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SUMO2Unity: An Open-Source Traffic Co-Simulation Tool to Improve Road Safety

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Abstract — **In traffic safety research, simulation tools are considered more straightforward and cost-effective than direct observations of real-world conditions, especially when dealing with scenarios that may not exist in reality. The tools include traffic micro-simulation tools (e.g., SUMO) and driver simulators developed in game engines (e.g., Unity). However, the tools also have limitations. For example, the equations used to simulate human behavior may not always reflect real-world behavior accurately, and driver simulators' lack of realistic traffic systems affect the interaction between the simulator vehicle and other vehicles. Co-simulation allows two different simulation tools to exchange data to enhance the capabilities of each tool, but many traffic safety researchers currently spend significant amounts of time, effort, and budget working on their own version of a co-simulation tool to integrate, for example, a traffic micro-simulation tool such as SUMO with a driver simulator such as the Unity game engine. This situation takes time away from focusing on the goal of improving traffic safety. In this paper, we developed an open-source traffic co-simulation tool. Development involved three tasks: 1. integration of SUMO and Unity; 2. development of a 2D and 3D environment (a 3D road environment in Unity was generated from a 2D road environment in SUMO); and 3. development of a 3D model of a simulator vehicle and development of a VR-based driver simulator. We named our tool SUMO2Unity and believe that it can significantly help traffic safety researchers to conduct future research aimed at improving traffic safety.**

Keywords: Co-simulation, SUMO, Unity, Open-Source Tool, Driver Simulator, Virtual Reality.

I. Introduction

The goal of this study is to develop an open-source, available free of charge co-simulation tool with the goal of helping other researchers to focus on their ultimate goal to improve traffic safety. The tool is available on GitHub [2].

A. Simulation Tools

Simulation tools play a pivotal role in understanding and analyzing various aspects of transportation systems. Investigating different traffic scenarios through simulation has been shown to be more straightforward and cost-effective than direct observations of real-world conditions, especially when dealing with scenarios that may not exist in reality. The two major simulation tools in traffic safety include:

1. Traffic micro-simulation tools: Traffic micro-simulation tools can use hypothetical scenarios to provide detailed insights into traffic and roadway characteristics. The tools enable comprehensive analysis of complex traffic situations and offer valuable data for transportation planning and safety studies. The tools available include PTV Vissim and SUMO (Simulation of Urban Mobility). SUMO was developed by the German Aerospace Centre in 2001. It is a 2-Dimensional (2D) microscopic and multi-modal traffic simulation tool that includes vehicles, trucks, pedestrians, public transport, bicycles, trains, electric vehicles, and combinations of various modes [1]. SUMO is open-source, free of charge, and available to everyone. SUMO's features have made it one of the most popular traffic simulation tools for research [2]. While micro-simulation tools are useful for traffic safety analysis, they are limited by our ability to construct equations that can simulate human behavior and real-world behavior accurately. For example, the equations may not accurately capture real-world behavior when a driver who is changing a lane sees a blocked lane ahead (e.g., due to construction).

2. Driver simulators developed in game engines: Both non-automated driver simulators and connected and automated vehicle (CAV) driver simulators developed in game engines are essential interactive tools in human factor and vehicle design studies in traffic safety. The simulators provide a controlled and safe environment for researchers to study driver behavior and CAV technologies (i.e., vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I)) in various driving scenarios. Both non-automated and CAV driver simulators require game engine software (e.g., Unity) for the virtual development of vehicle features. Unity is a 3-Dimentional (3D) and open-source tool. In the case of a non-automated driver simulator, researchers use Unity to create a virtual design of the interior of the vehicle (e.g., steering wheel and pedals). A driver using the simulator wears a virtual reality (VR) headset and controls the steering wheel and pedals. In the case of a CAV driver simulator, researchers develop V2V and V2I communication systems on top of a non-automated driver simulator. The Unity game engine is widely used by researchers and industry to develop driver simulators. These simulators include AirSim (Microsoft) [3] and SVL simulator (Life's Good (LG)) [4]. The simulators are useful for traffic safety analysis, but their limitation is their lack of a realistic traffic system reflecting interaction with other vehicles.

