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Transportation Research Procedia 90 (2025) 710–717

Transportation Research Procedia

www.elsevier.com/locate/procedia

AIIT 4th International Conference on Transport Infrastructure and Systems (TIS ROMA 2024), 19th - 20th September 2024, Rome Italy

A Novel Co-Simulation Platform for Driving Performance Evaluation of Various Road Users

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Abstract

Researchers widely acknowledge virtual reality in driving simulation as a very useful tool in the field of road engineering and safety, capable of investigating how various factors, both external and internal to the driver, may affect the perception of driving risk. These topics of research have been widely developed over the years, both from a hardware point of view, ensuring a diverse and comprehensive range of driving simulators capable of covering the different types of means of transport (vehicle, motorcycle, bicycle, etc.), and also from a software point of view, ensuring increasingly effective modeling capable of realizing realistic and efficient scenarios. However, the advent and ever-increasing use of Building Information Modeling (BIM) in the realization of digital twins in the infrastructural domain opens the way for multiple developments in driving simulation. Indeed, in the last few years, the need for investigating simultaneously the interactions and interferences among different road users, especially vehicles' drivers and vulnerable road users, has increased. The present study concerns the development of new and advanced tools that can effectively address this need, enabling the use of simulation systems that are highly faithful to reality and have an unprecedented degree of versatility. Such a development makes it possible to switch from virtual reality to metaverse logic, exploiting digital twins and related digital equipment, thus realizing simulation scenarios faithful in every part to as-built or planned projects. To this purpose, a real-time 3D platform has been opportunely developed by means of a process that allows to create scenarios with BIM-based modeling software to be made interactive, using metaverse viewing glasses as the user interface element, while also achieving the goal of streamlining the hardware configuration of the simulators and aimed at evaluating simultaneously the driving behavior and performance (such as speeds, distances, accelerations, …) of different road users (vehicles' drivers, pedestrians, motorcyclists, cyclists) experiencing at the same time the same road scenarios.

Keywords: human factors; virtual reality; co-simulation, driving simulator; driver-pedestrian interaction

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10.1016/j.trpro.2025.06.088

1. Introduction

Nowadays, driving simulation is a very powerful tool, widely developed and relatively common in the study of driver's behavior, capable of supplanting the safety and practical problems, as well as the boundary environment control issues that on-site driving research may involve (Calhoun and Pearlson, 2012). In the literature, there are several driving simulator-based studies aimed at evaluating the driver's behavior in a wide range of driving situations and conditions. Several studies (Calvi, 2018; Wynne et al., 2019; Calvi et al., 2020) report widespread validation of these tools worldwide, confirming a significant match between the driving simulation results and real-world driving.

However, since the majority of available simulators are single-user stand-alone, the researchers cannot easily analyze the behavior and performance of drivers involved in complex driving situations like interaction with other drivers or road users, especially regarding pedestrians and other vulnerable road users. Sometimes, the simplified traffic flow implemented in driving simulators has significantly limited the study of the impact of different drivers' behaviors on traffic flow (Sun et al., 2015). Driving is a multitasking phenomenon that requires drivers to consider not only numerous parameters, such as speed, lane position, or mutual distance from the other vehicles, but also a substantial sharing of information, direct and indirect, with other drivers and road users. The act of driving is a set of behavior that includes formal and informal rules dictated by the mutual interference and interaction that the users of the road and the environment impose (Björklund and Åberg, 2005). Furthermore, some specific road configurations, such as the intersection or the merging zone in the highway (Hidas, 2005), necessitate cooperative interference between the drivers. For example, during the crossing of an intersection, the drivers must communicate, with gestures, signs, and behaviors, their intention to cross or wait, creating a cooperative interaction with the other road users to avoid road crashes. This interaction is the same at the crosswalks with the pedestrians and the drivers, or during the merging zone on the highway between the driver in the right lane and the entering driver. In terms of road safety, it is crucial to study situations where the necessity of cooperation with other road users, such as lane changes, road intersections, merging zones, and crosswalks, characterizes and affects the driving behavior, while simulating interactions between all road users (Huang et al., 2020; Huang et al., 2022a; Huang et al., 2022b; Niu et al., 2013). Indeed, as analyzed by Heesen et al. (2012), cooperative behavior implies that the driver bases the driving choice on taking into account the actions of the other users. As an example, an efficient driving assistance system for cooperative lane changing should integrate the multiple and mutual actions and interactions between all road users to eliminate, or at least limit, the risk associated with lane-changing maneuvers. This highlights the importance that the drivers give to the other road users' decisions and behaviors in order to make a cooperative choice. Accordingly, defining a priori the behaviors of the other road users, which is typical for single-user stand-alone driving simulators, does not allow for taking into account a lot of important information based on cooperative behaviors (Feierle et al., 2020).

