Integration of an Autonomous Driving Simulator into V2X Simulation Framework for Testing Connected Vehicles

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ABSTRACT

Equipped with a multitude of advanced technologies such as artificial intelligence and communication technologies, transportation systems are becoming more intelligent. Intelligent transportation systems, connected vehicles, and autonomous vehicles are believed to offer new potentials to drastically improve the performance of traffic networks such as reducing traffic congestions and improving traffic safety. However, testing and validation of connected vehicles including autonomous vehicles is difficult to implement on the current public roads due to high costs, lack of support of transportation infrastructure with communication technologies, and safety issues, among others. Simulation has been leveraged as an alternative to test and validate connected autonomous vehicles in mixed traffic that includes conventional vehicles, vulnerable road users, connected vehicles, and autonomous vehicles. To facilitate the testing and validation of connected autonomous vehicles, this paper presents a novel V2X simulation system for testing connected vehicles including autonomous vehicles by integrating multiple open-source simulators such as an autonomous driving simulator, ad-hoc network simulators, a cellular network simulator, and an environmental event simulator as well as a traffic simulator. The autonomous vehicles can not only use on-board sensors to perceive the surrounding traffic environments but also use communication functionalities to share information with other vehicles. The proposed simulation system can be used to simulate multiple scenarios such as safety awareness among connected vehicles, road condition notification, blind spot monitoring, and road work notification.

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INTRODUCTION

With new technology in sensors, artificial intelligence, and network communication, Intelligent Transportation System (ITS) has attracted more attention due to its advanced functionalities and features (Dimitrakopoulos & Demestichas, 2010). For instances, ITS provides communication among different connected traffic entities, which enables connected vehicles to leverage information from other road users for facilitate driving. Specifically, drivers or passengers of connected vehicles can be notified in advance about potential hazards or obstacles, the possibility of collision, traffic accidents, traffic signal timing, and the approaching of emergency vehicles. Moreover, the shared information about traffic flow or road condition allows drivers to make early decisions such as changing routes when traffic is likely congested if a traffic accident has occurred. Therefore, ITS can contribute to the reduction of traffic accidents and improvement of traffic flow and efficiency. With the advancement of communication technology and automobile technology, connected vehicles become a future development trend in ITS. Connected vehicle technology enables drivers or passengers to have an enhanced knowledge of traffic environment through vehicle-to-everything (V2X) communication. V2X communication among vehicle and infrastructures includes vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-network (V2N), which is an important part for connected driving. The technology of connected driving is believed to transform transportation systems.

Recently, autonomous driving is attracting growing attention due to its potential advantages on traffic safety, energy efficiency, and reduction of traffic congestion (Yurtsever et al., 2020). Individual autonomous vehicles (AVs) only rely on the on-board sensors and cameras such as cameras, RADAR, and LiDAR, for perceiving its surrounding environments and driving along the planned routes. The emerging connected autonomous driving technology that enhances autonomous driving vehicles with connectivity, is expected to revolutionize transportation worldwide and transform urban life. Connected autonomous vehicles (CAVs) are connected to the communication network and as such can utilize other vehicle status information and road environment information broadcasted by the network in real time. Therefore, CAVs provide safe and efficient driving by utilizing the shared vehicle, road and infrastructure information.

In the foreseeable future, mixed traffic environments will exist that consist of traditional human-driven vehicles (HDV), connected human-driven vehicles, AVs, CAVs and other road users. Moreover, the current traffic infrastructure still lacks support of a communication network. Therefore, it is necessary to find a way to understand the challenges of mixed traffic environments and test the CAV technology before massive deployment of CAVs on the public roads.

Simulation-based virtual tests provide a solution for validation of autonomous driving systems due to the need for extensive testing of autonomous driving algorithms in mixed traffic environments. Considering the limitations of individual simulation platform, some researchers have proposed co-simulation frameworks that combine the strengths of different simulators accounting for the related aspects such as traffic on the road, communications and vehicle dynamics. For instance, Aramrattana et al. integrated the Swedish National Road and Transport Research Institute's driving simulator, SUMO traffic simulator, and platooning extension for veins network simulator for testing and evaluating cooperative intelligent transport systems (Aramrattana et al., 2019). Xu et al. proposed a cooperative driving automation simulation framework for developing and testing cooperative driving automation to address the existing simulation platforms only simulating single-vehicle (Xu et al., 2021). Due to the tight coupling of individual simulators, the possibility of extending these co-simulation frameworks is often challenging. To address this issue, Cui et al. proposed an extensible co-simulation framework for supporting autonomous vehicle testing and cooperative driving automation (Cui et al., 2022). However, V2X communication is not implemented for AVs. Therefore, the main objective of this work is to develop a comprehensive simulation system for supporting testing connected vehicles (including connected human-driven vehicles, CAVs) in mixed traffic environments. To this aim, this paper proposes a high-level-architecture based comprehensive simulation system for connected driving research in mixed traffic environments by integrating a state-of-the-art autonomous driving simulator to a V2X simulation tool. The contribution of this work is twofold: (1) a V2X communication simulation environment including ad-hoc and cellular communication networks is proposed for testing connected vehicles; (2) V2X communication is implemented for AVs in the autonomous driving simulator.

