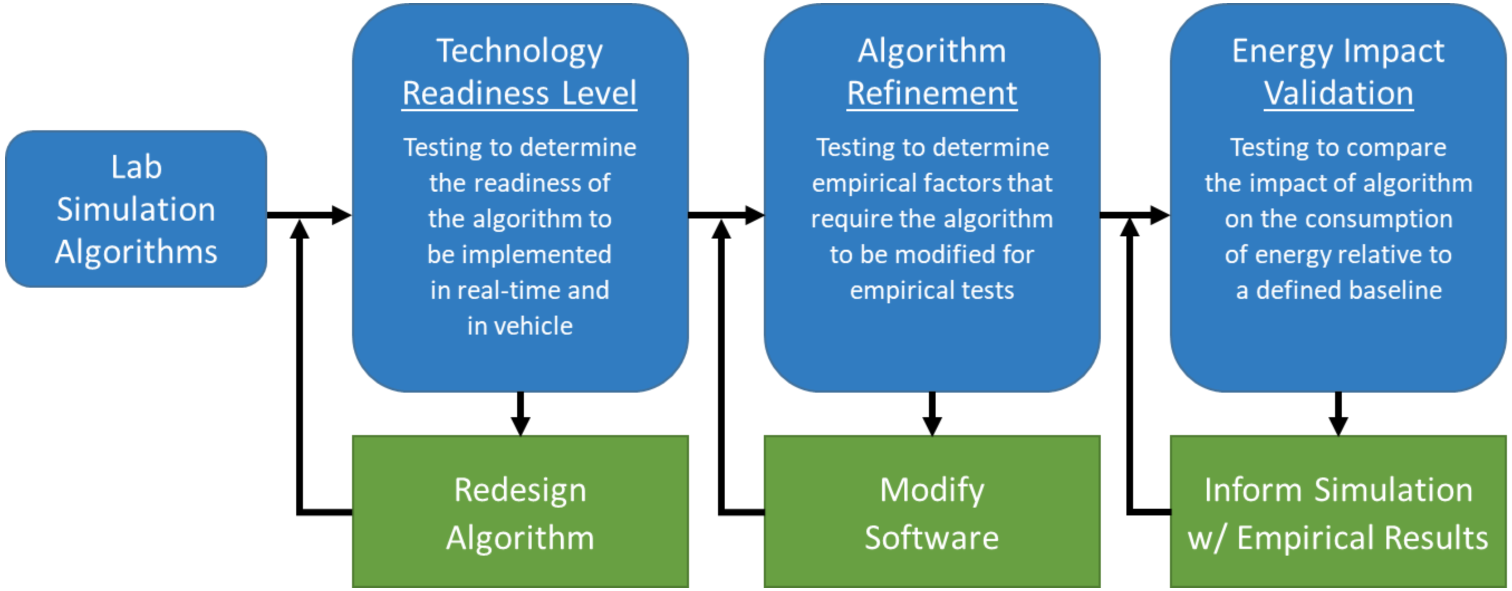
Validation of Connected and Automated Mobility System Modeling and Simulation



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American Center for Mobility

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Michigan Technological University

June 23, 2021

2021 DOE Vehicle Technologies Office
Annual Merit Review – Project ID: EEMS082

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Overview

- **Timeline**
  - Start: October 1, 2019
  - End: June 30, 2022*
  - 45% complete (milestone basis)

- **Budget**
  - Total $7,633,143
    - DOE $6,103,138
    - 20% Cost Share $1,530,005
  - BP1: 2020 $5,025,594
  - BP2: 2021 $2,607,549

** No cost project extension through June 30, 2022, due to COVID-19*

- **Barriers**
  - Real-world measurement of the energy impact of advanced controls enabled by connectivity and automation (multiplicity of noise and impact factors)
  - (Accurately predicting) the energy benefits derived from new mobility technologies in a mobility system context
  - Computational difficulty of accurately modeling and simulating large-scale transportation systems

- **Partners**
  - American Center for Mobility
  - Michigan Tech Research Institute
  - Michigan Technological University
  - Argonne National Laboratory
  - Oak Ridge National Laboratory
  - California PATH

Budget Period 1 on track to complete with results from Case 1

Relevance

Objectives

- Translate Lab algorithms into vehicle and infrastructure controls
- Conduct physical testing at a manageable scale
- Compare test results with simulation
- Interactively develop better models
- Integrate testing and simulation to expand the set of models that can be assessed

Impact on Barriers

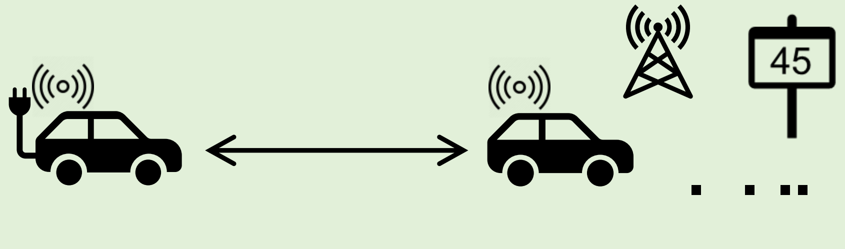
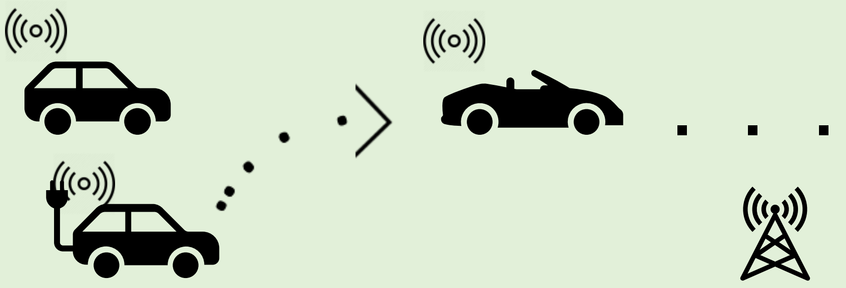
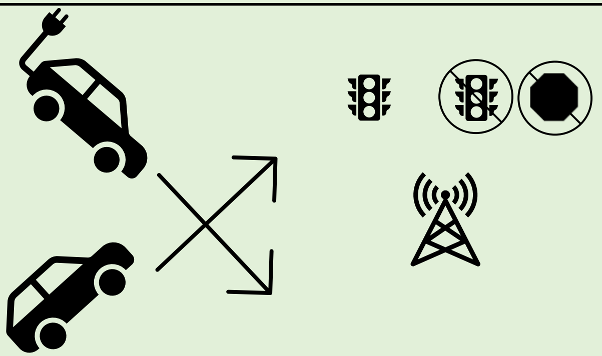
- Validated models reduces need for physical testing at large mobility system level scale
- Interactive development of models with the author improves its accuracy
- Validated models can provide an evaluation of proposed technology with reasonable cost and time