In fact, the stand-alone driving simulator simulates interactions between road users and traffic flow by utilizing the predefined behaviors of other road users in the scene. Modern video games function similarly: the simulated world resembles a metaverse, with all simulated features, such as vehicles and pedestrians, referred to as non-playable characters (NPC), and their behaviors predetermined and defined a priori. As previously reported, in the stand-alone driving simulator, it is possible to assign a predefined behavior (i.e., constant speed, lateral position, etc.) to all the other vehicles in the scene; in this case, such vehicles are defined as "traditional" vehicles, not able to adapt their driving parameters in relation to the other vehicles and road users in the scenario, just performing actions predefined by the experimenters. Conversely, it is also possible to include an "intelligent" vehicle, that can modify independently its behavior and performance according to the other vehicle's behavior and to the driver who is participating in the simulation during the running and development of the simulation (i.e., priority rules could be assigned in order to keep the safety distance from the other vehicles, to manage speed and lane position, or to turn and give priority at the intersection). However, both in the case of "intelligent" and "traditional" vehicles, there are some limitations in communication and cooperation with other road users as, in any cases, the vehicles follow predetermined instructions.

Moreover, the interactions between road users are significant in understanding the phenomena related to the use of cooperative intelligent transport systems (ITSs). These systems support the drivers by providing them with information from the infrastructure and other road users, improving safety conditions, flow management, and minimizing the environmental impact (Oeltze and Schießl, 2015). Nowadays, this type of research is of overriding interest, as referred to by Lorenz et al. (2011), who have defined the cooperative ITS tools as significant tools for improving safety and operation of roads.

In order to tackle the limitations in cooperation and communications among road users in the stand-alone driving simulator, it is possible to create multi-user driving simulators, generating scenarios designed and realized by means of BIM technology and multiverse immersive content (Johansson et al., 2024; Liu et al., 2023; Muehlbacher et al., 2011). Saeed et al. (2023) divide the metaverse into three different evolutionary phases that follow each other in the virtual world generation. The first phase is characterized by the Digital Twin (DT), the perfect reproduction of the real world that generates a link with the information assets. The DT realization is perfect for designing and building the base for the generation of BIM-based simulated scenarios (Dols et al., 2021). During the second phase, we can create digital native elements to integrate other simulated vehicles and road users into the metaverse. The third phase is the complete maturity of the multiverse, where the real world and virtual world are completely connected, and road users can interact with a long series of digital twins and NPCs. This stage of development can lead to interesting and useful research findings, such as how modern road users interact with each other in the same high-fidelity and strongly immersive simulation, and how their actions are affected by other users, simulated drivers, or both. The metaverse multi-user simulator is based on traditional interaction instruments and interfaces, such as the steering wheel, pedals, and car seat, with the addition of an optical viewer capable of providing the user with a very high degree of immersion (Kruachottikul et al., 2023). The primary graphics tools and software used to create the simulated scenarios are based on Unity and Unreal 3D. Recent research by Morschheuser (2022) showed that Unity permits a higher level of interoperability, which is a principal element of the BIM-based methodology.

The multi-user driving simulator communication structure is one of the system's focal points. There are two different kinds of structures utilized by the system: peer-to-peer and peer-to-server. When validating the instrument, Liu and Xie (2019) showed that the more effective and efficient structure is peer-to-server. Indeed, this structure successfully connects a single simulator to the system in a manner similar to that of a personal computer controller. This communicates with the server that individuates and categorizes the information of all the road users, considering at the same time all the controllers of the multi-users and ensuring the correct simultaneity of data and the respective information.

2. Methodology

Fig. 1 illustrates the structure of the proposed methodology for a multi-user simulator, which relies on Unity and Mirror, a network library system for creating multiplayer structures within Unity. To realize the structure of the multi-user simulator, there are four macro areas of the script and structure project:

1. The scenario interface side, where the BIM-based scenario is imported;
2. The network management side, where the structure of the Mirror-based network structure is implemented;
3. The data collection side, where the structure of the data storage manager of the users is implemented, and several data are collected, such as the user's position in the scenario, their mutual distance from other users or objects, their speed, acceleration, and so on;
4. The user’s interface side, where the road user’s features are implemented (such as pedestrians, vehicle drivers, cyclists, etc.).

