# Virtual - Physical Proving Ground (VPPG) for Development and Validation of Future Mobility Technologies (Core Tools)


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Project ID: EEMS067

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2021 Annual Merit Review

# Overview

## Timeline

- Start Date: Oct 1, 2018
- End Date: Sept 30, 2021
- Percent Complete: 70 %

## Barriers and Technical Targets

- Modeling and simulation environments are not all inclusive for all scenarios.
- Lack of standard co-simulation tools or hooks across vehicle and traffic environments.
- Computational requirements of complex environment simulation.

## Budget

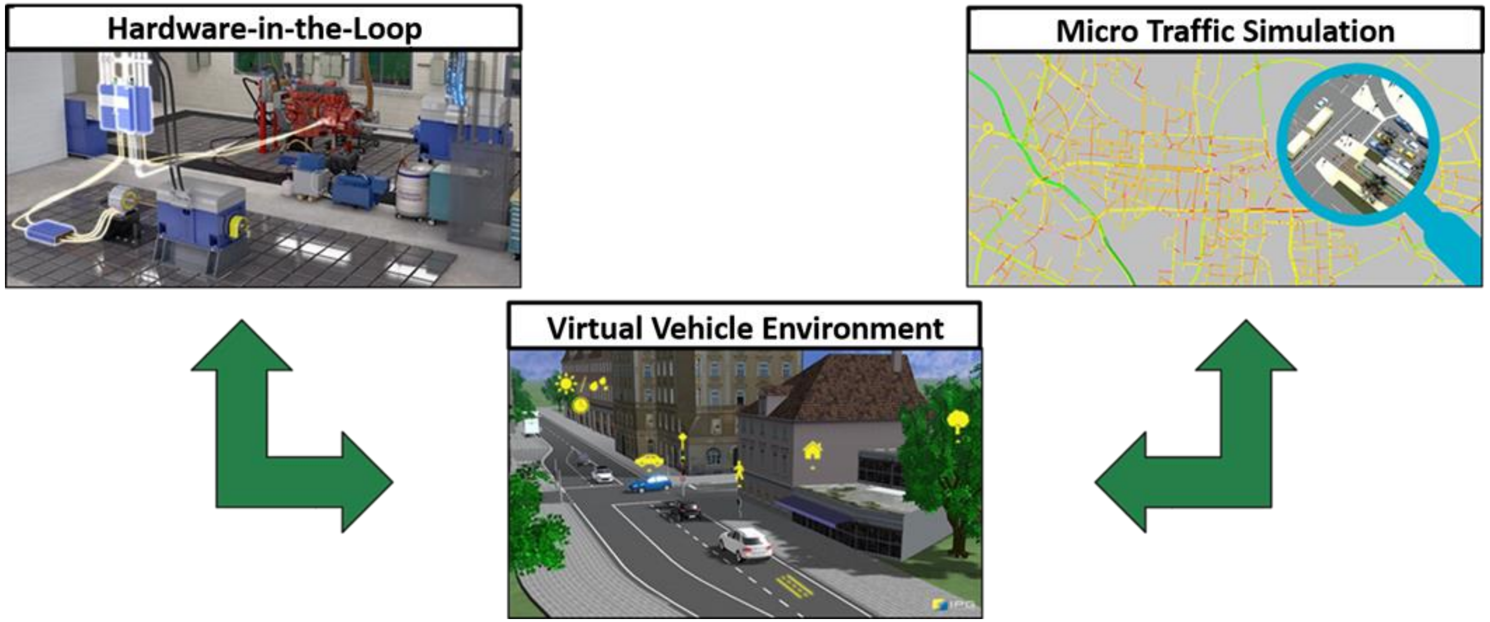
- Total Budget
  - DOE Share $6,860K* includes capital purchase
- Funding for FY 2021
  - $1,000K

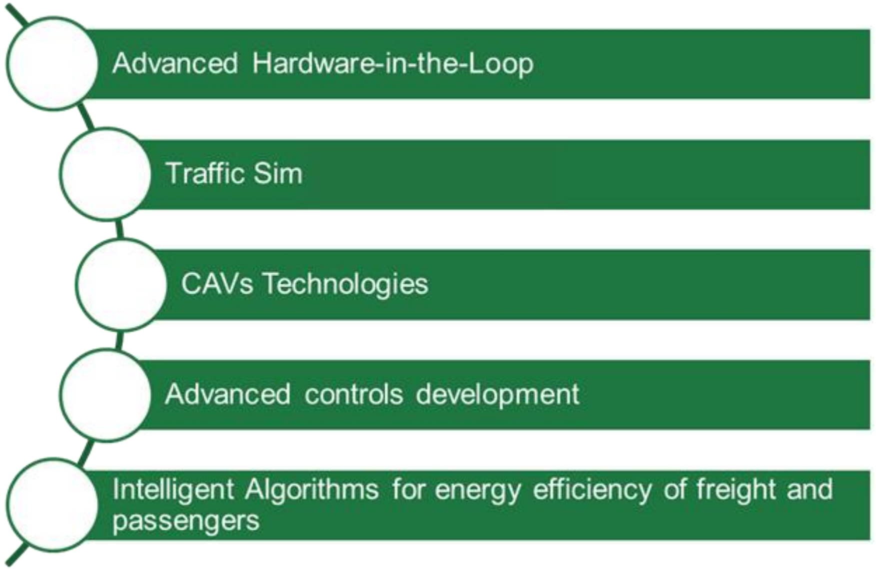
## Partners

- Collaborations
  - American Center for Mobility (ACM)
  - dSPACE
  - IPG Automotive
  - CARLA

# Relevance / Project Objectives

- **Relevance:** Currently there are many toolsets and toolchains utilized to simulate Connected and Automated Vehicles (CAVs), each with their own benefits and features, but none able to cover all applications.
- **Objective:** Develop an agnostic, standardized framework to allow for validation of EEMS and SMART Mobility models, tools, and data sets utilizing various combinations of modeling, simulation, hardware-in-the-loop (HIL), and vehicle-level testing.  This architecture will consider and allow for the integration of both DOE and Industry standard software and toolsets.



