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

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Project ID: EEMS067

June 21-23, 2022

2022 Annual Merit Review

OAK RIDGE National Laboratory

Overview

Timeline

- Start Date: Oct 1, 2018
- End Date: Mar 31, 2022
- Percent Complete: 100 %

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

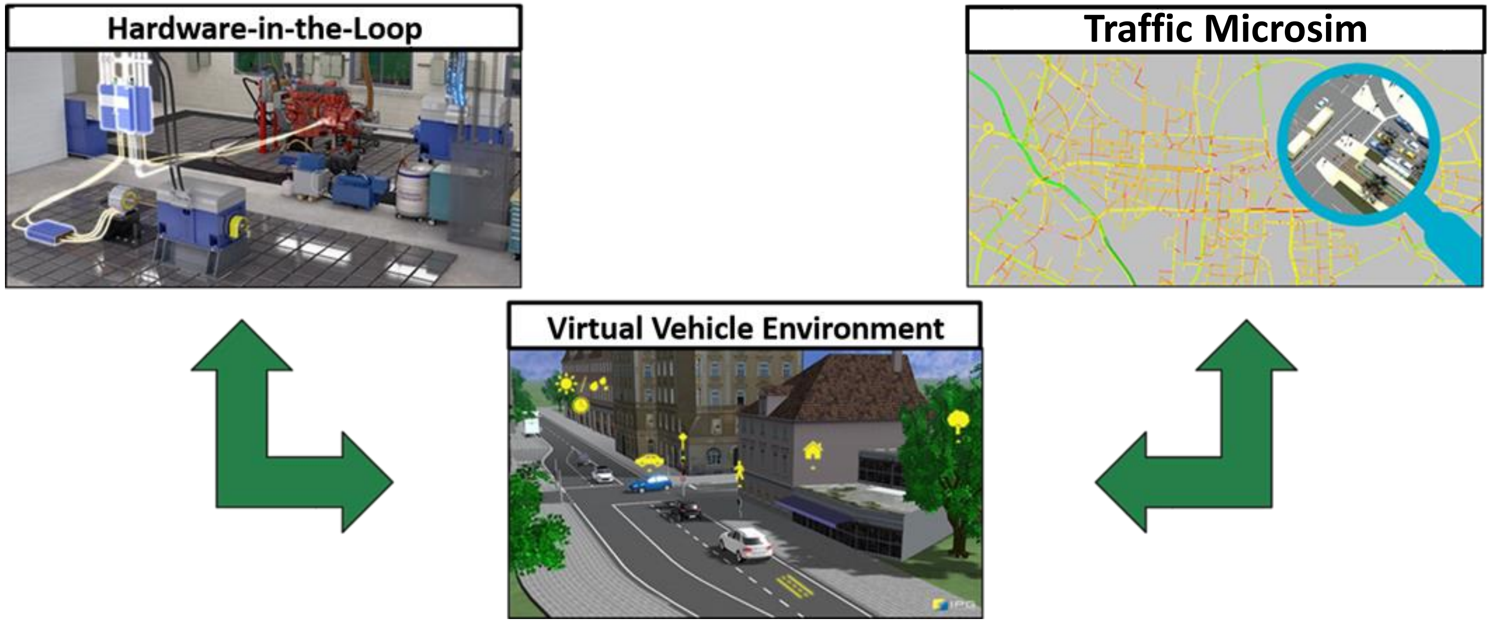
- Total Budget
  - DOE Share $6,860K* includes capital purchase
- Funding for FY 2021
  - $1,000K
- Funding for FY 2022
  - $0

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.



- Advanced Hardware-in-the-Loop
- Traffic Sim
- CAVs Technologies
- Advanced controls development
- Intelligent Algorithms for energy efficiency of freight and passengers

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 HD vehicle and one EV), or the VSI laboratories and the CAVE laboratory (One HIL setup and one BEV VIL setup) depending on lab availability.	**Complete**
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.	**Complete**
March 2022	**EEMS/SMART Mobility Validation Case Studies (Subtask 2.3)** Complete validation study of the EEMS SMART Mobility test case (merging) into the VPPG.	**Completed***

*Milestone was descoped due to delay in data from on-track testing coming after project completion.