The remainder of this paper is organized as follows. Section RELATED STUDY presents the related study of co-simulation environments for connected autonomous driving. Section METHODOLOGY describes our proposed V2X simulation system for connected driving and methodology. Section IMPLEMENTATION AND RESULTS demonstrates the implemented simulation system and its possible use cases. Section CONCLUSIONS AND DISCUSSIONS summarizes this paper and future study.

RELATED STUDY

Simulation provides a way to evaluate the performance of autonomous driving algorithms in a wide range of diverse scenarios and facilitate testing connected vehicles with low cost. The co-simulation system incorporates multiple simulation software with various functionalities such as autonomous driving simulation, traffic simulation, and vehicular network simulation. Some recent research has utilized co-simulation approaches for autonomous driving research. For example, Cantas et al. developed a customized co-simulation environment for development and evaluation of autonomous driving algorithms (Cantas & Guvenc, 2021). Selvaraj et al. presented a simulation framework called CoMoVe for assessment of connected vehicles on safety and traffic-efficiency applications (Selvaraj et al., 2021). The CoMoVe framework combines different simulators (e.g., ns-3 network communication simulator, CarMaker, Mathworks Simulink, and SUMO traffic simulator) in a single environment for vehicle communication, road traffic and dynamics. Xu et al. developed a cooperative driving automation simulation framework called OpenCDA for developing and testing cooperative driving automation (Xu et al., 2021). The OpenCDA framework integrated CARLA and SUMO for rendering the environments, simulating the vehicle dynamics, and generating the traffic flow. Zhao et al. created a co-simulation platform integrating Unity, SUMO, and Amazon web services for modeling and evaluating the performance of human behavior with cooperative automated driving systems under a mixed traffic scenario (Zhao et al.). Shi et al. presented a data-driven co-simulation framework for connected autonomous vehicles (Shi et al., 2022). Bai et. al. developed a co-simulation platform for simulating both real world and cyber world to support the development and evaluation of cooperative driving automation (Bai et al., 2022). Cui et al. presented an extensible co-simulation framework for supporting autonomous vehicle testing and cooperative driving automation (Cui et al., 2022).

In order to investigate V2X communication of connected vehicles, some studies have proposed co-simulation systems with V2X communication. Among them, Hussein et al. developed a Unity-based 3D Simulator for Cooperative ADAS and Automated Vehicles Simulator (i.e., 3DCoAutoSim), a modular tailored simulator, for investigating the influences of autonomous and V2X communication on drivers (Hussein et al., 2018). Aramrattana et al. incorporated the Swedish National Road and Transport Research Institute's driving simulator, SUMO traffic simulator, and platooning extension for veins network simulator for testing and evaluating cooperative intelligent transport systems (Aramrattana et al., 2019). Teper et al. proposed an integrated simulation framework for evaluation of cooperative driving (Teper et al., 2022). The integrated simulation framework includes the simulation tools of robotics, communication and control, i.e., ROS2, OMNeT++, and MATLAB. Anagnostopoulos et al. proposed an integrated simulation framework for cooperative autonomous vehicles research, which consists of CARLA simulator, ETSI ITS-G5 protocol of the Artery/OMNeT++ network simulator, ROS framework as well as SUMO traffic simulator (Anagnostopoulos et al., 2022).

METHODOLOGY

This section consists of three parts. First, the overall system diagram of the proposed simulation system is presented, and its integrated components are described. Afterwards, the methodology of CARLA integration with Eclipse MOSAIC is explained. Finally, the implementation of V2X communication among connected vehicles (including connected autonomous vehicles, connected human-driven vehicles) is discussed.

