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CENTER FOR CONNECTED AND AUTOMATED TRANSPORTATION

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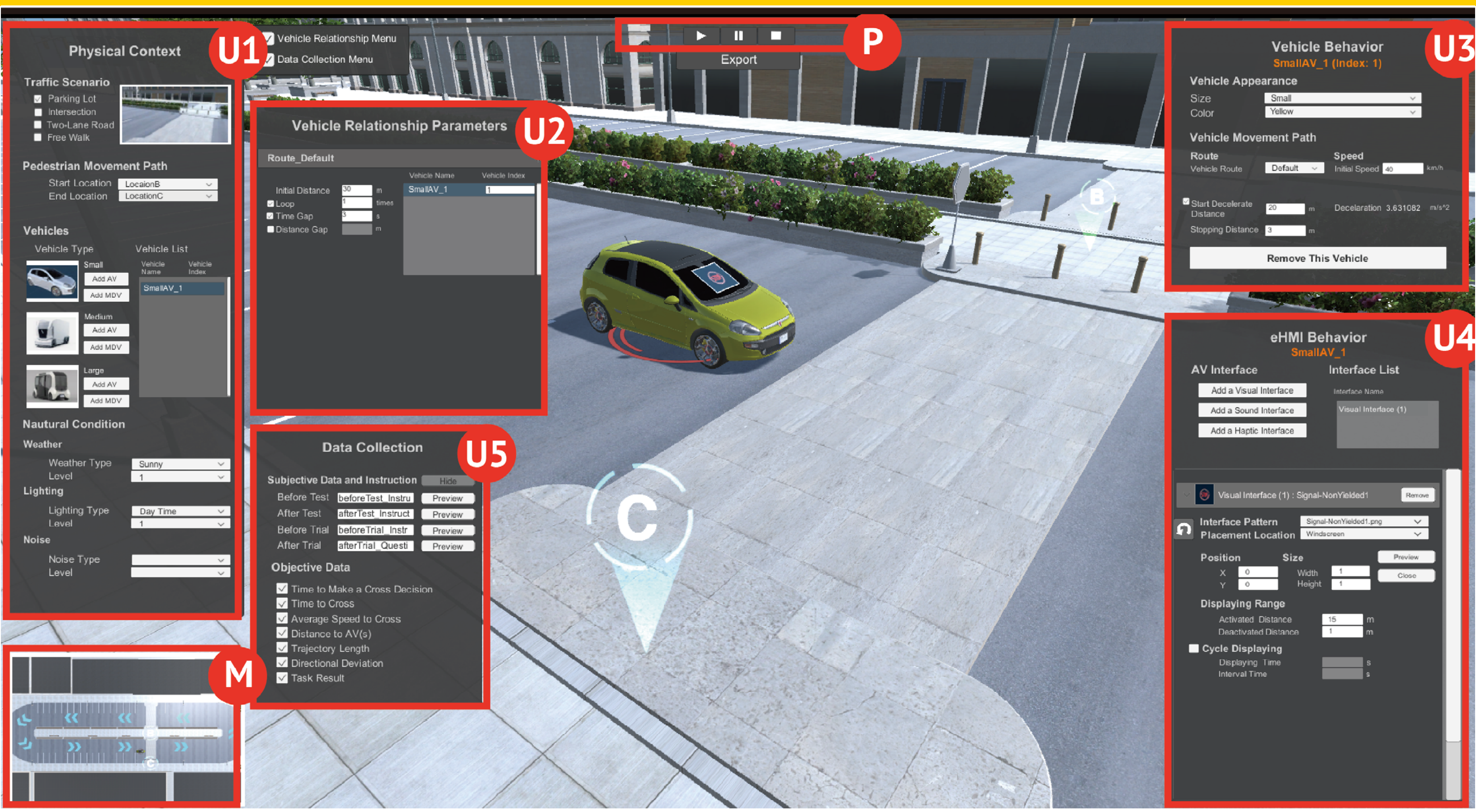


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CENTER FOR CONNECTED AND AUTOMATED TRANSPORTATION

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by

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DISCLAIMER

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**16. Abstract**
The study developed Human-Autonomous Vehicle Interaction Testbed (HAVIT), a VR-based platform that enables researchers and designers to quickly configure AV interaction scenarios and evaluate their design concepts during the design process in a holistic and consistent manner. The HAVIT presents an efficient workflow that combines the tasks of Scenario Configuration, Experimental Setting, and Batch Configuration. The developed workflow enables the user to quickly and flexibly configure motion behaviors of AVs and external human-machine interfaces (eHMIs) through visual panels and direct manipulation, and carry out experimental settings through its Data Collection and Testing Instruction components. It also readily enacts and enables the user to reasonably iterate and generate virtual scenarios for testing in an immersive manner. The study conducted usability testing with domain experts and designers, and thereby ascertained the effectiveness of HAVIT support of AV interactive design processes.

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# 1. Introduction

Autonomous vehicle (AV)-human interactions directly impact human safety, etiquette, and overall acceptance of AV technology [12]. It is vital to fully explore this emerging interaction type to address potential ambiguities and conflicts in the future of transportation. However, evaluating AV- human interactions is a challenging task due to the unavailability of AVs for experiments and the potential harm involved in physical field tests. As such, within these circumstances, virtual reality (VR)-based methods have received considerable attention from the research community and are increasingly being used to investigate human behavior in relation to AVs and to understand different interaction solutions [9]. Compared with other methods (e.g., the Wizard-of-Oz [21][51] and video-based [1][15][20] methods), VR-based approaches provide researchers with greater flexibility in parameter manipulation and greater experimental control [38].

While VR-based approaches are becoming increasingly powerful and popular in interaction studies, they can involve difficulties in achieving consistency and reproducibility in experiments [43]. The root cause of these issues is that the existing studies usually adopt different virtual environments or applications, leading to varying levels of fidelity in terms of traffic scenarios, communication interface prototypes, system settings, etc. [13]. Therefore, it is difficult to compare the results across different studies and reach a consensus on the knowledge gained by the research community. Prior work has implemented a few VR-based simulators [16][42] to improve the reproducibility of studies. However, they focus on evaluating certain factors related to AV- human interactions rather than general settings within the context of autonomous driving. Thus, existing testbeds have substantial limitations when attempting to fully address the needs of AV- human interaction studies.

At the same time, the implementation of experiments in VR-based studies require considerable effort from researchers. Developing interactive testing scenarios to fulfill the purposes of different research designs is time-consuming and labor-intensive [22]. As a result, new tools and methods need to be developed repeatedly to overcome the methodological and process issues raised above, impeding knowledge development in the research community.

In this work, we introduce the Human-Autonomous Vehicle Interaction Testbed (HAVIT), a VR-based research platform, as a possible solution for enhancing the reproducibility and encouraging the comparison of AV- human interaction studies. To implement our testbed, we identified key factors in high-impact studies on human behavior to develop the components of the generic parameters of the HAVIT in terms of Physical Context, Vehicle Behavior, and External Human-Machine Interface (eHMI) Behavior. Corresponding structured user panels in the HAVIT allow users to quickly and easily simulate scenarios and investigate different AV-human interaction designs. In addition, the HAVIT provides a coherent workflow, starting with the Scenario Configuration process, moving to Experimental Setting, and ending with Batch Exportation, minimizing the barriers to experiment preparation. A series of features and interactive methods are seamlessly crafted into the HAVIT workflow.

The remainder of the report is structured as follows. In the next section, we provide a survey of previous research on AV-human interaction. We then describe the HAVIT’s structure and functionalities and present each parameter component to demonstrate its utility and extensibility. Finally, we report the results of an evaluation of the HAVIT by eight professionals, and discuss the findings and future improvement directions.

# 2. Related Work

We place the related work into three categories: (1) AV-human interaction studies, (2) VR simulation for AV-human interaction research, and (3) VR simulation as a research platform. An exploration of the literature related to these three categories provides a solid knowledge base for our work.