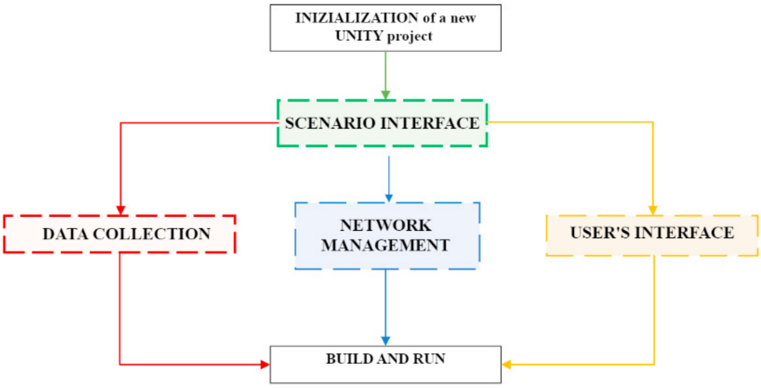

Fig. 1. Structure of the Unity and Mirror-based multi-user simulator.

2.1. Scenario interface side

According to Dols et al. (2016), simulation involves reproducing real-life situations that researchers can control, engaging the user in graphically realistic ways, and creating a sense of immersion within the driving simulation setting. Replicating the simulation in an environment as faithful as the real world is necessary to achieve this (Bayarri et al., 1996).

Scene realism is determined by a complex set of factors, including realistic appearance, realistic construction of the virtual world, and physiological and psychological aspects (Fuchs et al., 2003). To ensure that the simulation is as realistic as possible, the definition of the information assets that integrate the digital asset into the modeling process is of paramount importance. However, to strike a balance between the need to create a realistic Digital Twin and the computational complexity of the software and hardware system, one could remove elements and features that contribute negligibly to realism from the simulation. After creating the Digital Twin, the same must be extracted from the BIM Authoring Software (i.e., Autodesk Infraworks, Autodesk Civil 3D, etc.) in the format *.fbx (Filmbox, which is a proprietary file format developed by Kaydara Inc. and owned by Autodesk), in order to import it into Unity and generate the simulated driving scenario. Fig. 2 shows the scenario interface's structure.

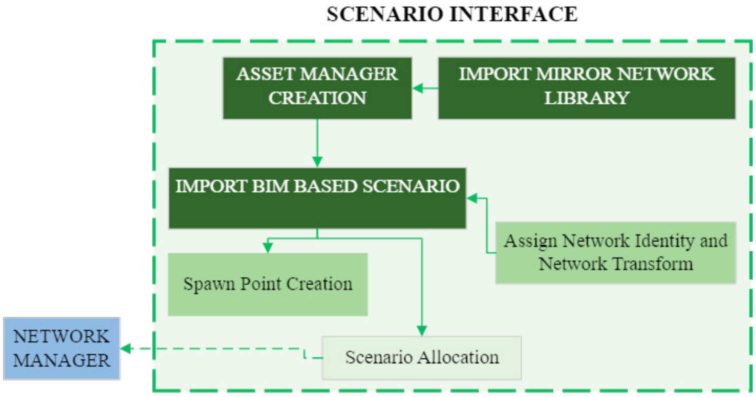

Fig. 2. Scenario interface structure of a multi-user simulator.

2.2. Network management side

The implementation of the network management side begins with the creation of a network manager, which is responsible for managing the network aspect of the multi-user simulation. It puts a lot of functionality in a single place and makes running and debugging a multi-user simulation as simple as possible. The system manages the simulation's state, spawns all users or players into the scenario, manages both online and offline scenarios, provides debugging information, and offers a variety of customizations to ensure the correct simulation implementation. A Head-Up Display (Network Manager HUD script) completes the network management side, enabling a quick start of a multi-user simulation through a simple interface. This interface allows users to choose whether to run the simulation as a host (server and client) or as a client or server alone. Mirror uses a separate transport component to connect over the network; such a transport component contains the protocols providing end-to-end communication services for the applications. The default transport component is the KERN Communication Protocol (KCP).

The Network Identity script allows each element in the scenario and simulation to have its own unique identity. It is the heart of Unity networking; it controls the unique identity of all the simulated objects on the network and uses this identity to make the network system aware of the simulated object. All simulated objects must have their movements registered throughout the simulation to complete the object's identity. The Network Transform script synchronizes the position, rotation, and scale of the simulated objects across the network.

