A Simulation Prototype for Testing and Validation of AV-to-Pedestrian Communication with Configurable eHMIs Targeting VRU Diversity and Distraction

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Abstract: External human-machine interfaces (eHMIs) are widely proposed to replace the implicit cues that disappear with driverless autonomous vehicles (AVs). Vulnerable road user (VRU) diversity, including but not limited to age, mobility, sensory capability, language, culture and emotional state, primarily determines eHMI effectiveness. Attention-reducing factors systematically affect pedestrian crossing behaviour, while none of the established AV simulators or VR laboratory setups simultaneously provide traffic dynamics, configurable eHMIs and VRU diversity. This paper, therefore, proposes a simulation prototype that targets the human-facing aspect of the AV-to-VRU communication.

Keywords: Autonomous Driving, eHMI, Simulation, Vulnerable Road Users

1 Introduction

Autonomous vehicles change the communication between road users in urban traffic in general, and particularly the vehicle-to-VRU communication. In conventional traffic, pedestrians, cyclists and other vulnerable road users rely on subtle interpersonal cues, such as eye contact, vehicle creep, hand gestures and head movements. If the driver is no longer in the loop, those communication cues disappear, and other means of communication become necessary. eHMIs have been proposed to fill this gap by communicating vehicle state and vehicle intent to nearby road users [1], [2], [3].

VRUs are inherently heterogenous. They differ in visual appearance, such as body size, age, hair colour and hairstyle, but also in their mobility, sensory performance, cognitive load and emotional state [4], [5], [6]. Their perception can also be negatively influenced by distractions i.e. using a smartphone, listening to music, travelling in a group or attending to a child [4], [7]. Depending on VRU attention, sensory capabilities, cognitive abilities and cultural backgrounds, eHMI communication may be perceived differently and even mistakably [8], [9]. Therefore, a much more flexible testing and validation method is necessary.

Prior work examined the crossing decisions of VRUs in AV scenarios, compared text-based and symbol-based interface approaches, and reviewed design principles and taxonomies regarding eHMI concepts [1], [2], [3], [8], [10], [11], [12]. Other publications address VRU behaviour models, social force models, and mixed-traffic scenarios [7], [13], [14], [15]. These research areas should be viewed holistically, but often remain separate [16], [17].

This paper proposes a simulation prototype derived from three core statements. First: VRU diversity is essential for road safety [4], [5], [6], [18]. Second: distractions and emotional state significantly impact the crossing behaviour and, therefore, road safety [7], [15], [19]. Third: Current simulation tools do not offer traffic simulation, configurable eHMIs, and a VRU diversity layer with the required fidelity simultaneously [17].

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2 Related Work

2.1 eHMI Design and Information Content

eHMIs should communicate the vehicle's state and intent to surrounding road users. Prior empirical work investigated different eHMI concepts and their impact on pedestrian crossing decisions by varying yielding behaviour, vehicle size, eHMI type, and message timing [1]. Dey et al. proposed an eHMI taxonomy that spans 18 dimensions and coded 70 eHMI concepts. They also emphasised that the research field lacks standardisation and a systematic treatment of special-needs VRUs [2].

According to Faas et al., pedestrians at unsignalized crossings want the AV to signal its situational awareness and its intent [10]. Bazilinskyy et al. investigated eHMIs in the context of displayed text, colour and perspective and highlighted the difficulty of clear signalling to a broad audience [8]. Wilbrink et al. synthesised empirical findings into 17 principles for eHMI design and proposed standardisation [12]. Kato et al. demonstrated that a recurring failure mode is message-receiver ambiguity, and that more familiar pictograms of pedestrians outperform abstract symbols in message understanding [9]. These prior works support the methodological requirement that eHMI testbeds need to be configurable in content, timing, modality and placement.

A prototype therefore has to be able to configure relevant eHMI parameters such as brightness, colour, animation, symbols, language, wording, duration, fallback state and placement [2], [12].