### 2.1 Interaction Between AVs and Humans

Many factors have been explored and proven to influence the decision-making processes of humans. Rasouli and Tsotsos [36] provided a comprehensive summary of the factors influencing human behavior through a review of the related literature. These factors can be divided into two main categories: environmental factors and human factors. Environmental factors include traffic characteristics (e.g., vehicle appearance and traffic flow), dynamic factors (e.g., vehicle speed and spacing), and the physical environment (e.g., road structure, traffic signs, and weather). Human factors include demographics, status (human physical status includes attention, walking pattern, speed, and trajectory), ability, characteristics (features that define how humans' think and behave, including culture, past experience, and faith), and social factors. It is worth noting that the above influences are often interrelated in real-life traffic scenarios, and they combine to influence road user perceptions and understandings of the state and intent of AVs [43]. Studying the interaction between these influences is essential to understand traffic situation complexity and to facilitate safer AV-human interactions.

Another important aspect of AV-human interactions is the eHMI, which is the form of communication external to an AV that is typically used to communicate the AV's current state and future behavior to humans; it can help in overcoming AV trust issues and improving the effectiveness and experience of AV-human communication [21][44]. Various eHMI concepts have been proposed and tested, such as text [8][27], symbols [1], street projections [31], light animations [4][11], and information from mobile devices [23]. However, researchers have not yet reached a consensus about how different eHMIs should be used [38].

Contemporary research is increasingly focusing on details related to the implementation of eHMIs to achieve the best interactions in terms of usability, security, and efficiency. For example, many eHMI studies have started to explore in-depth the dimensions of communication perspectives [12][14], communication subjects [48], and covered states [20]. Other studies have analyzed the design of the interactive elements of a particular type of eHMI, such as color [37][41], placement location [4][17], and display mode [15].

The scalability of eHMIs is another aspect that needs to be explored in the long term [45][43]. Most eHMIs have been tested in relatively simple and unrealistic situations, which has led to many eHMI concepts becoming viable options. The problem, however, is that the results of these studies often only show that the eHMIs improve simple interactions; most studies do not provide insights into using eHMIs in more complex traffic scenarios [42]. Therefore, more evaluations of interactions between humans and eHMIs in diverse traffic scenarios—such as those involving multiple humans [47] or different weather conditions—are needed in the future [13].

Most of the previous research has focused on common traffic scenarios and strategies for communicating the status or intent of AVs to the normal road user. However, research on AV-human interactions are equally critical in special cases and situations [24], such as sensor failure, a lack of system action, or action errors. As such, future research should include evaluations of (1) how humans should be informed and instructed to act depending on the type of extant malfunction, (2) how to optimize safe interactions between eHMIs and humans in special scenarios, and (3) how to conduct interactions in a way that ensures the public acceptance and trust of AVs [22]. In addition, while people with disabilities are among the most vulnerable road users in traffic, only a few studies have addressed the forms of external communication for people with disabilities (e.g., physical, visual, or hearing impairment) [3][6][7]. In conducting studies on these specific conditions and populations, a high degree of safety and flexibility in the experimental methods is required.

Many dimensions of AV-human interaction have not yet been adequately studied, and research on each dimension is indispensable. More importantly, the complexity of the study of AV-human interaction will increase with the number of studies being conducted and the aspects being studied, making several traditional research methods infeasible. In the face of such challenges, a VR-based method can provide more flexible, scalable approaches that can support more aspects of AV-human interaction research. This was one of the critical motivations behind the development of the HAVIT.

### 2.2 VR Simulation for AV-Human Interaction Research

VR simulation has been widely used to study AV-human interactions. Compared to traditional, non-immersive virtual environments (e.g., paper-based [18], video-based [1][15][20], or real-world-based [21] environments), the VR-based method combines the advantages of the above approaches to allow for strict experimental control and simulations under highly realistic conditions. For example, Chang et al. [49] evaluated an eHMI concept using the “eyes on the front of the car” eHMI; specifically, they developed two VR scenarios, each including five components: the environment (i.e., streets and buildings), the user (i.e., a three-dimensional computer-generated [3DCG] human model), the car, the eHMI (i.e., the “eyes on the front of the car”), and the car movement route (i.e., a straight line). Within the Chang et al study, the participants expressed their crossing decisions by pressing buttons on a motion controller.

Similarly, de Clercq et al. [8] used VR simulation to evaluate the impact of four interfaces on human crossing intentions. In their case, VR showed a higher degree of control over the simulation of vehicle behaviors and eHMI information. Specifically, VR was used to simulate the vehicle behavior (e.g., giving way or not giving way), vehicle size, eHMI (four types), and display time of the eHMI (i.e., early, middle, and late). Recently, studies have also begun to evaluate sound interfaces using VR simulations [6]. To evaluate auditory concepts for people with visual impairments, VR-simulated scenarios have included background noise (e.g., a mixture of human voices and engine sounds) and have given participants the ability to control the direction and location of the sounds so that testers can immerse themselves in a realistic sound experience. Although the objective measurement of immersion (including the overall realism and fidelity of the virtual environment) is complex, and some articles have suggested differences in distance perception [32][34] and speed judgments [25] between VR and real scenarios, previous studies have shown that these differences do not have a measurable impact on human behavior [5]. Overall, the highly realistic conditions of VR-based studies and rigorous experimental controls have positively influenced the field of research on AV-human interaction.

Furthermore, one of the important reasons VR-based studies have produced convincing evidence is that they primarily utilize objective measures [38], such as reaction time, duration, and accuracy. In addition, VR can capture information about the test taker's body movement. For example, Schmidt et al. [50] used an immersive VR environment to explore the intricate social cues that underlie the non-verbal communication involved in humans' crossing decisions. They collected motion trajectories generated by moving the body, legs, arms, and head of each subject in the physical and virtual world.

From the above literature review, we can conclude that the current VR-based AV-human interaction studies tend to use different virtual applications. Because there is no standardized testbed available to the community—which is the next logical approach identified in many of the research directions mentioned in the first part of the literature review—we decided to create the HAVIT to fill this gap.

### 2.3 VR Simulation as a Research Platform

A few simulator tools have been developed to explore the relationship between AVs and humans. The development of related simulators was initially motivated by human safety concerns. For example, Doric et al. [16] implemented a VR-based human simulator that provides a simple, uncontrolled human crossing scenario in which virtual vehicles are continuously generated at regular intervals. The simulator is capable of exploring human crossing behavior, analyzing risk acceptance, and investigating pre-collision phases through motion-capture techniques. A key limitation of such simulators is that they lack control over relevant conditions in the traffic scenario (e.g., vehicle behavior and road conditions) and can only implement a limited set of relationships between a predefined set of objects in the scene.

The closest related work to ours describes the On-Foot [42], a VR-based simulator that can be used to simulate mixed traffic scenarios and control the autonomy level of vehicles, traffic and street characteristics, and other virtual human behaviors utilizing code modifications and the integration of a partial AV-human interface. Although it empowers users with richer control modules, it is more limited in defining the specific behavior of the modules, despite the fact that the simulation of complex traffic scenarios usually requires flexible behavior controls (e.g., vehicle travel patterns, human movement routes, and eHMI state changes) to support rich system events.

## 3. Design Goals

Our primary aim with the HAVIT was to create a research tool that could improve consistency and facilitate the comparison of AV-human interaction studies. To achieve this, we identified three key design goals (DGs).

**DG1: Support the exploration of diverse scenarios.** Most VR simulators today focus on a single aspect the authors of a specific study want to evaluate. The HAVIT builds on previous works and focuses more on factors known to influence humans in their crossing decisions to derive a set of common methodologies and evaluation metrics. This is done by creating an easily configurable and reusable VR simulator for AV-human interaction studies.

**DG2: Allow an intuitive and flexible configuration workflow.** The simulation of an AV-human interaction scenario often requires researchers to set various parameters, which is a repetitive and time-consuming process. Our goal was to achieve an intuitive and flexible configuration process. As such, in the HAVIT, all core functionalities and most parameters can be configured visually without programming and support real-time parameter modification and rapid scenario iteration.