# Milestones

| Date | Milestones | Status |
|---|---|---|
| **March 2021** | **Connected Laboratory Coordination Testing (Subtask 2.3)** / Complete coordination testing of real-time cooperative and automated vehicle merging of on-ramps utilizing either the VSI powertrain and component test cells (Two HIL setups - one MD vehicle and one EV), or the VSI laboratories and the CAVE laboratory (One HIL setup and one HEV VIL setup) depending on lab availability. | **Delayed**<br>Due to COVID shutdowns and laboratory equipment failures. |
| **June 2021** | **Virtual Physical Proving Ground Validation (Subtask 1.1)** / Finish and demonstrate proof-of-concept that transfers development for the virtual-physical proving ground to real on-track/road data collection and/or testing. | **On Track** |
| **September 2021** | **Scenario Based Testing/Validation for Advanced MD Delivery Vehicle (Subtask 1.2) /** Utilizing an advanced natural gas range extender battery electric powertrain, test the powertrain in multiple realistic scenarios and traffic densities on realistic road networks generated for real interstates and arterials. | **On Track** |
| **September 2021** | **EEMS/SMART Mobility Validation Case Studies (Subtask 2.3)** Complete validation study of the 3 selected EEMS SMART Mobility test cases (speed harmonization, merging, intersection) into the VPPG. | **On Track** |

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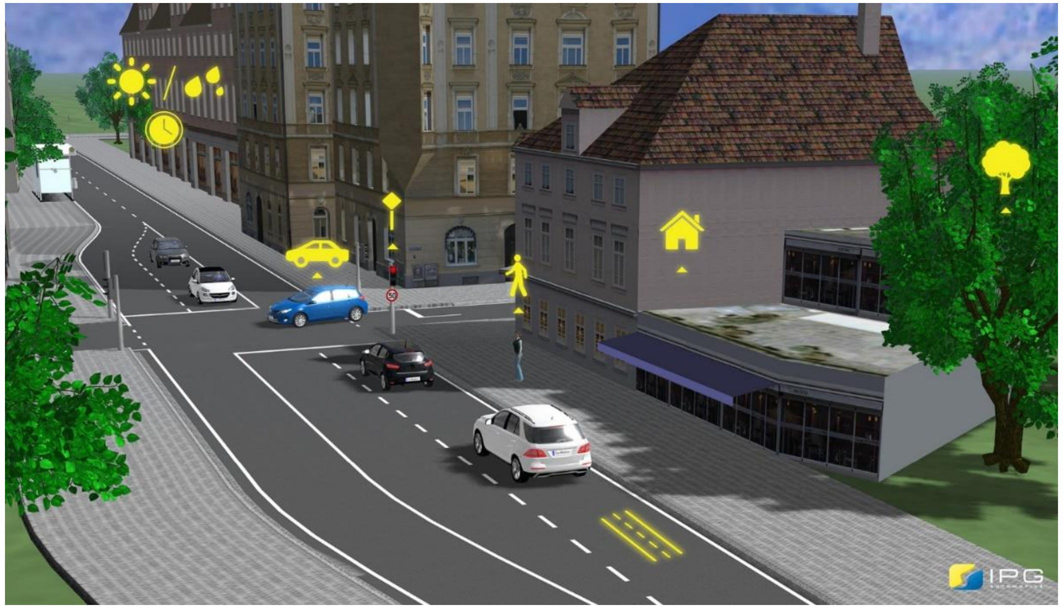
# Approach

## "Virtual-Physical" Proving Ground (VPPG) – Task 1

- Improve the ability to accurately verify the large-scale energy benefits and emissions impacts of CAV technologies in considering physical powertrain hardware subjected to virtual traffic conditions.
- Integration of microscopic traffic and virtual environment simulation tools with advanced HIL-enabled laboratories to investigate the impact of CAVs on energy efficiency and other advanced transportation technologies currently untested in laboratory settings.

## Communication (V2X) Modeling, Development, and Validation – Task 2

- Provide a platform to couple laboratories to real-time, high-fidelity traffic simulations while subjecting actual powertrain(s) to emulated, real-world traffic conditions utilizing Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication provided by real hardware.
- Development of control strategies and algorithms specifically targeted at advanced vehicle technologies, central traffic controllers, as well as infrastructure controls.



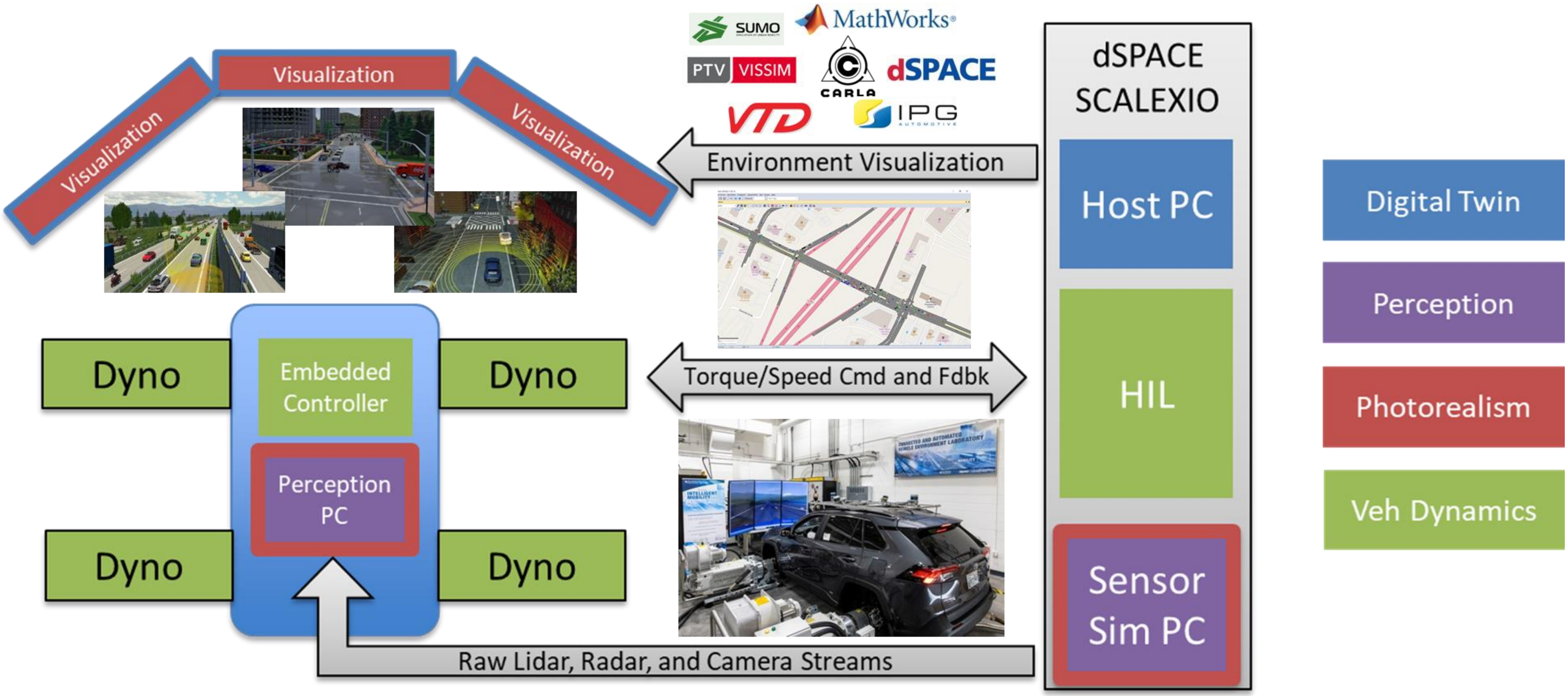
# Accomplishments and Technical Progress – Task 1

# Accomplishment Task 1 – Functional Connected and Automated Vehicle Environment (CAVE) Laboratory

- A Vehicle-in-the-loop (VIL) setup using dSPACE ASM was completed using the RotoTest Dynamometer in the CAVE Lab.
- A tire & visualization model developed for a 2019 RAV4 was constructed for testing and executes on a dSpace real-time HIL rack.
- A combination of measured, road-load based torque feedback at the wheel hubs and reverse engineered steering CAN messages provided feedback to the vehicle’s tire model.
- The control loop provides the driver of the vehicle with a real-time visualization of their driving inputs.

