Final Scientific and Technical Report

Project Title: Energy Optimization of Light and Heavy-Duty Vehicle Cohorts of Mixed Connectivity, Automation and Propulsion System Capabilities via Meshed V2V-V2I and Expanded Data Sharing

Award Number: DE-EE0009209

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Report Number: EERE.FY23.Final Technical Report

Date of Report: October 28, 2023

Reporting Period: October 1, 2020 – June 30, 2023

Acknowledgement and Legal Disclaimer Statements:
This material is based upon work supported by the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) under the Vehicle Technologies Office Energy Efficient Mobility Systems award number DE-EE0009209.

Project Executive Summary

Vehicle connectivity and automated driving technologies individually have the potential to decrease energy consumption and/or increase safety on light, medium or heavy duty vehicles to varying degrees depending on the traffic infrastructure and specific driving scenarios. Due to advances in sensing, perception and computing power, research and development emphasis in the mobility sector has shifted away from connectivity. Prior research has shown that driving automation with the absence of connectivity can in certain circumstances increase energy consumption [1]. The effectiveness of synergizing connectivity and driving automation technologies is the focus of this work, specifically applied to vehicle cohorts of mixed composition, light and heavy duty, and powertrains ranging from all electric to conventional internal combustion engine.

The project team is led by Michigan Technological University (MTU) and partnered with AVL Mobility Technologies Inc. (AVL), Borg Warner (BW), Traffic Technology Services (TTS), American Center for Mobility (ACM) and Navistar (NAV). The main thrusts for the team are to develop a micro-traffic simulation environment with specific VD&PT system attributes and CAV capabilities, 2) field a vehicle test fleet of mixed classification, propulsion and CAV capacity, 3) develop artificial intelligence (AI) and machine learning (ML) based multi-agent optimization methods for various traffic infrastructures, 4) integrate the virtual environment and the optimization methods then deploy the system as a CAV hardware in the loop (HiL) for the vehicle test fleet and 5) conduct closed track and public road testing to validate simulation and demonstrated energy and mobility improvements at multiple scales. For a cohort of mixed vehicles, the team will demonstrate a reduction of energy consumption of 10-50% [2, 3] at intersection, arterial roadway and limited access highway scenarios through connectivity and automation in simulation and at a closed test track . The energy reduction objectives of the project are summarized in Table 1, indicating the infrastructure and over what distances are relevant considered. Single scenario energy reductions are not relevant and thus, the research team took the approach to vary parameters associated with the infrastructure, vehicle cohort composition and dynamic behavior to generate energy consumption distributions for both unconnected and connected scenarios.

Table 1. Project energy reduction objectives as a function of infrastructure, distances and factors associated with vehicle, cohort, connectivity and traffic signal timing.

Infrastructure	Maneuver Description	Distance	** Energy Savings	Results Method	Number of Vehicles in Cohort
1.) Signalized Intersection	Approach	~ 0.4 km	20 to 50 %	Simulation, Closed Test Track, Public Roads	2 to 6
	Departure	~ 0.3 km	10 to 40 %	Simulation, Closed Test Track, Public Roads	2 to 6
2.) Arterial Corridor	Multi-lane, intersection corridor	up to 8 km	10 to 25 %	Simulation, Closed Test Track, Public Roads	4 to 8
	Speed changes & merging	up to 8 km	15 to 25 %	Simulation, Closed Test Track, Public Roads	2 to 4
3.) Highway Driving	Limited access highway driving	up to 16 km	10 to 15 %	Simulation, Closed Test Track	4 to 8
4.) Integrated Drive Cycle	Includes infrastructures 1 thru 3 in an amalgamated closed test track configuration	20 km	10 to 25 %	Simulation, Closed Test Track	4 to 8
** Anticipated range of energy savings, but highly dependent on infrastructure, maneuver, cohort composition and					

Simulation & Test Factors
of Vehicles in Cohort
Propulsion Systems
Connectivity Penetration
Automation Penetration
of Lanes & Utilization (where appropriate)
Vehicle mass & road load attributes

Project Objectives and Accomplishments Relative to SOPO

The project award allowed the research team of MTU, ACM, AVL, BW, NAV and TTS to demonstrate energy savings of connected and automated vehicle cohorts on various traffic infrastructures both virtually and utilizing five CAV test vehicles on closed test track. The focus of the project was developing simulation capabilities correlated with test vehicles in parallel with developing predictive control tools governing optimal behavior relative to energy, safety and comfort, followed by establishing cellular data communications from infrastructure, vehicles and a centralized compute platform providing optimal control commands for the vehicle cohorts and finally physical demonstration on closed test track.