**DG3: Provide a quick and easy testing process.** In terms of performing VR-based testing, conventional studies typically consist of a VR scenario building phase, an experiment setup phase, and a performing testing phase. Most previous simulators focused only on scenario simulation and did not consider other obstacles faced by researchers. With the HAVIT, we aimed to provide a solution that covers more aspects of the needs of researchers, such as configuring multiple scenarios for quantitative experiments, setting up experiments (e.g., providing guidance and feedback to participants), and collecting data within the VR, which can increase the ease with which researchers can effectively explore and conduct experiments.

## 4. The HAVIT System

This section presents the HAVIT, providing descriptions of the user interface (UI), the main process it enables, and the relevant components. As Figure 1 shows, the HAVIT supports three processes at the highest level: Scenario Configuration, Experimental Setting, and Batch Exportation. Each process can be configured via user panels and scripts provided by the HAVIT.

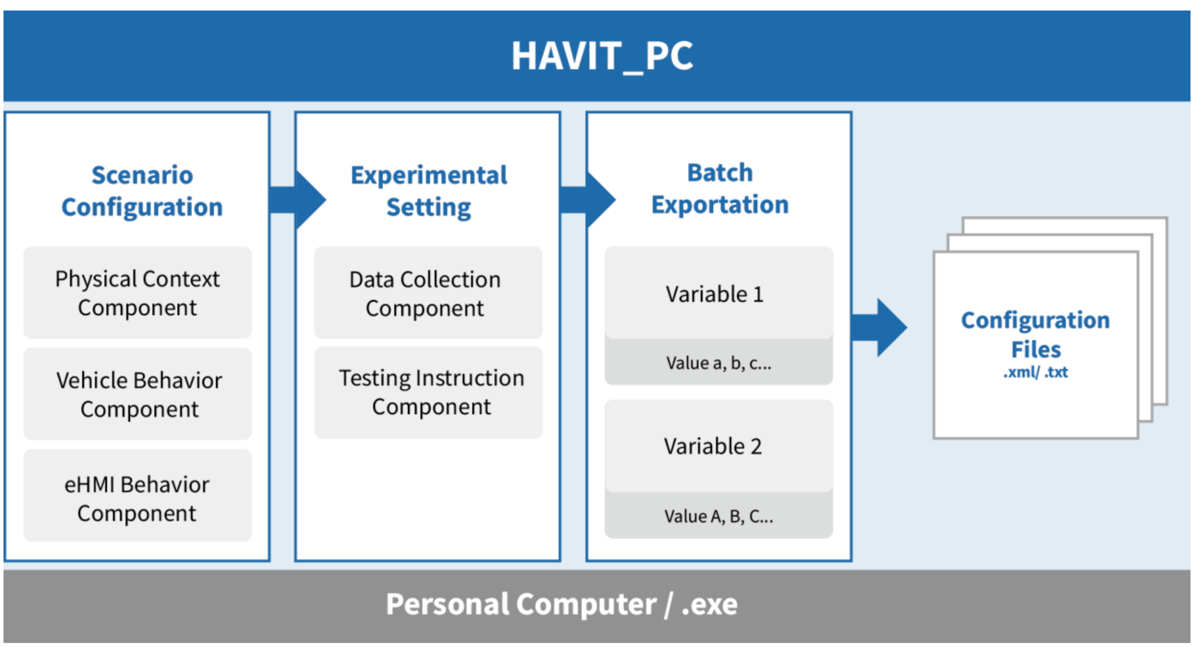


*Figure 1. The main processes of the HAVIT.*

**Scenario Configuration.** We organized the key parameters into three user panels—Physical Environment, Vehicle Behavior, and eHMI Behavior—to guide users to create the scenario. The HAVIT also allows users to quickly add and remove objects from the scenario by interacting directly with them. In addition, users can preview the current scenario at any time during the configuration process.

**Experimental Setting.** The HAVIT enables the rapid setup of experiments by providing a Data Collection component and a Testing Instruction component. The Data Collection component allows researchers to collect assigned quantitative data (e.g., the start/end time of crossing behavior, time required for decision-making, distance traveled, and average speed) and qualitative data (i.e., the participants' subjective experiences). The Testing Instruction component provides a set of adjustable panels that will be displayed in the VR environment to enable the guidance of participants during the testing.

**Batch Exportation.** Studies often involve manipulating a group of variables and, thus, generating a set or several sets of trials for an experiment. Repetitive manual configuration reduces the development efficiency and increases the risk of human error when many test scenarios are required [42]. The HAVIT allows users to add variables and values according to the experimental requirements and generate multiple scenarios simultaneously to enhance testing the development efficiency of the scenarios.

The HAVIT (Figure 2) is a Unity-based desktop program that can easily be used on a personal computer at the system level. With the HAVIT, users can configure interaction scenarios and export configuration files according to their needs. These configuration files can then be read easily by a VR device, such as an Oculus, and loaded with the appropriate environment and parameters to generate scenarios for testing. Below, we detail the parameter components, UI, and design of each system component.

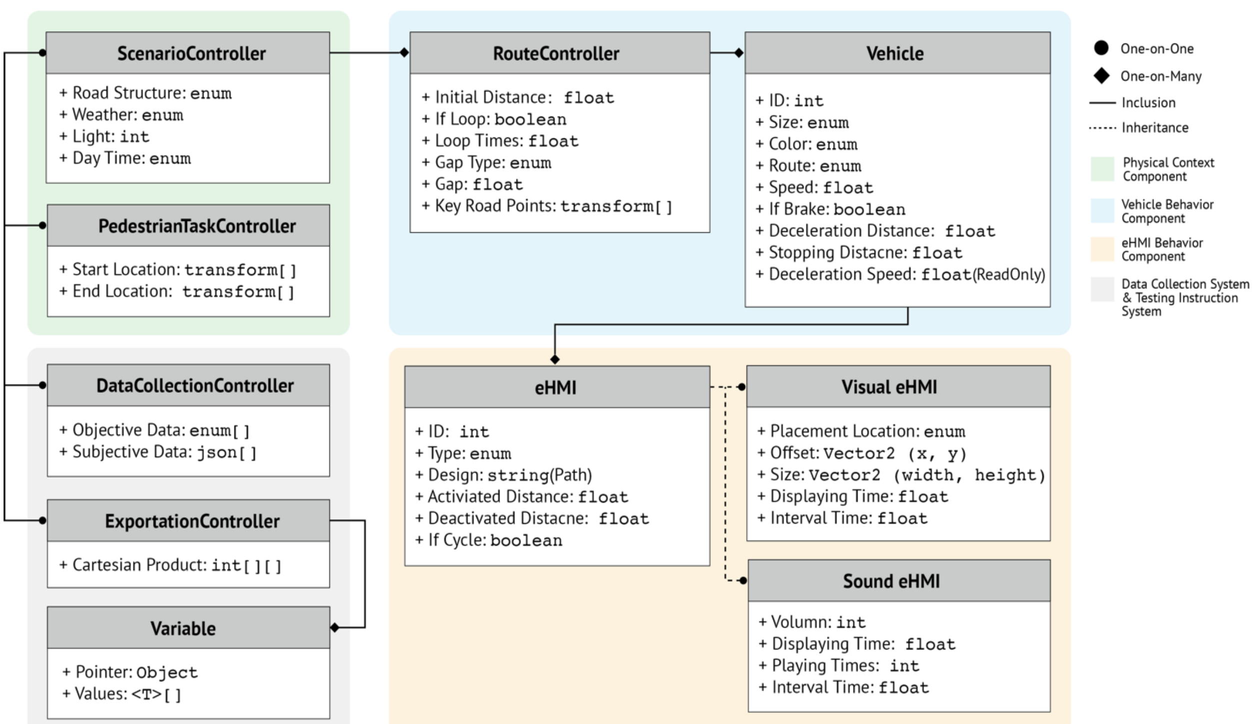


*Figure 2. Summary of the parameter components and key classes of the HAVIT.*

### 4.1 Parameter Components

Figure 2 summarizes the key classes of the HAVIT. A `ScenarioController` manages the road structure, and the natural conditions show the corresponding scenario to the user and contain several `RouteControllers.` A `RouteController` controls a specific route in the current scenario, as well as the set of vehicles driving on this route. In addition to a vehicle's appearance and behavior information, a `Vehicle` can display several `eHMIs` when interacting with humans. Also, the `eHMI` class has two child classes: `Visual eHMI` and `Sound eHMI`. Each child class has different properties to control the display behavior of the eHMI. The `HumanTaskController` and `DataCollectionController` manage the testing task and the data to collect in the VR experiment. The `ExportationController` contains several variables, each of which points to a specific parameter and has multiple values.