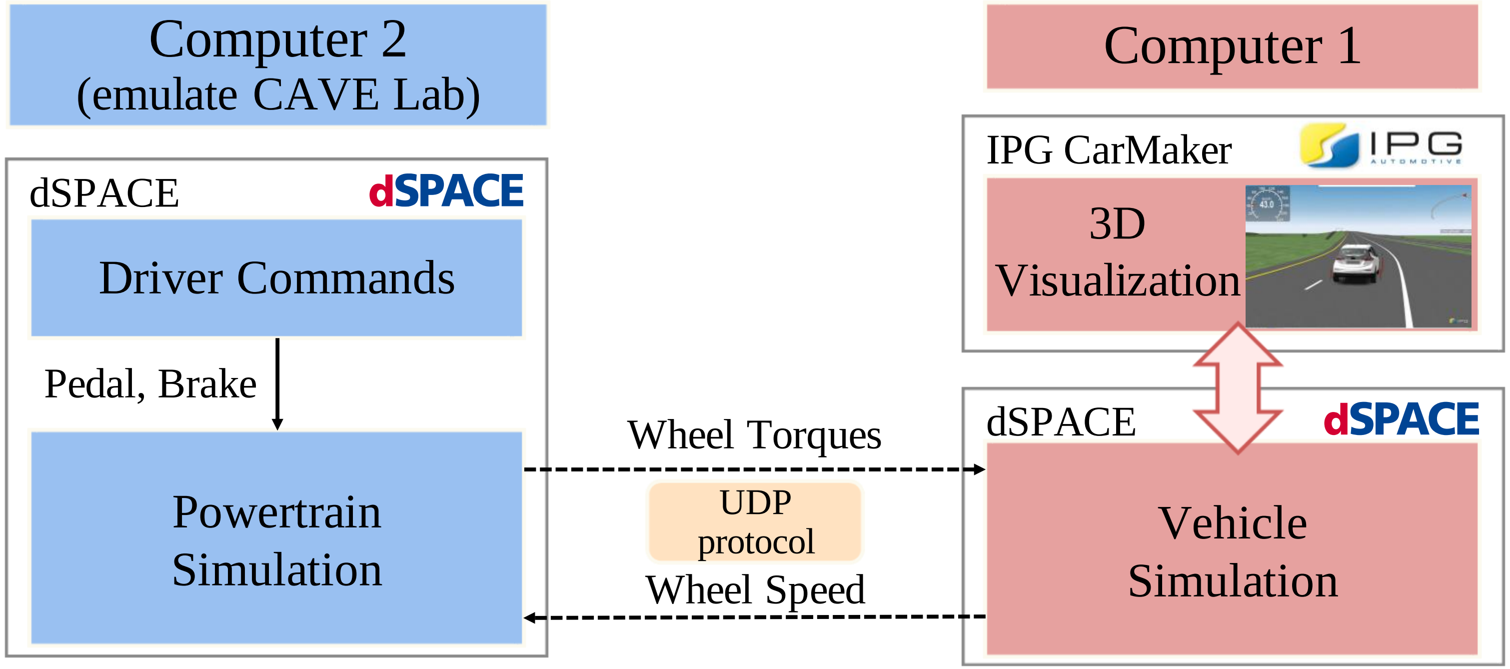

# Accomplishment Task 1 – Functional Connected and Automated Vehicle Environment (CAVE) Laboratory (cont.)

# Technical Progress Task 1 – CAVE Laboratory Layout and Block Diagram

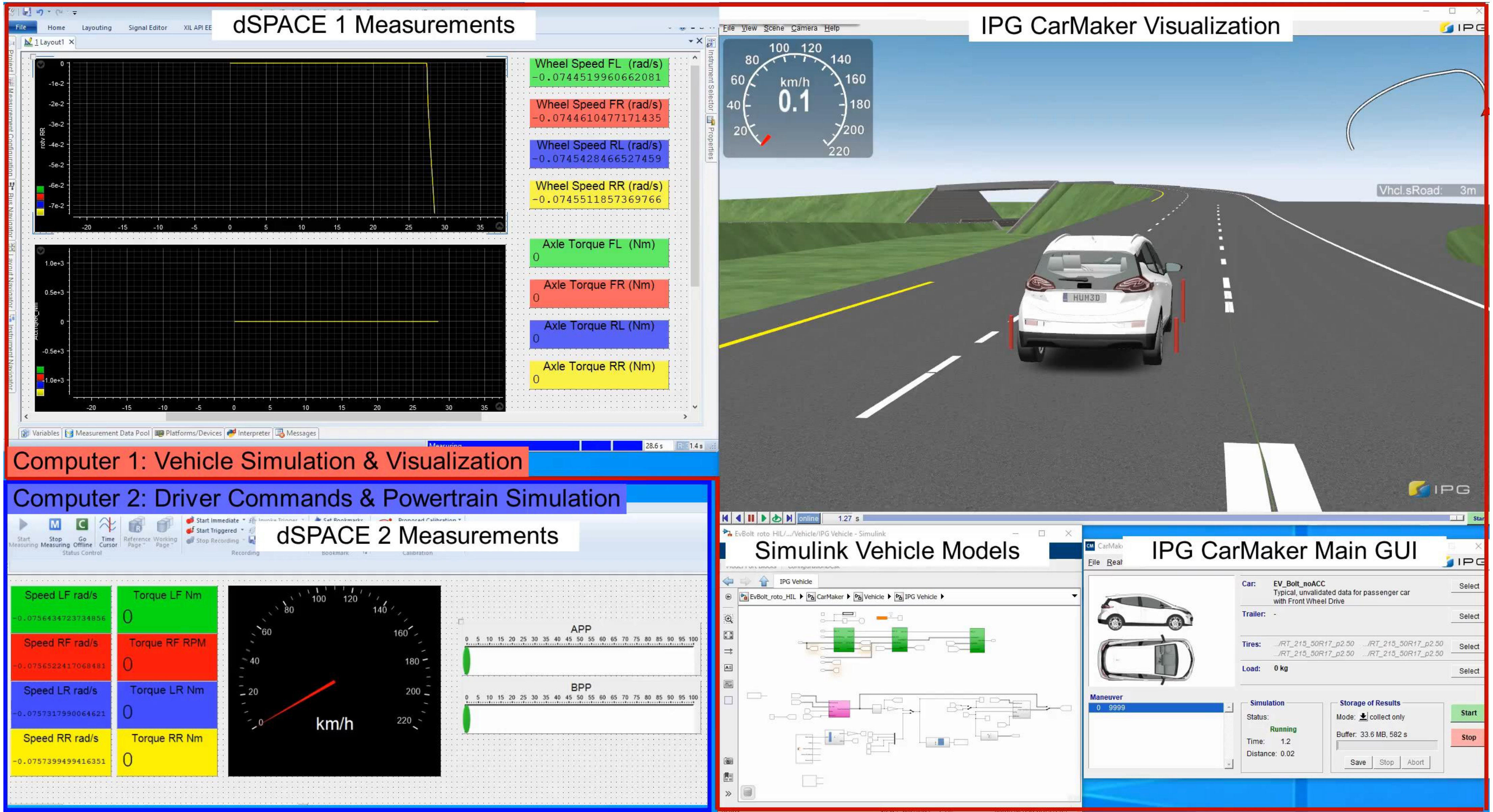


# Technical Progress Task 1 – IPG CarMaker HIL integration with CAVE Lab

- COVID has impacted the ability to fully utilize the laboratory. As such, we have had to use a simulated lab for further work, that will be tested in Q3 and Q4.
- The integration of IPG CarMaker with the CAVE Lab model provides a complete solution that can represent the ego vehicle with high fidelity. Dynamics are applied per wheel, which is necessary for modern vehicle traction control and ABS systems.
- A customized interface was developed using UDP protocol to synchronize IPG CarMaker and the CAVE Lab at every simulation time step.