EEMS Relevant Goal

- Develop new tools, techniques, and core capabilities to understand & identify the most important levers to improve the energy productivity of future integrated mobility systems when adopted at scale

Approach

1) Build-up & configure test vehicles and infrastructure for testing of algorithms
2) Translate, integrate, and refine Lab algorithms into real-time vehicle and infrastructure controls
3) Test vehicles on track with Lab algorithms and models in coordinated scenarios
4) Compare results and modify accordingly

Energy Efficiency – Study Cases	
Case 1: Speed Harmonization	
Case 2: Merging	
Case 3: Intersections & Eco-Driving	

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Common approach for energy efficiency estimation for 3 study cases

Milestones

Milestones	BP1 (including COVID extension)							BP2				Success Criteria
	2019	2020				2021				2022		
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	
Integrate National Lab Model Criteria	Task 1.1, 2.1, 3.1 ✓							Task 2.1		Task 3.1		Key data elements agreed
Design Experiments Complete	Task 1.2, 2.2, 3.2 ✓											Experimental design complete
Test Vehicle Setup	Task 1.3, 2.3, 3.3 ✓											Highly automated vehicle experimental platform complete
Conduct Experiments				Tasks 1.4, 1.5, 1.6		Tasks 1.5, 1.6 Ongoing						Model integration and, Functional testing
Exp complete **(Go/No Go)**	***(1) Speed Harmonization***						Task 1,7, 1.8 Ongoing					Experimental testing
Design Experiments Complete								Task 2.2		Task 3..2		Experimental design
Test Vehicle Setup									Task 2.3		Task 3.3	Highly automated vehicle experimental platform
Conduct Experiments							***(2) Merging***	***(3) Intersection EcoDriving***	Task 2.4, 2.5, 2.6		Task 3.4, 3.5, 3.6	Experimental testing
Exp complete **(Go/No Go)**										Task 2.7, 2.8	Task 3.7, 3.8	Experimental testing is complete

45% complete on milestone basis, with COVID extension

Technical Progress and Accomplishments

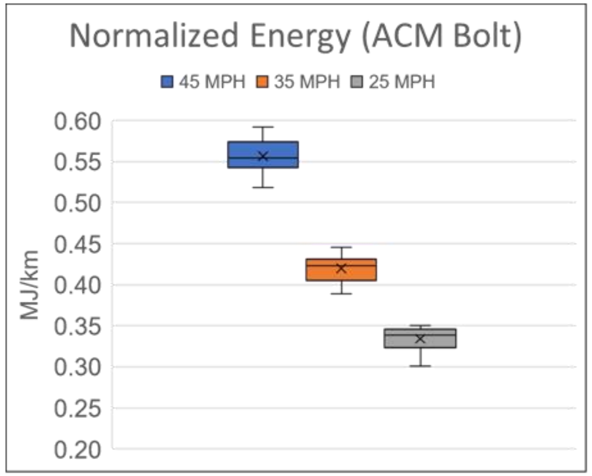
Michigan Tech Research Institute
Michigan Tech

- Five automated and connected vehicles developed for model integration and testing
- Model refinement, integration, and functional testing of centralized controller (ORNL) and in-vehicle controller (ANL)
- Facility network optimized for experiments (enabled immediate routing of information without buffering)
- Designed and conducted experiments on-track using trajectories recorded in virtual twin
- On-track vehicle baselining for energy and vehicle dynamics with automated vehicles
- Speed harmonization testing with optimized and human driver comparison
- Integration and functional testing for EcoDriving

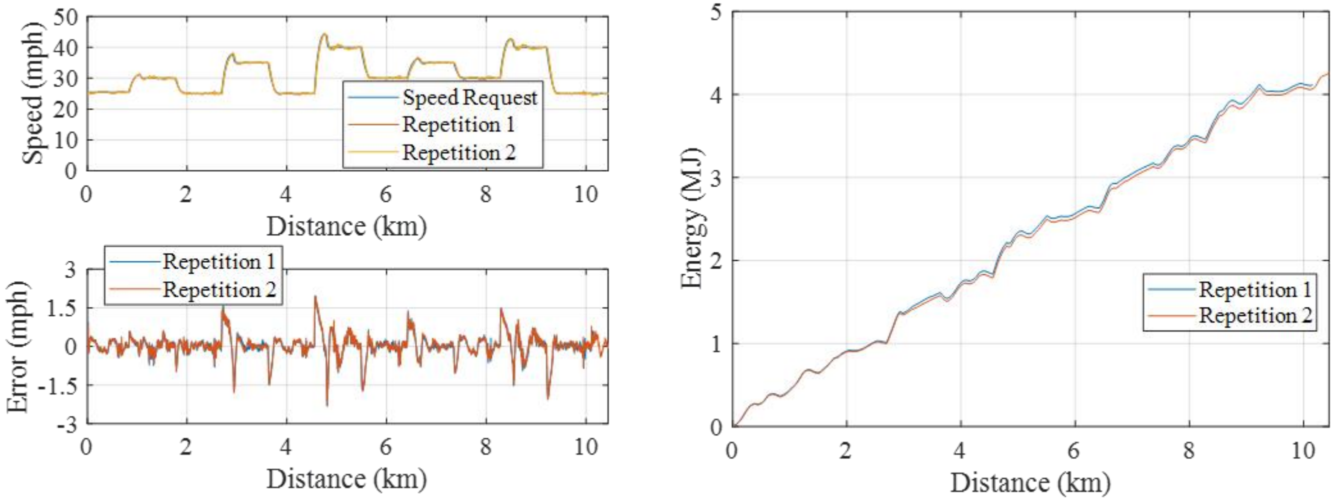
10 test programs conducted
100's of individual tests
Extensive data sets shared with Labs