B. Problem Statement

The integration of traffic micro-simulation tools and driver simulators offers a way to overcome the limitations of traffic micro-simulation tools and driver simulators. We use the word "co-simulation" to describe this integration. Co-simulation is a procedure that can enhance the capabilities of each tool by allowing two different simulation tools to exchange data including, for example, the trajectories (X, Y, Z) of vehicles

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[2] https://github.com/SimuTraffX-Lab/SUMO2Unity

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[5]. Researchers can use co-simulation to improve safety in, for example, the selection of alternative designs/countermeasures and also in the design of CAVs.

B.1. Selection of alternative design/countermeasures:

Following the diagnosis of a roadway safety problem, traffic safety engineers and transportation planners need to select and evaluate the most appropriate alternatives/countermeasures from a number of options. This approach has traditionally relied only on the outputs from traffic micro-simulation tools. Co-simulation implies that a driver equipped with a VR headset uses a physical steering wheel and pedals to control a vehicle in the game engine. The game engine allows drivers to interact with traffic movements generated by the traffic micro-simulation tool (e.g., SUMO) and to make their own decisions when responding to various situations. As this interaction with other traffic is not possible with existing traffic micro-simulation tools, co-simulation clearly offers a more realistic representation of driver behavior than can the traditional approach. Xu et al. [6], for example, used co-simulation to evaluate driving behaviors on ramps. The authors investigated the impact of merging decisions and traffic conflicts with/without ramp metering. The study involved 23 participants and employed a surrogate safety assessment model to extract conflict data. In a 2022 study, Xu et al. [7] extended their co-simulation to investigate compulsory merging at freeway on-ramps within construction zones.

B.2. Designing CAVs

Traffic safety engineers have traditionally developed V2V and V2I communication systems for CAVs using driver simulators some of which have included a simple traffic system, but recent studies have used co-simulation to enhance the simulator traffic system [8-10]. Co-simulation used to develop V2I and V2V communication systems that consider the interactions the vehicles and the surrounding simulated traffic implies the seamless integration of CAVs into a simulated environment. The approach includes data collection from camera sensors (vision technology) and from vehicles. This approach enables researchers to evaluate the performance, safety and efficiency of CAVs in a range of scenarios and provides crucial insights for the advancement and validation of CAVs technologies. For example, Olaverri-Monreal et al. [11] used co-simulation to develop a CAV simulator in which the driver simulator can communicate with a traffic light to reduce hard braking (V2I technology). Traffic lights transfer information about green time to the approaching vehicle and the vehicle adjusts speed to reduce hard braking. The study also considered interactions with the surrounding simulated traffic (which was generated by SUMO). Smirnov et al. [12] used co-simulation to address urban traffic challenges for CAVs. The study's goal was to investigate whether human drivers asked to change lane due to a request from the CAV through V2V communication would in fact change lane. The experiment included one CAV, one non-automated vehicle and several SUMO traffic vehicles. The CAV received data about the position and speed of nearby vehicles and decided whether to request a lane change by using a game theory model. The results showed that all eight human drivers in the study accepted the CAV's request to change lane.

Each of the studies mentioned above invested considerable time, effort, and money in developing a co-simulation tool that integrated SUMO and Unity. Each study 're-invented the wheel' and therefore sacrificed resources that could have been used to focus on the ultimate goal, i.e., improving safety.