2.2 VRU Diversity

Kwok et al. systematically reviewed eHMIs for diverse VRUs, such as elderly people, children and people with disabilities and found that these groups are underrepresented in empirical literature [4]. Davis interviewed elderly people and found that they need explicit, legible signals while also wanting to be considered in eHMI design concepts [5]. Yan et al. discuss requirements for inclusive HMIs in shared autonomous services, and Colley et al. investigated eHMIs for blind and visually impaired road users and found that visually dominated eHMIs aren’t suitable, because of a lack of auditory or tactile communication [6], [18].

Cultural, linguistic and rule-familiarity differences also influence whether a text or symbolic eHMI message is understood or misinterpreted. A text-based eHMI message may be misunderstood if language proficiency is lacking. Symbol-based eHMIs may be ambiguous due to differing cultural symbolism, colour conventions, or gestures [2], [9]. Other empirical surveys indicate that text and text-symbol eHMI concepts are particularly important for elderly people and tourists [12].

2.3 Distraction, Attention and Emotional State

Variability in pedestrian behaviour can be traced to distractions and sensory degradation caused by smartphone use, headphones, sunglasses, and other accessories that impair attention, as well as to different emotional states that reduce situational awareness and affect crossing behaviour. Group behaviour and the social force model also impact crossing decisions in AV interactions. Pedestrians follow group decisions even though eHMI signals may contradict those decisions [7], [15]. VR studies on perceived risk show that the same eHMI message is judged differently depending on the VRU’s stress level and prior trust [19].

Adaptive eHMIs could be a solution to this variability [20], but the evaluation of those systems requires controlled experiments on distraction, sensory capabilities, and the emotional state of the VRU. Common video studies and questionnaires cannot translate the fidelity of those conditions [3], [11]. A simulation tool must, therefore, include distractions and impairments as experimental factors, accurately representing them like shown in figure 1.

Figure 1: Original (left), brown tinted sunglasses (middle), protanopia colour-blindness (right)

2.4 Simulation Tools and the Methodological Gap

Simulation tools already support AV development, but there are no dedicated tools for eHMI development in a diverse VRU context. A common open-source simulation tool is CARLA, which can be used for development, training and validating AV systems. It provides vehicle and environment assets, configurable sensors, differing environmental conditions, actor control, and an API for simulation control [21]. CARLA also supports SUMO co-simulation with operational synchronisation of vehicle properties and traffic lights [22]. Proprietary simulation tools such as IPG CarMaker focus on vehicle dynamics and virtual testing of ADAS systems, but are not suited for eHMI implementation and VRU simulation [23].

SUMO is an open-source traffic simulation that can model common road vehicles, public transport, bicycles and pedestrians in mixed-traffic scenarios. It also supports common road network imports, like OpenStreetMap, VISUM, VISSIM, MATSim and OpenDRIVE [24]. ASAM OpenDRIVE is a standardised file format that describes static road networks for driving simulation programs and enables exchange between simulators [25]. ASAM OpenSCENARIO XML describes the dynamic content of a driving scenario, such as manoeuvres, trajectories of pedestrians and other traffic participants, supports parametrisation and is intended for vendor-independent scenario exchange [26].

VR laboratories often use a custom Unity/UE setup for AV-to-pedestrian communication research, but it lacks a scalable traffic backend and offers only limited configurability. They are very specialised and mostly developed for one-off research projects [1], [3], [11].

As the proposed prototype's design target is the human-facing aspect of the AV-to-VRU communication, it needs to simulate diverse VRUs and various eHMI implementations and enable the user to easily adjust VRU distractions and impairments.

Table 1 summarises the resulting positioning of the proposed simulation prototype relative to these tool classes.

Table 1: Positioning of the simulation prototype relative to existing simulation approaches and VR laboratories.