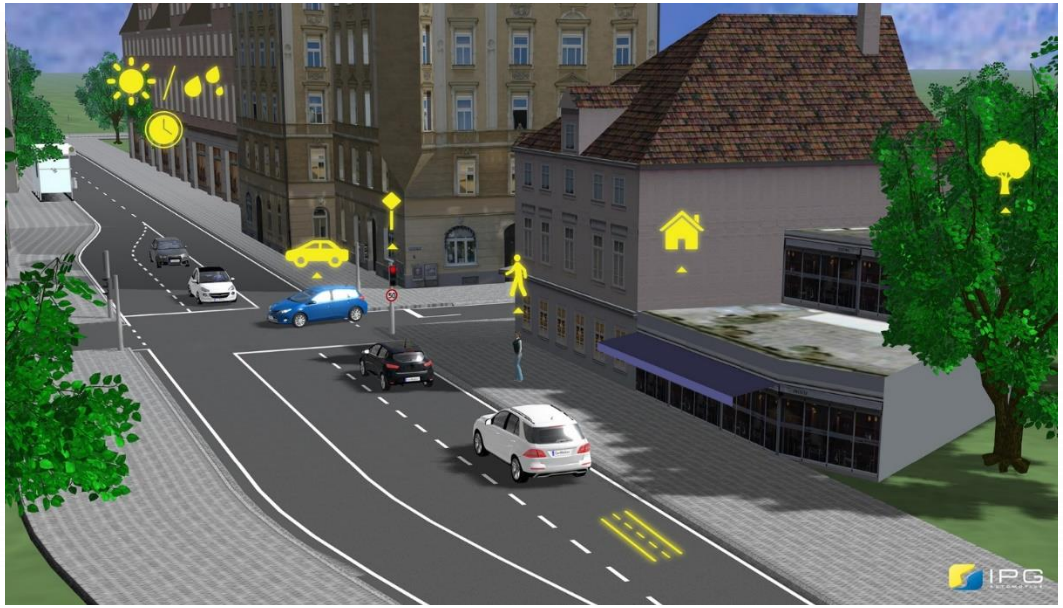
Approach

"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

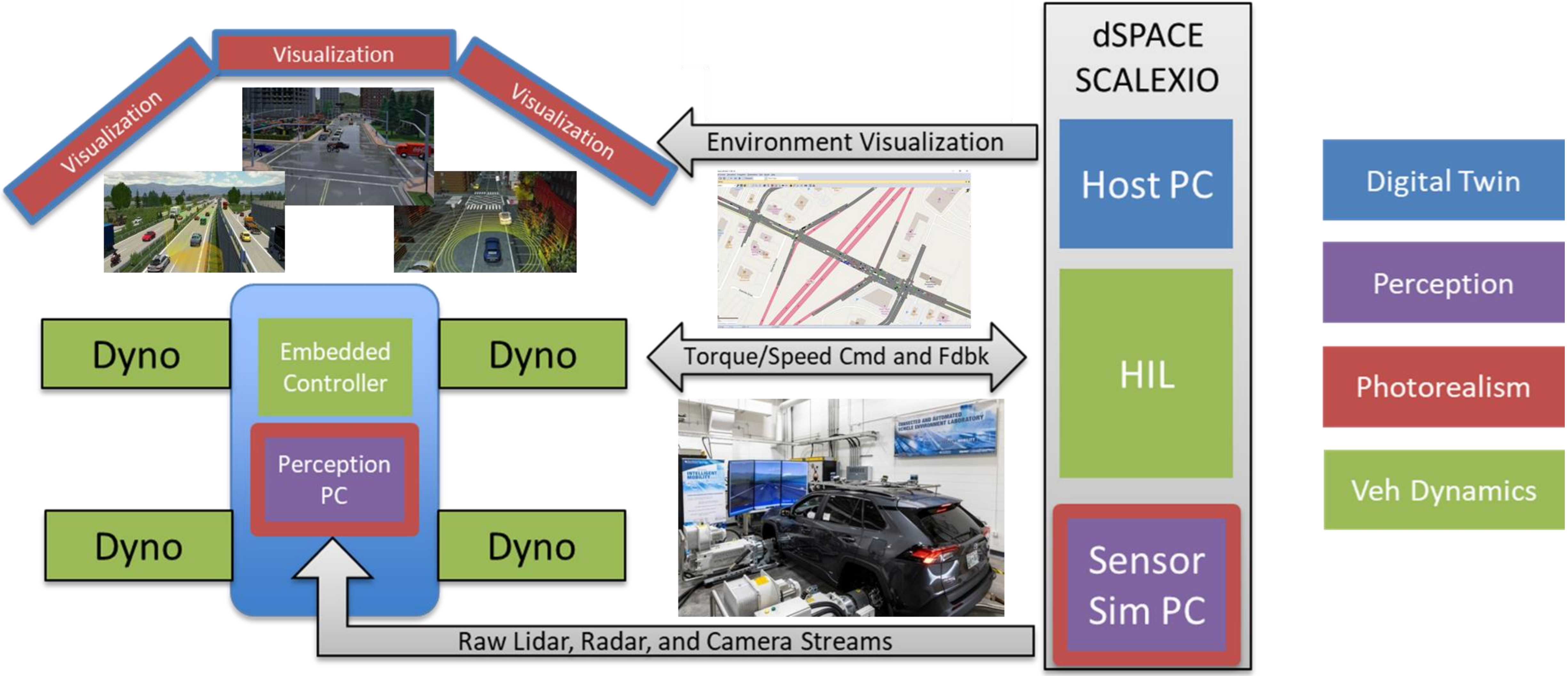
- Provide a platform to couple laboratories to real-time, high-fidelity traffic simulations while subjecting actual powertrain(s) to emulated, real-world traffic conditions utilizing Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication provided by real hardware.
- Development of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



Accomplishments and Technical Progress – Task 1

“Virtual-Physical” Proving Ground (VPPG)

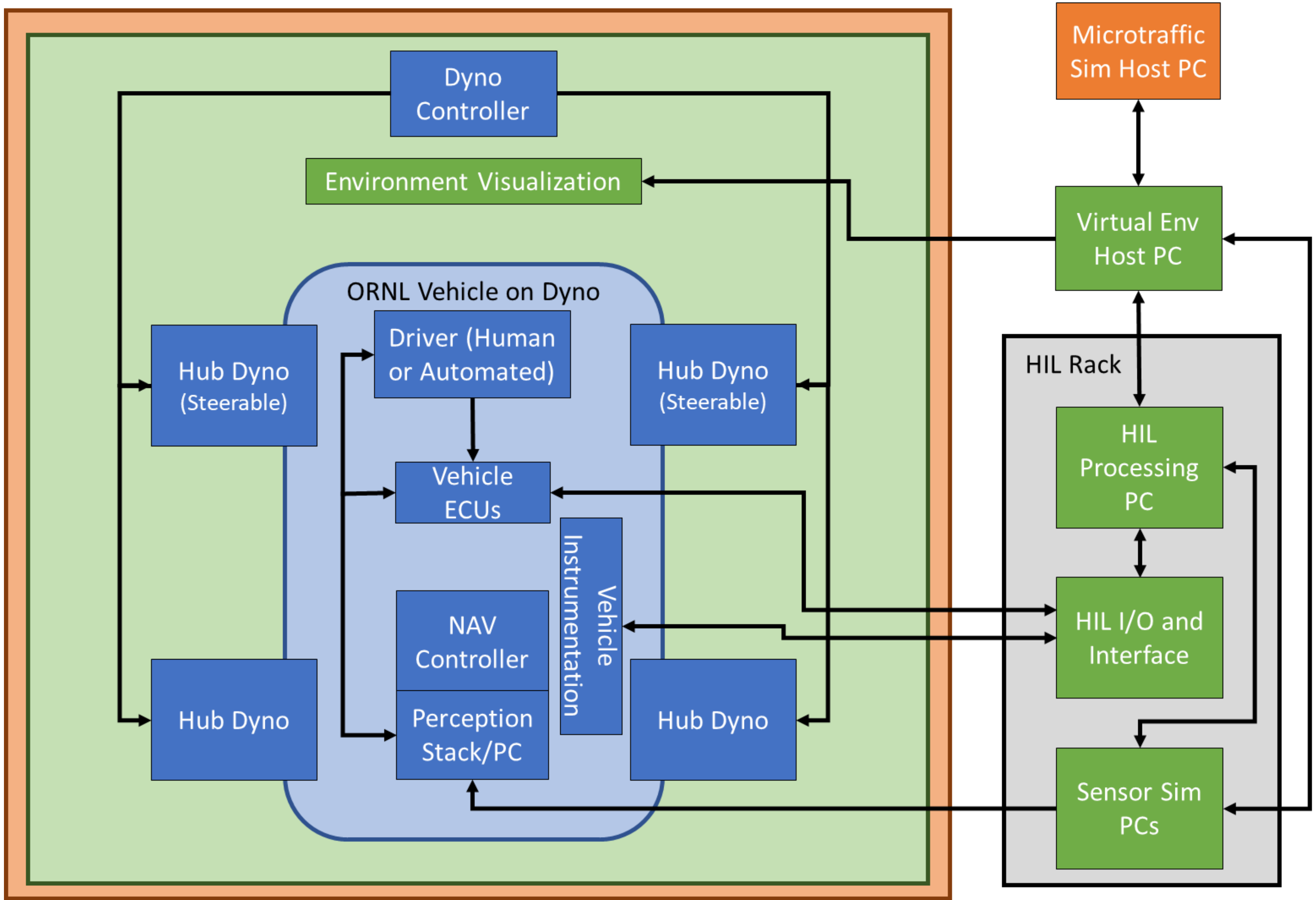
Accomplishment Task 1 – Functional and Vetted Connected and Automated Vehicle Environment (CAVE) Laboratory – VPPG Refresher Slide



Technical Progress Task 1 – Finished HIL integration with the CAVE Laboratory and subsystems.

