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An X-in-the-Loop (XIL) Testing Framework for Validation of Connected and Autonomous Vehicles

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***Abstract*—Validation methods for growing connected and autonomous vehicle (CAV) technologies hold the key to their real-world implementation. Setting these up is challenging owing to the number of components and safety concerns involved in CAV testing. This paper presents a modular XIL framework for the validation of CAVs. The framework allows the interfacing of an in-house instrumented drive-by-wire vehicle with roads, traffic microsimulations (virtual vehicles, traffic lights, etc.), autonomy software, computing resources, and human drivers through the use of a mixed-reality headset. Three case studies in recent and ongoing work are shown, demonstrating the suitability and versatility of the XIL framework for verifying the safety and efficiency of automated vehicle control strategies via vehicle-in-the-loop, as well as ensuring realistic human driver reactions inside of emergent mixed-autonomy traffic environments via humans-in-the-loop.**

***Index Terms*—connected and autonomous vehicles, validation, intelligent systems**

I. Introduction

The traditional automotive development process has historically been focused on the integration of mechanical and electronic components on a single vehicle with physical interfaces to human drivers and passengers. With the introduction of Advanced Driver-Assistance Systems (ADAS) and Connected and Autonomous Vehicle (CAV) technologies, the development process calls for additions to traditional infrastructure for high-level function testing and validation frameworks such as chassis dynamometers and isolated track testing. To address the growing market demands for CAV technologies, rapid and customizable validation techniques are needed to accelerate the transition between concept and reality.

During the initial vehicle development stages, model-in-loop and software-in-loop (SIL) tests are undertaken to validate the behavior of the software aspect of a function. Next, physical components are tested along with the associated software functions in a hardware-in-loop (HIL) setup such as powertrain performance, suspension dynamics, etc. These frameworks and their sophistication levels are detailed in [1].

Towards the later stages of CAV development, where high-level functions such as active safety, ADAS, autonomous driving (AD), route planning, etc. need to be validated, in-vehicle tests with connectivity between the physical CAV, sensors, lane maps, surrounding vehicles, off-board computing, road infrastructure, etc. are essential. SIL and HIL test benches do not suffice, due to the model mismatch of the system and the environmental components.

Some research groups have addressed this challenge by setting up connected corridors on sections of public roads with vehicle-to-everything (V2X) connectivity to on-road CAVs and road infrastructure for validation, as in [2], [3]. Self-driving vehicle fleet operators continually validate and improve routing, planning, and control for their CAVs on public roads as in [4]. However, testing routines that do not require CAVs to drive on public roads are safer and easier to rapidly prototype. So, a more versatile *X-in-the-loop* (XIL) environment framework that allows CAV validation in a more controlled environment is valuable.

Efforts have been directed towards the integration of CAV testing capabilities with chassis dynamometers as in [5], [6]. These set-ups are safe but need benchmarking against track-tests. Some groups have termed this setup as vehicle-hardware-in-loop (VeHIL) as in [7], where they utilized this for ADAS validation. The fidelity of sensor stimulation, simulated environment, and road infrastructure to emulate the realistic test scenarios is crucial and a challenge in these setups as running CAVs on chassis dynamometers still lacks the essential interactions between the vehicle and real road conditions. Therefore, some recent works [8], [9], [10] exploit a physical test field like Mcity [11] that allows physical vehicles to run in a closed and controlled environment with physical road and traffic infrastructure to conduct CAV studies and data collection.

As one of the early efforts towards on-track XIL testing for CAVs, a test framework was developed and utilized by our group in [12], [13], where a real vehicle ran on a test track with CAV traffic microsimulation in the loop to validate an intersection control scheme without requiring physical road infrastructure such as traffic lights for testing. More recently, we have utilized this framework in [14], [15] to validate energy-efficient control for CAVs. A similar framework has been independently utilized in [16], [17].