### 4.2 User Interface

As Figure 3 shows, the HAVIT consists of three UI components: the Main View, user panels, and Mini-Map. The Main View allows users to inspect the entire scenario two modes: (1) Edit Mode, in which users can directly interact with objects within the scenario, such as turning the vehicle to move in a different direction or moving the position, and (2) Preview Mode, in which users can check the effect of the scenario in the current configuration conditions. Users can also freely move the camera to change the viewing angle. Next, the key parameter components and functionalities are implemented and presented to users through the user panels, of which there are five: the Physical Context Panel (Figure 3a [U1]), Vehicle Behavior Panel (Figure 3a [U2 and U3]), and eHMI Behavior Panel (Figure 3a [U4]), which are used to manipulate the parameters for creating scenarios; the Experimental Setting Panel (Figure 3a [U5]), which is used to set up the collected data and the testing instructions in the VR environment; and the Batch Exportation Panel (Figure 3b [U6]), which is used to generate multiple scenarios at the same time. Last, the Mini-Map (Figure 3a [M]) is used to provide an overview of the current scenario. Also, location markers and vehicle routes are displayed on the Mini-Map to allow for quick checks.

Figure 3 presents the UI of the HAVIT. (a) Edit Mode - Main View, (b) Edit Mode - Batch Exportation Panel, and (c) Preview Mode. The panels and interactive components are marked with red borders in the image.

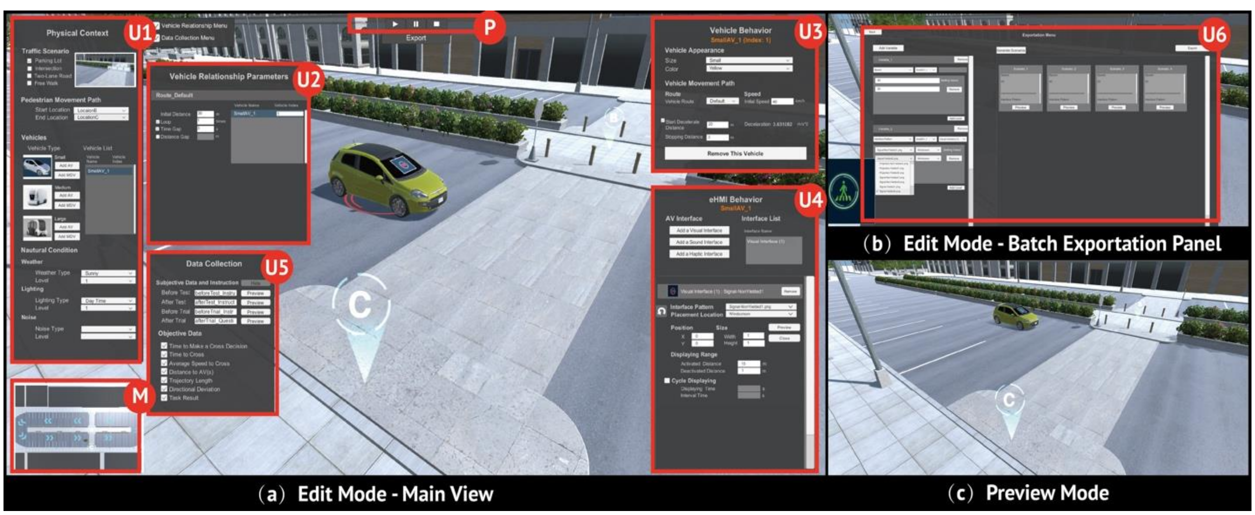


*Figure 3. The UI of the HAVIT.*

### 4.3 Scenario Configuration

The first main process enabled by the HAVIT is scenario configuration. Users can quickly and easily configure various AV-human interaction scenarios using a set of user panels.

#### 4.3.1 Physical Context

The Physical Context parameter allows users to define the road structure, the participant's movement path, the test vehicles, and the natural conditions. These elements are discussed in greater detail in this section.

**Road Structure.** The HAVIT contains a street map showing an area of 396 × 561 square feet (as shown in Figure 4) that includes four road structure types: (1) Parking Lot, (2) Free Walk Area (i.e., the entrance/exit area of a parking lot), (3) Four-Way Intersection, and (4) Two-Lane Road. All of these are locations where AVs and humans frequently interact in daily traffic. Each road structure has a predetermined travel route for vehicles. The initial settings do not include traffic signals, and users can add traffic signals (e.g., traffic lights, crosswalks, and stop signs) to the scenarios as needed. The detailed information related to each road structure is as follows:

- **Parking Lot:** This is a one-way circuit, and the width allows only one car to pass. Vehicles in the scenario will enter from the parking lot entrance, pass through two stop signs and a 180-degree circular route, and exit through the exit (see Figure 4 [1]).
- **Free Walk Area:** This refers to the area at the entrance/exit of a parking lot; there are no stop signs or crosswalks, so users can walk freely through the scene. There are two routes for vehicles: entering and leaving the parking lot (see Figure 4 [2]).
- **Two-Lane Road:** This is a two-lane straight-ahead road. Vehicles drive in a straight line away from users. Also, the users can specify the direction of traffic in each lane and whether to set stop signs or zebra crossings (see Figure 4 [3]).
- **Four-Way Intersection:** This is a typical intersection with traffic lights and zebra crossings. Vehicles in the scenario can come from four directions, and users can choose whether to go straight, turn left, or turn right at the intersection (see Figure 4 [4]).

Figure 4 presents the road structures in the HAVIT. The aerial-view map of the HAVIT is shown in the middle. The yellow dotted lines represent the routes on which a vehicle can move. The four road-structure scenarios are visualized on either side of the aerial-view map: (1) Parking Lot, (2) Free Walk Area, (3) Four-Way Intersection, and (4) Two-Lane Road. The blue markers with capital letters represent the optional locations that are used to specify the human movement path in each scenario.

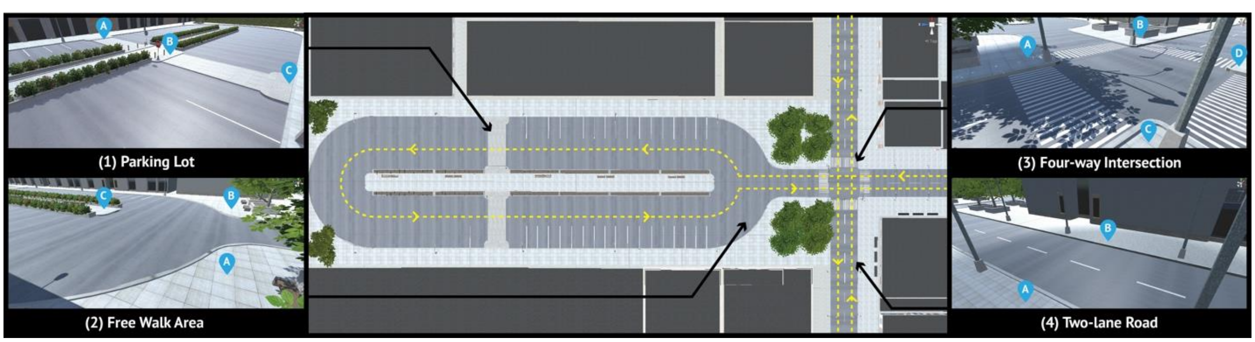


*Figure 4. Road structures in the HAVIT.*

**Human (Participant) Movement Path.** Once the road structure scenario has been decided on, the user needs to assign the movement path for the participants in the testing scenario. Users can determine the path by specifying the start location and end location, which are dynamically generated according to the road structure selected by the user. For example, in the Parking Lot road structure, users can choose two points from the three selectable locations—A, B, and C—as the starting point and endpoint, which form the assigned path for the testing scenario. Different routes imply different spatial relationships, interaction sequences, and interaction complexities, thus supporting richer interaction scenarios.