Comprehensive Data Sets

Repeatability & Noise Factors



Speed Harmonization Optimal Profile Test Results



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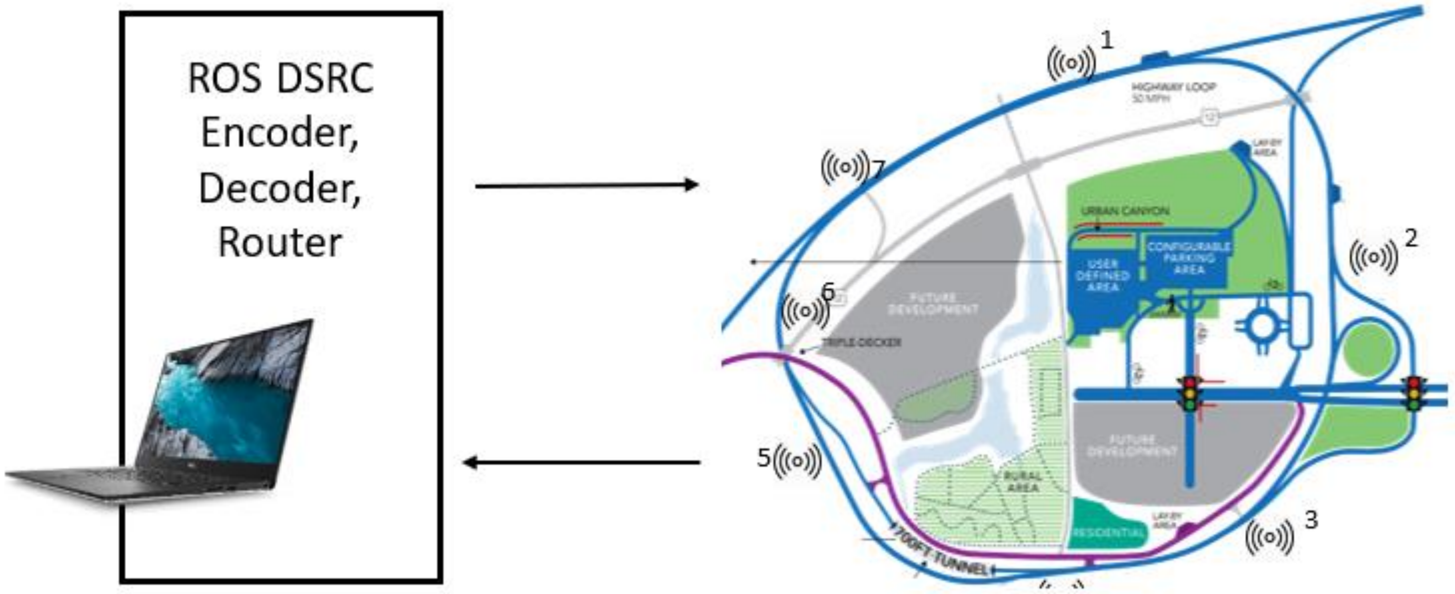
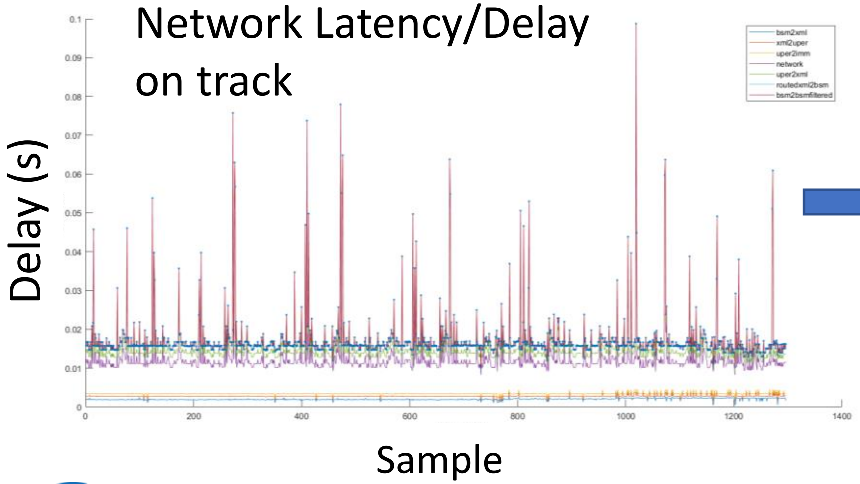
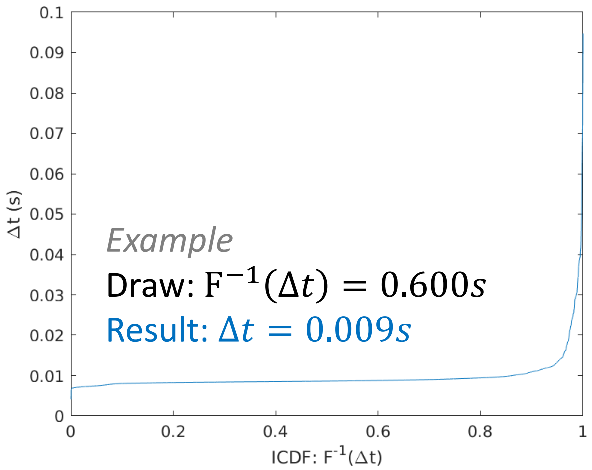
The in-vehicle controller for speed harmonization and functional testing is completed, with energy assessment to be complete in BP1.
Results show good performance and repeatability

Setup, Test, and Assessment of V2X Network







Network Profiling Methodology:

- Simulation sends out BSMs, RSU A transmits it, RSU B receives and sends it back to the simulation.
- Timestamp outgoing and incoming messages, as well as individual spots along the pipeline to profile the system.
- Network support for real time control is feasible, though traffic density will impact performance

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Network latency estimated ~10ms

Test Vehicle Setup: Instrumentation and Facility

ACM (Pacifica and Bolt)

- DBW and AV control

MTU (Bolt and 2 Volts)

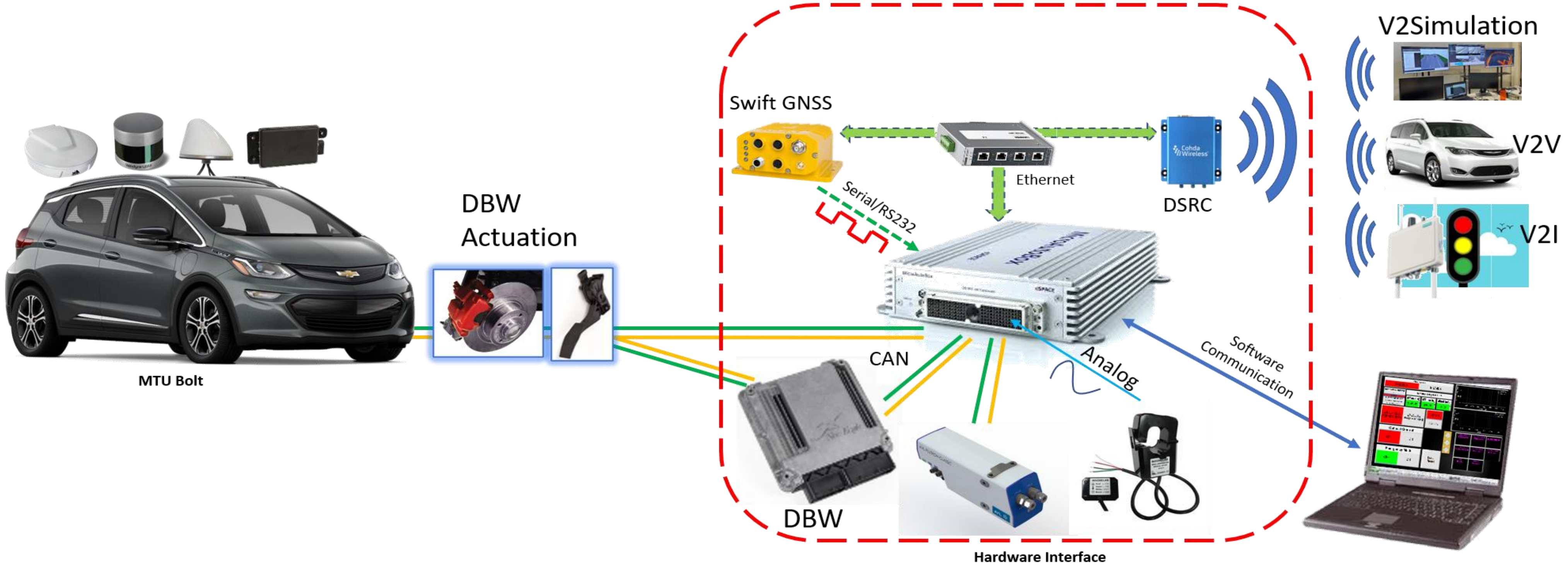
- DBW control

All vehicles

- Instrumentation
- Comms (V2x +)
- Controls and model integration
- Realtime interface
- Data recording and logging