To further advance the CAV validations in our group, we have developed a more expansive and modular XIL framework by incorporating a variety of CAV components via blending the physical and virtual worlds to orchestrate CAV test setups for various validations. The major contributions of our framework primarily stand out for the following CAV validation aspects:

- Real CAV on a real road with autonomy and computation

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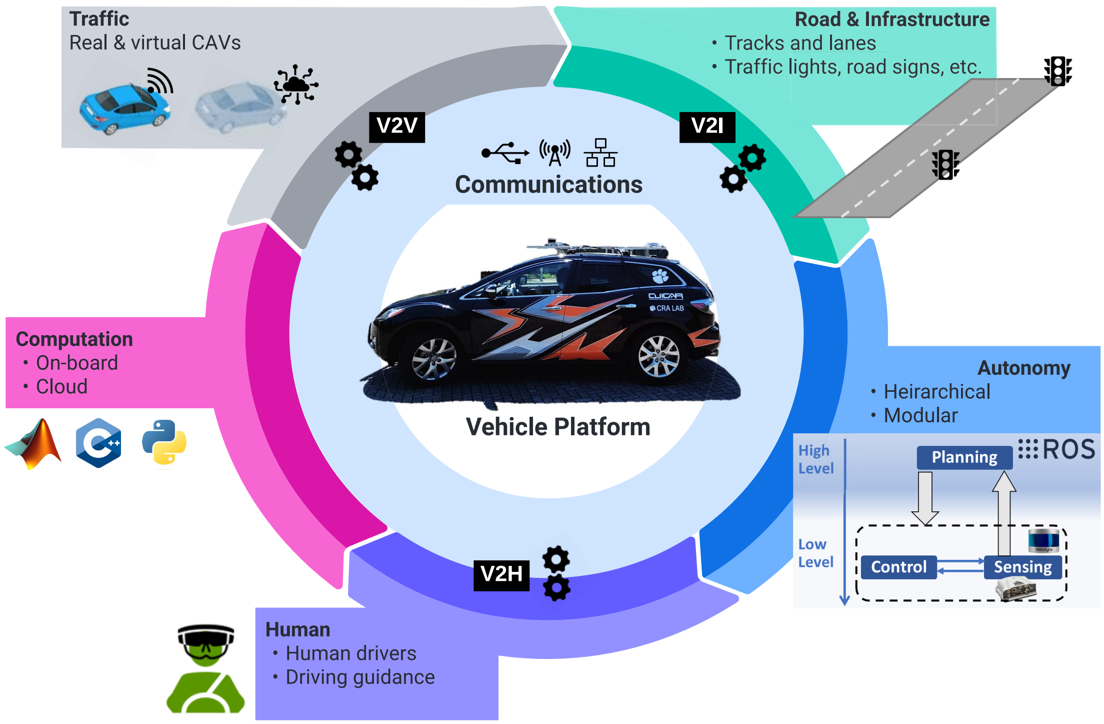

Fig. 1. Modular XIL framework for experimental validation of CAVs.

interacting with in-situ virtual microsimulation in parallel.
- V2X connectivity to enable real CAV to communicate with other assets such as virtual vehicles, infrastructure, and the cloud via communication channels.
- Mixed reality to enable human-in-the-loop for mixed (human and autonomously driven) traffic studies.

II. Test and Validation Framework

Our XIL platform was designed to rapidly validate CAVs, and it:

1) provides a test-bed that can cater to autonomous technology validation for up to SAE Level 4 with V2X connectivity,
2) allows for easy inclusion and omission of physical and virtual traffic agents so that testing scenarios can be designed and swapped as necessary,
3) and features a modular structure so that individual components can be prototyped in a time-inexpensive manner.

The developed architecture for XIL testing is shown in Fig. 1. Through communications, the physical vehicle platform interfaces all individual components - physical and virtual, hardware and software. These components are discussed below and are chosen based on the scope of validation for a given research problem.

A. Drive-by-Wire Vehicle Platform

A Mazda CX7 model was retrofitted in-house to be drive-by-wire (DBW) capable through a real-time controller board that drives two motors for steering, throttle and brake actuation. The vehicle powertrain characteristics were recorded on a chassis dynamometer and modeled through a data-driven approach to ensure accurate DBW control as detailed in [14]. Through the two control inputs for steering and acceleration, any reference trajectories can be executed by this vehicle safely. The vehicle was also equipped with a sensor suite to enable localization and potential mapping of the surroundings, as detailed in Section II-I.

B. Road-in-the-Loop

CAVs sometimes require testing the physical and virtual vehicles on predefined test tracks and roads. We conduct our validation tests at the International Transportation Innovation Center (ITIC) Greenville testing facility as shown in Fig. 2, which allows us to run single-lane and multi-lane test scenarios for CAVs. The GPS coordinates of the test track are fed to the DBW controller and the autonomy algorithms to run road-in-the-loop tests and enable global planning and virtual object placement as in Section II-C.