To enable the simulated objects to use physics and synchronize their speed and other properties across the network, the Network Rigid body script is added. This component is useful to provide each element with gravity, the force entity, and their variability. The Network Start Position script, which defines each individual user's starting position in the simulation, can control where the users spawn within the scenarios.

It is necessary to opportunistically modify the Network Manager to accommodate the simultaneous presence of various user types, such as pedestrians, cyclists, and vehicles, as well as to unambiguously associate the start position of each user in the scenario. Additionally, the Network Manager utilizes the coordinates and orientation of the start position as the client connects to the server. Fig. 3 shows the structure of the network management side.

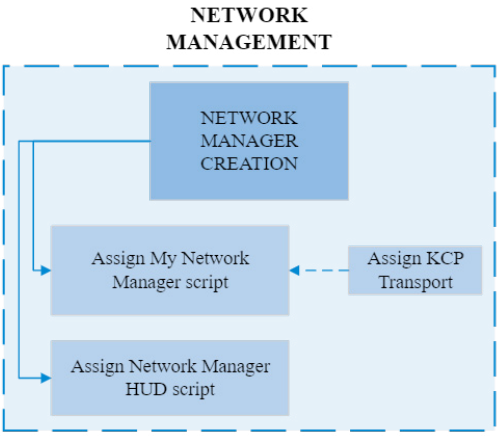

Fig. 3. Network management structure of a multi-user simulator.

2.3. Data collection side

The data collection side is based on the implementation of a data collection manager capable of managing the saving and storing of data and placing them in specific files on the server device (see Fig. 4). The Network Manager script embeds a client search script that identifies all clients connected to the server from the simulation's start, saves their IP addresses, and tracks them for data saving. The data saving process involves two scripts: the first is spatial-based, allowing the definition of invisible trigger colliders to indicate the position for data saving, and the second is time-based, allowing the user to specify the time interval for data saving. The output file consists of a table in Comma Separated Values format (*.csv) that reports all the data related to the user's positioning within the scenario, the user's rotation around the reference axes, speeds, accelerations, and other parameters related to the inputs provided by the user to the specific simulator (i.e., the driving simulator, head-up display, bicycle/motorcycle simulator, etc.).

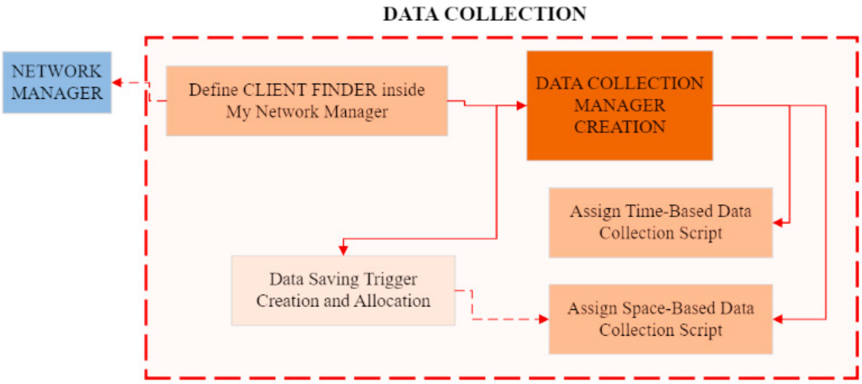

Fig. 4. Data collection structure of a multi-user simulator.

2.4. User’s interface side

The creation of a Unity prefab, the user's character that can be spawned within the scenario, serves as the basis for the user's interface (see Fig. 5). We created the prefab element by modeling the user's "avatar" within the scenario. The "avatar" point of view, its own network of rigid bodies, and its own movement script complete the prefab element, enabling the user to navigate within the scenario using physical simulation tools such as a head-up display, vehicle, bicycle, and pedestrian simulator. As previously discussed, it is necessary to assign to each simulated object a network identity to make it unique in the simulation, and a network transform to synchronize its movements in the scenario. After this, the network manager can assign the user's character ("avatar") and manage the scenario spawning. This specific framework utilizes Vehicle Physics Pro, a prefab library that enables the simulation of the vehicle's physical characteristics.