DSRC performance improvements at ACM:

- 9 RSU's replaced and with software updates for all RSU's
- Firmware updates to 14 RSU's



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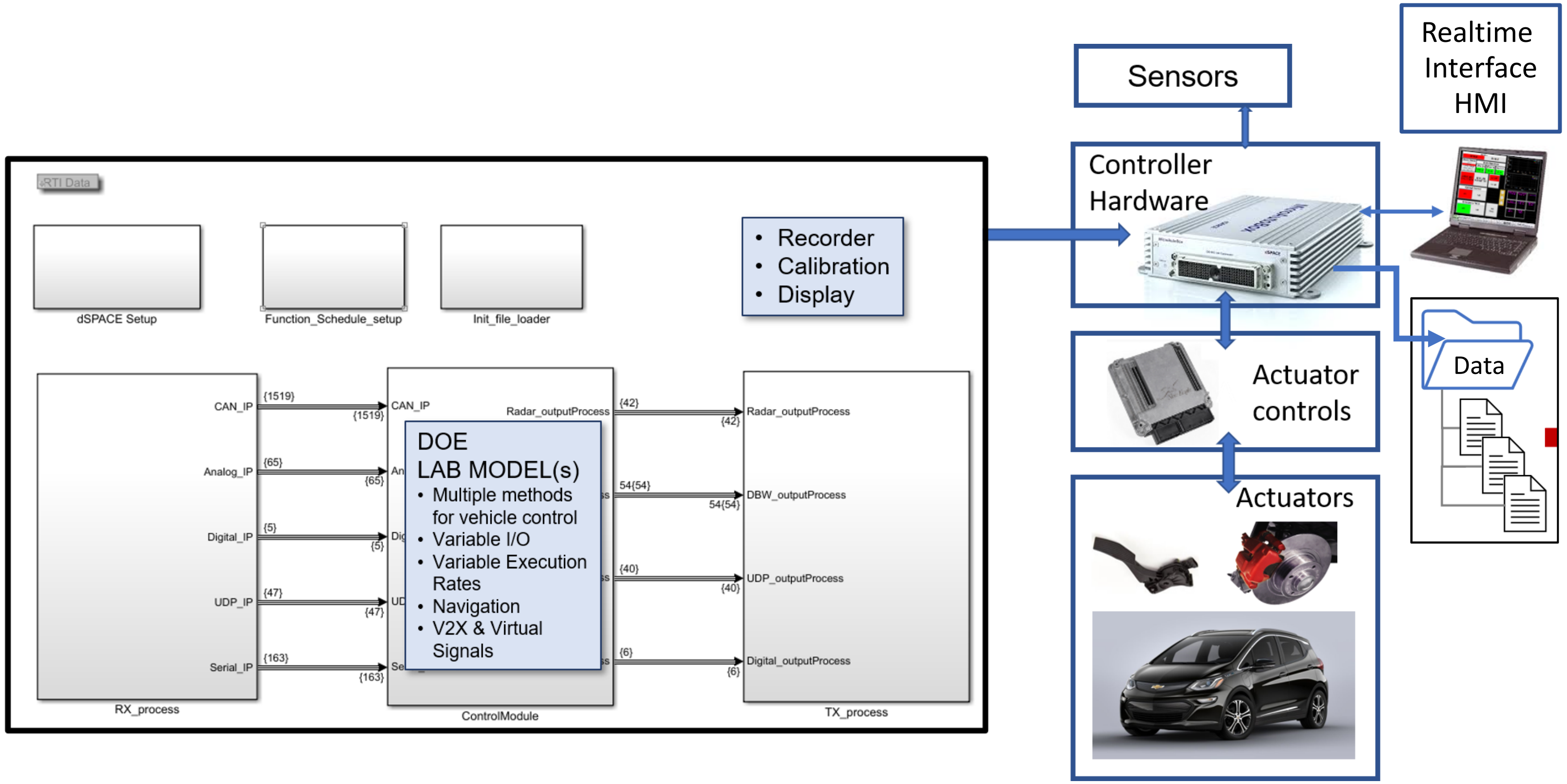
Five automated and connected vehicles developed for model integration and testing

Test Vehicle Setup – Software Architecture and Lab Model/Controller Integration



- Architected for adaptability with I/O wrapper to efficiently pass data
  - Multiple sources synced with model input requirements
  - Navigation module
- Customizable/variable update rates
- Configurable output to direct control longitudinal vehicle dynamics or high level speed control
- Scalable to expand and incorporate additional real-time control algorithms, estimators, and HMI

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Software/Control architecture developed to integrate variances in Lab controllers and controllers for baselining

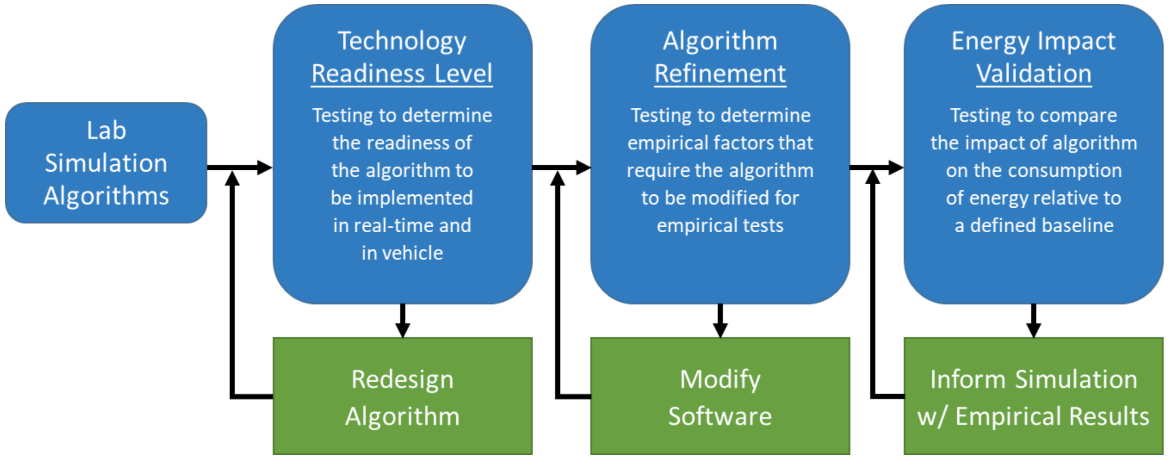
Integrate National Laboratory Algorithms