C. Microsimulation-in-the-Loop

1) Traffic-in-the-Loop: Central to the XIL platform, the virtual environment is realized via traffic microsimulation software – which populates the surrounding virtual vehicles, traffic lights, road signs, etc. Each virtual vehicle is programmed with an interaction model to either replicate human driving patterns or autonomous driving behavior. Importantly, the virtual environment can interact with the real experimental vehicle – which broadcasts its current orientation, position, velocity, and acceleration to then be populated as a digital twin in the simulation. The effects of the digital twin behavior can be realized and propagated in microsimulation to study its performance on surrounding traffic [14].

Deployment of connectivity is then enabled and tested by messaging the status of all connectivity-enabled virtual objects within a hardware-realistic communications range of the ego vehicle. Although not shown here, integration of wireless communication characterization platforms, such as NS-3, is also possible to simulate packet loss and delay [18], [19].

2) Infrastructure-in-the-Loop: When testing CAVs, the test loop needs to include information from the virtual infrastructure synthesized in Section II-C1, along with supporting visuals as represented in Fig. 1.

As one of the most important traffic infrastructures, virtual traffic lights with vehicle connectivity are included in our XIL testing framework. To help the human driver and passengers better understand where they are, we modify the traffic light object by adding a signal marking on the ground ahead of the traffic light object to let drivers know where to stop or start. The marking is aligned with the road profile to facilitate the driver's estimation, and it will also align its color with the traffic light status. This is shown in Fig. 3.

D. Autonomy-in-the-Loop

Robot Operating Software (ROS) is leveraged as the middleware to implement autonomy on the vehicle platform. The modular and hierarchical nature of ROS accelerates the integration and deployment of self-driving algorithms of interest. The hierarchy is set up as follows:

1) High Level: Shown in Fig. 1, the high-level planner has the ability to take into account the surrounding vehicles, traffic lights, road lanes, etc. from Sections II-B to II-C2 and plan energy- or time-efficient paths for the ego vehicle.

2) Low Level: Here, the DBW control algorithms are executed based on the reference trajectory input from the planner, with sensors closing the feedback loop for the trajectory following. The steering and acceleration commands from this layer are further passed down to the DBW vehicle platform detailed in Section II-A.

Safety features are incorporated into the architecture by utilizing watchdog counters for the hierarchical level communications and the automated control is relinquished to the safety driver in case of missed command and response messages between the planner and controller nodes.

E. Human-in-the-Loop

As shown in the vehicle-to-human (V2H) depiction in Fig. 1, the framework allows including human-driven vehicle into the CAV traffic flow to help investigate how their interaction affects the autonomous vehicle's control and energy consumption. Therefore, we also add a mixed reality device as an onboard simulation platform for human drivers to wear while driving on the test track so that the driver can visualize the augmented testing site with virtual traffic objects included. A schematic for the information flow in the Human-in-loop framework is shown in Fig. 3.

Fig. 2. ITIC facility track map.

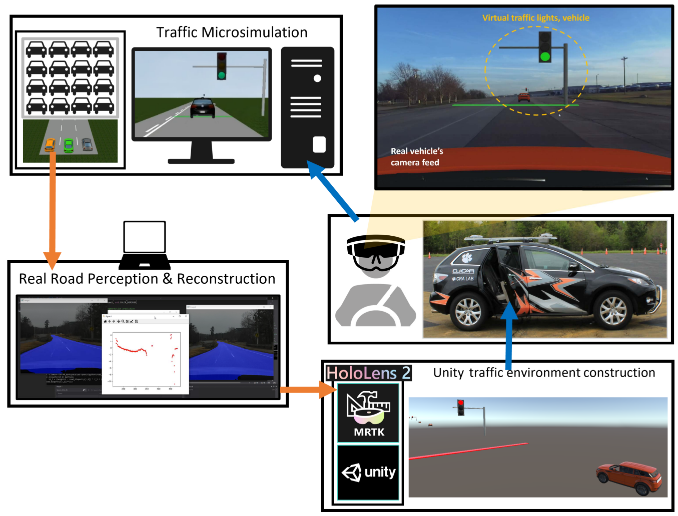

Fig. 3. Human-vehicle-in-loop under a mixed-reality framework.