**Vehicles**. The HAVIT provides three vehicle model sizes: Large (i.e., buses and trucks), Medium (i.e., vans), and Small (i.e., passenger cars). This is because prior works showed that vehicle size leads to differences in the subjective risk perception and objective distance perception of humans [13]. Also, users can choose to add an AV or conventional vehicle, which are distinguished by the presence or absence of a virtual driver. The user can add any number of vehicle models all scenarios. The system generates each selected vehicle in the Main View and adds it to the global vehicle list (see Algorithm 1).

ALGORITHM 1. ADD VEHICLES

```
GameObject Add Vehicle(VechicleType type){
    Vehicle v = new Vehicle(type);
    initializeVehicle(v, type);
    VehicleList.Add(v);
    VehicleListByRoute[v.route].Add(v);
    Return v;
}
```

**Natural Conditions.** The natural condition parameters supported by HAVIT include Weather Condition, Lighting Condition, and Noise. Currently proposed external communication interfaces mainly rely on visual cues and auditory cues. Lighting and weather factors are critical to examining the visibility and interactive performance of visual-based interface concepts. In addition, noise is an important consideration when designing auditory-based interfaces, which are effective solutions for visually impaired people [6]. Taking Weather Condition as an example, the system will update the background skybox, the global light intensity and color, and the particles (rain, snow, etc.) in the current scenario according to their corresponding parameters (see Algorithm 2).

ALGORITHM 2. WEATHER CONDITION

```
void UpdateWeather(){
    Update Skybox(weather, lighting, day_time);
    Update LightIntensityandColor(weather, lighting, day_time);
    Update Particle(scenario, weather);
}
```

### 4.3.2 Vehicle Behavior

One of the critical features of the HAVIT is the ability to provide the flexible control of vehicle behavior. There are two control modes offered for users to achieve this: controlling the behavior of vehicle groups and controlling the behavior of individual vehicles. These act on vehicle groups and on specific vehicles within the scenario, respectively.

**Vehicle Relationship Behavior.** The HAVIT allows users to control the vehicle behavior for multiple vehicles at the same time based on the vehicles' travel routes. The controllable parameters include the sequence of vehicles, the initial distance (i.e., the distance between humans and the generation point), the number of travel loops, and the generation gap (i.e., the time gap or distance gap) between vehicles.

In the generated scenario, the vehicles added by the user generate in the preset order at the generation points. The interval of generation is determined by the time interval or distance interval set by the user. The vehicles in the list are generated repeatedly according to the number of loops set by the user. For example, if the list shows Vehicle A and Vehicle B, and the number of loops is 2, then the system will generate vehicles in the order A, B, A, B.

**Individual Vehicle Behavior.** The HAVIT also allows users to configure parameters for each vehicle in a scenario. This control mode is useful when the vehicles in the scenario all have different behaviors or when more complex changes in vehicle behavior need to be simulated. Specifically, the HAVIT supports the initial speed (in km/h) of the vehicle, the acceleration/deceleration distance (i.e., the distance at which the vehicle starts to decelerate, in meters) of the vehicle, and the stopping distance of the vehicle (i.e., the distance to humans, in meters). When the user selects the above three parameters, the acceleration/deceleration speed is calculated and shown on the user panel.

The HAVIT system uses Unity's artificial intelligence (Unity.AI) mechanism to control the overall driving logic of the vehicles. By baking a navigation mesh in the scenario, the vehicle can identify the road path to reach its destination. For each route, the system creates several key path points in the scenario. When the vehicle is adequately close to one point, its destination is set to the next one. Using this method, vehicles can drive under different complex trajectories. After the vehicle starts to move, it travels at its initial speed and dynamically loads the path points according to its driving route, set by the user.

After ensuring that the vehicle is driving on its route, a behavior tree is used to control behaviors such as yielding. Vehicles use raycasting to detect and judge the types of obstructions ahead of them, and different behaviors occur when detecting certain obstacles. For example, users can decide if a vehicle needs to stop in front of stop signs, and if so, the brakes will start within the braking distance and come to a complete stop at a preset distance from the stop sign. When a vehicle stops at a stop sign, it will only stop for a specific time—specified by the user—unless a person is walking on the crossing street, which will cause the vehicle to wait only until the road is empty again. If there is another vehicle in front of it, it will decide whether it needs to start slowing down by comparing the speed of the two vehicles and gauging whether the vehicle in front of it is braking. If the distance between the vehicles reaches a dangerous distance (0.50 m), it will stop immediately. Stopping at a traffic light can also cause vehicles to behave differently, depending on several factors, such as which light is activated and whether someone is passing through the intersection.

Before a vehicle starts to brake, the system will recalculate its deceleration speed in real time to ensure that it can come to a complete stop at the preset stopping distance to prevent certain special cases such as the following example: A vehicle stops 3 m in front of a stop sign, and a vehicle behind it is 1 m away from the front vehicle. After waiting, the front vehicle drives past the stop sign, and the rear vehicle is already less than the brake distance (2 m) from the stop sign, so the deceleration speed needs to be recalculated to ensure that the rear vehicle can also stop 3 m in front of the stop sign.

### 4.3.3 The eHMI Behavior

The HAVIT provides a library of the incorporated interface designs, which were selected from studies with high citation rates (≥ 60). The HAVIT also supports the import of user-defined interfaces. Further, the HAVIT allows the simultaneous placement of multiple eHMIs on an AV to evaluate the effects of multiple eHMI combinations. To enable the exploration of the functional details of these interaction concepts, we also provided controllable parameters related to visual and auditory eHMIs and ensured that the parameters of each added eHMI could be adjusted independently. The HAVIT's parameters are as follows:

- **Placement Location (Only for Visual eHMIs):** This refers to the placement area of an eHMI on an AV, which can be the windshield, bumper, roof, side windows, front road, or front cover of the vehicle.
- **Display Position (Only for Visual eHMIs):** This refers to the specific position of an eHMI in the placement area, controlled by the offsets in the horizontal and vertical coordinates based on the center of this area.
- **Display Size (Only for Visual eHMIs):** This refers to the exact size of an eHMI, controlled by width and height.
- **Activate and Deactivate Distance (for Both):** This refers to the distance to humans from where an eHMI starts to appear and disappears on the AV.
- **Cycle Display (for Both):** This refers to whether an eHMI is displayed periodically or not. It can be controlled by setting the displaying time and the interval time.
- **Play Volume (Only for Auditory eHMIs):** This refers to the sound volume of an auditory eHMI.

When a vehicle is generated, the system will spawn a thread for each eHMI, allowing the eHMIs not to interfere with each other. When the thread detects a human in the activated distance, it will start to display the corresponding eHMI; if the eHMI needs to cycle through displays, it will periodically turn on and off. As such, having different threads prevents conflict even if the eHMIs' behaviors are different.

### 4.4 Experimental Setting

#### 4.4.1 Data Collection Component

Considering data collection is an indispensable part of the experimental process, we implemented a Data Collection component in the HAVIT to allow users to collect the data generated by tests. We classified the types of data collected by the HAVIT, based on previous research, as subjective data and objective data.