- Since Last AMR the CAVE Lab has fully integrated:
  - V2X Comms
    - Road-Side and On-Board
  - Level 2 Charger
  - Exhaust Ventilation
  - Traffic Control Devices
    - Siemens
    - Econoline
  - Multi-GPU Host PC's for separation of sensor simulation.
    - GPU 1 – Camera and 3D Render
    - GPU 2 – Radar, Ultrasonic, and Lidar

Legend	
(R) Real	Vehicle in Loop
(S) Simulated	Virtual Veh Env.
	Microtraffic Sim



Accomplishment Task 1 – NTRC is a DOE User Facility

- CAVE Lab User Agreements utilized work and capabilities developed from this project.
  - Ford Proof of Concept (POC)
    - POC Powertain Testing
    - POC for ADAS Testing
  - University of Tennessee Knoxville Driver Metrics
    - Project focused on HMI and vehicle-driver interaction.

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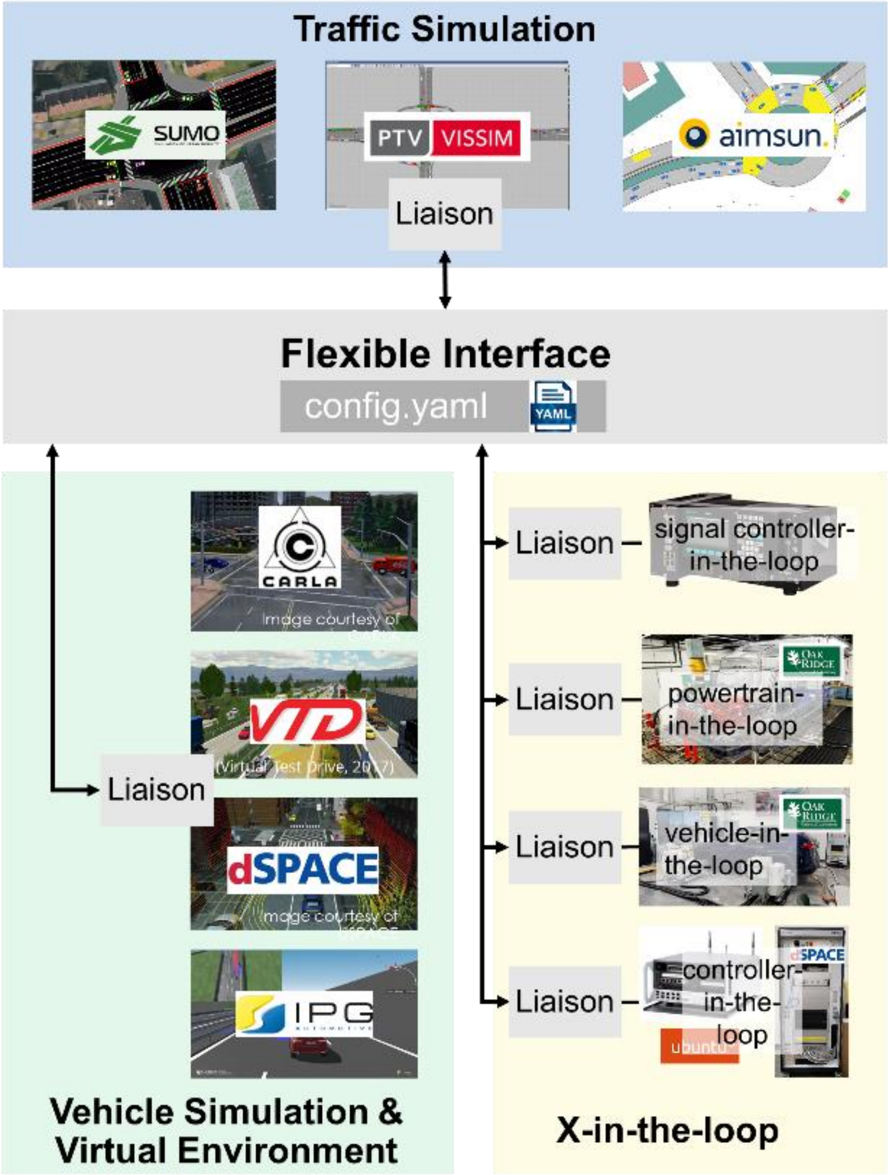
Technical Progress Task 1 – Fully Functional Flexible Interface Completed



- Current interface can support SUMO, VISSIM, control algorithms in cpp, python, Matlab/Simulink, IPG CarMaker, dSPACE ASM, CARLA, dSPACE HIL units, RT Linux units, and Econolite and Siemens traffic control devices. Expansion to other simulation tools is under development.
- Switch simulation tools and control can be flexibly achieved change the config.yaml.
- The connections to different simulation tools and XIL components are handled internally by the interface using TCP/IP and are transparent to the user.
- **An early released executable version of the interface is shared with Toyota to support internal co-simulation work.**
- **Ford will be using the interface during a new CRADA project being kicked off in May 2022.**

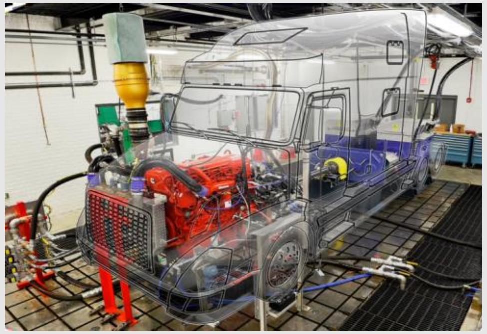
Accomplishments and Technical Progress – Task 2

Communication (V2X) Modeling, Development, and Validation

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

- Work was completed connecting the ORNL CAVE VIL (building 1) setup with a Powertrain-in-the-loop setup in the VSI lab (building 2) by leveraging the ORNL ethernet backbone (virtual communications).