Tool/approach	Primary Use-Case	Gap addressed by the simulation prototype
SUMO	Microscopic, multimodal traffic simulation with remote control and broad network-format import.	No immersive UE5/VRU-centred perception layer or eHMI study menu by default.
CARLA	Open-source AV simulator for development, sensors, actors, maps, and traffic scenarios.	Human-factor manipulation of VRU perception and eHMI comprehension is not the central workflow.
CARLA + SUMO co-simulation	Synchronous co-simulation distributes traffic tasks between the two simulators.	Vehicle/traffic oriented. Does not directly provide configurable profiles for impairment, culture and eHMI.
esmini	Efficient OpenSCENARIO playback and lightweight scenario execution.	No first-person VRU perception, no distraction/impairment modules, no eHMI configuration.
IPG CarMaker	High-fidelity vehicle dynamics and virtual sensor models for ADAS development.	Vehicle-focused. Not designed for VRU perspective or eHMI testing.
VR eHMI labs	High ecological validity for first-person crossing decisions.	Limited scenario scale, no shared traffic backend, and limited reusability of configuration for VRU diversity factors.

3 Design Principles

For designing the prototype, five design principles need to be derived. First, the prototype must use standardised file formats, such as OpenDRIVE and OpenSCENARIO, to enable exchange between simulators [25], [26]. Second, the SUMO backend and the UE5 front-end have to be handled separately. SUMO simulates the mixed-traffic scenario, while UE5 renders the AV and VRU perspectives and hosts the VRU and eHMI configuration menus [22], [24]. Third, the configuration for the VRU profiles and eHMIs must be easily accessible to iterate quickly and adjust parameters.

Fourth, the AV and VRU perspectives need to be accessible. The AV perspective provides insight into sensor perceptions, while the VRU perspective displays eHMI visibility and visualises sensory impairments or distractions [3], [11]. Fifth, data needs to be collected and logged to draw meaningful conclusions. The data must contain actor states, eHMI states, time-to-collision, time-to-arrival and all configuration parameters. A screen capture complements the data and adds a layer of subjective interpretation to the data generation process. Biosignals and eye-tracking can be used to test and validate the impact of eHMI systems in a human-in-the-loop setting.

Table 2 summarises the resulting requirements.

Table 2: Requirements derived from eHMI, VRU-diversity and simulation-tool gaps.

Requirement	Prototype realisation	Differentiation from existing tools
Configurable eHMIs	Menu-based selection of type, message, position, colour and symbol set.	Treats eHMI systems as dedicated experimental variables
Configurable VRUs	Profiles for pedestrians, cyclists, wheelchair users and mobility-constrained	Moves beyond a generic pedestrian model by exposing diversity assumptions.

Requirement	Prototype realisation	Differentiation from existing tools
	users with avatar, gait and sensory parameters.	
Distraction and impairment modules	Phone overlay, headphone audio masking, sunglasses shader, visual acuity filters, narrowed field of view and mobility constraints.	Adds human-perception manipulations.
Language and culture settings	Language, symbol set and local traffic conventions.	Makes cross-cultural comprehensibility testable without changing the core scenario.
Standards-aware scenarios	OpenDRIVE/OpenSCENARIO import where feasible, plus JSON for study-specific VRU parameters.	Combines standards with an additional eHMI/VRU layer.
Human-in-the-loop operation	UE5 VR or conventional display solutions. HMIs for control.	Prioritises VRU perception and repeatable eHMI exposure.

4 Prototype Architecture

The prototype architecture consists of the SUMO backend for traffic simulation and the UE5 front-end, which renders visual details, manages audio, and serves as the user interface. UE5 connects to SUMO via the TraCI bridge to obtain vehicle and pedestrian states, which can then be mapped to the actors managed by the UE5 front-end. UE5 can also send user-driven changes back to SUMO to create a dynamic simulation scenario in which traffic reacts to VRU behaviour. The communication between UE5 and SUMO uses synchronous stepping to avoid drift between the traffic simulation and visual rendering [27].

Figure 2 illustrates the architecture of the proposed prototype. The Scenario Manager loads the traffic network, vehicle and VRU routes, and scenario metadata such as locale, weather conditions and time of day. The SUMO backend simulates the traffic network in a next step and sends data through the TraCI bridge to UE5, where the visuals are then rendered. Based on VRU behaviour, the UE5 front-end can then send updates to SUMO to adapt the traffic simulation accordingly. The VRU profile library and eHMI config library are containers for saving and loading configurations for later test runs. The UE5 front-end afterwards generates measurement data via the data logger.