Simulation System for CVs

Eclipse MOSAIC is an open-source V2X simulation framework for supporting multi-domain and multi-scale simulation (Eclipse MOSAIC, 2023). It has already coupled multiple simulators including a microscopic traffic simulator (i.e., Eclipse SUMO), ad-hoc communication network simulators (OMNeT++, ns-3, MOSAIC Simple Network Simulator (SNS)), a cellular communication network simulator (MOSAIC Cell), an application simulator (MOSAIC Application Simulator), an application mapping simulator (MOSAIC Mapping Simulator) and an environment event simulator (MOSAIC Environment Simulator). Since Eclipse MOSAIC employed the high level architecture (HLA) co-simulation standard, it makes easy to couple new simulators by wrapping the new simulators into federates. CARLA is the state-of-the-art autonomous driving simulator which supports simulation of human driving vehicles, autonomous vehicles, and pedestrians. However, CARLA does not support V2X communication among vehicles and infrastructures.

By leveraging the framework of Eclipse MOSAIC, this paper develops a simulation system for testing connected vehicles (connected human driving vehicles and connected autonomous vehicles) in a mixed traffic environment. Figure 1 presents the simulation system for connected driving in mixed traffic environments. The proposed simulation system consists of an autonomous driving simulator (CARLA), a cellular network simulator (MOSAIC Cell network simulator), ad-hoc network simulators (MOSAIC Simple Network Simulator (SNS), OMNeT++, and ns-3), a microscopic traffic simulator (Eclipse SUMO), an environment simulator, a mapping simulator, and an application simulator for processing V2X communication.

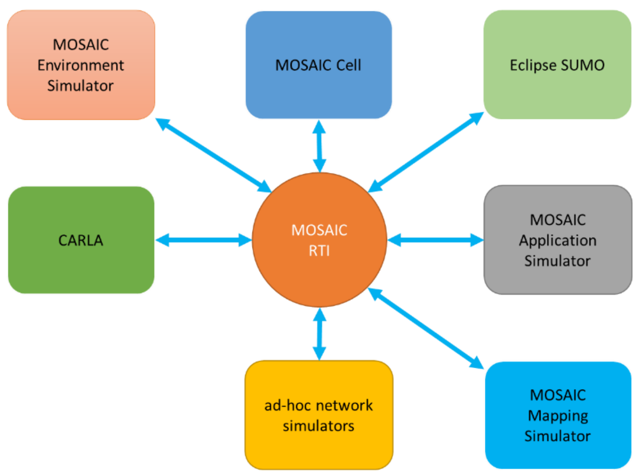


Figure 1. Simulation System for Connected Vehicles in Mixed Traffic

The functionalities of each component in the simulation system are described as follows:

(a) **MOSAIC RTI** is a simulation controller that handles management of activated simulators, the synchronization among simulators, and acts as middleware for data exchange among activated simulators.
(b) **CARLA** is a state-of-the-art open-source autonomous driving simulator that is built on Unreal Engine. It provides high fidelity 3D simulation environments. CARLA also supports diverse sensor suites such as LiDAR, cameras, depth sensors and RADAR. Moreover, it employs a server multi-client architecture and provides API for users to manipulate the simulation. Multiple clients can participate in the simulation simultaneously. It allows users to spawn human-driven vehicles, AVs and pedestrians. CARLA also provides an ROS-bridge for integration autonomous driving simulation stack such as Autoware and Apollo (Dosovitskiy et al., 2017).
(c) **Eclipse SUMO** is a popular open-source microscope traffic simulator. It provides an API, i.e., TraCI (Traffic Control Interface), which allows users to interact with traffic simulation within SUMO. SUMO can be used to simulate the various realistic traffic environments.
(d) **Ad-hoc network simulators** includes OMNeT++ simulator, ns-3 simulator and MOSAIC SNS. OMNeT++ simulator and ns-3 simulator are open-source and discrete-event based network simulators. They were integrated to Eclipse MOSAIC by two federate implementations for ad-hoc communication simulation, and

only support TopoCast mode and UDP protocol type. MOSAIC SNS is a simulator that is implemented in Eclipse MOSAIC for simulating ad-hoc communication with simplified models. It supports GeoCast and TopoCast modes.

(e) **MOSAIC Cell** is an Eclipse MOSAIC's built-in cellular network simulator for the simulation of cellular communication. It supports GeoBroadcast, GeoCast, and TopoCast modes, and both protocol types UDP and TCP.