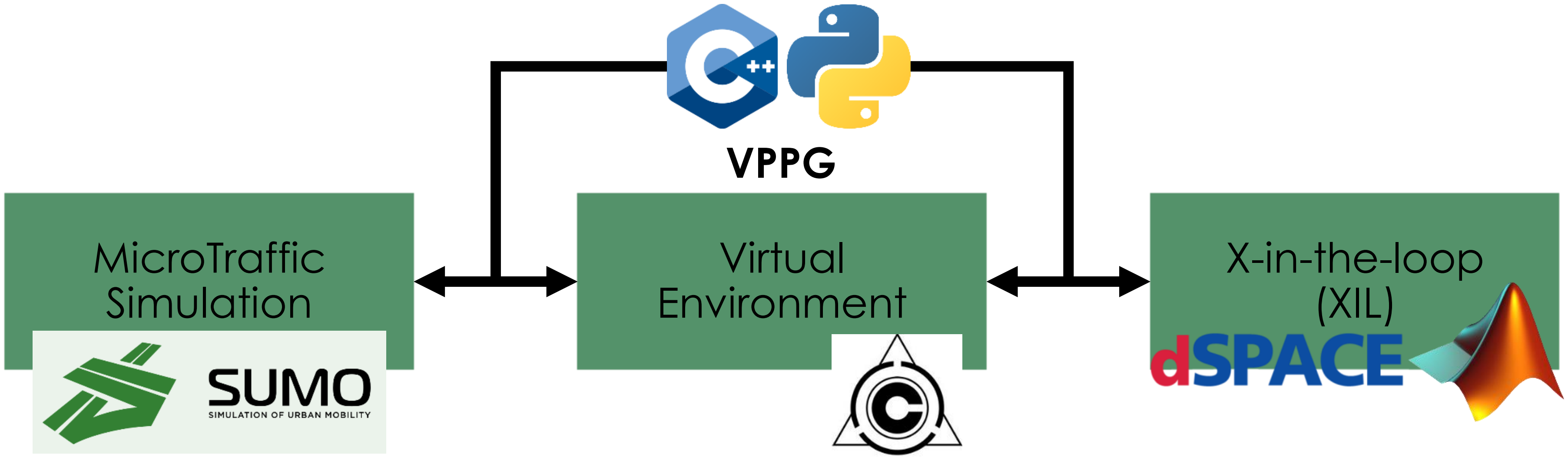


# Technical Progress Task 1 – IPG CarMaker HIL integration with CAVE Lab (Video)

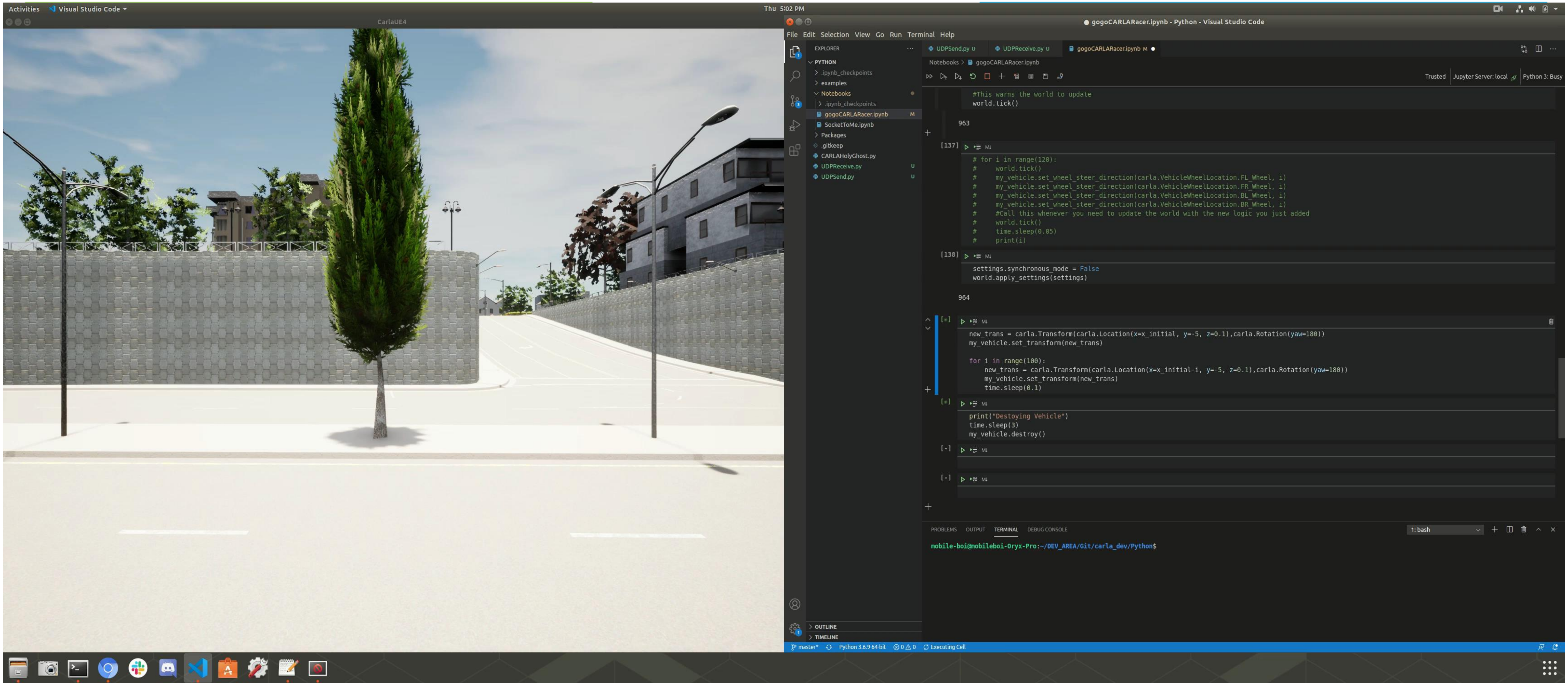


# Technical Progress Task 1 – Virtual Proving Ground Applied to Open-source Tools

- Open-Source Co-Simulation
  - Integration of open-source tools in the VPPG requires collaboration between several toolchains.
  - To interact with SUMO, we utilize the Traffic Control Interface (TraCI) to support TCP based coordination with the simulation.
  - CARLA leverages a Python API that must query the simulator and pass TCP/UDP packets from the Host PC to the Target.
- Commercial Tools Supporting Real-World Applications
  - MATLAB/Simulink provides the higher fidelity vehicle modeling for CARLA
  - dSpace provides the real-time HIL platform and necessary IO hooks