1) Online Simulation - Traffic Microsimulation: All the traffic information, including vehicles, pedestrians, traffic light, stop sign, and their relative position in a traffic flow, are generated from a 2D online traffic simulator. The microsimulation as in Section II-C1 will include a digital twin of the human-driven vehicle on the testing track and provide updated surrounding traffic information to an onboard computer that will upgrade the 2D traffic information to 3D realistic traffic information that aligns with our testing site environment.

2) Testing Environment Perception and Reconstruction: Once the onboard computer receives the 2D traffic information, it uses both pre-recorded GPS coordinate data from Section II-B and image stream captured by an onboard camera to approximate the road profile and drivable region, then add the height and grade information to the 2D virtual traffic objects based on the road profile. The image stream is also utilized to extract road boundary information for correcting any potential sensor noise.

3) Hololens 2 Mixed Reality Virtual Hologram Projection: Once the 3D traffic information is correctly generated, it is sent to a mixed-reality device that human drivers can wear while driving a real car on the track. We use Hololens 2 as our wearable headset since it allows the projection of holograms onto the physical environment and uses a reflective projected hologram rather than an LED screen display so that driver can still see the real environment even when the power is turned off. Human drivers can thus perceive these projected traffic objects (Fig. 4) and the human-driven vehicle's information is

Fig. 4. Virtual front vehicle displayed through the Hololens 2 device while driving.

sent back to microsimulation to form a closed-loop simulation.

F. Computation-in-the-Loop

The functions listed in all the previous sections need computational resources. Since our architecture is modular and over ROS, the framework provides choices for computation both on-board and off-board. The physical vehicle tests can be conducted on the test facility while a high-level planning optimization runs off-board on a remote lab server. Fig. 5 shows how we use the cellular network gateway to communicate between the vehicle controller and the remote computation servers. This lends versatility to the framework because it is often difficult to install high-performance computing infrastructure on-board.

G. Communication-in-the-Loop

To bring all the above functions together and interface them with the vehicle, the communication architecture shown in Fig. 5 was set up. A network router hosts the vehicle's private network for the sensors, human interfaces, and computers to communicate with each other over Gigabit Ethernet.

For wireless communication, a cellular router is set up to enable a gateway to cellular communication. This cellular communication is used to subscribe to Real-time Kinematic (RTK) corrections for GPS over the cellular network and transmit it to the Novatel unit over the ethernet or a wireless channel. This also enables interfacing the vehicle with any cloud computing resources required for planning, simulation, etc.

H. Time Synchronization

In order to ensure that sensing, planning and control nodes are synchronized and exchange data without time-stamp inconsistencies, Network Time Protocol (NTP) is employed for the high-level planning and the on-board systems. This allows hardware clock synchronization of the network machines within a few milliseconds.

For test scenarios with higher accuracy requirements, Precision Time Protocol (PTP-v4) is employed to synchronize the on-board network devices within a few microseconds of the time server hardware that accesses GPS time. The network router shown in Fig. 5 acts as the boundary clock for the PTP synchronization in this case.

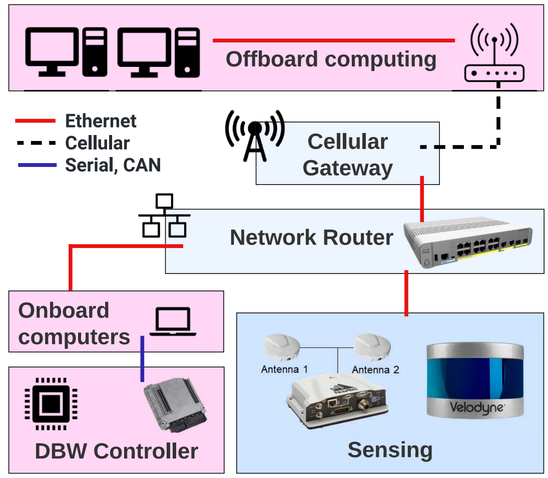

Fig. 5. Communications architecture to interface computation, controls, and sensing.