(f) **MOSAIC Application Simulator** is an Eclipse MOSAIC built-in simulator for modeling the application logic of simulation entities and prototyping and simulating V2X applications.

(g) **MOSAIC Mapping Simulator** is an Eclipse MOSAIC built-in simulator for configuring simulation units and mapping V2X applications to simulation units.

(h) **MOSAIC Environment Simulator** is an Eclipse MOSAIC built-in simulator for simulating environmental events such as road work events, hazards, or obstacle events.

CARLA Federate and V2X Communication

In our previous work, CARLA simulator has been integrated into Eclipse MOSAIC (Cui et al., 2022). Since the previous work had very limited time and CARLA has been directly integrated with SUMO via the TraCI protocol, the TraCI protocol was utilized for communication between CARLA simulator and Eclipse MOSAIC. Figure 2 illustrates the previous integration of CARLA with Eclipse MOSAIC using TraCI Relay approach. The TraCI client in the CARLA-MOSAIC bridge uses TraCI commands such as state change commands, data retrieval commands, and control commands to synchronize simulation between CARLA and Eclipse MOSAIC. For example, the TraCI command "simulation step" is [simulationStep, time] which means TraCI server performs the simulation until the given time is reached. The information between CARLA and SUMO are exchanged via interactions through Eclipse MOSAIC RTI. TraCI commands that are sent from TraCI client in the CARLA-MOSAIC bridge to the TraCI relay sever are published as interactions in CARLA ambassador and processed in SUMO ambassador. The TraCI commands are then sent to SUMO via TraCI client in the SUMO ambassador. The interactions that consist of TraCI responses from SUMO are published in SUMO ambassador, processed in CARLA ambassador and sent to TraCI client in the CARLA-MOSAIC bridge for synchronizing information about vehicles and traffic lights between CARLA and SUMO. The details of the previous integration of CARLA, SUMO, and Eclipse MOSAIC were in (Cui et al., 2022). The TraCI Relay approach indicates that the integration of CARLA with Eclipse MOSAIC was dependent on SUMO to some extent for processing TraCI commands sent from the TraCI client in the CARL-MOSAIC bridge. To make CARLA a completely independent federate, we redesign CARLA integration with Eclipse MOSAIC and a new communication protocol is designed and developed for communication between CARLA and Eclipse MOSAIC. Moreover, the V2X communication is also implemented for vehicles simulated in CARLA.

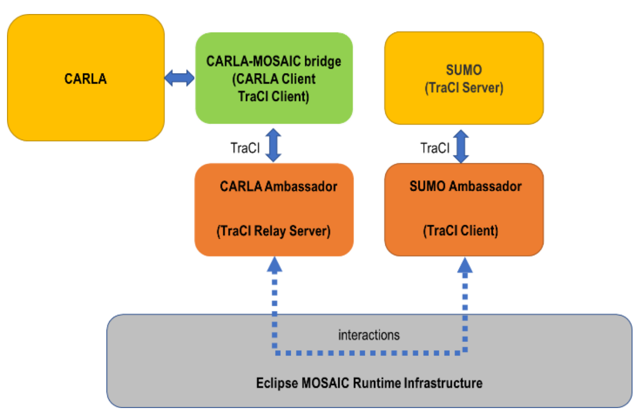


Figure 2. TraCI Relay Approach for Integration of CARLA with Eclipse MOSAIC

Utilizing HLA, a federate is implemented for integrating CARLA with Eclipse MOSAIC. Figure 3 shows the structure of the CARLA federate. The CARLA federate includes CARLA simulator, CARLA MOSAIC Bridge Server, and CARLA MOSAIC Bridge Client, and CARLA Ambassador and MOSAIC Ambassador. CARLA Ambassador and MOSAIC Ambassador are a communication interface between CARLA federate and Eclipse MOSAIC RTI. CARLA MOSAIC Bridge Server and Client are a communication bridge between CARLA and CARLA Ambassador and are implemented using TCP socket communications. CARLA MOSAIC Bridge client is embedded in the CARLA Ambassador while CARLA MOSAIC Bridge Server is a set of standalone python modules that also include a CARLA client for controlling and synchronizing simulation in CARLA.