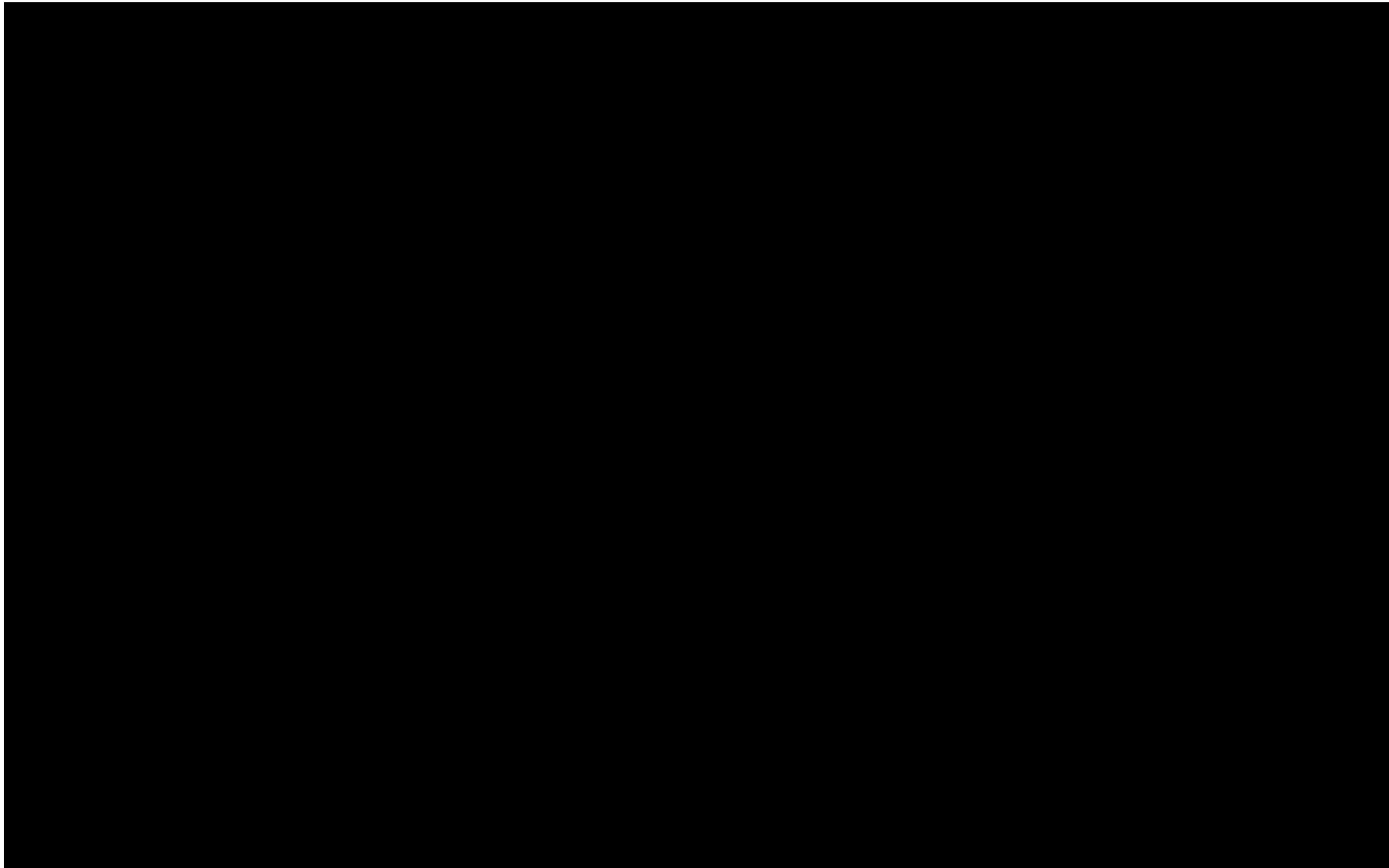


# Technical Progress Task 1 – CARLA-HIL Co-Simulation (Video)



# Technical Progress Task 1 – SUMO-CARLA Co-Simulation (Video)

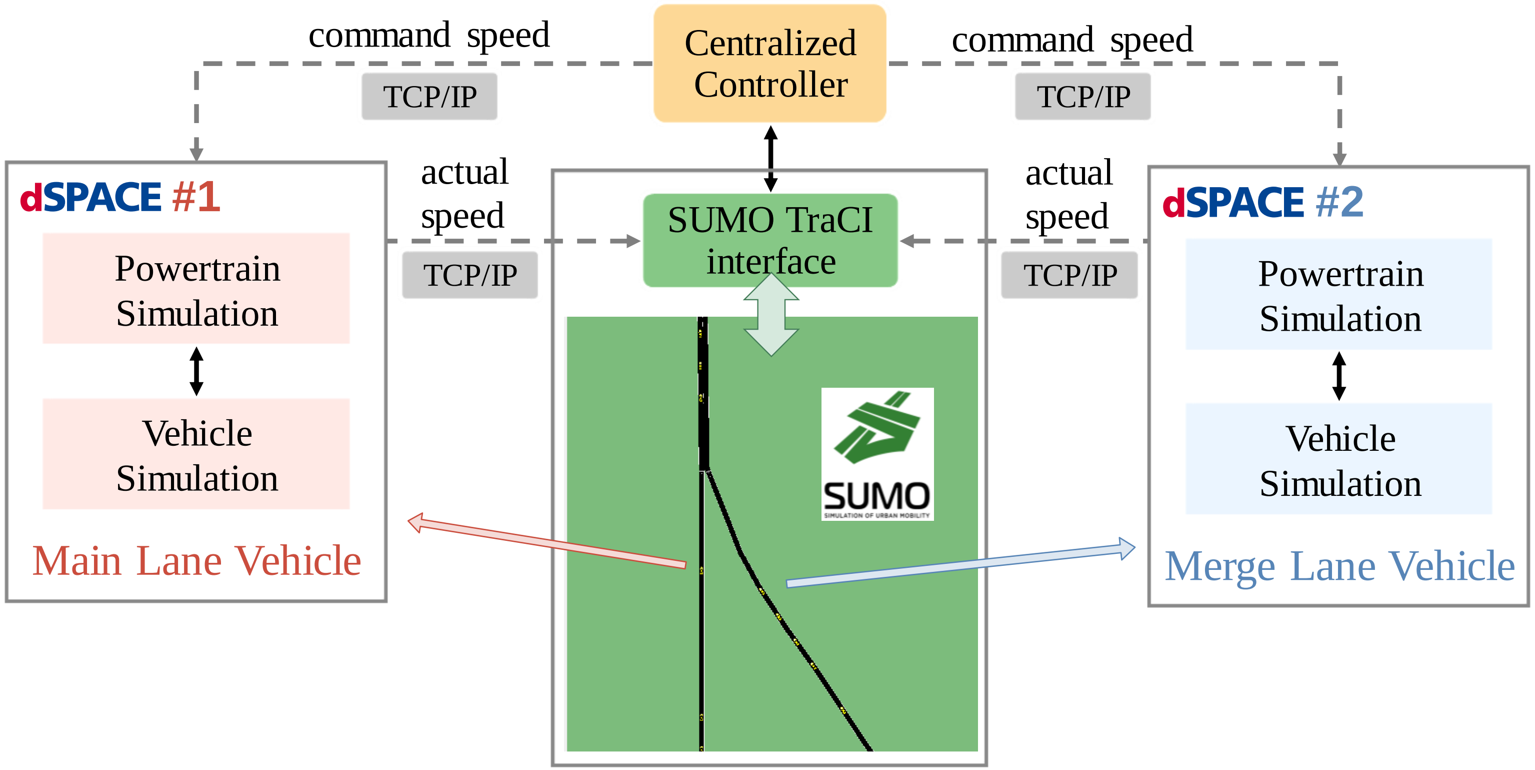
- SUMO and CARLA are synchronized at every time step using SUMO’s TraCI interface. SUMO simulates all the background traffic. CARLA simulates the ego vehicle and visualize the 3D environment.



# Accomplishments and Technical Progress – Task 2

# Technical Progress Task 2 – Coordination testing of real-time cooperative and automated vehicle merging utilizing two of ORNL's HIL test cells