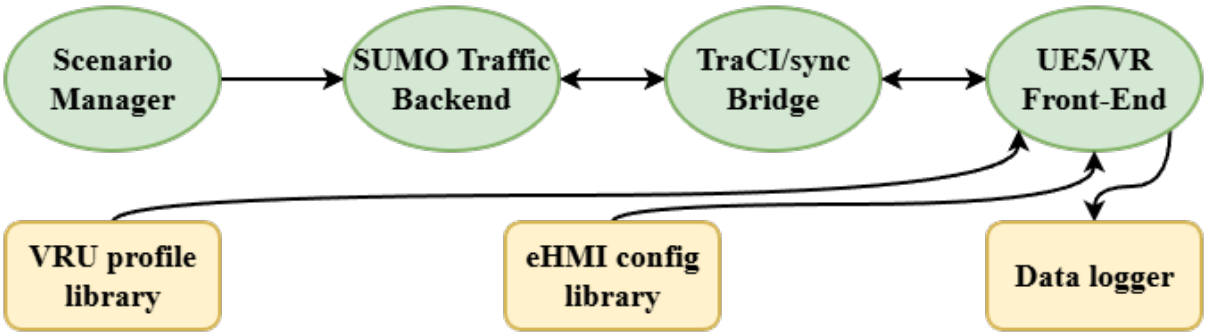

Figure 2: Modular UE5/SUMO architecture for configurable AV-to-VRU communication studies.

4.1 Core Managers

The UE5 front-end acts as the simulation manager. It consists of the Actor Factory, which spawns vehicles, VRUs and environmental objects and builds the scene. The eHMI manager

attaches the configured eHMIs to the AV and links states to the eHMI outputs. The eHMIs can be positioned anywhere on the AV, and therefore, a fully configurable eHMI concept can be implemented. The VRU manager manages camera positioning, visualises distractions, impairments, and emotional states, and applies the configured movement modes. The VRU manager also provides VR functionality via native OpenXR support from UE5 [28].

4.2 eHMI State Machine

The eHMI system is implemented as a state machine with states such as inactive, yielding, not yielding, waiting, priority conflict, emergency stop, and error. Each state is mapped to a corresponding message, symbol set and audio cues. The eHMI type is preconfigured and acts as a generic implementation that can be configured to scenario needs. It's important that the eHMI system is separate from the vehicle controller, so that the same scenario can be simulated with different eHMI systems and implementations. The design follows the harmonisation principle proposed by Wilbrink et al. and can support adaptive eHMIs [12], [20].

4.3 VRU Profile System

The VRU profile consists of two layers. The appearance layer contains body type, body height, age, skin tone, posture, hairstyle, and the VRU category, such as wheelchair user, e-scooter driver, or walking pedestrian. It also contains the corresponding animation set to accurately visualise movement.

The second layer, called the behaviour and perception layer, contains the movement profile and metrics on sensory capabilities, such as hearing, vision, colour blindness, etc. and language and rule familiarity. It is important that implementing additional metrics for the VRU profile is easy and fast, so the tool can manage increasing VRU diversity and therefore enhance testing and validation of eHMI systems [4], [5], [29].

Figure 3 depicts the minimum required attributes for the VRU- and eHMI-module, that are needed to represent a VRU with realistic diversity and eHMIs that are freely configurable.