The data exchanged between CARLA and other simulators includes vehicle data (such as vehicle position, signal, speed, and vehicle type), traffic light data (traffic light programs and phases), and V2X messages. Since the data exchanged between CARLA and Eclipse MOSAIC just consists of three types of information, i.e., vehicle information, traffic light information, and V2X messages, this paper utilizes the MessagePack to develop a communication protocol for data flow between CARLA MOSAIC Bridge Server and Client. MessagePack is an open-source binary serialization format and is supported by multiple programming languages such as Java and Python (MessagePack, 2023). MessagePack is similar to JSONs but more compact. For example, the number 100 takes 3 bytes in JSON but only 1 byte in MessagePack. Therefore, it allows users to efficiently pack data, and exchange data among different languages. In the developed MessagePack protocol, each MessagePack message includes two parts - the first part is information type while the second part is the information contents. For example, vehicle information is packed as [vehicleInformationType, numberOfVehicles, an array of vehicle status].

At each iteration, the information from Eclipse MOSAIC is packed in CARLA MOSAIC Bridge Client using MessagePack and then sent to CARLA MOSAIC Server. The CARLA MOSAIC Bridge Server decodes the received messages and updates the vehicles, traffic lights and V2X messages in CARLA via the CARLA client. Meanwhile, the information of vehicles simulated in CARLA is retrieved through the CARLA client and is packed in CARLA MOSAIC Bridge Server. After that, the information of vehicles simulated in CARLA is sent to CARLA MOSAIC Bridge Client. The information of vehicles is decoded and published in CARLA Ambassador for other simulator processing.

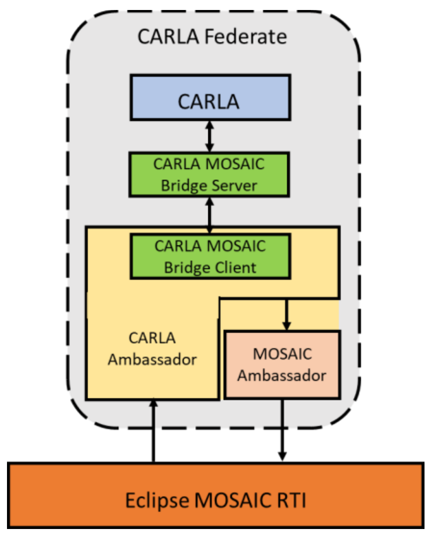


Figure 3. CARLA Federate Structure

V2X Implementation

Applications are used in Eclipse MOSAIC to send V2X messages to network simulators and process the V2X messages received by simulation units. The applications are compiled Java classes, which inherits from a predefined interface called AbstractApplication. The AbstractApplication defined an OperatingSystem which allows the users to retrieve information (e.g., position and current simulation time) and control some actions about units (e.g., slowdown for vehicles). The operating system of a unit can consist of the following modules: Navigation Module, Routing Module, AdHoc Module, and Cell Module (Eclipse MOSAIC, 2023). Among them, AdHoc Module and Cell Module are used for sending V2X messages communication via ad-hoc network and cellular network, respectively. The developed V2X applications are attached to simulation units by Eclipse Mapping simulator so that simulation units can use their applications for communication. Figure 4 demonstrates an example V2X message propagation. Vehicle *i* uses its application to generate a V2X message and then send the V2X message to network simulators through its

AdhocModule. The V2X message is broadcast by network simulators and received by Vehicle *j*. The application of Vehicle *j* processes the received V2X message and trigger slow down action for Vehicle *j*.