Oak Ridge National Labs

- Centralized controller algorithms implemented
- Speed Harmonization algorithm has been implemented and tested in simulation.
- Interfaces for VTD to communicate with ROS for testing at track, to communicate with DBW systems, has been implemented
- Network latency model implemented and demonstrated using V2X application based on BSM-C. Requires empirical data measured on ACM track
- Performance tests for Period 1 Speed Harmonization complete

Argonne National Labs

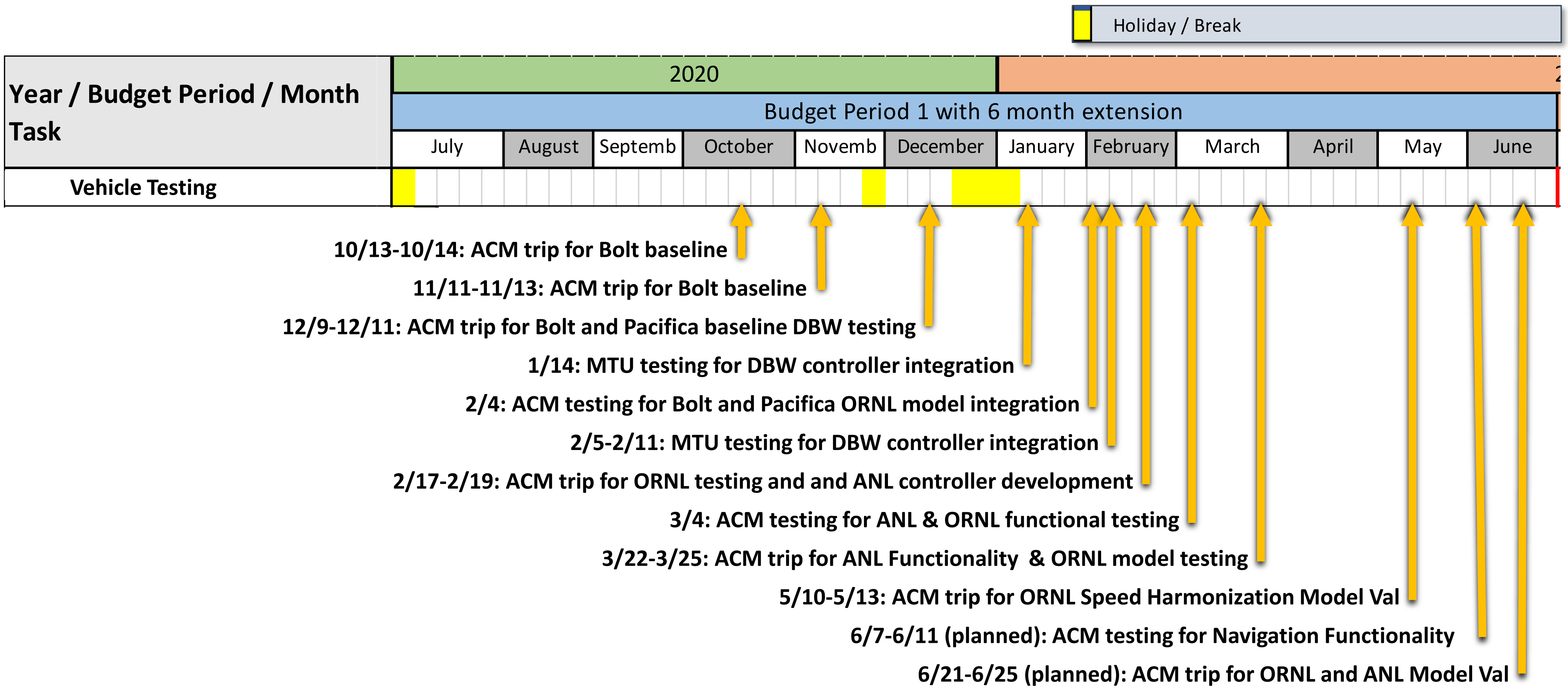
- Control integration, refinement, and functional testing in vehicle nearing completion
- Finalize functional testing in Q1 BP2. Complete Model Val testing



Iterative Process

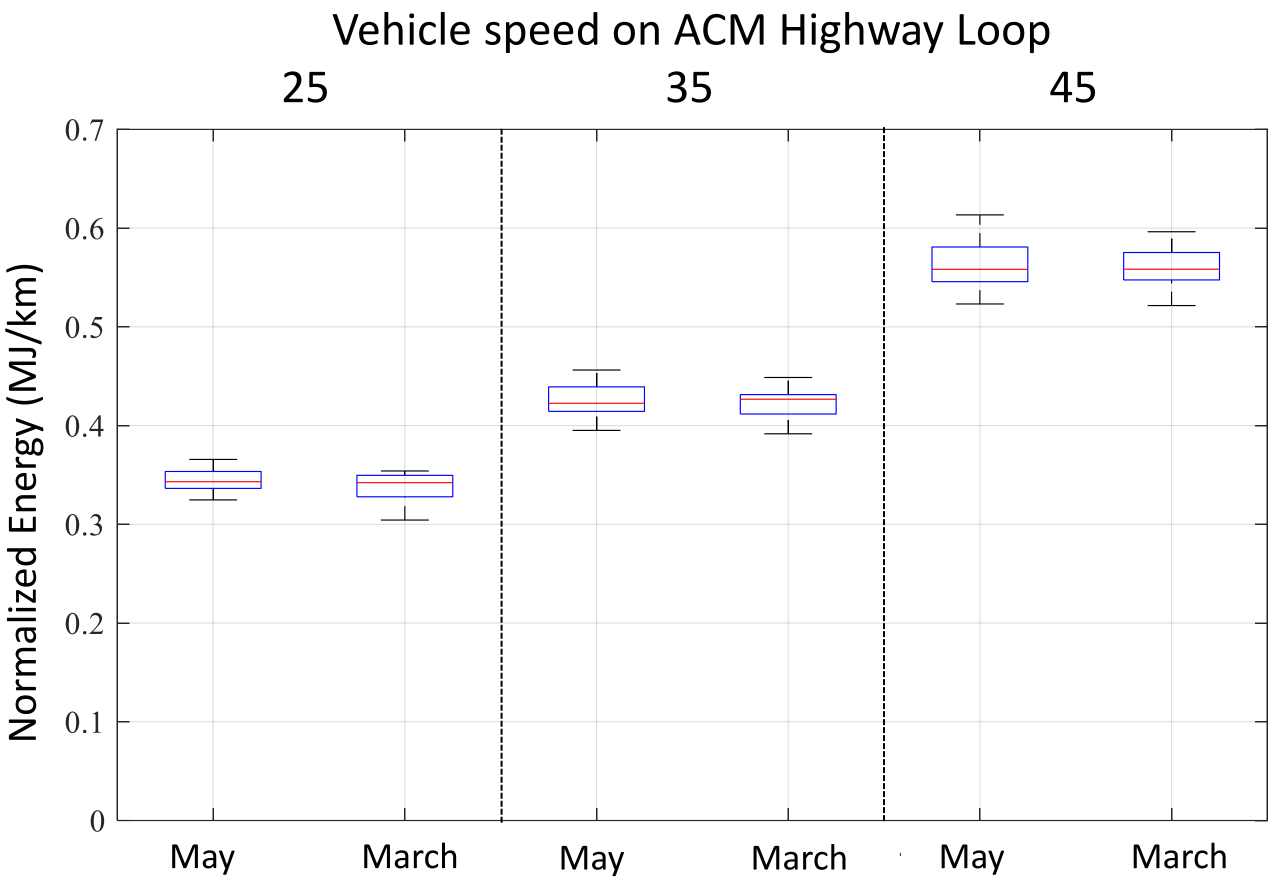
ORNL and ANL controllers integrated and tested; data shared via Livewire