**Objective Data.** One of the key reasons that VR-based approaches can produce convincing results is the use of objective measurements. The HAVIT provides a variety of human task-related metrics that can be automatically activated through the provided scripts. When the task is completed for each scenario, the tracking component automatically reports data information for the corresponding metric. The metrics currently covered by the HAVIT are as follows:

- **Time to Make a Cross Decision:** This measures the time participants spend in making a street-crossing decision.
- **Time to Cross:** This measures the time it takes for participants to cross the road.
- **Trajectory Length:** This measures the total path length of participants moving between the start and end locations.
- **Average Speed to Cross:** This measures the average speed of the participant crossing.
- **Distance to AV(s):** This measures the straight-line distance to the AV object(s) in the scenario when the participant starts the crossing behavior.
- **Directional Deviation:** This measures the directional deviation between the participant's start location and end location.
- **Task Result:** This records whether the participant made a crossing decision (which can be judged by the user's actions on the motion controller or by whether the user enters the crossing area).

**Subjective Data.** To improve the validity of subjective data collection, we utilized InVRQs [52], an existing VR questionnaire toolkit, as a complement to the HAVIT. This toolkit was useful, as it provided the questionnaire structure and question types. The HAVIT allows the user to determine where the questionnaire panel appears in the VR scenario.

#### 4.4.2 Testing Instruction Component

The Testing Instruction component is provided to display experimental instructions for participants in VR testing scenarios, which rely on a set of panels inside the VR that are shown to the participants. Four display timings are provided: before the test, after the test, and before and after each trial—all of which support the customization of the questionnaire or text presentation. Taking the "after trial" timing as an example, users can make changes to the template we provide. Then, users can preview it by clicking the Preview button or hide it by clicking the Hide button.

### 4.5 Batch Exportation

To reduce the repetitive manual configuration process, the HAVIT provides a Batch Exportation component. Specifically, after configuring one testing scenario, the user can specify one or more variables (i.e., parameters in the HAVIT) required for batch configuration and assign specific values accordingly through the user panel. After the user specifies all the variables and their values, the system will create a set for each of them and perform the Cartesian product operation on these sets. For example, for the set A{a1, a2, a3}, B{b1, b2}, C{c1, c2}, $A \times B \times C = \{(a, b, c): a \in A \ and \ b \in B \ and \ c \in C\}$. This will return 12 (3 x 2 x 2) combinations.

The HAVIT also provides a scenario list to allow users to preview the generated scenarios. When a user previews a specific scenario, the system will modify the values of each involved parameter according to the corresponding combination. Also, when exporting batch scenarios, the system will iterate through all combinations and export the corresponding configuration file for each combination.

### 4.6 Preview Mode

To allow users to check the effect of the configured scenario, the HAVIT supports Preview Mode. Specifically, the system refers to the Unity game engine's Play Mode and provides three buttons in game Game window: Play, Pause, and Stop. The user can click the Play button to preview, click again or click the Stop button to exit. When entering Preview Mode, each vehicle will show up from the generation point, move forward according to its driving route, stop according to its yielding behavior, interact with humans according to the logic of its eHMIs, and finally disappear at the end of the route. The system will simulate the whole process. The system logic for entering Preview Mode is shown in Algorithm 3.

ALGORITHM 3. PREVIEW MODE

```
void Preview(){
    hideInteratcionMenu();
    recordVehiclePositionandRotation(VehicleList);
    copyVehicles(VehicleListByRoute, loopTimes);
    addPathPointsandStopLogic(VehicleListByRoute);
    StartAllVehicles(VehicleListByRoute, gapType, gapValue);
}
```

## 5. Implementation

The HAVIT was developed in the Unity game engine (v. 2020.1.9f1), with all related scripts written in C#. The project has been packaged to the Windows platform to work independently from the engine. After testing on an HP OMEN Gaming Laptop with a GTX 1650 graphics processing unit (GPU), the HAVIT was found to have a guaranteed a framerate of 60 Hz (default setting) when 20 vehicles are running simultaneously.

Figure 5 shows the system logic of the HAVIT. When users interact with the system's interfaces, the system will set the corresponding parameters to the input value. Alternatively, when users upload their local files onto the system, the system will load these files into memory. Then, the system will judge whether the value of the file is reasonable; for example, the vehicle's stopping distance must be less than its decelerating distance, and the vehicle's initial distance cannot be larger than the limit of the scenario. If the system finds these problems when updating the data, it will give the user the corresponding feedback on the interface. Simultaneously, the system will modify the attributes of the objects in the scenario corresponding to the new data.

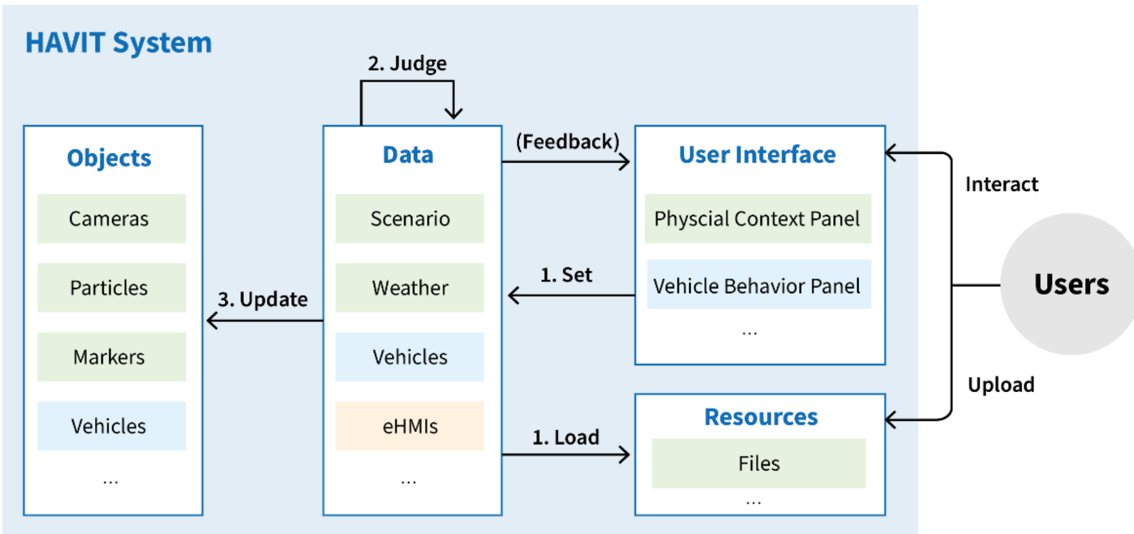


*Figure 5. The system logic of the HAVIT.*

# 6. Evaluation

We conducted a user study to evaluate whether the HAVIT is understandable and easy to use for our intended users. We were also interested in participants' qualitative impressions of their experience.

### 6.1 Participants

We relied on the intended users of the HAVIT to gain insights from their workflows, and we expect that this initial feedback will help distill the strengths and areas for improvement of the HAVIT for the future. As such, we recruited professionals in fields related to human-computer interaction (HCI; n = 8; 3 females), including VR experience researchers (P2, P3, P4, and P5), intelligent systems researchers (P6 and P8), and user experience designers (P1 and P7). None of the users had prior experiences with our testbed.

### 6.2 Procedure

The participants were first introduced to the HAVIT, and they then were instructed to configure a set of testing scenarios for an AV-human study that featured a within-subject study design, 2 independent variables, and a total of 9 (3 × 3) testing scenarios (trials). We chose this study topic because its complexity allowed us to demonstrate and test many of the HAVIT's features. The participants then completed questionnaires evaluating the HAVIT's main features and answered interview questions from the researchers. The testing process lasted about 50 minutes. One researcher took observational field notes, which were analyzed and used to help interpret the results from our survey data.

**Introduction and Training (15 minutes).** Following the signing of informed consent forms and obtaining recording permission, the participants were provided with some background knowledge about the AV-human interaction study and all the features of the HAVIT system. They were then guided through configuring a simple scenario and allowed to explore freely.