NTRC Building 2



- HD PIL
- dSPACE SCALEXIO, assigned static IP

Ethernet ⟷ Host PC

Host PC
- SUMO
- Centralized Coordinator

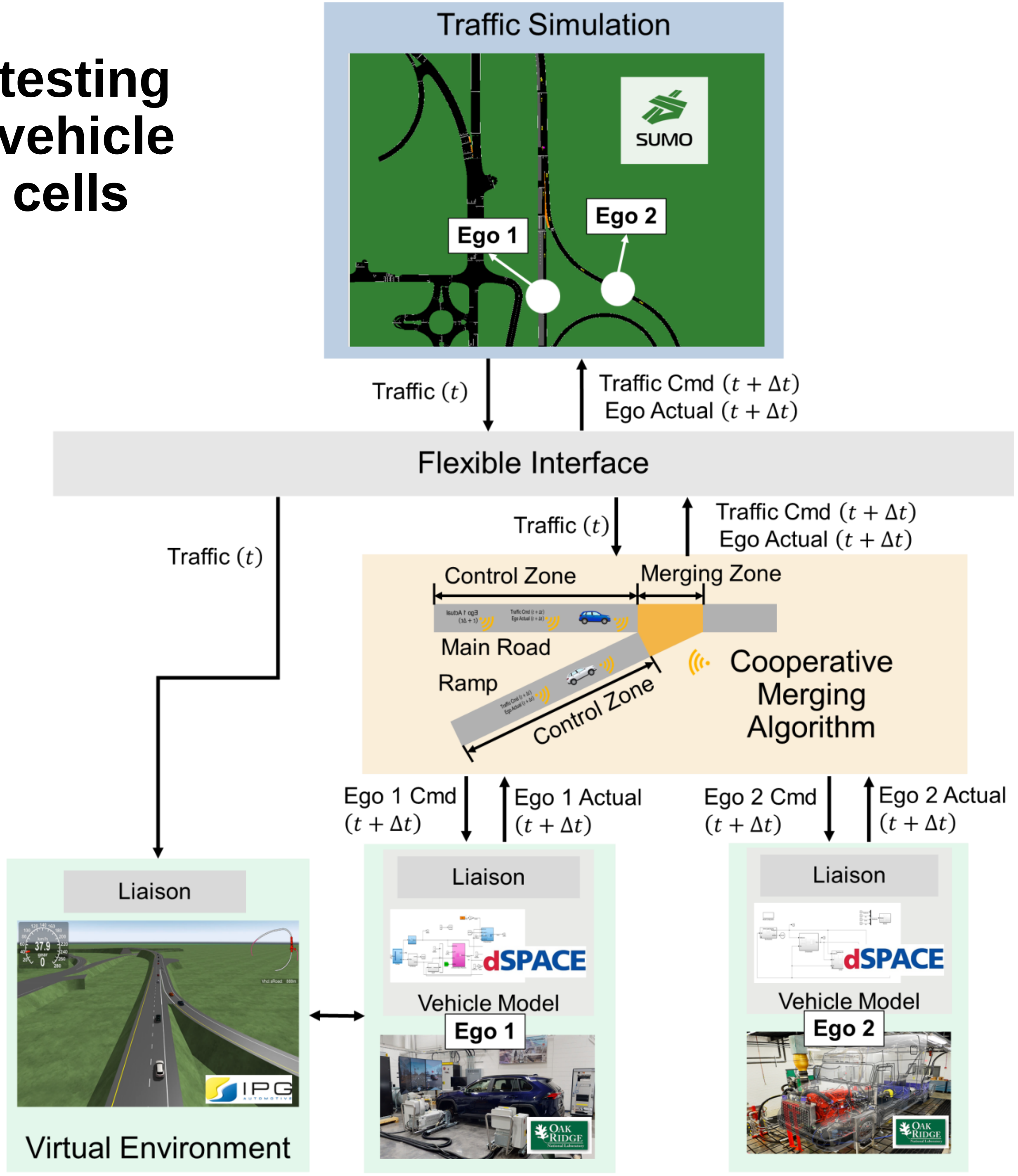
NTRC Building 1

- BEV VIL
- dSPACE SCALEXIO, assigned static IP

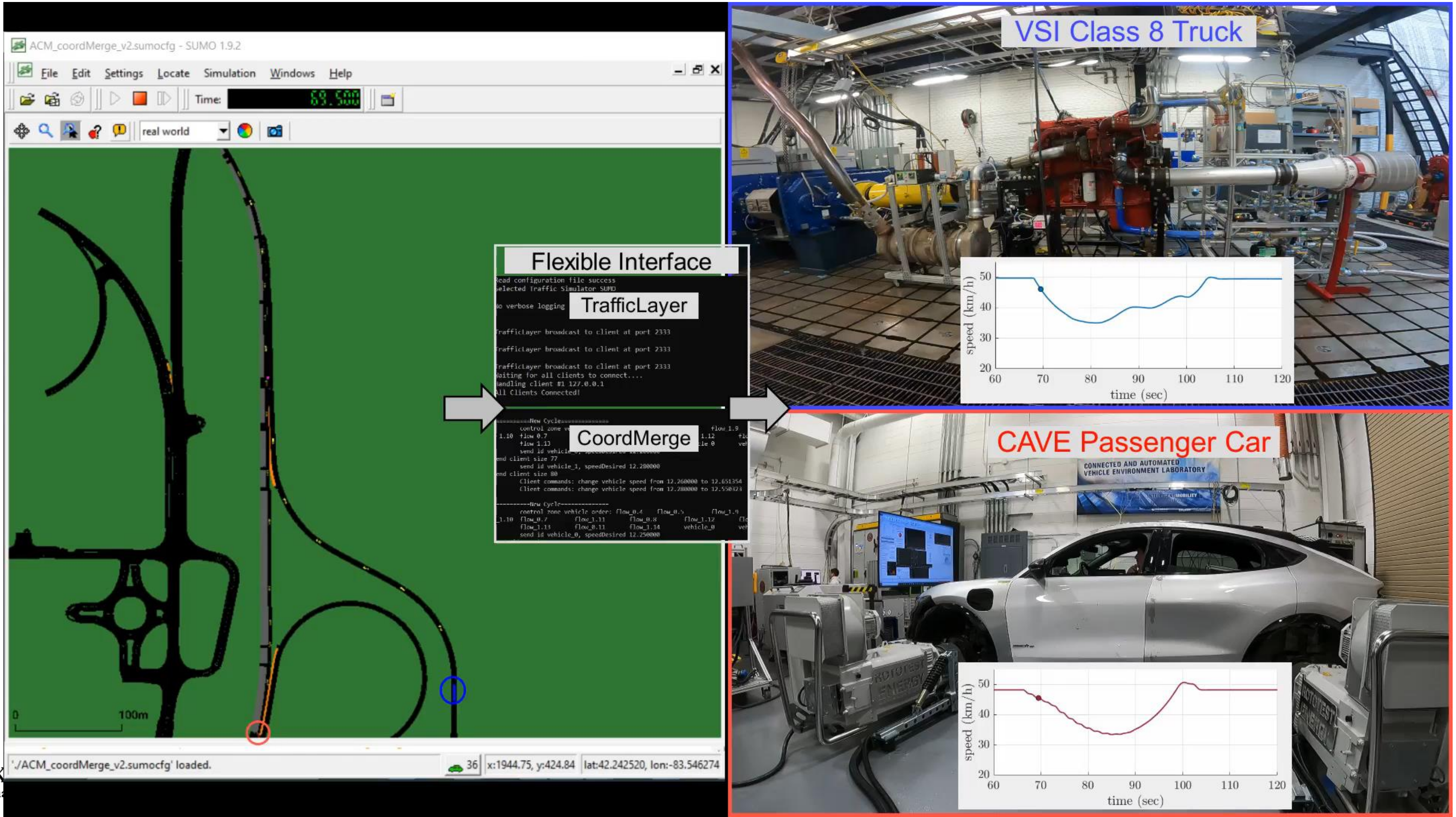
ORNL Ethernet Hardline

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

- Two ego vehicles emulated by CAVE Lab and VSI Lab.
- Coordinated merging at a merging ramp of the digital twin of ACM.
- Flexible interface establishes co-simulation of two labs, control algorithm, traffic simulation and virtual environment.
- All of this is executing in real-time.