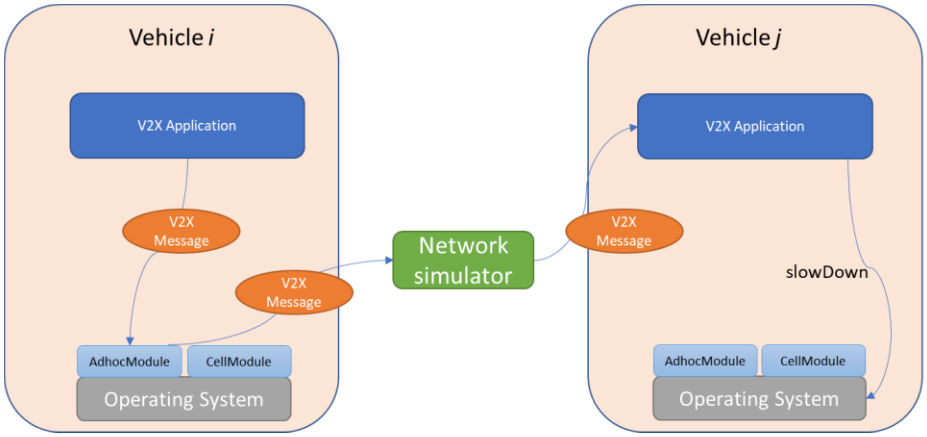


Figure 4. Illustration of V2X Communication

Since TraCI does not have commands for V2X communication, the previous integration does not support Eclipse MOSAIC to send V2X messages received by simulation units to CARLA. To address this issue, in this paper, the information about V2X messages can be sent from Eclipse MOSAIC to CARLA via the MessagePack protocol that includes V2X messages. Since CARLA currently does not support any V2X communications, it is also modified by enabling V2X messages to be stored on V2X message receivers. Moreover, CARLA API is also updated for clients to retrieve V2X messages received by simulated vehicles. As shown in Figure 5, a connected vehicle can retrieve its received V2X messages via Python API and drivers can make better decisions based on the received V2X messages.

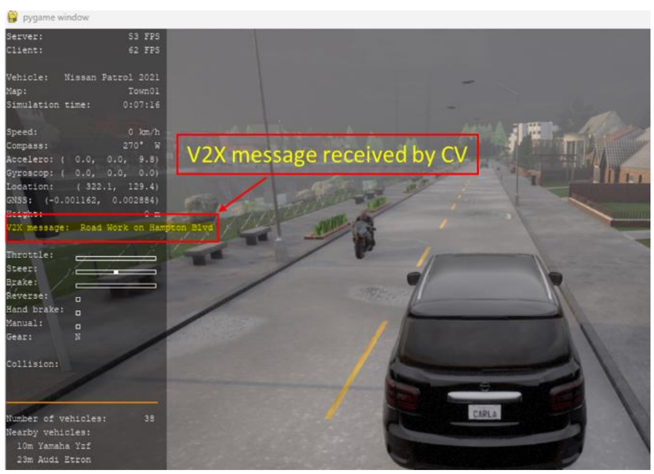


Figure 5. V2X Messages Received by a Connected Vehicle

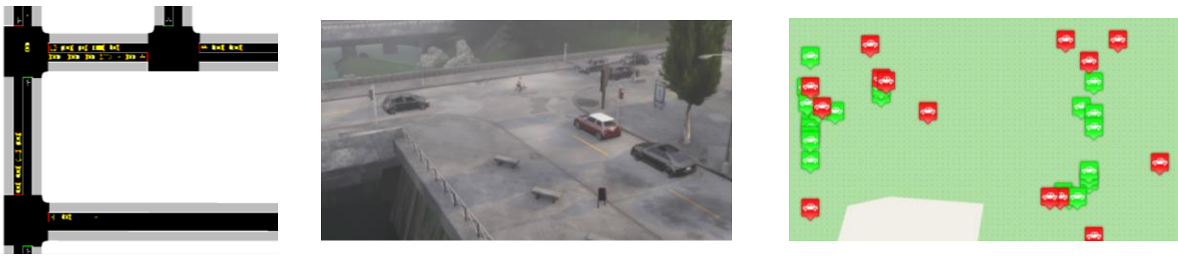
IMPLEMENTATION AND RESULTS

This section first demonstrates the V2X communication simulation, then compares the performance between the proposed integration of CARLA and Eclipse MOSAIC with the one implemented in (Cui et al., 2022), and finally demonstrates some use cases that the proposed V2X simulation system can be exploited for connected driving research in mixed traffic. We implement the proposed V2X simulation system using the latest version Eclipse MOSAIC 22.1. Java 17 and Apache Maven are adopted since Eclipse MOSAIC is written in Java. CARLA 0.9.13 and SUMO 1.50 are used for vehicle simulation and traffic simulation, respectively. Python 3.7 is used to develop the bridge server for communication between CARLA ambassador and CARLA. For external ad-hoc network simulators, ns-3 version

3.36.1 and OMNeT++ version 5.5 with INET framework version 4.1 are utilized in the simulation system. All the other simulators are built in Eclipse MOSAIC. V2X applications are developed using the interface of V2X application in Eclipse MOSAIC and Java. The simulation system is developed in a desktop with Intel(R) Core(TM) i7-12700 processor at 2.1GHz, 32GB RAM memory, 24 GB NVIDIA GeForce RTX 3090 and Windows 11 operating system.

Simulation Demonstration

Figure 6 demonstrates the simulation in SUMO and CARLA as well as V2X communication among connected vehicles. Connected vehicles can send and receive V2X messages in the proposed simulation system.