Vehicle Testing Overview



Testing ongoing through June 2021 to support BP1

ACM Bolt - Baseline Tests – March and May comparison



Multivariable regression analysis underway to determine noise factors

	March			May		
Speed (MPH)	# of Tests	Mean normalized energy (MJ/km)	COV (%)	# of Tests	Mean normalized energy (MJ/km)	COV (%)
45	10	0.558	3%	20	0.558	4%
35	10	0.427	4%	20	0.423	4%
25	10	0.342	6%	20	0.343	4%

Two sample t test, assuming unequal variances (Welch's t-test)

$$t = \frac{\overline{X_1} - \overline{X_2}}{\sqrt{\sigma_{X1}^2 + \sigma_{X2}^2}}, \sigma_{X1}^2 = \frac{s_{X1}^2}{n_1}$$

For 95 % confidence,
→ t-statistic < 1.7,

∴ **2 sample populations are the same**.

Speed (MPH)	t- Statistic
45	0.4
35	0.3
25	1.1

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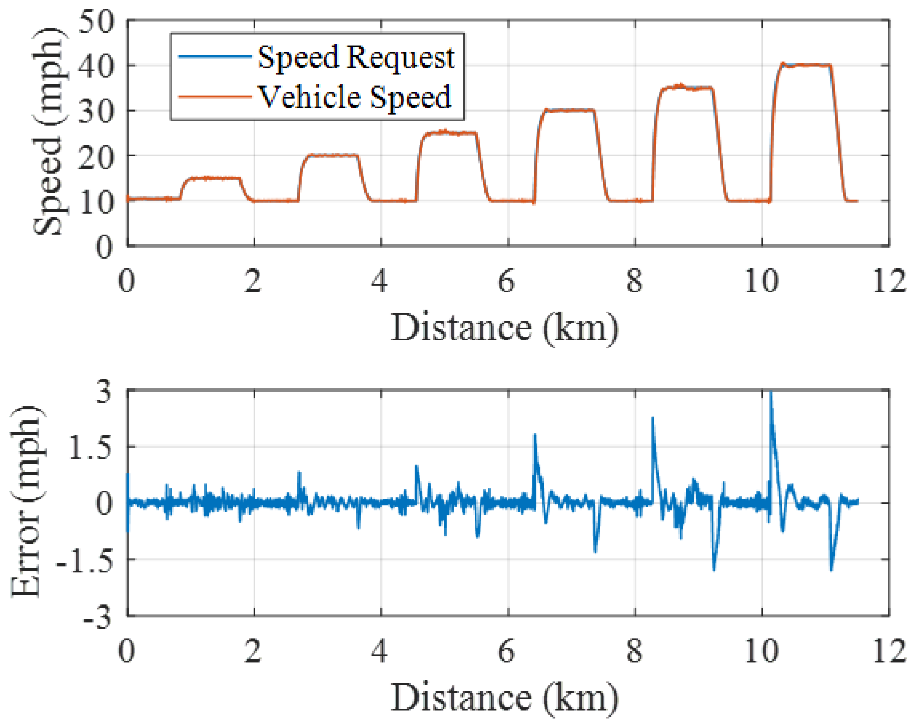
Control Tests: High number of tests conducted to determine vehicle baselines, repeatability, and track for changes