**Tasks (25 minutes).** In this part, the participants configured a set of testing scenarios using the HAVIT, following specific instructions. They were provided with a *Study Method* document that included the study goal and the experimental design (i.e., independent variables, dependent variables, human tasks, and experimental setup). We took care to ensure that the content was as short and concise as possible. The instructions were as follows: (1) *Manual Configuration (Task 1*): Configure 1 of the 9 testing scenarios (a total of 15 parameters need to be set); and (2) *Batch Configuration (Task 2*): Generate the 9 required testing scenarios at the same time (a total of 6 parameters need to be set). We emphasized that there was no correct order for the configuration of the scenarios and that they could complete the task according to their understanding of it. The participants were asked to verbally report, "I'm done" after completing the first task. The researcher checked the configuration results and informed the participants to make adjustments if necessary, after which they continued with the second task. The participants were also told to complete the tasks as quickly and accurately as possible. The whole process was screen recorded.

**Questionnaire (5 minutes).** After the two configuration tasks were completed, each participant was then asked to answer Likert-type questions related to the system features. Each Likert-type item was graded by users from 1 to 5 in relation to the usefulness of the feature and their level of agreement with the item. Our questions were inspired by the "first-use study" in Exemplar [53].

**Semi-Structured Interview (5 minutes).** Finally, we conducted a semi-structured interview with each participant, which addressed the following: (1) the ease of configuration with the HAVIT, (2) its usefulness, (3) the scenario results achieved and the participant's satisfaction with those, and (4) the potential for the future use of the add-on. The interviews were all audio recorded.

### 6.3 Measurements

To test this first version of the HAVIT, we defined two basic metrics for analysis: (1) completion time, which refers to how much time the participants required to complete each task (the timing started when the participants verbally reported, "I'm ready" and ended when they stated, "I'm done"); and (2) task success result, which refers to whether the task was completed successfully (i.e., if all parameters were set up correctly) or was failed. A thematic analysis of the experts' opinions was conducted; these opinions were collected during the semi-structured interviews. The themes also stemmed from the observations of the participants' behavior during the tasks and the observer's debriefing after the VR testing scenario configuration session.

### 6.4 Results

**Objective Data.** Table 1 shows a summary of the participants' completion times and task success. In general, the participants were able to understand the features provided by the HAVIT. All participants completed both tasks. In Task 1 (T1, Manual Configuration), all participants except P1 and P7 finished in approximately 10 minutes (mean [M] = 9.02). P1 and P7 had less quantitative experimental experience and spent extra time on reading the study method documentation. Four participants (P1, P3, P7, and P8) were unsuccessful in completing T1, and the errors they made are shown in Table 1. In Task 2 (T2, Batch Configuration), 7 out of the 8 participants completed the task successfully, and P4 was unsuccessful because of one omission error. The average completion time of T2 was 4.22 minutes.

*Table 1. Summary of the participants' task-completion times (T1 and T2) and success results.*

| Participants | Task 1 (Minutes) | Task 1 (Success & Accuracy Score) | Task 1 (Error Type & Number) | Task 2 (Minutes) | Task 2 (Success & Accuracy Score) |
|---|---|---|---|---|---|
| P1 | 12:05 | Fail (14/15) | Input error: 1 | 4:41 | Success (6/6) |
| P2 | 7:56 | Success (15/15) | None | 3:28 | Success (6/6) |
| P3 | 8:32 | Fail (13/15) | Input error: 1<br>Omission error: 1 | 4:24 | Success (6/6) |
| P4 | 5:24 | Success (15/15) | None | 5:37 | Fail (5/6) |
| P5 | 6:18 | Success (15/15) | None | 3:43 | Success (6/6) |
| P6 | 6:35 | Success (15/15) | None | 3:35 | Success (6/6) |
| P7 | 17:46 | Fail (14/15) | Omission error: 1 | 5:17 | Success (6/6) |
| P8 | 9:43 | Fail (14/15) | Omission error: 1 | 4:58 | Success (6/6) |

**Subjective Data.** Here, we report the results from the Likert-scale questions, in terms of mean (M), median (m), and standard deviation (SD). Most participants reported that the HAVIT enabled them to quickly understand a wide range of impact factors related to AV-human interaction and that it encouraged exploration (Q1: M = 4.38, m = 4.50, SD = 0.74). Likewise, 7 participants held positive views about the HAVIT's ability to reduce the time needed to prepare for an experiment (Q5: M = 4.75, m = 5.00, SD = 0.71). For the Batch Exportation process, most participants reported that the HAVIT could help decrease the time needed to configure multiple scenarios (Q4: M = 4.50, m = 5.00, SD = 0.76), and the Batch Configuration method is easy to understand (Q3: M = 4.00, m = 4.00, SD = 0.93). Further, the participants were generally confident about uploading their self-defined interface to the HAVIT (Q8: M = 4.88, m = 5.00, SD = 0.35) and ranked it highly in relation to the statement that the HAVIT "allows people with no programming skill to use [it]" (Q9: M = 4.63, m = 5.00, SD = 0.74). Several participants also agreed that the parameters are intuitive and easy to understand (Q2: M = 4.38, m = 5.00, SD = 0.91), but they would like some video illustrations and more detailed information. Several participants suggested that enhanced user panels for managing related parameters could help improve the "time to configure the scenario" and "rapid modification" (Q6: M = 3.75, m = 3.50, SD = 0.89). Finally, the HAVIT's workflow received positive feedback from the participants (Q7: M = 4.25, m = 4.00, SD = 0.71). Across all questions, the median ratings were at or above 4 on a 5-point Likert scale (5 = best; see Figure 6).

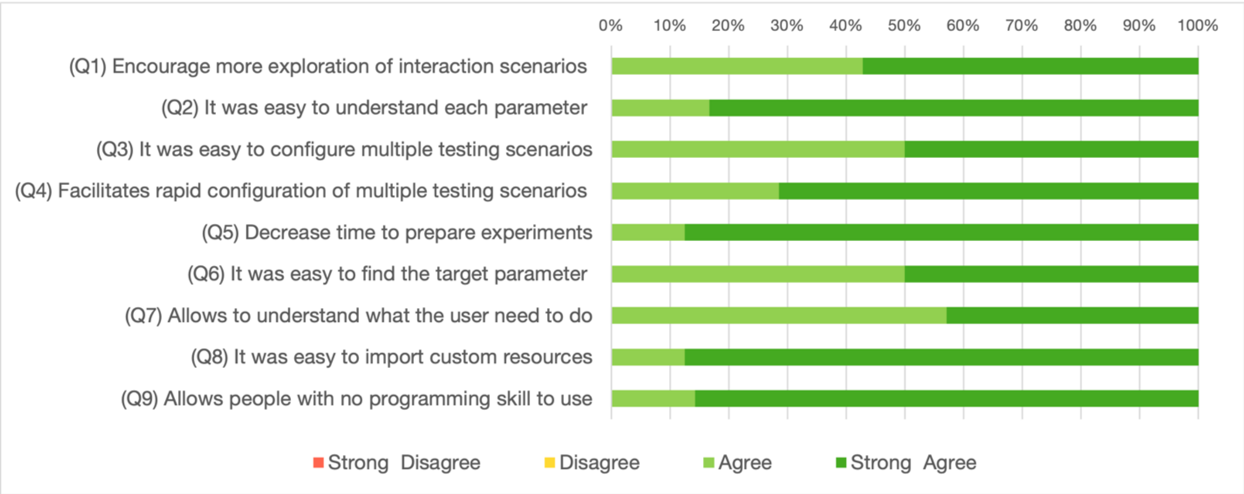


*Figure 6. System feature-related Likert-type question results (n = 8).*

# 7. Discussion

### 6.1 Effectiveness at Encouraging Exploration

This work presented the HAVIT as a promising solution for encouraging the exploration of AV-human interactions in studies. From the feedback from the questionnaire and interviews, we found that the promotion of exploration mainly comes from three key features of the HAVIT.

The category-based user panel design was found to guide researchers and designers to explore more AV-human interaction scenarios, even if they have limited knowledge about this field. P2 and P6 mentioned that the HAVIT provided a framework to improve the efficiency of gaining an understanding of this research topic. For example, P2 explained, "The panels are organized logically, with the relevant parameters all together, which gives me a quick idea of which types of the factors to focus on."