C. Study Goal and Objectives

In this study, our goal was to develop an open-source co-simulation tool that will be available free of charge allowing other researchers to focus on using the tool. We call the tool "SUMO2Unity." The study had three objectives:

1. *Integrate SUMO and Unity.* This objective included programming the data exchange between the trajectory coordinates (X, Y, Z) of the vehicles and the signal timing (phase and duration) every 0.02 seconds;
2. *Develop a 2D environment for SUMO and 3D environment for Unity.* The SUMO and Unity environments were designed to allow researchers to develop and modify their own scenarios and test the tool's integration. The 3D environment included 3D models of vehicles, traffic lights, and various road configurations including two-lane/four-lane roads and signalized and unsignalized intersections; and
3. *Develop a 3D model of a simulator vehicle and develop VR-based driver simulator.* The 3D model of simulator vehicle includes creating a realistic interior design and adding vehicle dynamics and the VR-based driver simulator adds functionality by allowing us to control the simulator vehicle.

II. Tool Development

Tool development comprised three key tasks. **Figure 1A** shows Task 1, **Figure 1B** shows Task 2, and **Figure 1C** shows Task 3.

*Task 1. Integration of SUMO and Unity (**Figure 1A**)*

The integration of SUMO and Unity involved programming the exchange of vehicle trajectory data and signal timing. As in other traffic simulation software, SUMO adds a 2D vehicle based on input parameters (e.g., vehicle ID and length) and generates the trajectories (X, Y, Z) of the vehicle in a fraction of a second (e.g., 0.02 sec in our study). In Unity, we received these data in real-time, generated a 3D vehicle with the same input parameters (e.g., vehicle ID and width) and assigned the same trajectory for each 0.02 sec. As this procedure results in sending data from SUMO to Unity (one-way communication), the trajectories of the vehicle were similar in SUMO and Unity. We applied the same process for all the vehicles. SUMO allows the user to take control of one vehicle in the simulation and identify this vehicle as the "simulator vehicle." We created a simple 3D simulator vehicle inside Unity with the same input parameters (e.g., ID and width) and sent the trajectories of the vehicle for each 0.02 sec to SUMO. This resulted in two-way communication between SUMO and Unity and meant that the simulator vehicle inside Unity observed the traffic generated by SUMO and we could move the vehicle by keyboard interface.

Exchanging data for signal timing was different. We designed signal timing in SUMO for each signalized intersection. SUMO can generate signal phase and duration for each 0.02 sec. In Unity, we received the data in real-time, generated the required number of 3D traffic signals for each signalized intersection, and assigned the same signal phase and duration. Exchanging data for signal timing does not require two-way communication.

*Task 2. Development of a 2D and 3D environment (**Figure 1B**)*

Generating a 3D road environment in Unity from a 2D road environment in SUMO is a difficult task. The task does not require two-way communication since the environment is static (fixed), but the road location and geometry (coordinates and lane specifications) must match in both tools or the SUMO vehicles will not move on the right path inside Unity and vice versa. OpenDrive format allows us to solve this issue. OpenDrive format is a standard language introduced by the Association for Standardization of Automation and Measuring Systems and defines road network specifications, such as the number of lanes and lane width, in a programming format. 3D modelling tools including MathWorks RoadRunner or Blender have the capability of importing/exporting OpenDrive format allowing researchers to generate a 3D road environment from a 2D road environment. We developed a 5 km by 5 km section of a town containing a 2D environment for SUMO and a 3D environment for Unity. The town was based on a 5 km by 5 km real-world location in Pickering, Ontario, Canada. We selected this area because it contains different types of roads including two-lane roads (one lane in each direction), four-lane roads (two lanes in each direction), roads with a median barrier, roads with right and left turn storage lanes, and roundabouts. The town also includes three signalized intersections and six unsignalized intersections. In addition, the 3D environment included 3D models of vehicles, traffic signals, streetlights, construction zone cones, different types of trees, and a river. This variety allows researchers to modify the environment and develop their own scenarios.

*Task 3. Development of a 3D model of simulator vehicle and development of a VR-based driver simulator (**Figure 1C**)*

Development of a 3D model of simulator vehicle (C1)

This task included creating a realistic interior design and adding vehicle dynamics (movement of vehicle due to forces and inputs including acceleration/deceleration).