Controller Vehicle Performance Summary

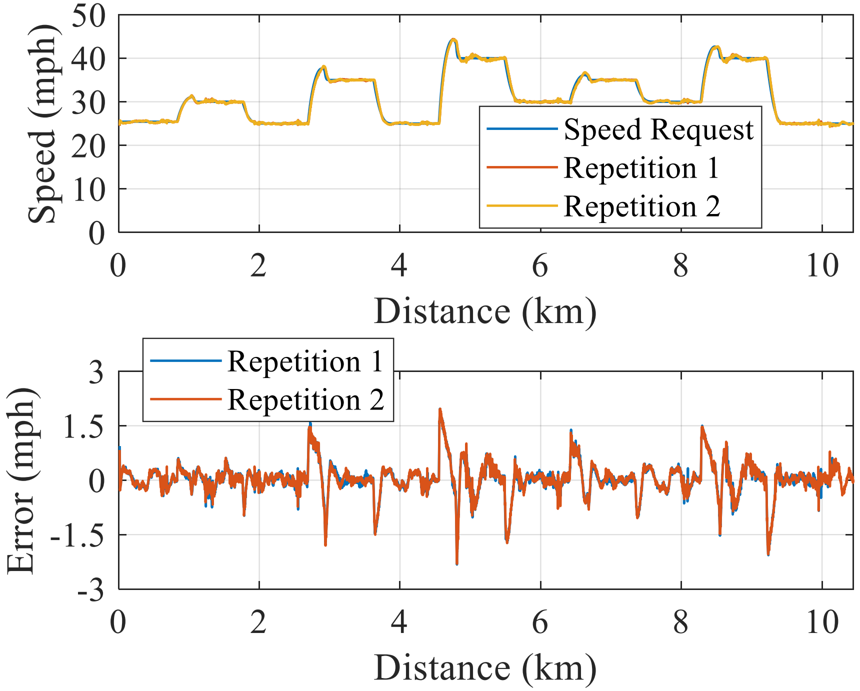


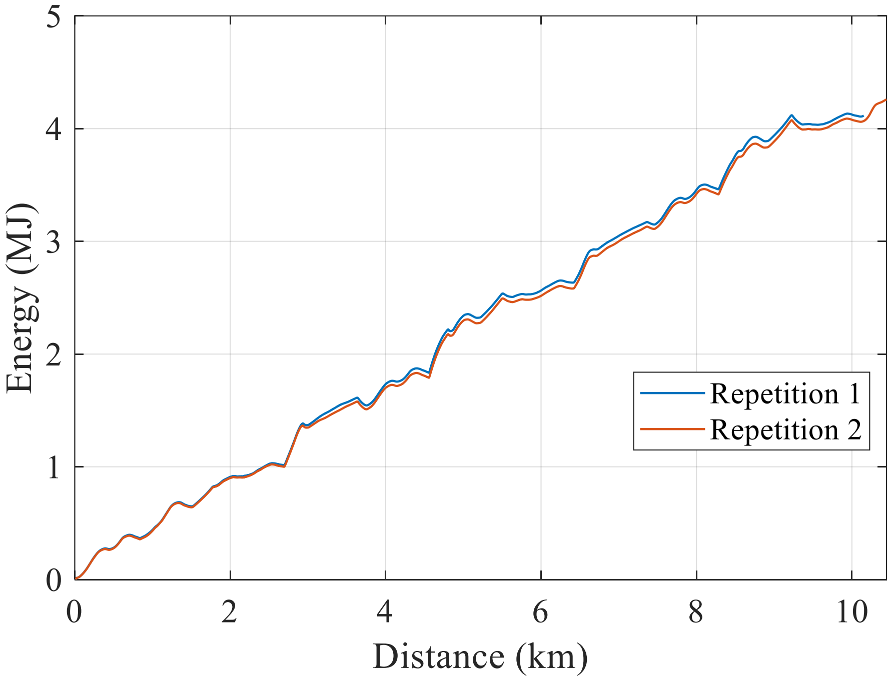
S.No	Speed Profile Details	Mean Error (mph)	RMS Error (mph)	Maximum Error (mph)
1	MTRI Speed Profile 1	0.14	0.5	2.0
2	MTRI Speed Profile 2	0.17	0.6	2.8
3	MTRI Speed Profile 3	-0.05	0.7	0.9
4	MTRI Speed Profile 4	-0.01	0.4	0.9
5	ORNL Speed Profile 1	0.01	0.3	3.0
6	ORNL Speed Profile 2	0.01	0.2	2.3
7	ORNL Speed Profile 3	0.03	0.4	2.0
8	ORNL Speed Profile 4	0.03	0.4	1.6
9	ORNL Speed Profile 5	0.04	0.2	0.8
10	ORNL Speed Profile 6	0.03	0.2	0.6

- 10 scenarios tested: combination of simple profiles (MTRI), ORNL optimized speed harmonization, and simulated human driven profiles.
- Profiles provide baseline and comparisons for energy savings for model validation.

Vehicle longitudinal vehicle dynamics controller tuned and validated Lab Model Testing

Repeatability – ORNL Speed Profile 3





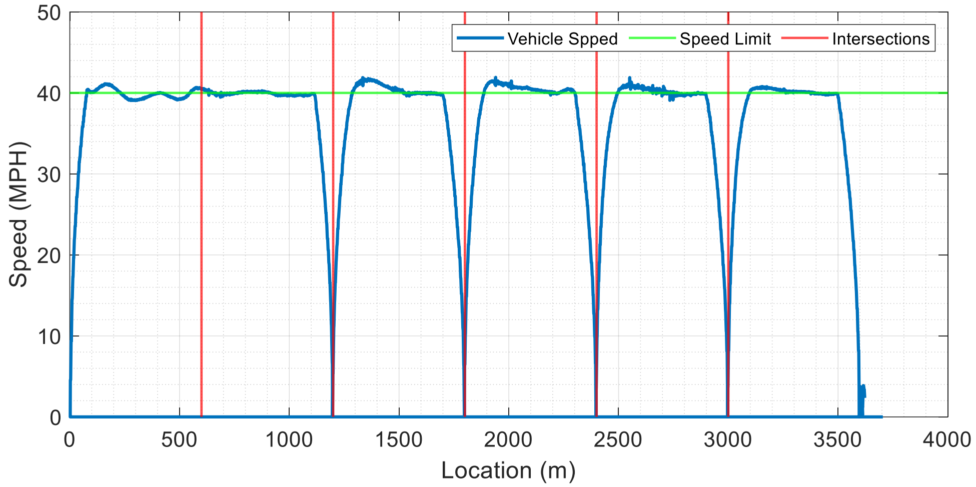
Property	Mean error (mph)	RMS error (mph)	Normalized energy (MJ/km)
Repetition 1	0.03	0.41	0.403
Repetition 2	0.03	0.41	0.411

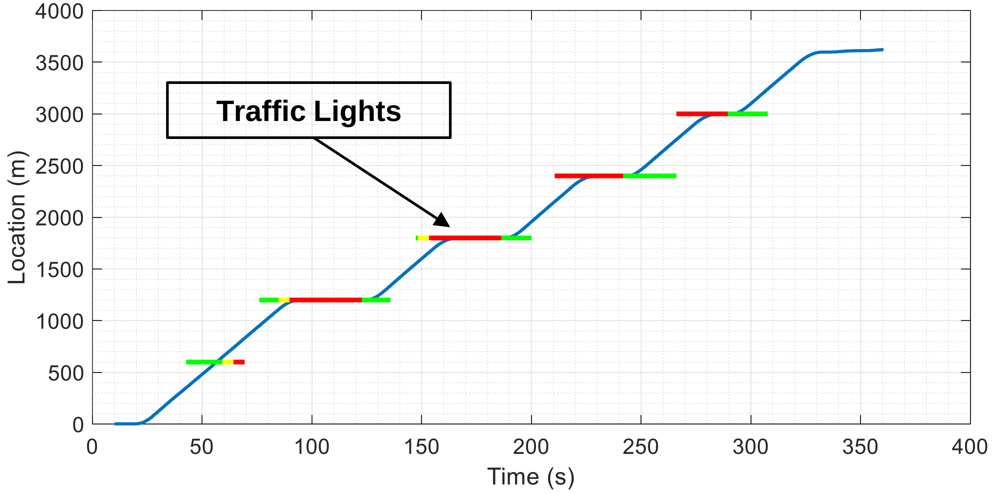
Profiles set and being repeated over multiple trips. Analyze for energy and noise factors in comparison to human models.