The flexible workflow—such as being able to preview the scenario at any time during the configuration process—not only helped users explore ideas directly but also helped them focus more on the humans and the potential interactions. P5 explained the main benefit of the HAVIT as being that it, "Immediately gets you into a headspace for thinking of spatially instead of having to extrapolate in a text document." P4 also explained that previewing the generated scenarios enabled a quick assessment of the reasonableness of the parameter settings by comparing the effects of multiple scenarios.

The HAVIT combines the authoring phase and evaluating phase in a coherent workflow by implementing the Batch Configuration, Data Collection, and Testing Instruction components. P4 mentioned that quickly generating multiple testing scenarios was helpful for avoiding the repetitive configuration process, which might have discouraged exploration and led to thought fixation. P3 and P6 said that being able to collect data and provide instruction tools in the VR environment was a significant advantage, explaining, "the design of these features is reasonable; they fit the needs of the VR-based experiment process and are very convenient for researchers." P5 added, "I like how fast it is from planning the task to acting it out; [it] encourages me to try more."

### 7.2 The Ease of Use of the Configuration Process

The participants' questionnaire responses were mainly positive and encouraging. Still, from the performance data and researchers' observations, we identified some key usability aspects that needed to be improved during the configuration process.

First, all our participants completed the configuration task in a relatively short period; however, 4 of them made a few errors (1-2 omission errors or input errors) in the first task. Two participants reported that, "it would not be easy to find a specific parameter and adjust it when many parameters are involved." P2 added, "Sometimes I don't realize that I have adjusted this parameter, so I don't check if its value is correct." Although the participants who made these errors reported that they were confident in the configuration process and believed that they would not make similar errors if they used the HAVIT one or two more times. This issue could be circumvented by either providing highlight cues or by implementing a panel to show the parameters that have been set by the user.

In addition, the current user panel features a hierarchy that shows less information, which aimed to improve the efficiency of information access for users. While most users appreciated the usefulness of the user panels in terms of gaining a quick understanding and overview of the information, five of the eight participants mentioned in one way or another that the user panels occasionally became obtrusive and distracting: "There are too many user panels in front of me when I am trying to see and set up parameters" (P5). This feedback emerged after the users became familiar with the system, when they started to feel as though they did not need the user panels to be displayed all the time. This finding raises an important question when designing such systems: how can we strike a balance between an intuitive parameter structure and a clear user view, while providing both to the user? We believe a further comparative evaluation study with two groups of participants who are given different experiences might help in understanding this phenomenon and identifying a well-balanced solution.

### 7.3 Prospective Applications of the HAVIT

Based on our investigations using the HAVIT, we observe its significant generative power and provision of a flexible testbed for AV-human interaction studies. Here, we discuss the potential applications made possible by the HAVIT: (1) Scalability studies of interface concepts related to AVs, which need to evaluate the ability of eHMI concepts to be used in various scenarios with different numbers and types of vehicles, different human behavior, etc. (2) The HAVIT can be used to investigate the finer details of the implementation of interaction concepts, which need to explore how to use and organize interactive elements (e.g., display location, time pattern, and color) in design to communicate crucial messages. (3) It can be used to explore human behavior under extreme situations, such as sensor failures and interface display errors. The above applications are critical to the universality and standardization of AV interaction technology, and they are also significant challenges facing AV-human interaction research at in the current era.

# 8 Limitations and Future Work

There are some limitations related to the parameter components of the HAVIT. First, although our testbed is based on generic parameters applicable to AV-human interaction studies, it provides a limited choice of some parameters. This is because we recognized that some aspects of AV-human interaction scenarios and influencing factors cannot be fully predicted in advance. We envisioned the HAVIT to be based on core processes and critical functions rather than an all-encompassing solution. To improve the extensibility of the HAVIT, future versions could include additional road scene types, human interaction methods, and eHMI interaction prototypes.

Second, the current version of the HAVIT does not support the exploration of interactions among humans. To address this limitation in the future, an initial step could be utilizing characteristically controllable (e.g., in terms of gender, age, moving speed, and group size) virtual humans. Furthermore, we would like to allow multiple participants to be present and tested simultaneously in a scenario. By embedding additional sensory input and body tracking to capture critical features in a user's motion, the HAVIT can support a more realistic, accurate investigation of the effects of interactions between humans. In addition, the HAVIT provides a Preview Mode designed to allow users to preview the final effect of a scenario; however, this preview is based on a two-dimensional (2D) display of the 3D scenario, so there are still some differences in immersion and fidelity between the preview and the final VR scenario.

Last, there is a limitation in relation to the evaluation method. Given the different levels of familiarity of the recruited participants with this research topic, giving them the freedom to construct simulation scenarios may have led to significant differences in the difficulty of the final scenario configuration. Therefore, we assigned them configuration tasks that needed to be completed. However, this may have limited their exploration of the system's functionality. Further validation is essential to establishing the HAVIT as a research tool. For example, it will be necessary to benchmark the HAVIT in relation to existing simulators and simulator research, perhaps by developing quantitative measures of simulation quality.

# 9 Conclusion

In this work, we introduced the HAVIT, a VR-based testbed for investigating AV-human interactions. The proposed testbed presents concepts and features designed to facilitate the consistency and efficiency of VR-based AV-human studies. We also structured the components of generic parameters in a set of panels that users can flexibly manipulate, and we provided the Experimental Setting and Batch Configuration components to further ease the experiment development effort. Experimental results showed that the HAVIT enables users to configure fairly complex testing scenarios in less than 20 minutes, which previously required hours of VR development effort. Our evaluation results also showed that the workflow of the HAVIT is usable and easy to understand. We hope that the HAVIT will enable progression toward the fuller use of such VR testbed platforms. Future research, including usability studies, should seek to determine how other researchers may use and extend tools such as the HAVIT to fit their needs. We hope the HAVIT will broaden the pool of researchers who can design interactions and interfaces for AVs and encourage further empirical testing to understand the human response along the road ahead.

# 10 Synopsis of Performance Indicators

### 10.1 Part I

One graduate student participated in the research project during the study period.

### 10.2 Part II

Research Performance Indicators: The researchers of this project are preparing journal articles and conference presentations from this project. The outputs, outcomes, and impacts are described in the following sections.

# 11 Outputs, Outcomes, and Impacts

### 11.1 List of research outputs (publications, conference papers, and presentations)

[1] Dalipi, A. F., Liu, D., Guo, X., Chen, Y., & Mousas, C. (2020, September). Vr-pavib: the virtual reality pedestrian-autonomous vehicle interaction benchmark. In 12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (pp. 38-41).

[2] Koilias, A., Mousas, C., Rekabdar, B., & Anagnostopoulos, C. N. (2020, October). Passenger Anxiety About Virtual Driver Awareness During a Trip with a Virtual Autonomous Vehicle. In International Symposium on Visual Computing (pp. 654-665). Springer, Cham.

### 11.2 Outcomes

The research increases the body of knowledge on how researchers could use virtual reality to understand human-autonomous vehicle interaction. This is achieved by developing a virtual reality framework that stakeholders and researchers could use to customize virtual reality experiences and conduct human subject studies. Humans would interact with the provided simulations and understand what factors could affect such interaction. The developed framework also helps us understand the potentials and limitations of adopting virtual reality technologies. Lastly, although this is a virtual reality framework, and the provided stimuli are simulations and not based on real-world conditions, such a framework could help us increase the understanding and awareness of transportation issues by simulating various real-world situations in a safe environment.

### 11.3 Impacts

Our virtual reality formwork provides several functionalities to allow researchers to simulate human interaction with autonomous vehicles and understand what factors are essential to improve such interactions. Also, by understanding how humans interact with autonomous vehicles, researchers could propose and develop novel interfaces and interaction metaphors to increase human comfort in their interactions with self-driving cars. The findings will help expand knowledge on human-autonomous vehicle interaction (human factors) in VR in preparation for the inevitable era of self-driving cars.

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