(a) SUMO Simulation **(b) CARLA Simulation** **(c) Communication Visualization**

Figure 6. Simulation Demonstration: (a) SUMO Simulation; (b) CARLA Simulation; (c) Communication Visualization (red car icon shows vehicles sending V2X messages and green car icon means vehicles receiving V2X messages.)

Performance Comparison

In order to demonstrate the simulation efficiency of co-simulation, the performance of simulation is compared between the current co-simulation and the previous one in (Cui et al., 2022). Two scenarios have been setup using Town01 map in CARLA. One scenario has no traffic signal enabled while the other one with signal enabled. One vehicle is added to simulation every second and the simulation time is 200s. Since the previous integration did not implement V2X communication, no V2X communication is simulated in these scenarios. We employ a performance metric called Real Time Factor (RTF). The RTF is defined as the ratio of preset simulation duration to the time to complete a simulation run. The RTF can indicate the simulation speed. An RTF greater than 1.0 indicates that the simulation is running faster than real time. Table 1 presents RTF for each scenario. The results in the Table 1 show that this co-simulation implementation is more efficient.

Table 1. Performance Comparison

	RTF	
	w/o signal	**w/ signal**
This paper	6	4
(Cui et al., 2022)	2	0.78

Use Cases

The above simulation demonstration shows that the proposed and developed simulation system can be utilized for connected driving research. For example, the developed simulation system can be leveraged in the following use cases.

Case 1: Safety Awareness among Connected Vehicles

The vehicle status information can be used for connected driving to avoid traffic accident. V2V communication enables vehicles to share their vehicle status such as position, speed, acceleration, and turning signals among nearby vehicles. As illustrated in Figure 7, each connected vehicle is connected to ad-hoc network and periodically broadcasts its vehicle status, and at the same time receives vehicle status of other vehicles via network. It should be mentioned that the radius of signal and car size are not proportionate. To simulate this use case, a V2X application is developed and mapped to each simulating vehicles. MOSAIC SNS is used as ad-hoc network simulator. CARLA is used to simulate vehicle dynamics. Eclipse SUMO does not need to be enabled if the background traffic is not needed or generated in CARLA.