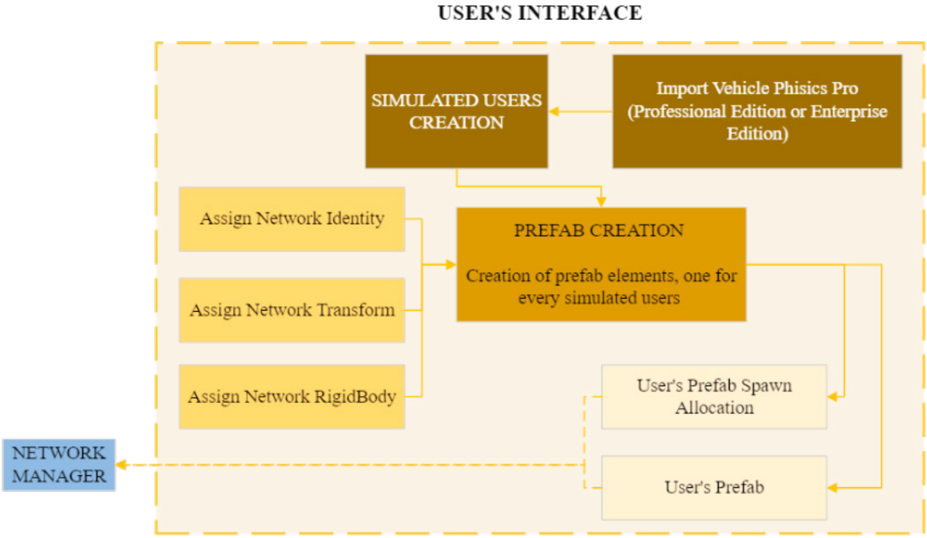

Fig. 5. User’s interface structure of a multi-user simulator.

3. Functional structure

Two components make up the functional structure: a host, which consists of a client and a server on the same PC, and a network of clients. A simulation tool connects each client to a personal computer, constructing the input for the system. In Fig. 6, the host, a desktop personal computer, connects to a fixed-based driving simulator that includes an instrumented vehicle for the user to drive within the scenario. Three users, each with their own simulation tool (head-up display, vehicle, bicycle, etc.), replicate a different road user on the client side of the network.

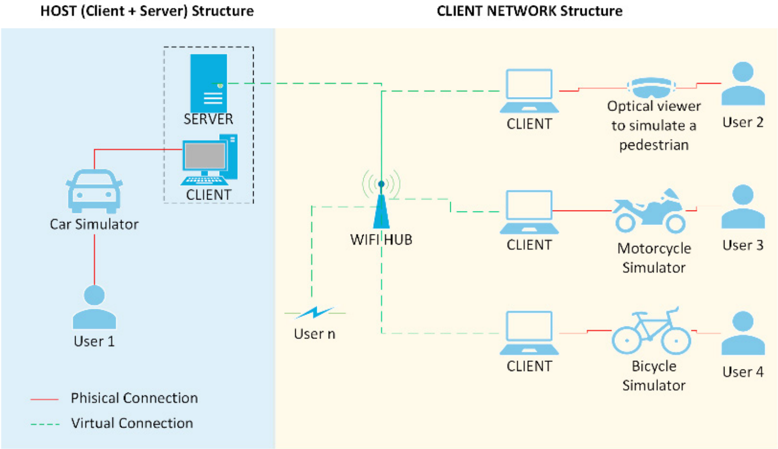

Fig. 6. Host and client network structure.

4. Conclusions

In conclusion, the previously illustrated framework allows for a simulation in the Unity environment using a host-client structure. Such a tool makes it possible to study the behavior of users mutually influenced by their presence in the same scenario, which is no longer managed exclusively by the simulation (as occurs for single-user stand-alone driving simulators) but also directly by other users participating in the simulation itself (see Fig. 7). Such a tool, which is very effective and versatile, poses research objectives related to the study of users' behavior under interference conditions, including cooperative ones. Such a framework also allows the collection of a multitude of parameters, including those related to vehicle physics, which allow extensive considerations related to user behavior. This procedure's limitations primarily stem from the internet network's power, which can cause small inconsistencies in cases of higher computational complexity due to server/client synchronization time, high network latency, or even the simulated scenario's overcomplexity. Another area of inquiry is the ability to generate simulated traffic within the scenario and share it from the server with each client on a consistent basis. We implement relevant user interface elements and simulate the physics of two-wheeled vehicles and humanoids to include pedestrians and motorcycles in the scenario. This solution will enable us to investigate the behavior of other susceptible road users. Future researches will be dedicated to optimize the procedures and protocols here presented in order to validate the co-simulation platform.

Fig. 7. Pedestrian and driver interaction in the multi-user simulator.

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