ANL Eco-Driving Functionality Testing (5 stop light corridor)

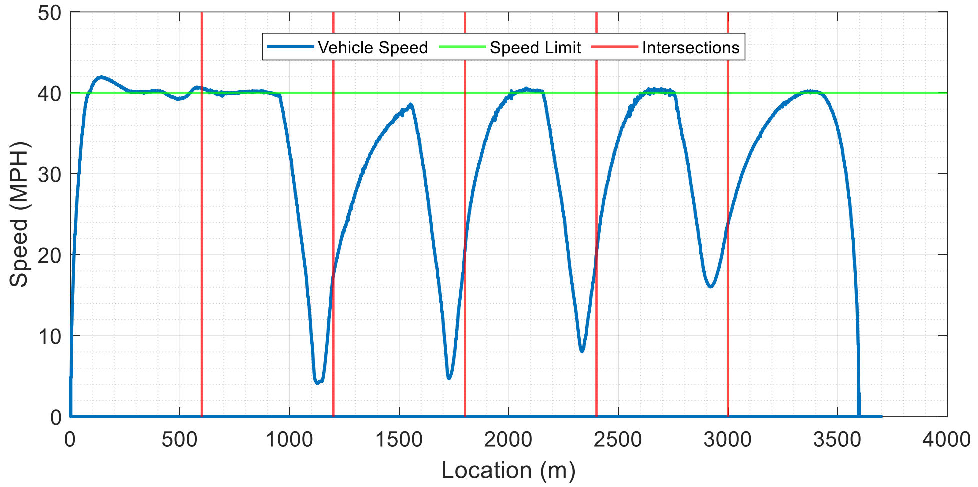
- Vehicle accelerates to speed limit, slows and passes through green phases at traffic lights
- With V2I On, vehicle adjusts its speed to pass through Traffic Lights without stopping

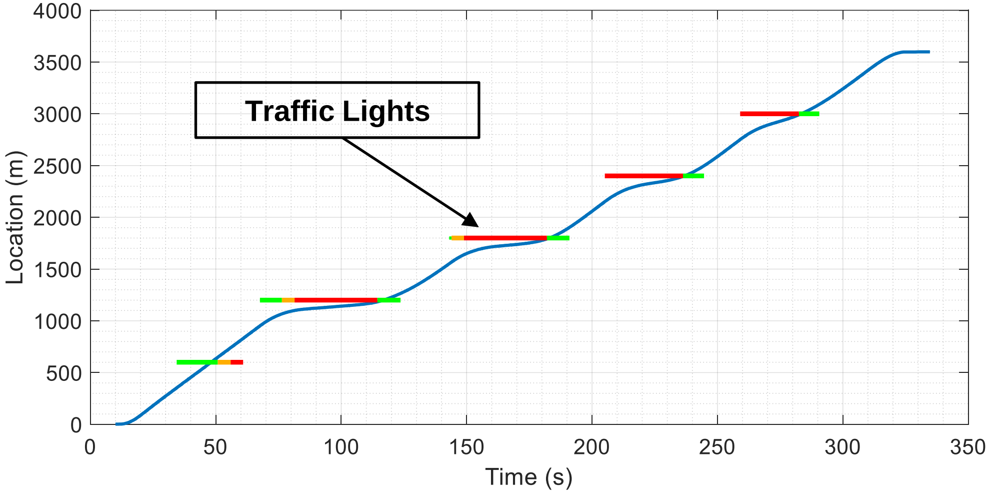
V2I Off





V2I On





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Complex scenarios with multiple intersections developed for testing.
Navigation with V2X interface provides input controller & optimizer.

Response to Previous Years Comments

Comment	Response
Ensure human drivers are properly represented in the simulation. Calibrate VISSIM for human driver behavior, by using trajectory-level data	Human model driving may be considered in a future extension of the project
No performance indicators in presentation for identifying progress towards project goals	Success criteria for each milestone have been defined upfront in the PMP and is now shown in the Milestone slide
Project seems slightly behind planned progress, but fairly understandable considering COVID-19	No cost Project Extension approved through June 30, 2022 – Extensive testing in last Q's
There is a clear chart of responsibilities and regular meeting cadence; Collaboration appears to be well coordinated.	Comments are very well appreciated by the team
It is important to start validating transportation system-level benefits (e.g., can 4,000 vehicles per hour per lane capacities using CACC). This project is a huge step towards getting such data	Mixed reality systems have been developed through this project to enable getting such data
Should have an industry partner	Consortium team was identified by DOE, without industry partner

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Majority of previous year comments addressed
in current year's work

Team Collaboration and Coordination

Partners

American Center for Mobility — PI, PM, Test Facility

Michigan Tech Research Institute — Virtual Traffic, Data Analysis, Robotic Control

Michigan Technological University — Algorithm Translation, Data Analysis, Vehicle Control

Collaborating (Separately Funded)

Oak Ridge National Laboratory · Argonne National Laboratory · NREL Transforming ENERGY

Algorithms, Models, Simulation, Vehicle Characterization, Livewire

- ORNL engineer representing all Labs, co-located at ACM through June 2021
- Special consultant team support appointed by U.S. DOE
- MTU/MTRI team co-located at ACM during development and testing – participation by lab members when possible
- Weekly meetings – Quad chart-driven (Progress, Goals, Lessons, Help Needed)

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Active collaboration across all groups and labs, supported by DOE

Remaining Challenges and Barriers

- Conversion, updating, and integration of models to work in distributed real-world environment in vehicle
- Enable message encoding-decoding across network of infrastructure, and virtual and physical vehicles utilizing standard DSRC message protocols
- Implementation of multiple realistic vehicles in simulation working in real-time with on-track vehicles
- Develop test cases for successful acceptance of algorithms in transition to test platforms
- Identify potentially confounding variables in simulation and approach to limit impact in design and conduction of experiments
- Quantify sensitivity of models to input parameters
- Determine and quantify variability and noise factors for on-track testing

Planned and Future Research

PLANNED: Budget Period 1 (2021)

- Complete experiments related to Speed Harmonization test case
- Characterize network performance

PLANNED: Budget Period 2 (2021-2022)

- Complete Cases (2) Merging and (3) Intersection and EcoDriving
  - Complete Experimental Design
  - Complete Vehicle Setup and Model Integration
  - Run experiments
- Publish Results

FUTURE

- Extend scope to include new use cases:
  - Highway corridor (public smart roadway)
  - Dynamic wireless power transfer roadway
  - Traffic-aware intersection
  - Impact of congestion
  - Multi vehicle physical testing
- Evaluation with more highly automated vehicles
- Cyber-security issues
- Integrations with vulnerable road users
- Include additional complexity related to mixed traffic, CAV penetration, and weather

Any proposed future work is subject to change based on funding levels

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BP1 plan on-track for completion. BP2 tasks well-defined and future scope identified

Summary

Objectives	Approach	Accomplishments	Planned & Future
• Translate Lab algorithms into vehicle and infrastructure controls • Conduct physical testing at a manageable scale • Compare test results with simulation • Interactively develop better models • Integrate testing and simulation to expand the set of models that can be assessed	• Prepare Lab algorithms for implementation into vehicle and infrastructure controls • Build physical vehicles and infrastructure for testing of algorithms • Test vehicles with lab algorithms and models in coordinated scenarios at a specialized track • Compare results and modify accordingly	• Automated vehicle controls and instrumentation • Vehicle baselining • Lab model refinement and integration • Real-time implementation of lab controllers • Speed harmonization testing • Data generated and shared.	**Planned:** • Virtual traffic integration • Speed harmonization, Merging, Intersection tests **Future:** • Public highway corridor • Dynamic wireless power transfer roadway • Traffic-aware intersection • Congestion, Cyber, VRUs • Weather

Any proposed future work is subject to change based on funding levels

Project on target to meet goals, with future objectives identified