We used a 3D model of a vehicle developed by Unity. Unity has an immersive and realistic interior and exterior design. The interior design includes a seat, dashboard, speed gauge, steering wheel, mirrors, and the exterior design includes wheels and doors. **Figure 1.C.1** shows the interior design of the simulator vehicle.

The vehicle is only a model and has no functionality. It is as if one purchased a vehicle, but the steering wheel does not rotate, the speedometer needle does not move, and the mirrors do not work. We used Unity game engine and programming to assign these functionalities.

As the 3D model of the vehicle does not move, it was also necessary to assign vehicle dynamics equations. Fortunately, Unity provides a sample of vehicle dynamic design for simulation and testing.

Development of a VR-based driver simulator

The VR-based driver simulator added functionality by allowing us to control the simulator vehicle. To train and test the algorithms required in the development of a CAV, we added vision technology (camera) and the ability to collect video data from the environment.

To develop a driver simulator, we used VR technology. With VR, we can control and reproduce different scenario conditions [13] and expose drivers to the scenarios and dangerous driving conditions without physical risk to the drivers. VR has usually been associated with high costs and huge computational power, but affordable VR devices are now available. VR headsets track the head's orientation. We developed a VR-based driver simulator that included a VR headset as the display system, and a Logitech G25 Racing Wheel and pedal as the driving system. The VR headset was a Meta Quest 2 which provides stereoscopic vision at 90 FPS, 3,664 x 1,920 pixels (1,832 x 1,920 per eye) resolution and a field of view of 90 degrees. **Figure 1C2** shows the VR-based simulator that we developed.

To allow other researchers to collect data for the development of technologies in CAV driver simulators (e.g., V2V technology), we needed vision technology in the VR-based simulator. With Unity, we could install a 3D model of a camera in front of the simulator vehicle. The camera can capture images/videos within a field of view (90 degrees) that is similar to that of the camera installed in CAVs. The model of a camera allows the simulator to collect real-time images from the environment including road geometry (lanes and markings), surrounding SUMO vehicles, roadside elements (trees and streetlights), and obstacles (traffic cones). We also provided a module with a .txt file for storage of the vehicle state including simulation time, vehicle coordinates, vehicle speed, rotational degree (yaw and pitch), and gears. Other researchers can use our model of a simulator vehicle to develop a wide range of scenarios to train and test CAV technologies. For example, they can modify the 3D environment (e.g., add traffic cones to block one lane of the road due to construction) and collect a wide range of data including captured images and details of the vehicle state.

III. Discussion on Potential Research Topics

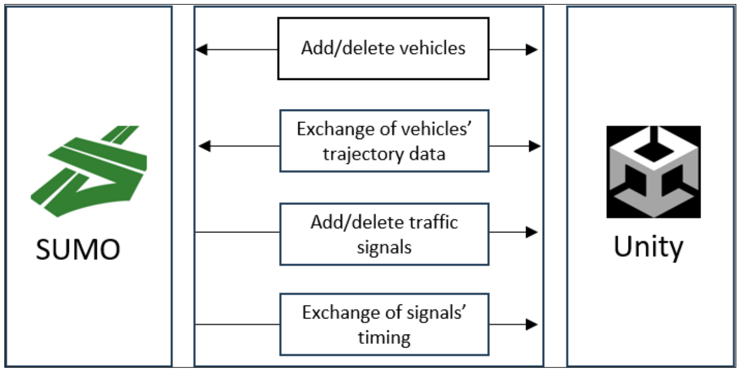
In this section, we discuss three new research topics which may benefit from the development of our SUMO2Unity tool: road safety education and training, enhanced decision support systems for near real-time decision-making in traffic management centers, and CAV road safety in mixed traffic.