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



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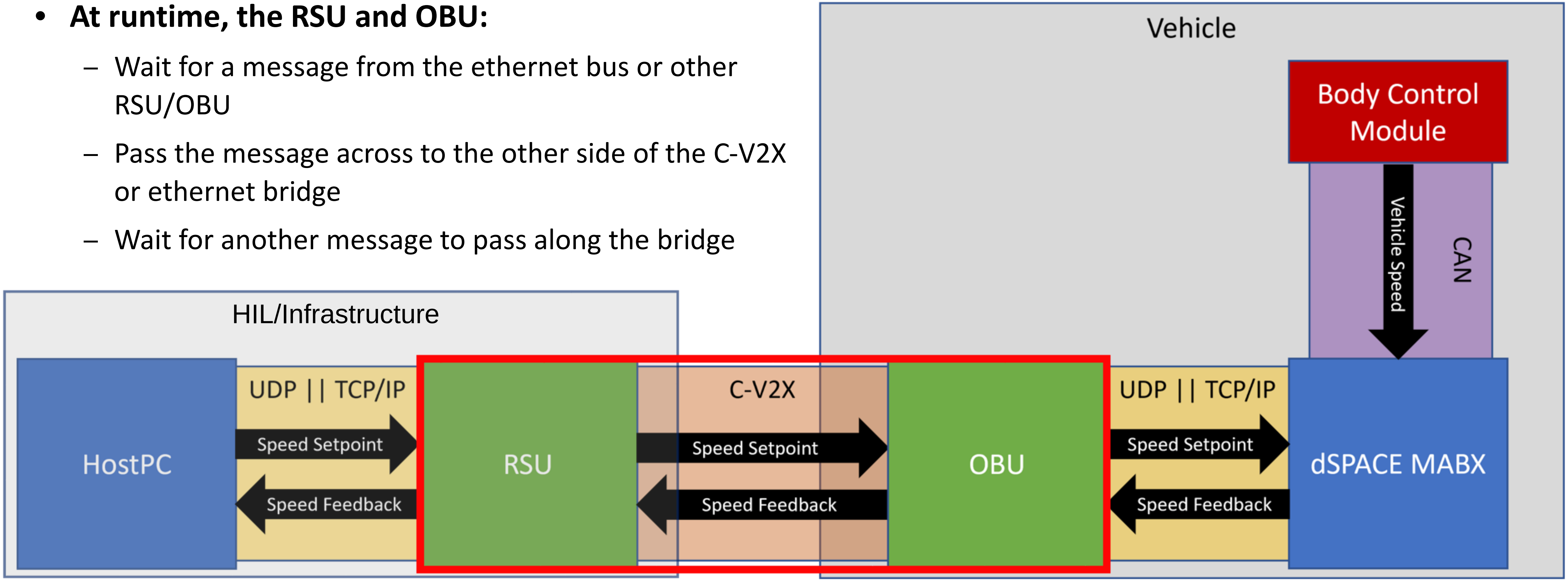
Accomplishment Task 2 – Coordination testing of real-time cooperative and automated vehicle merging utilizing full C-V2X hardware

- **C code was developed onboard the RSU and OBU units to facilitate physical C-V2X communication in laboratory.**
- **RSU and OBU work as a wireless (UDP similar) passthrough for coordinator, traffic, and vehicle data**
- **At runtime, the RSU and OBU:**
  - Wait for a message from the ethernet bus or other RSU/OBU
  - Pass the message across to the other side of the C-V2X or ethernet bridge
  - Wait for another message to pass along the bridge