The tasks and milestones were created to achieve these objectives and successfully demonstrate energy reductions through synergy of connectivity and automation as laid out in Attachment 1 SOPO at the beginning of the project. The actual performance relative to these tasks and milestones are summarized as follows:

Task 0.0 – Project Management and Planning:
The prime recipient, MTU along with sub-recipients BW, AVL, NAV, TTS and ACM shall develop and maintain the Project Management Plan (PMP).
Start: 10/01/2020 Scheduled End: 06/30/2023 Percent Complete: 100%

- The task is complete.

Task 0.1- Kick-Off Meeting:
All teaming partners (MTU, AVL, BW, NAV, ACM, and TTS) will participate in a project kickoff meeting with the DOE within 30 days of project initiation.
Start: 10/01/2020 Scheduled End: 10/23/2020 Percent Complete: 100%

- The task is complete.

Task 0.2 – Setup Data Distribution on EEMS Repository
All teaming partners will work with the EEMS Livewire Data Platform f and select the best route for integrating data per intellectual property concerns for all project team members.
Start: 10/01/2020 Scheduled End: 06/30/2023 Percent Complete: 90%

- MTU has set up a LiveWire account and has access to the site.
- The team has completed five test trips to ACM and SE Michigan to collect data for model correlation, verification of the System of System model environment, optimization algorithm and C-V2x all operating real time with multi-vehicle cohort.
- The research team continues to organize data and create detailed descriptions of data files to be posted and is initiating the process of uploading to Livewire. All vehicle test data to upload has been identified and signal list to post has also been generated for each vehicle. The data uploading process will begin and be completed by the end of calendar year 2023.

Budget Period 1: Phase 1 - Technology Development

Task 1.1 – Simulation environment development – infrastructure-traffic:
Start: 10/01/2020 Scheduled End: 09/30/2021 Percent Complete: 100%
The team has completed the simulation environment setup and infrastructure required for the project and objectives. Minor efforts will continue the refinement of the interfaces for broad DoE's, maneuver visualization and specific test environment conditions.

Subtask 1.1.1 – AVL in conjunction with MTU, BW and NAV will perform initial setup of a micro traffic co-simulation system of systems environment that includes traffic infrastructures (intersection, arterial roadway, and limited access highway), LD and HD vehicle types, diverse propulsion systems, variable vehicle traffic, V2x and I2x connectivity and driver models for human and automated driving levels. The vehicle propulsion systems will include BEV, HEV, PHEV and ICE architectures with suitable component hardware details for the class of vehicle (LD or HD) that meet typical on road performance criteria. Driving automation will range from SAE L0 to L3+ as described by SAE in J3016.
Start: 10/01/2020 Scheduled End: 06/30/2021 Percent Complete: 100%

- The task is complete but will continue to see continuous improvements to the modeling environment until the conclusion of the project.

Subtask 1.1.2 – BW, NAV and MTU will begin full order VEHICLE-PROPULSION model creation for all vehicle types that are part of the project followed by model order reduction for computation efficiency.
Start: 10/01/2020 Scheduled End: 09/30/2021 Percent Complete: 100%

- The matrix of virtual vehicle-propulsion systems has been completed.

Subtask 1.1.3 – AVL in close cooperation with BW, NAV and MTU will begin integration of VEHICLE-PROPULSION and infrastructure-traffic simulation models within the co-simulation environment. The number of agents in the co-simulation environment will not be limited to the number of or the specific vehicle-propulsion system architectures of the test vehicles available. Exploration of the size of cohort that can be managed by the optimization algorithms and maintaining near real-time behavior will be explored.
Start: 01/01/2021 Scheduled End: 09/30/2021 Percent Complete: 100%

- The matrix of virtual vehicle-propulsion systems has been completed.

Task 1.2 – Expand connectivity data sharing communication stream(s) for energy considerations:
Start: 10/01/2020 Scheduled End: 06/30/2021 Percent Complete: 100%
MTU and AVL have developed the full list of expanded V2x signals that encompasses various powertrains and vehicle classifications and linked the ability to share this data using Model.Connect within the simulation environment. The list includes those found in SAE J2735 and those deemed necessary to develop a comprehensive optimization algorithm for coordinating a diverse cohort for reduced energy consumption.