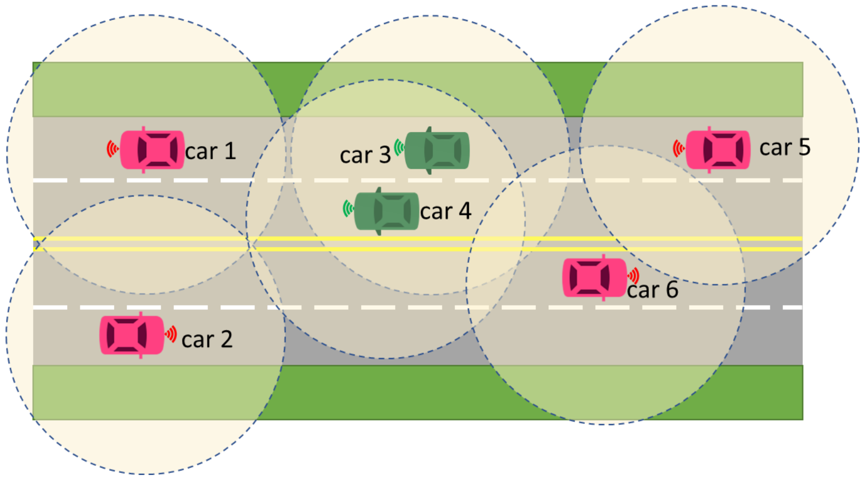


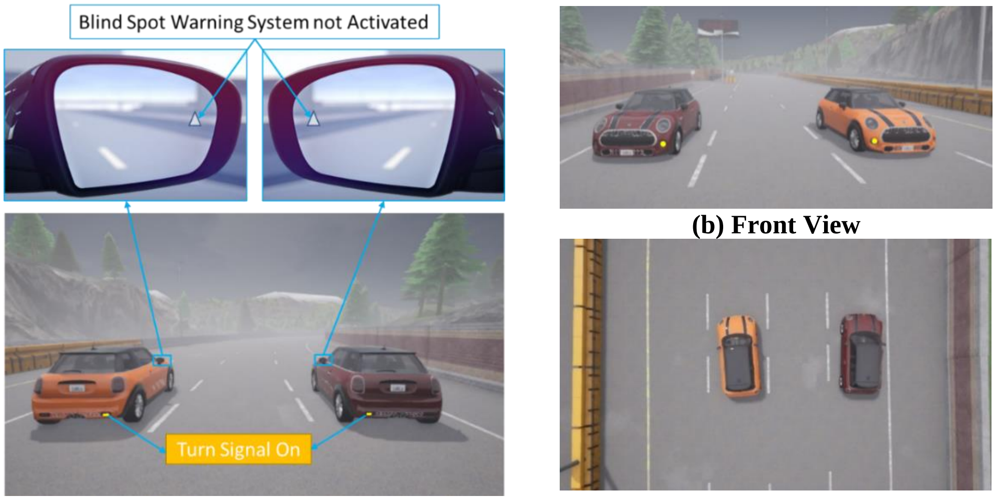
Figure 7. Vehicle Basic Safety Message (BSM) (cars with red icon sending BSM, cars with green icon receiving BSM of other vehicles. The circle enclosing cars indicates the radius of signal.)

Case 2: Road Condition Notification

The hazards or obstacles on the roads bring safety issues to vehicles and passengers. They can cause traffic accidents and traffic congestion. The information of hazards, obstacles, and traffic accidents on the road can be detected by one vehicle and then transmitted to other vehicles as well as roadside units (RSU). The RSU will broadcast the road condition information to connected vehicles. To simulate this use case, V2X applications are developed and mapped to each simulating vehicles and roadside units. MOSAIC SNS is used as an ad-hoc network simulator and MOSAIC Cell is used as a cellular network simulator. CARLA is used to simulate vehicle dynamics. MOSAIC environment simulator is utilized to simulate road condition events. Eclipse SUMO does not need to be enabled if the background traffic is not needed or generated in CARLA.

Case 3: Blind Spot Monitoring

Blind spot warning systems in modern cars can detect vehicles in the blind spots or quickly approaching vehicles from behind, and then provide a visual warning or notification to drivers in the side mirrors. The drivers can be alerted that it is unsafe to change or merge lanes. This feature helps drivers avoid a crash. However, the blind spot warning system only detects vehicles in the adjacent lanes. Consider the scenario in Figure 8, two vehicles (Car 1 and Car 2) change to the same lane at the same time. The connected vehicle technology can provide instant alert to both drivers. In this case, vehicles can broadcast their signals. Other vehicles can receive the message and provide warning to drivers for caution. To simulate this use case, a V2X application is developed and mapped to simulated vehicles. MOSAIC SNS is used as an ad-hoc network simulator. CARLA is used to simulate vehicle dynamics. Eclipse SUMO does not need to be enabled if the background traffic is not needed or generated in CARLA.



(b) Front View

(a) Rear View **(c) Bird View**

Figure 8. Two Connected Vehicles Signaling to Change Lanes.

Case 4: Road Work Notification

Road work can cause traffic delay or traffic congestion. Early notification of road work can enable road users to find alternative routes so that it can alleviate the traffic flow near the road work zone. This road work information such as the location and time of scheduled road work can be communicated among connected vehicles. The connected vehicles can make decisions based on the messages about the road work. To simulate this use case, V2X applications are developed and mapped to simulated vehicles. MOSAIC SNS is used as an ad-hoc network simulator and MOSAIC Cell is used as a cellular network simulator. CARLA is used to simulate vehicle dynamics. MOSAIC environment simulator is utilized to simulate road work event. Eclipse SUMO does not need to be enabled if the background traffic is not needed or generated in CARLA.

CONCLUSIONS AND DISCUSSIONS

This paper proposed an advanced simulation system for connected driving research in mixed traffic environments. The proposed simulation system was developed by integrating an autonomous driving simulator with a V2X simulation framework. The simulation system includes multiple simulators across multiple domains. Specifically, CARLA was integrated with the V2X simulation framework Eclipse MOSAIC which enables human driven vehicles and autonomous driving vehicles to be equipped with communication capabilities. CARLA simulator allows users to simulate human driven vehicles and autonomous driving vehicles. The implemented simulation system provides ad-hoc simulators and cellular network simulators for V2X communication of connected vehicles. Moreover, MessagePack was employed to develop an efficient communication protocol between CARLA and Eclipse MOSAIC and CARLA was modified for supporting V2X communication. Four use cases were presented for application of the proposed simulation system. One drawback of the simulation system is that there is no pedestrian communication in the simulation system. This will be addressed in our future work.

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