey including demographic questions, questions on their driving experience, the overall impressions of the simulator study and the interaction with the simulators after the whole simulation run. The results of the survey part regarding the overall impressions and interaction with the simulators are presented below.

IV. RESULTS

For the evaluation of the simulator setup, we analyzed questions from the survey the test subjects filled in after a simulation run (see Figs. 5 and 6). The content of these questions concerns the impressions of the simulation and the interaction with the simulators. The questions regarding the individual simulators differ from bicyclist to AV-passenger. Each parameter could be evaluated from 1 (very unrealistic) to 5 (very realistic).

The overall impression of both test subjects tends to be positive (Bicycle: 3.20, AV: 3.75). The same trend is found for the parameter 3D graphics (Bicycle: 3.13, AV: 3.81). Some other evaluations differ significantly between the bicyclist and the AV-passenger. The behavior of other traffic participants was rated with 3.93 points from the bicyclists. On average 1.00 points higher than the AV-passenger's rating. Because only these two traffic participants, the bicycle and the AV, were in the simulated environment, the bicycles behavior is rated more poorly than the AV's behavior. The reason for that may be that the tilt angle in a curve wasn't visualized in the simulation to avoid motion sickness for the bicyclist subject. A possible solution to this would be different visualization for each test subject. The bicyclist will see a model synchronized to the simulator to ensure intuitive control; the AV a highly detailed, realistically-behaving model. Besides the tilt angle parameter, the head movement and therefore eye contact as a common communication pattern between cars and bicyclists [34] was not represented in the simulation at all. The sound was rated with 3.80 points for the bicyclist and with 2.31 for the AV. Some AV-passenger subjects noted that they did not recognize any sound. It seems that they got used to the sound scenery in the simulated world, which did not include many sound sources. The field of view evaluation is highly dependent on the simulator setup. It was rated at 2.67 points by the bicyclists and 4.25 point by the AV-passengers. For the bicyclist only one screen was available. The natural field of view of about 50° is artificially extended by modifying the recording angle of the simulated camera to 90°. Much less, compared to the 165° field of view for the AV-passenger. In future studies, more screens or virtual reality technology will be applied to increase the bicyclist's field of view. The remaining parameters are vehicle dependent. The bicyclists evaluated the speed, braking and pedaling behavior somewhat favorably. The steering behavior was evaluated as less realistic, with 2.67 points. Two influencing factors are the already discussed tilt angle in a curve and the restricted field of view. The AV-passengers rated parameters regarding the AV's driving behavior (speed, acceleration, steering) tending unrealistic. This is mainly caused by the algorithm that controls the AV's acceleration and deceleration, as discussed with study participants. The AV in the simulation must adjust to the bicyclists speed to arrive at the same time with the bicycle at the investigation scenarios. This can lead to unnatural speed choice and acceleration behavior. This behavior is only recognized in between investigation scenarios, and is thus not critical for the scenarios themselves. The 3D model of the car was rated very realistic. For the model, a slightly modified version of the car model used in [1] was applied. This detailed model includes for example mirrors, lights and a speedometer. For the investigation of traffic scenarios with human-human interaction, the parameter "behavior of other traffic participants" is especially important. The bicycle model will be improved with regard to important communication patterns like hand signals and eye contact [34]. The networking solution can here solve the problem of road-user-dependent visualization.

V. CONCLUSIONS

A coupled driving simulator including an automated or non-automated vehicle and a bicycle is implemented. It enables traffic participants to interact in a virtual environment. Mobile devices are included to represent HMI components in the simulation. The visualization and interaction with the HMI is implemented with a web application. It is possible to provide the HMI user with information linked to the driving simulation and also let the user decide about priority rules in specific conflict scenarios. The mobile devices can thus also be used as input devices to influence the vehicles behavior.

Moreover, the following points will be implemented in the future:

- *Interface to SUMO*
  In the presented study, only two vehicles interact in the simulation. For more realistic and complex traffic scenarios, an interface to the traffic simulation software SUMO will be implemented [35].
- *Full body motion tracking of the bicyclist*
  The movement of all body parts, especially the arms for realistic hand signals, will be animated and compared to the discrete animations currently used (give a hand signal or not). This increases the simulation validity of hand signals and enables communication methods like eye contact.

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