TABLE I
AVAILABLE VEHICLE SENSING SIGNALS

Source/Type	Measurement/Perception	Max. Frequency
INS odometry	$\ddot{x}$, $\ddot{y}$, $\ddot{z}$, $\ddot{\psi}$ $\dot{x}$, $\dot{y}$, $\dot{z}$, $\dot{\psi}$ x, y, z, ψ	200 Hz 200 Hz 200 Hz
RTK-GPS	Latitude, Longitude, Altitude	20 Hz
OBD-II	Mass Air Flow Rate Commanded Eqv. Ratio Fuel Trim Engine Load, RPM	10 Hz 10 Hz 10 Hz 10 Hz
360° Lidar	Pointcloud	20 Hz
Cameras	RGB feed	30 fps

I. Measurements and Sensing for Testing and Validation

The Novatel PwrPak7 unit with dual antennas provides high-confidence INS data (accelerations, velocities, position, and heading) with a centimeter-level accuracy through the fusion of RTK, GPS, and IMU data. Perception hardware such as the Velodyne and Ouster lidars, Mako and Zed cameras for object detection, and Continental radars for tracking objects can be utilized to close the loop for autonomy, and are accessible over the ROS server. For measurements such as energy consumption data, OBD-II data logging has been set up as well.

Table I summarizes the class of measurements and sensing available through the instrumentation, with flexibility as needed for the research validation of interest.

III. Case Studies

To demonstrate the versatility of this setup, we discuss three case studies where parts of this framework were utilized to quantify the research related to Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Human (V2H) connectivity.

A. V2V: Autonomous Multi-Lane Highway Driving

Connected autonomous vehicle driving on the multi-lane highway is considered. A high-level path planner was developed that interacts with other connected vehicles (i.e., V2V) along the corridor. This information helps plan lane changes along the corridor ahead of time for energy-efficiency and safety.

Validation of this planner and low-level controller was conducted for the case where one of the virtual CAVs breaks down on the highway and comes to a halt in one of the lanes at highway speeds of around 50 mph.

The setup used the following XIL components:

- Physical vehicle: DBW Mazda CX7 on the ITIC track
- Virtual vehicles: Instances with independent controllers in traffic simulation
- Sensing: Novatel GPS+IMU unit for odometry and localization on track
- Computing: Onboard for high-level planning and low-level controllers

The trajectory of the real CAV based on the planner and the accuracy of the control implementation is visualized in Fig. 6. The real CAV was able to safely overtake the simulated stalled CAV and return to its original lane once the lane was clear. The instrumentation onboard the vehicle allows us to monitor and tune the control performance of the low-level controller as needed. In this case, it was decided that the acceleration tracking in the low-speed region needed tuning and improvement.

B. V2I: Efficient City Driving with Connected Intersections

Energy-efficient driving of automated vehicles is well-enabled through connectivity [20]. This is experimentally demonstrated as in [15], in which idling time at red lights is minimized via look-ahead control that leverages advance knowledge of the upcoming signal phase and timings (SP&T) of nearby traffic lights as made available via V2I communication. Here, a segment of the Peachtree street in ATL, GA USA was replicated in microsimulation as according to its NGSIM dataset.

To measure the performance, the experimental ego automated vehicle was placed in a corridor containing both simulated human vehicles (HVs) and simulated connected and automated vehicles (CAVs). The virtual corridor and ego vehicle trajectories are shown in Fig. 7, and notably virtual CAVs are shown to avoid idling at red lights - and rather coast through the lights as they turn green.

Overall, XIL testing measured energy improvements of up to 36% on the ego vehicle via connectivity-enabled optimal control as compared to the manually-driven case [15].

C. Human-Autonomy Mixed Traffic Study

For our testing framework, we also allow human-driven vehicles to be involved in the CAV traffic flow and analyze its impact on traffic and AV control. In this case, we tested a connected longitudinal traffic flow where a connected autonomous traffic flow is projected in front of a human driver from the Hololens and the human driver is following the traffic flow.