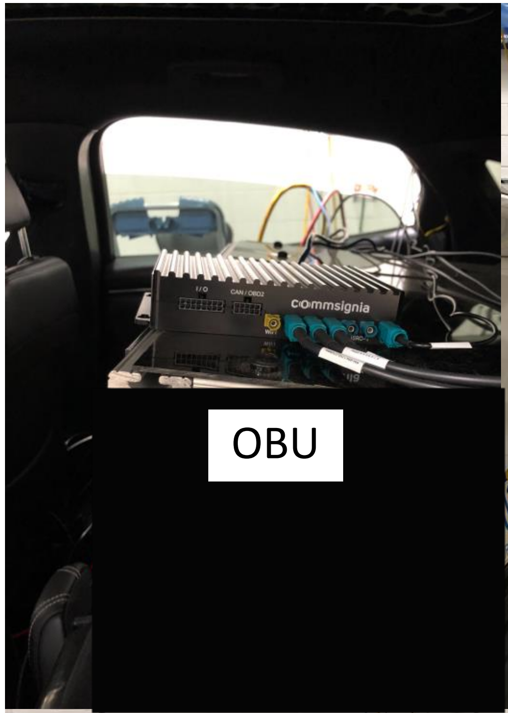


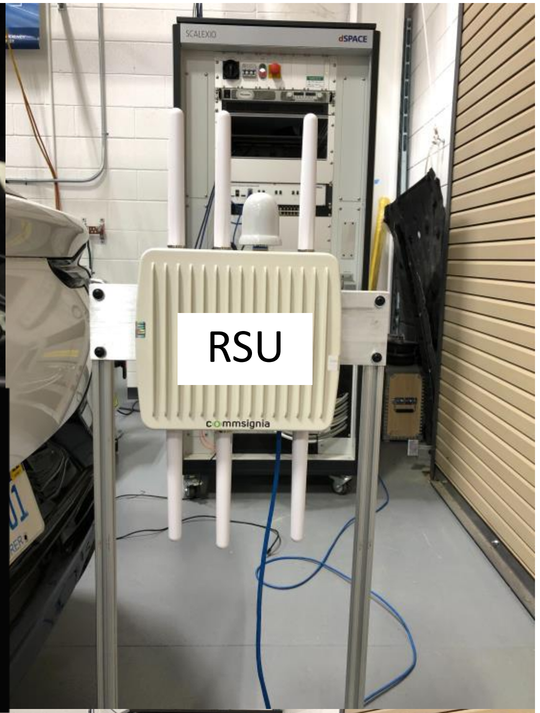
Accomplishment Task 2 – Comms Workflow

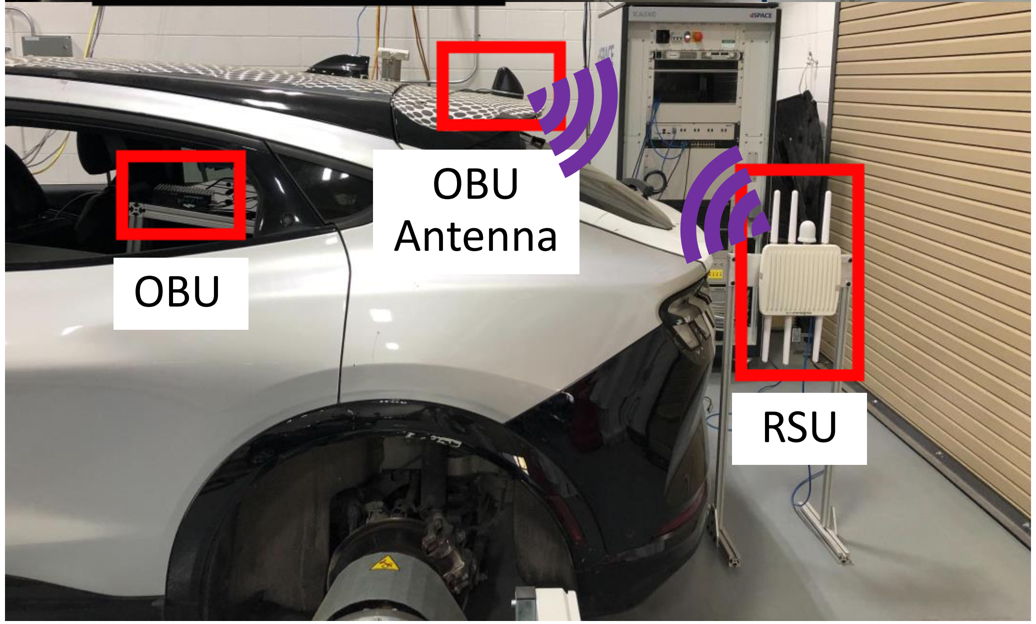
- Fully functional Commsignia On-Board Unit (OBU) and Roadside Unit (RSU). Workflow to switch between simulation and physical comms complete.

```
// include v2x headers, macros
#include somev2x.h
// globals, functions
static void my_clever_func();
// executing code
intitalizeCV2XRadios()
initializeSockets()
while(1) {
  waitForData() // ethernet or CV2X
  sendData() // ethernet or CV2X
}
```