Subtask 1.2.1 –In close cooperation, MTU, AVL, BW and NAV will establish virtual connectivity flow and communication in the simulation environment, expanding upon SAE J2735 standard to include vehicle data such as propulsion state and energy consumption projections as well as vehicle automation level and automated driving state information.
Start: 10/01/2020 Scheduled End: 03/31/2021 Percent Complete: 100%

- The task is complete.

Subtask 1.2.2 – TTS will set up cellular communication at ACM's closed test track facility's signalized intersections, enabling cellular V2I-I2V that utilizes algorithms to estimate intersection SPaT that is required for EcoAND optimization. Test fleet vehicles and closed test track facility will also have DSRC based hardware that can be utilized, if necessary, in place of, in parallel with, or to confirm predicted SPaT from cellular system.
Start: 01/01/2021 Scheduled End: 06/30/2021 Percent Complete: 100%

- The task is complete.

Task 1.3 – Develop cloud-based cohort optimization algorithm(s)
Start: 04/01/2021 Scheduled End: 12/31/2021 Percent Complete: 100%

MTU and AVL have completed development of AI based optimization techniques for connected vehicle cohorts on single lane intersections, multi-lane arterial roadways and multi-lane, limited access highways. Results from parameterized Design of Experiments have established energy savings probability distribution functions that fit within the bounds of the AI training. Continuous improvements in implementation and training have taken place in Q7 that results in cohort based energy consumption with fewer energy increase events.

Subtask 1.3.1 – In close cooperation, MTU, AVL, BW and NAV will develop a real-time cloud-based cohort optimization algorithm(s), optimizing primarily on energy of the cohort, for cohort operation in various infrastructure scenarios. Traffic infrastructure speed limits with a lower tolerance will be obeyed and transit time of the infrastructure will be a cost function constraint within the optimization to prevent unreasonably long transit times or vehicle speed profiles that simply match the lower tolerance of the speed limit.
Start: 04/01/2021 Scheduled End: 12/31/2021 Percent Complete: 100%

- The task is complete.

Subtask 1.3.2 – In close cooperation, MTU, AVL, BW and NAV will integrate existing propulsion system optimization tools created from other federally funded projects that utilized connected vehicle data to reduce energy consumption based upon forward prediction horizons of varying time scales (e.g., 10 sec, full route). These existing ego vehicle propulsion system optimizations will be the starting point for the cloud based cohort optimizer for cohort coordination. These propulsion system optimization algorithms will remain onboard the individual vehicles and not be part of the cloud based cohort optimizer.
Start: 04/01/2021 Scheduled End: 12/31/2021 Percent Complete: 100%

- The task is complete.

Task 1.4 – Vehicle baseline testing for energy and emissions:
Start: 10/01/2020 Scheduled End: 12/31/2021 Percent Complete: 100%
The team has completed four test trips to ACM and southeast Michigan to collect baseline data and to develop and define routes for final technology demonstrations. Data was collected as individual vehicles and as vehicle cohorts on all four planned infrastructures, the fourth being an integrated drive cycle. The data has been and is still actively being processed and compared with modeling environment to hone in on characteristics to match energy consumption at the powertrain level and match unconnected and connected vehicle dynamic behavior.

Subtask 1.4.1 – MTU and NAV with the support of BW and AVL will conduct vehicle testing of each unique vehicle-propulsion system combination at ACM's test track on three infrastructure scenarios with cohorts of connected and unconnected vehicles and various states of automation to establish baseline performance in terms of energy consumption, behavior, and mobility efficiency. Where feasible, some vehicles may be tested on public road infrastructures if no automated driving capability is present, or funding precludes transporting the vehicles to ACM's closed test track facility.
Start: 10/01/2020 Scheduled End: 12/31/2021 Percent Complete: 100%

- The task is complete.

Subtask 1.4.2 – In close cooperation, MTU, AVL, BW and NAV will perform simulation and model correlation with baseline vehicle testing data acquired during public road testing and from closed test track facility site visits. AVL will lead the simulation and modeling efforts.
Start: 10/01/2021 Scheduled End: 12/31/2021 Percent Complete: 100%

- The task is complete.

Budget Period 1 Phase 2 - Implementation

Task 1.5 – Integrate cloud-based cohort optimization algorithm(s) into virtual environment:
Start: 04/01/2021 Scheduled End: 12/31/2021 Percent Complete: 100%
MTU and AVL have worked to get the three cohort based optimization methods integrated into the virtual environment. The task is complete and continuous improvements will occur during the remainder of the project.