- The real-time connected lab testing enables multiple test cells/powertrains/vehicles running at the same time to simultaneously evaluate multiple ego vehicles.
- Two HIL systems were connected to a SUMO traffic simulation running on a host PC. A cooperative merging algorithm communicating through TCP/IP was also active.
- Both HIL systems run a complete vehicle and powertrain Simulink model to simulate higher fidelity vehicle dynamics, rather than the typical SUMO agents, all interacting in real-time.



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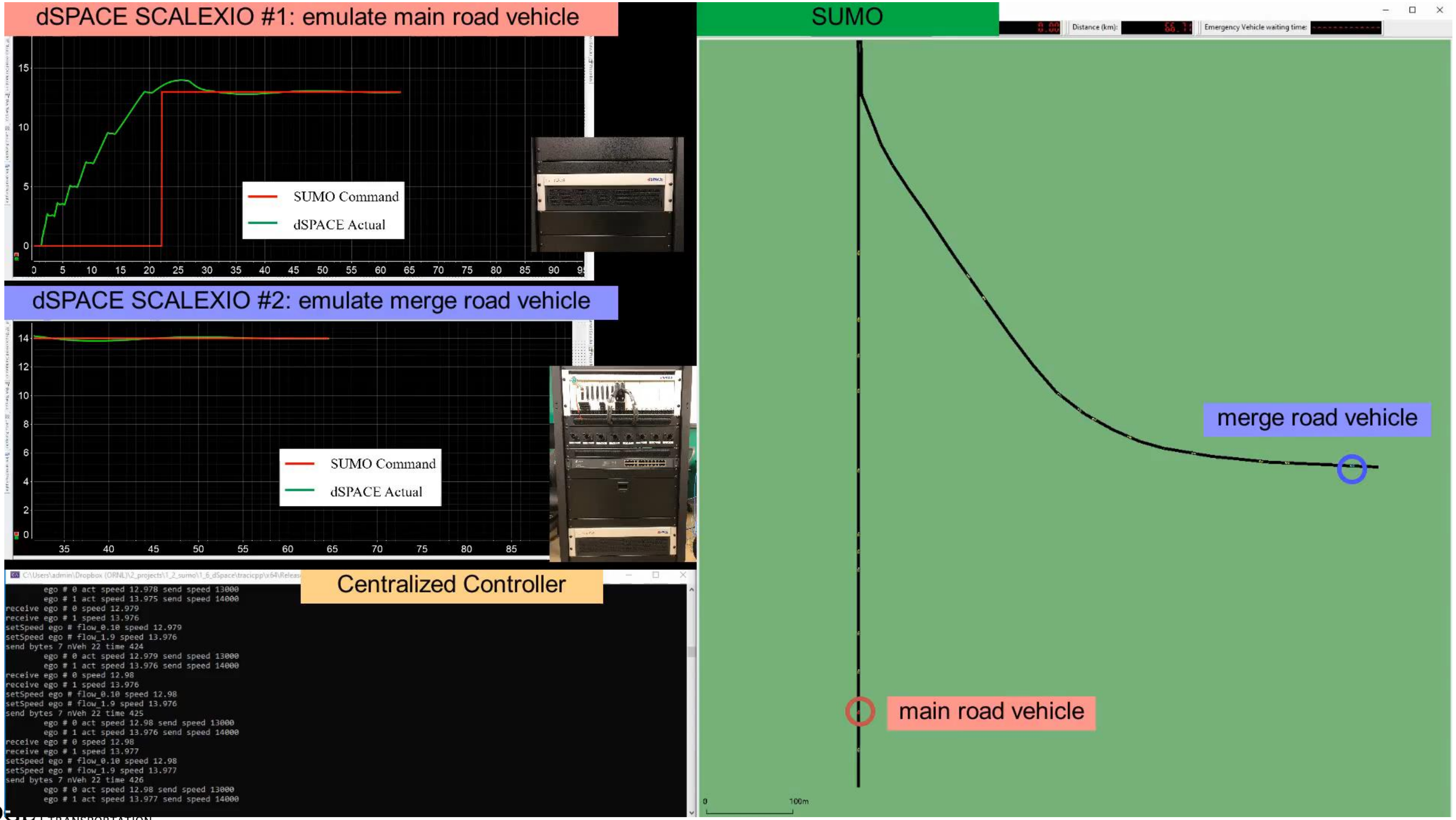