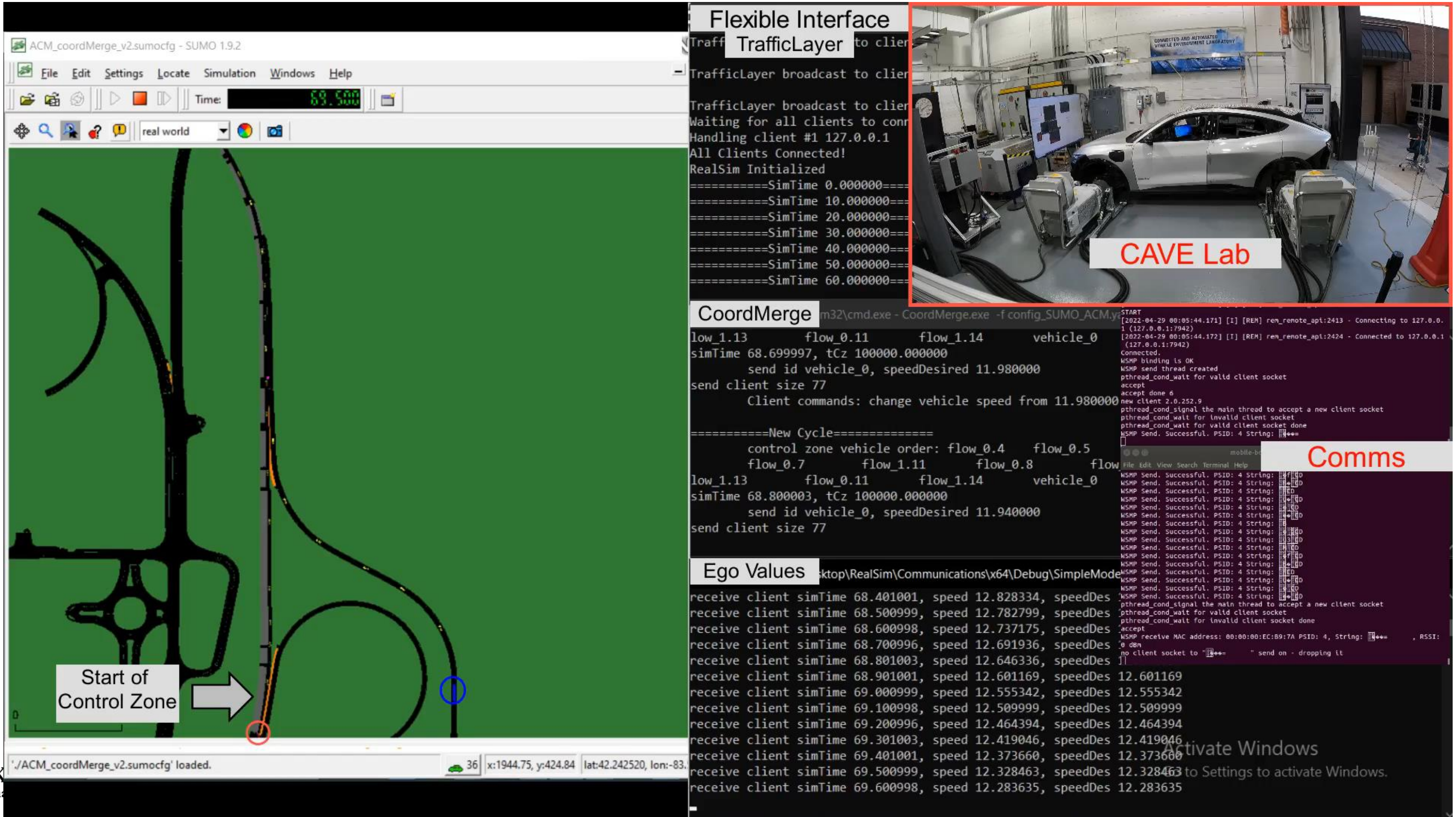
Passthrough while loop



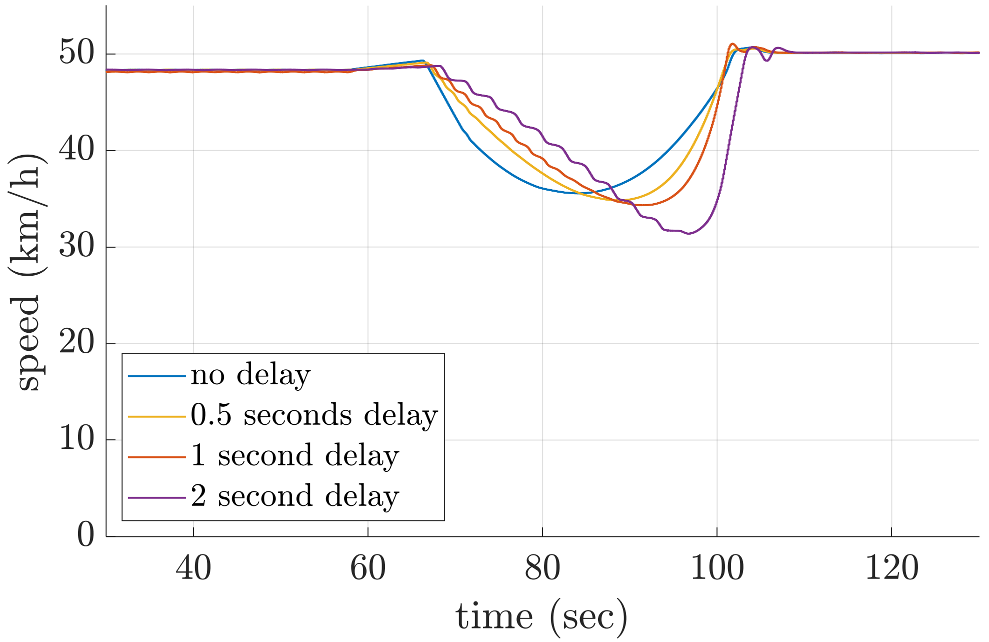


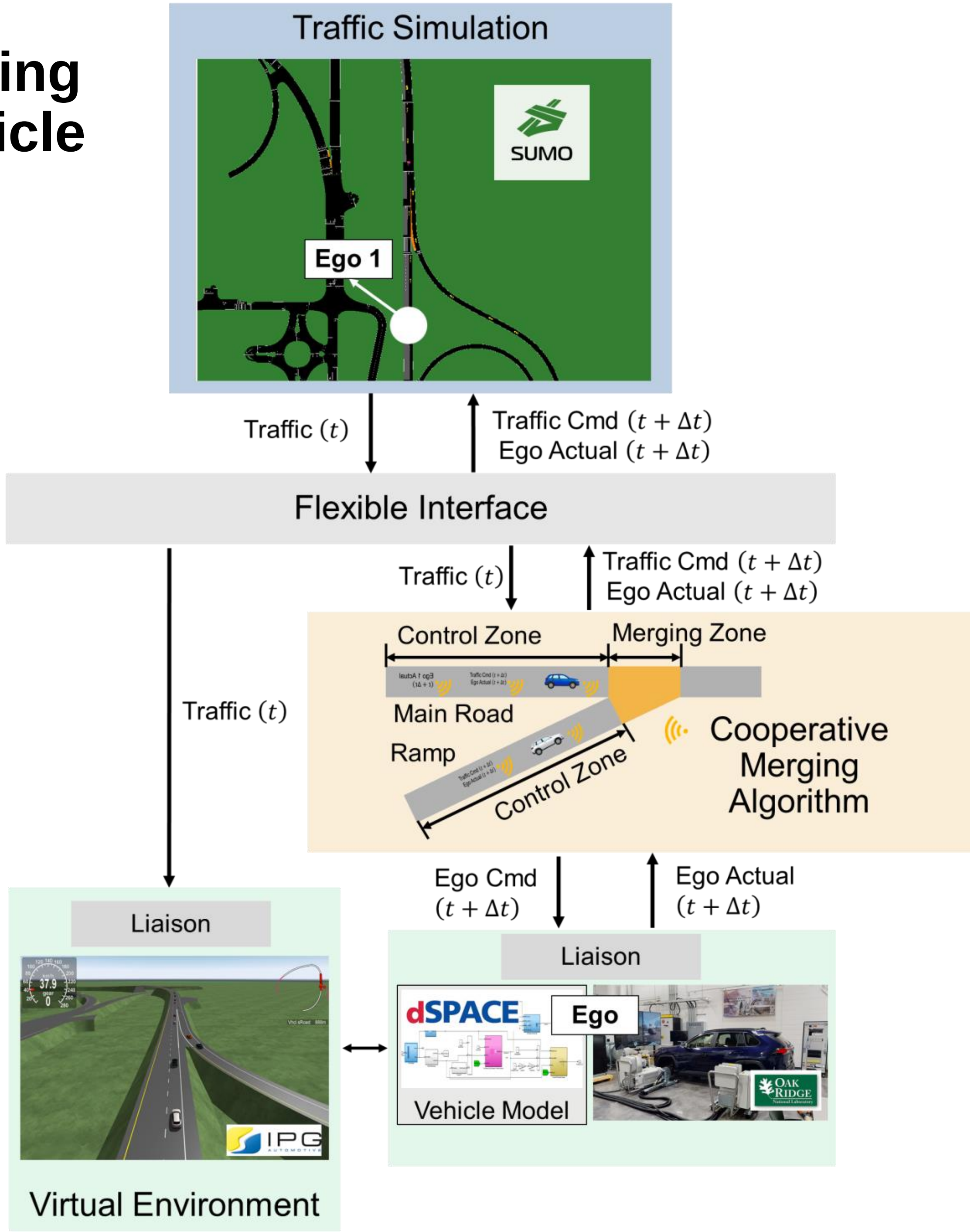


Accomplishment Task 2 – Coordination testing of real-time cooperative and automated vehicle merging utilizing full C-V2X hardware (video)



Accomplishment Task 2 – Coordination testing of real-time cooperative and automated vehicle merging utilizing full C-V2X hardware





- Constant delay has been added to between the control algorithm command (RSU) and the vehicle (OBU).
- The vehicle speed shows more oscillations (instability) and undesirable responses as communication delay increases.

Responses to Previous Year Reviewer Comments

- **"The approach was realistic and appropriate, although large in scope (which was acknowledged by the presenter). The reviewer wanted to know if the approach can be translated to MD and HD vehicles and if the CAVE Laboratory allows for translations to MD and HD."**
  - *Unfortunately, the CAVE Lab dynos are unable to handle vehicles class 2b or higher. However, all the approach and tools developed under this project can transfer over to MD/HD quite easily. There are aspects of J1939 and others MD/HD standards the actually make the task a little easier.*
- **"…good progress in integrating the various software. It may, perhaps, be worthwhile to talk with various software vendors, researchers overseas, and perhaps OEM labs as well to have them share what non-proprietary information they can share on how they intend to perform the same tasks laid out in the scope of this project, because it does seem that a process such as the one this project is developing would be of great interest to OEMs working on advanced driver-assisted systems (ADAS) and autonomous vehicles (AVs)"**
  - *With the field as large as it currently is (40+ companies in the space) it gets very difficult. We do however stay in contact with many of the OSS teams and solutions since that is also our main focus. We also have a handful of OEMs and software venders that we have NDAs with to have open discussion to help us better understand the space.*
  - *It has thankfully been of big interest to 3 different OEMs, 2 Universities, and 1 software vendor! For 2 of the OEMs we are actively sharing our VIL methods/interfaces as well as our flexible interface OSS in support of their work. We will be releasing an open-source version of the flexible interface this year. It will continue to be improved and supported through the EEMS101 Real-Sim 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.
IPG	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.
dSPACE	Support for the co-simulation bridges allowing for virtual environments to be executed in real-time with Vissim and SUMO. As well as collaborating on work with sensor emulation and ROS bridges.
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.

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.