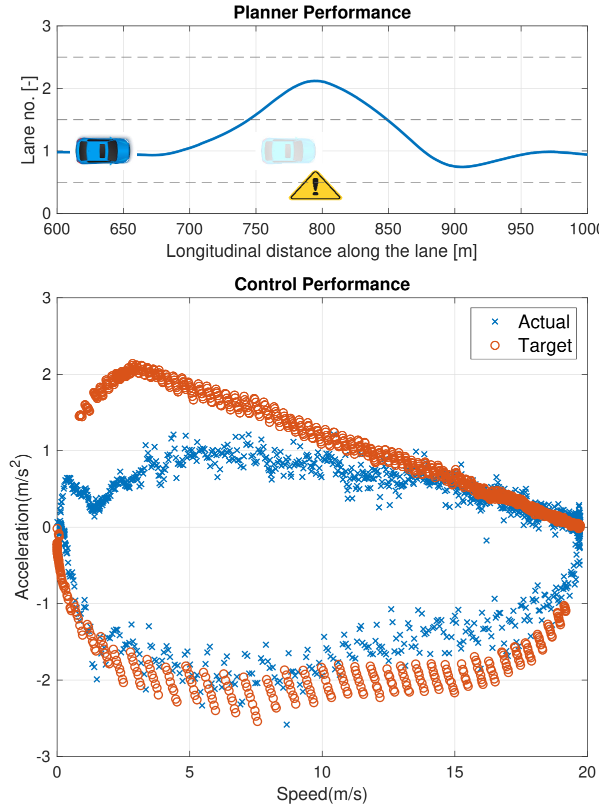

Fig. 6. Performance of the planner and controller for evasive lane change maneuver.

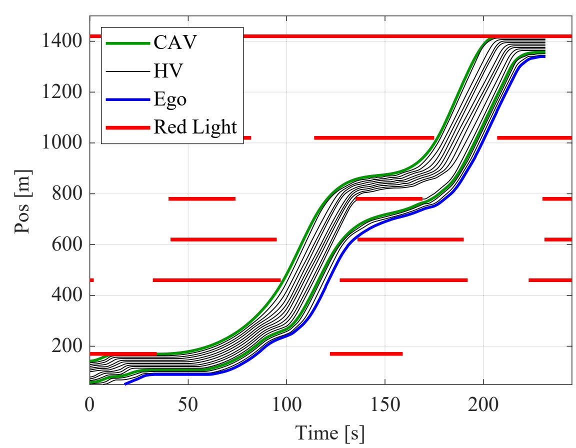

Fig. 7. Experimental validation of energy-efficient driving as if Peachtree Street, ATL USA is equipped as a connected corridor.

In our test framework, we have the freedom to design the traffic scenario as desired and get data from both human-driven vehicles and virtual CAVs. To validate if virtual traffic following is good enough to replace real traffic following scenario, we conducted an experiment where a human driver followed a real traffic vehicle and a virtually projected vehicle based on the same speed profile so as to compare how humans

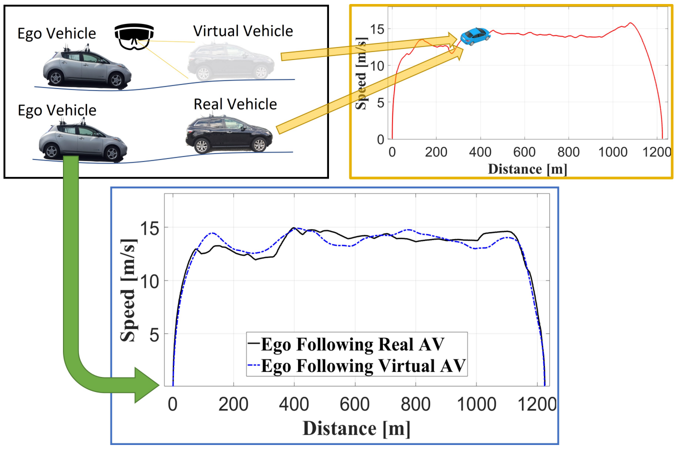

Fig. 8. Comparative study for human-driving behind a real autonomous vehicle and virtual autonomous vehicle.

drive differently when following these two traffics. The testing diagram is shown in Fig. 8.

In this validation test, a real AV was made to track a predefined speed profile that was one portion from US06 driving cycle. When following the real AV, the real AV's speed and the human-driven ego vehicle's speed were recorded. In the virtual vehicle following test, the human-driven ego followed a virtual AV's hologram projected from Hololens 2 which moves based on the speed recorded from the real vehicle following scenario, and the human-driven ego vehicle's speed was recorded for comparison. The speed plot in Fig. 8 suggests that human-driven vehicle speed trends were close in the two cases with small deviations.

IV. Conclusion

In this paper, we discussed the need for XIL testing frameworks for validation and how different groups have approached this. We present the XIL test framework we developed and utilized for the validation of CAV technologies and discuss the role of each of the component functions in this framework. Additionally, we demonstrate the versatile and effective application of this XIL framework to three use cases, each with its own specific goal.

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