# Responses to Previous Year Reviewer Comments

- **"The project objective is quite broad, so breaking it down into two tasks helps bring focus to specific areas of the effort. The reviewer assumed it would be hard to tell if the final objective of integration has been reached since there are so many aspects to address. Completing the goals of the tasks helps to chip away at the overall objectives. It seems like any one aspect of this effort could be considered its own stand-alone project."**
  - We agree with the reviewer, the project is quite broad and touches on many topic areas that could be separate projects. The specific focus of this project is to develop the framework and interfaces of the various pieces into a cohesive platform, that while not fully fleshed out is fully functional across the continuum of the project.
- **"Hardware-in-the-loop (HIL) (vehicle connected to dynamometers in the laboratory and driven in accordance with traffic simulations) is typically an approach that seeks to provide real-world driving realism, without the need for actual on-road driving. Yet, in later planned tasks of the project, there will be track testing. With track testing planned, it is unclear why was there a need for HIL."**
  - We apologize for any confusion made during last year's AMR. This project will not be doing track testing, however EEMS082 ran by ACM is supporting us by providing data to validate our simulation models and HIL results.
- **"This project is very timely and important in terms of creating an advanced, cost-effective, immersive CAV modeling and testing platform to support future DOE research."**
  - We greatly appreciated the feedback and could not agree more. This thankfully has been mirrored by industry interest, collaboration opportunities, as well as requests for information and support base on work from this project.

# Collaborations

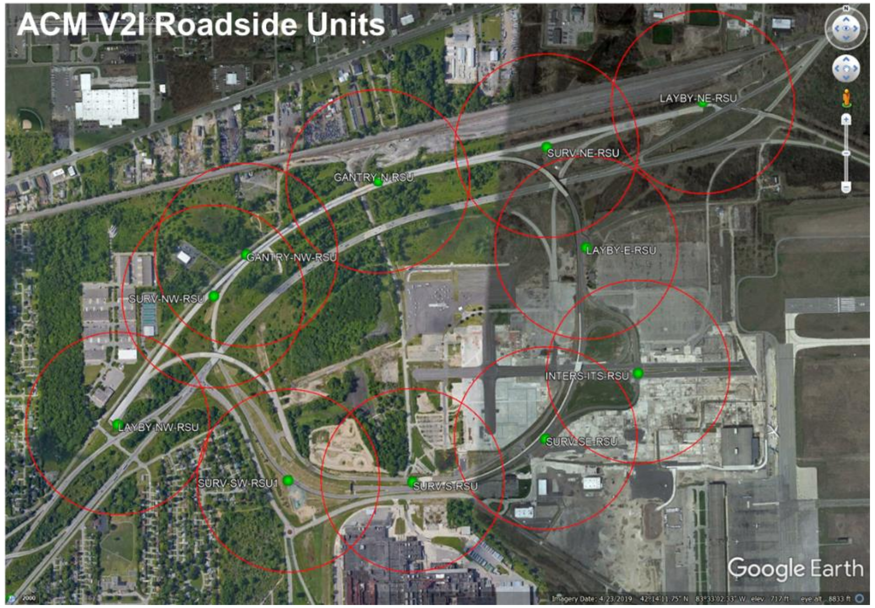
| | |
|---|---|
| American Center for Mobility | High fidelity mapping of the ACM facility is being provided to ORNL to allow for a digital twin to be generated and utilized in joint work from this project and EEMS082. |
| dSPACE IPG | Both are providing support for the co-simulation bridges allowing for virtual environments to be executed in real-time with Vissim and SUMO. dSPACE is supporting HIL applications for sensor emulation of lidar, radar, and cameras. IPG is supporting ORNL with software support for sensor modeling and emulation. |
| CARLA | CARLA and ORNL have begun collaboration to improve this open-source solution by developing better vehicle dynamics as well as being one of the first testing grounds for CARLA HIL implementation. |
| Cummins® | Cummins will be supplying the advanced powertrain that will be utilized for the Q4 scenario-based testing of a medium-duty delivery vehicle.  They will also be supplying engineering support for control changes as required based on test results. |