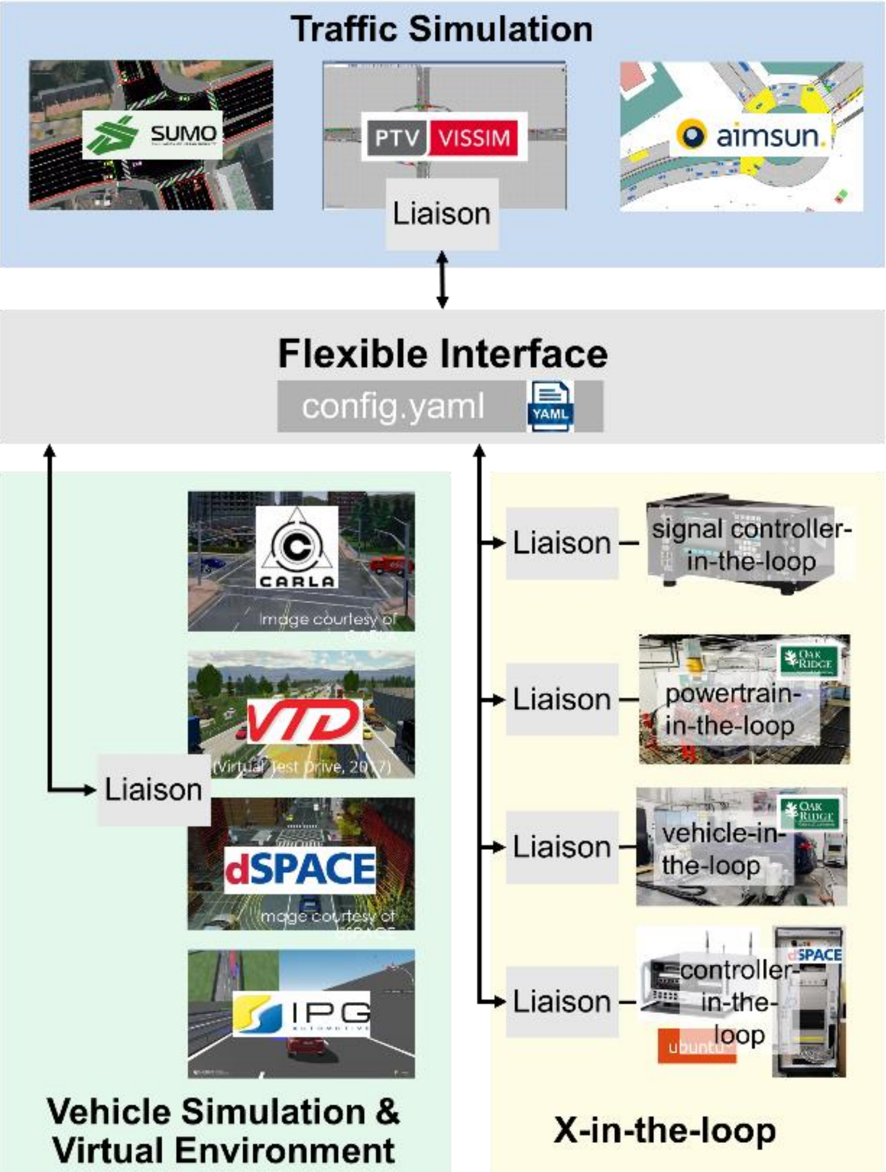
Enabled Future Research

VPPG → FOAs: UTC, U of AL

VPPG → Real-Sim

Real-Sim → EEMS095

Real-Sim → Real-Twin Lab Call; CDA Lab Call; Ford CRADA



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

- Project is completed but:
  - EEMS101 (RealSim) leverages this project as the basis for its current work.
  - The tools and facilities that were produced from this work are being used under User Agreements, FOAs, CRADAs, and other DOE Lab Call projects.
  - The Flexible interface for co-simulation and XIL will be released this year as OSS and will be supported under EEMS101 Real-Sim.

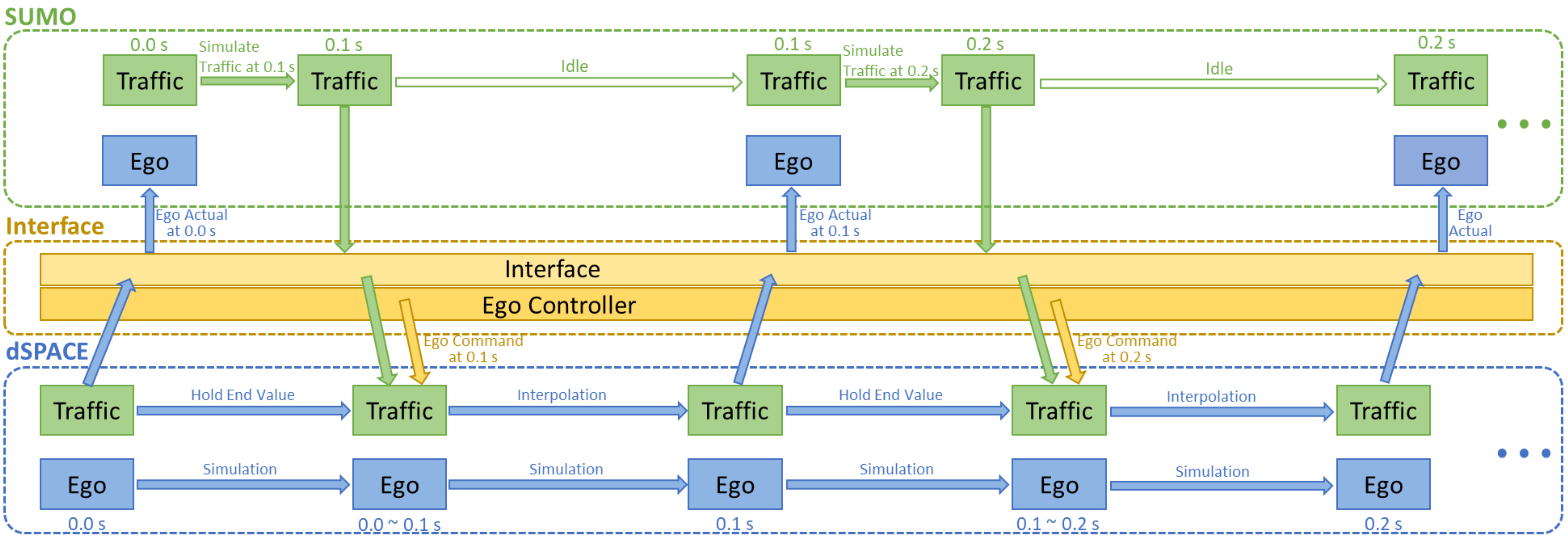
Technical Accomplishments

- New Connected and Automated Vehicle Environment (CAVE) Laboratory dyno system is fully functional and being used by the community.
- Flexible interface for co-simulation functional and ready for use by the community. Multi-Ego vehicle setup for multiple real-time connected labs enables multiple test cells/powertrains/vehicles.
- Laboratories include the possibilities of real V2X and traffic control systems.

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.