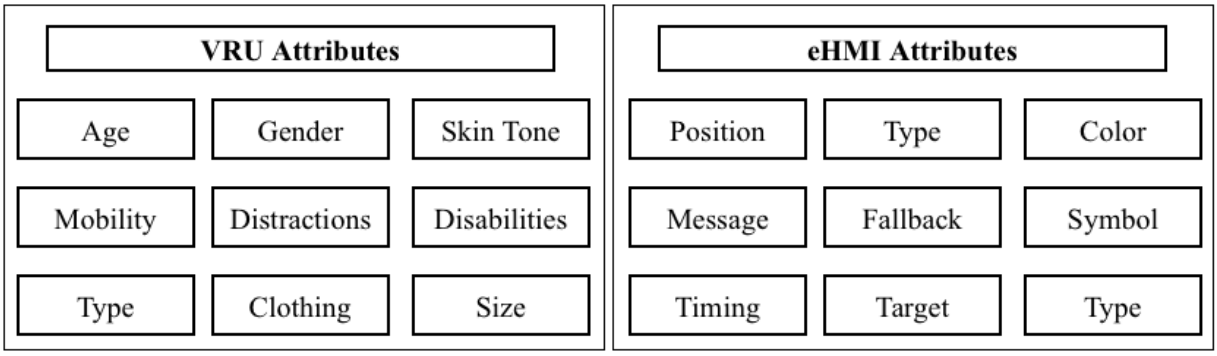

Figure 3: Minimal required attributes of the VRU- and eHMI-Modules

4.4 Distraction, Impairment and Cultural Modules

Distraction and emotional state are visualised via shaders and vision filters. While stress can be visualised as field-of-view narrowing and reduced contrast in peripheral vision, distractions such as listening to music with headphones on can be presented by attenuating environmental audio and overlaying it with music or podcast audio. Smartphone use can narrow the field of view but can also lengthen reaction time. Sunglasses or visual impairments are implemented via colour shifts, brightness changes and contrast changes. The mobility limitations that affect

acceleration, turning radius and movement speed are configured via the VRU movement profile [7], [15], [19].

Language and cultural differences, on the other hand, are implemented through different languages, symbol sets, and colour palettes. The resulting eHMI profile can be saved and quickly iterated for fast testing and validation.

4.5 Data Logging

To log data, the simulation prototype collects data at fixed time step intervals and writes it to a file with corresponding timestamps. The measurement file is in a proprietary format, but can easily be converted to common formats such as .mat or .csv. Every test run has its own measurement file containing data on actor states, eHMI states, configuration settings, and scenario-critical data such as time budgets, time-to-collision, and distances to objects. Biosignals and eye-tracking can also be logged if hardware is available.

5 Conceptual Assessment

The proposed architecture fits and fulfills the given design requirements. eHMIs are configurable and easily adaptable. VRUs can be modelled with sensory and movement impairments, while the appearance can also be configured. The parameterised VRU profiles can improve VRU diversity and enable more inclusive research regarding VRU road safety. This fact narrows the research gap for underrepresented VRUs and enables rapid iteration of eHMI concepts without requiring costly AV prototypes.

The most important result is the separation between the simulation layers. Existing simulation tools already tackle traffic scenes, sensor data and controlled actors in AV-specific simulation environments [21], [22]. The addition of a dedicated VRU layer with highly configurable profiles and rapid eHMI iteration can improve understanding of AV-to-pedestrian communication and the effectiveness of eHMI systems in conveying message clarity and understanding.

6 Summary and Outlook

This paper proposes a simulation prototype for testing and validating AV-to-pedestrian communication, with a focus on VRU diversity, by adding configurable eHMIs and VRU profiles and using SUMO as the traffic simulation backend, while UE5 serves as the front-end user interface and the 3D rendering engine. The tool is able to manage distractions, disabilities, language proficiency, and cultural norms, and allows to represent them visually and audibly with state-of-the-art, realistic rendering performance.

Three key findings were made: First, empirical research on eHMI systems, VRU behaviour, underrepresented VRUs and the impact of distractions and disabilities on eHMI perception has been synthesised into design principles and the corresponding prototype architecture. Second, a human-centred simulation layer is added to the conventional vehicle-centric simulation of AV-vehicles in order to treat human factors as the primary experimental variables. Third, a distinction from established simulation tools was made by addressing the research gap and adopting an open simulation framework that uses UE5 as a highly modifiable physics and rendering engine.

Future work includes the technical implementation of the prototype and the preparation of an extensive VRU profile and eHMI library. Based on current research, the simulation tool will be tested and validated to accurately simulate AV-to-VRU communication and to become a practical tool for researchers, manufacturers, suppliers and regulators to test eHMI systems and generate and test even rare edge cases.

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