A. Road Safety Education and Training

Universities and colleges offer a wide range of transportation safety courses which familiarize students with the fundamentals of the geometric design of roads and with traffic micro-simulation modeling, but learning usually takes place using books or images/videos, i.e., flat displays of information that do not provide an immersive experience for students. To provide an immersive experience, Veronez et al. [14] examined a new approach in a geometric design course including geometry problems (e.g., a bad superelevation design on a horizontal curve). They imported the 3D model into Unity and allowed students to use a VR-based driver

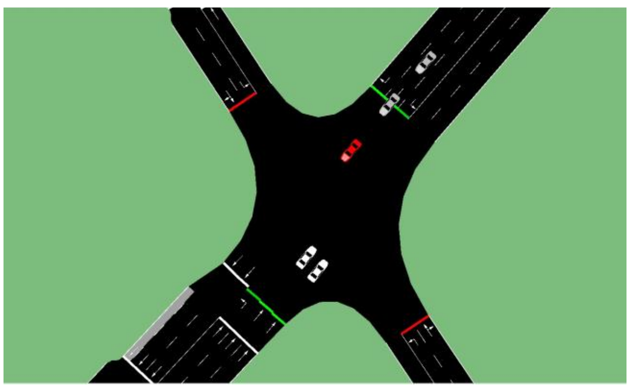
Figure 1. The Three Tasks Required for Tool Development

A. Task 1: Integration of SUMO and Unity



B. Task 2: Development of a 2D and 3D environment

B.1. Development of a 2D environment in SUMO



B.2. Development of a 3D environment in Unity

C. Task 3: Development of a 3D model of simulator vehicle and development of a VR-based driver simulator

C.1. Development of a 3D model of simulator vehicle

C.2. Development of a VR-based driver simulator

simulator to drive along the corridor virtually. The results showed that 73% of the 53 students who participated found this approach to be a helpful tool when identifying and learning about geometric design problems for undergraduate students. The authors developed a 3D model of an 8 km section of a real-world corridor containing several

We can imagine three ways in which our tool can help traffic safety instructors:

1. Geometric design of roads course. SUMO2Unity can be used to import a 3D road environment with various geometric design issues created by the course instructor or students. The students can use a VR headset to explore the environment and design issues. For example, students can use the VR-based driver simulator to experience the 3D road environment as a driver driving through the environment. Students can also use VR headsets to experience the environment as a pedestrian. They can walk or teleport from one desired location to another desired location of the 3D environment. This learning opportunity does not require a physical steering wheel and pedal.

2. Traffic micro-simulation modelling courses. Instructors can use our tool to immerse students in a micro-simulation tool. Students can act as pedestrians or drivers and observe the interactions between vehicles and signal timing. This experience will improve their understanding regarding signal phases/scheduling, car-following models and lane changing behavior inside SUMO.

3. Intelligent transportation systems course. Instructors can use our tool to teach the fundamentals of a CAV car including vision technology and vehicle state data. We can imagine a scenario where students can control a CAV using either a traditional approach (keyboard and flat screen) or a novel approach (VR headset). The student can then analyze the wide range of data produced by the CAV, and instructors can explain how the data are used for CAV training, testing and design.

We envisage a completely new "Virtual Reality in Traffic Safety" course that includes the geometric design of roads, traffic micro-simulation modelling, and intelligent transportation systems.

B. Enhanced decision support systems for near real-time decision-making in traffic management centers

Municipalities usually have a traffic management center where operators can watch the video material produced by cameras installed along roads and highways. The traffic management center may also collect traffic data from detectors (sensors) installed in the road network. Operators use this information to make appropriate decisions. For example, in the case of a collision, operators disseminate messages through dynamic variable message signs. Traffic management centers may include a simple decision support systems to help operators to make appropriate decisions. For example, in Ontario, Canada, operators cannot disseminate optional content for variable message signs. They use established message content and if, then rules to disseminate each type of message. For example, "if weather is snowy," the message would be "Bad Road Condition."