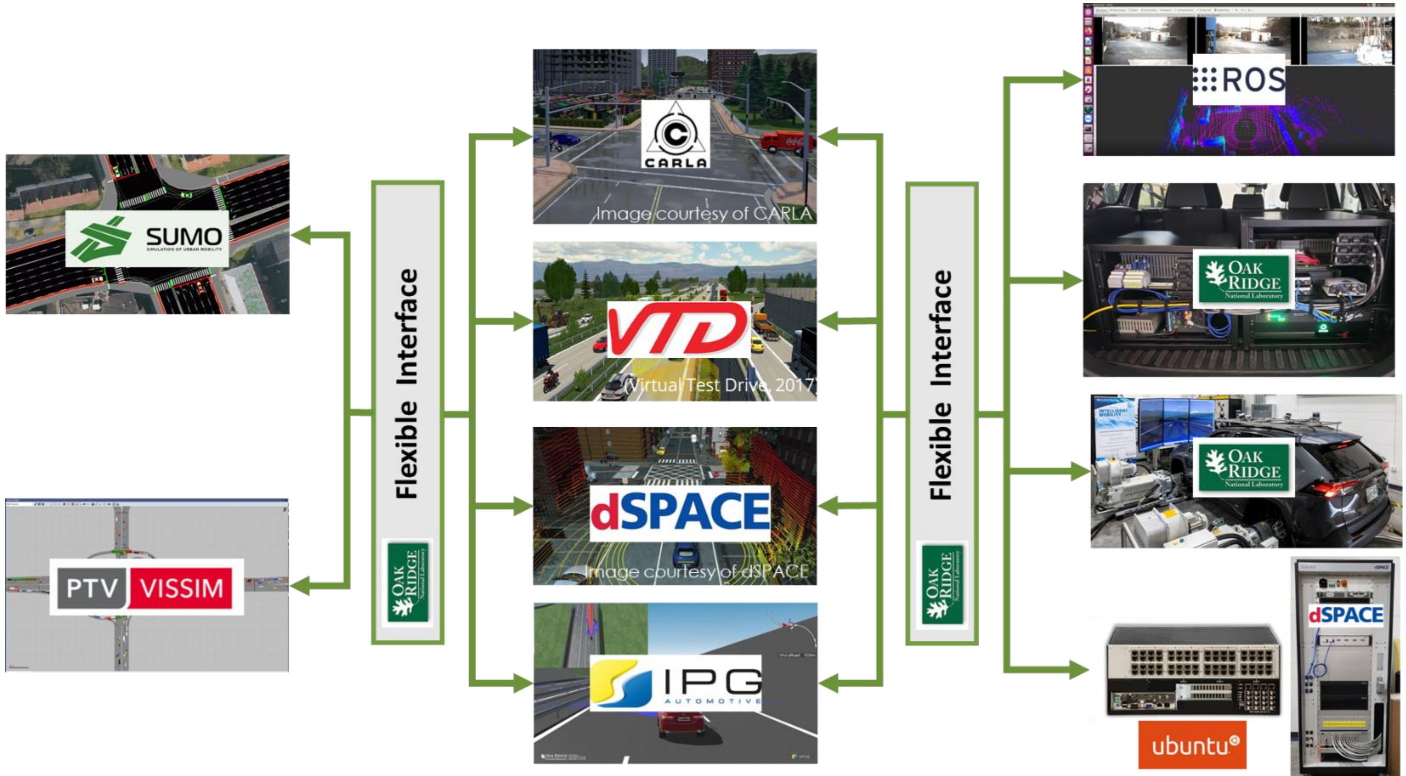
# Remaining Challenges and Barriers

- Much of this project requires advanced application methods that originally utilized simplified simulation environments to be applied to real vehicles in the new CAVE Lab. The integration or expansion of this work is a difficult integration task.
- A primary challenge of this project is determining the correct integration approach for various applications. Some applications require co-simulation of various tools, some require HIL techniques as well as real-time hardware, and others are satisfactory with a single simulation tool.
- Determining the computational requirements for these various applications is a major challenge as well as a barrier to some applications. To run the most demanding sensor simulations (i.e. lidar and radar) on HIL applications requires an extremely powerful PC to apply ray tracing techniques utilizing GPU calculation and a powerful real-time node.

# Proposed Future Research

- **Remainder of 2021**
  - Finish VPPG proof-of-concept by comparing on-road tests with a mirrored test using the full VPPG.  This process will utilize the same environment (road and scenario) as well as the same vehicle.
  - Utilizing an advanced electrified powertrain, explore scenario-based testing's impacts versus traditional time series-based duty cycles.
  - Using the data generated from testing at ACM as part of EEMS082, complete a HIL study of V2X degradation’s effects on the 3 ORNL test cases (speed harmonization, merging, intersection) by emulating these case in the VPPG. Examine control limitation for each case.



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# Summary

## Relevance

- Create an agnostic, standardized framework to allow for validation of EEMS and SMART Mobility models, tools, and data sets utilizing combinations of modeling, simulation, HIL, and vehicle-level testing.
- This architecture enables integration of DOE, open source, and industry standard software solutions and toolsets.

## Approach

- “Virtual-Physical” Proving Ground
- Communication (V2X) Modeling, Development, and Validation

## Future Work

- Remainder of 2021:
  - Finish POC for VPPG continuum vs real-world test analog.
  - Explore scenario-based testing's impacts versus traditional time series-based duty cycles.
  - Complete a simulation and HIL study of V2X degradation’s effects on centralized control algorithms being used as part of project EEMS082.

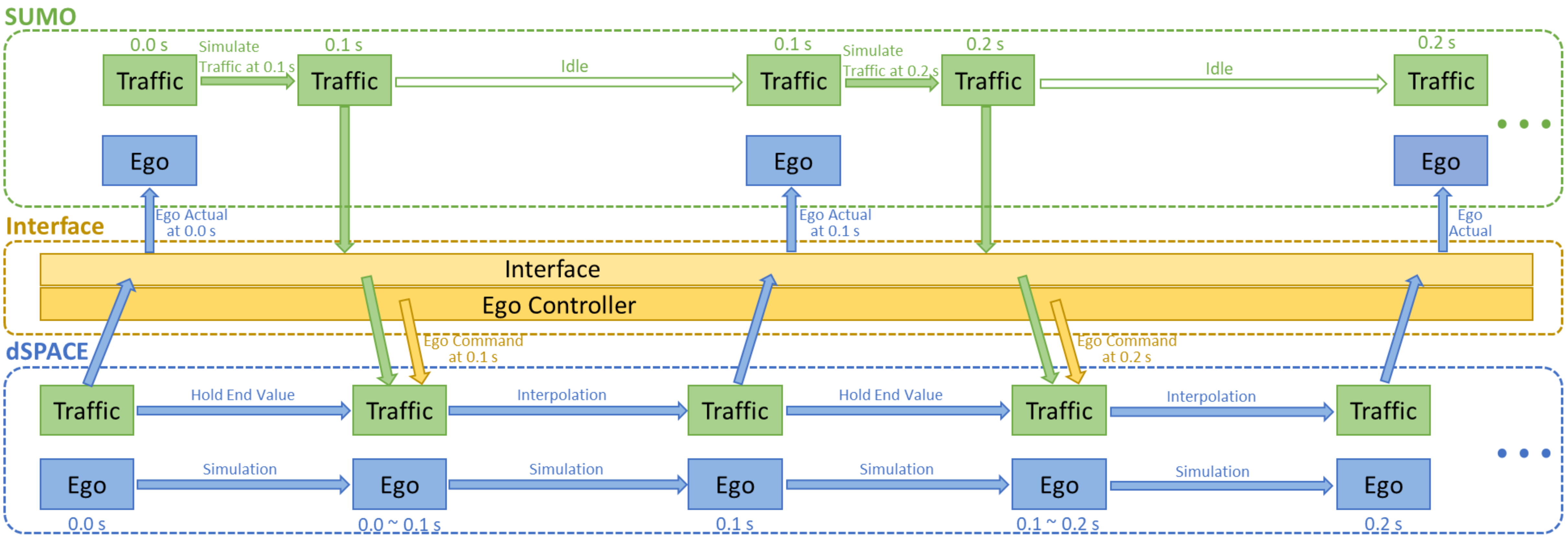
## Technical Accomplishments

- New Connected and Automated Vehicle Environment (CAVE) Laboratory dyno system and HIL rack is fully functional.
- Successful VIL testing performed with per-wheel dynamics and control.
- Open-Source tools interface for co-simulation functional and ready for testing.
- Multi-Ego vehicle setup for multiple real-time connected labs enables multiple test cells/powertrains/vehicles

# Questions?

# Technical Backup Slides

# SUMO Multi-EGO Interface Block Diagram




*Note: Currently one dSPACE is shown, the same flow equally applied to multiple dSPACEs but with multiple connections to the Interface.

Traffic simulation SUMO normally runs much faster than dSPACE simulation. An ego controller sends speed command to dSPACE. The controller currently lives inside the Interface, but it can also live inside the dSPACE. dSPACE simulates the actual speed of ego vehicles and sent to SUMO.

# Hardware Layout Diagram of ORNL CAVE Laboratory