Kusic et al. [15] developed an enhanced decision support system for near real-time decision-making for using variable message signs to disseminate variable posted speed limits, in this case regarding appropriate speed limits for the next few minutes of roadway to reduce overall travel time. The goal of the decision support system was to minimize overall travel time by proposing the best posted speed limit for each lane. The user interfaces were 2D and very simple. The study was conducted on both directions of 13.2 km of a motorway in Switzerland. The researchers developed a 2D version of the corridor in SUMO. SUMO received traffic data each minute from cameras installed at entry and exit ramps, and ran in an instant mode which generates outputs in a few seconds. The output was the proposed different posted speed limits and corresponding travel time in each lane.

Enhanced decision support systems such as those described here represent a very promising area for development. The tool can help. Current systems rely heavily on micro-simulation tools which may contain weaknesses in their representation of human behavior, and these weaknesses could even result in output that increases travel time. For example, the lane changing behaviors of human drivers after seeing a dynamic variable sign may differ from the assumptions made by SUMO. If, for example, a collision occurs in one lane, that lane is then normally blocked in SUMO, but human drivers may not act as assumed. The problem is that enhanced decision support systems usually rely on fixed behavioral parameters defined during development of the systems. The tool can help by deploying a human-in-the-loop simulation to test, develop and modify SUMO's parameters as part of the development of enhanced decision support systems.

C. Road Safety in CAVs in Mixed Traffic

The third research topic that may benefit from the development of our SUMO2Unity tool is CAV road safety in mixed traffic. Under some conditions, CAVs do not require their drivers to constantly monitor the driving environment allowing drivers engage in secondary activities such as reading, writing emails, and watching videos. The CAV's automated system requests the driver to resume control of the vehicle when the system encounters an unexpected situation (e.g., an obstacle or the absence of lane marking) which it cannot handle. This is called a take-over request. The implications of CAV drivers' secondary activities and the handling of take-over performance when unexpected situations arise are gaining increased research interest (Zeeb et al., [16]; Sportillo et al., [17]; Happee et al., [18]). For example, Zeeb et al. [16] studied how visual-cognitive load impacts take-over performance. The study examined engagement in three different secondary tasks (writing an email, reading a news text, and watching a video clip). The authors found that the drivers' engagement in secondary tasks affected the time required to regain the control of the vehicle, but that the increase in time was not statistically significant.

CAV related studies usually use no traffic or simple traffic systems comprising only CAVs. Real-world scenarios for present and future circumstances may be very different. SUMO2Unity can help researchers to examine more realistic scenarios and produce more reliable results.

IV. Study Limitations and Future Research

Our first objective was to integrate SUMO and Unity. Our study focused on the integration of vehicles and signal timing between SUMO and Unity. Future research should include other modes of transportation including pedestrians [19], bicycles, and electric vehicles. This research would require the development of 3D models and programming for two-way data communication between SUMO and Unity.

Our second objective was to develop a 2D environment for SUMO and a 3D environment for Unity. Our 3D environment was based on sunny conditions and did not consider other weather conditions. For example, snow may negatively affect road conditions and visibility. Future study needs to review the impact of weather conditions and then try to model the impact of different weather conditions on traffic safety.

Our third objective was to develop a 3D model of a simulator vehicle and to develop a VR-based driver simulator. Our study focused on the development of a VR-based driver simulator. The development of extended reality technology is promoting CAV technological innovation and can allow a physical CAV to be replaced by 3D model CAV developed in SUMO2Unity. The physical CAV may contain sensors that can simultaneously observe the digital environment (SUMO vehicles) and surrounding physical environment (obstacles).

Future research should develop an extended reality capability for SUMO2Unity to allow researchers to test physical CAVs with the presence of SUMO vehicles.

We also recommended future studies to provide a quantitative analysis on co-simulation accuracy and possible latency of data exchange between SUMO and Unity.

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