Subtask 1.5.1 – In close cooperation, MTU, AVL, BW and NAV will integrate cloud-based cohort optimization algorithm(s) into virtual environment.
Start: 04/01/2021 Scheduled End: 12/31/2021 Percent Complete: 100%

- The task is complete.

Task 1.6 – Integration of Optimization Algorithms:
Start: 10/01/2021 Scheduled End: 06/30/2023 Percent Complete: 95%

Subtask 1.6.1 – In close cooperation, MTU, AVL, BW and NAV will integrate existing propulsion system optimization algorithms onto the test vehicle fleet compute platforms. Each unique vehicle-propulsion system combination will receive a unique implementation specific hardware application.
Start: 10/01/2021 Scheduled End: 06/30/2023 Percent Complete: 90%

- This task has morphed from applying previously developed selfish CAV predictive energy management and powertrain controls to developing new AI based optimization methods that are like the AI methods developed for the traffic infrastructure.
- MTU will be the sole teaming partner responsible for creating the AI based powertrain predictive energy management methods to be referred to as AI PrEM. AI methodology and training has started for parallel and powersplit xEV powertrain configurations by MTU. The vehicle applications are Chevy Volt II, Ram 1500 mHEV and Pacifica PHEV.
- Progress on AI training occurred during Q11, with key learnings on how to train the neural network and results for powersplit electrification architectures. This enabled results to be generated for the Chevy Volt. The results are based on results from the arterial design of experiments.
- Training for optimal controllers will continue for the Volt, Pacifica and Ram during the fall of 2023. The goal is to finish the controllers and analysis to report in journal and conference papers. Results ready for the project final quarterly report will be summarized.

Subtask 1.6.2 – In close cooperation, MTU, AVL, BW and NAV will integrate the cloud based cohort optimization algorithms and methods onto the compute platform(s).
Start: 10/01/2021 Scheduled End: 12/31/2021 Percent Complete: 100%

- The task is complete.

Task 1.7 – Vehicle dynamics assessment tool setup in vehicles:
Start: 10/01/2021 Scheduled End: 06/30/2023 Percent Complete: 100%
This task has been completed.

Subtask 1.7.1 – AVL with the support of MTU will set up instrumentation and sensors in vehicles to assess drive quality and perceived safety of vehicles in coordinated cohort maneuvers, particularly for automated driving scenarios.
Start: 10/01/2021 Scheduled End: 06/30/2023 Percent Complete: 100%

- This task is complete.

Task 1.8 – Vehicle fleet connectivity setup – 4/5G wireless and/or DSRC:
Start: 10/01/2021 Scheduled End: 12/31/2021 Percent Complete: 100%

The research team has established the basic connectivity bus infrastructure for the test vehicle fleet. Connectivity between MTU vehicles is functional in both directions. Connectivity with Navistar's truck was verified and is now bi-directional, receiving and sending over the custom C-V2x network.

Subtask 1.8.1 – MTU, TTS and ACM will demonstrate functionality of cellular connectivity with onboard EcoAND, and cloud based optimization for cohort coordination at signalized intersections on ACM's closed test track facility. Public road testing for the baseline will be for functionally and gathering data in real world traffic situations to bolster virtual environment calibration. DSRC based hardware is also present in the test vehicle fleet and can be a secondary means of I2V communication if necessary if the primary method of cellular has limited success or proves difficult in implementation.
Start: 04/01/2021 Scheduled End: 12/31/2021 Percent Complete: 100%

- The task is complete.

Subtask 1.8.2 – MTU will demonstrate vehicle and cloud computing connectivity is fully operational. The vehicle test fleet and cloud computing platform(s) are fully setup and all cellular V2V, V2I, V2C, C2V communication is operational and includes the expanded data sharing required to coordinate and optimize cohort operation based primarily on energy consumption.
Start: 04/01/2021 Scheduled End: 12/31/2021 Percent Complete: 100%

- The task is complete.

Task 1.9 – Vehicle fleet automated driving integration:
Start: 010/01/2021 Scheduled End: 06/30/2023 Percent Complete: 100%

Subtask 1.9.1 – MTU and NAV will integrate and demonstrate the ability to control vehicle longitudinal (speed profile) and lateral (lane change) dynamics from statically provided profiles loaded onto the vehicles compute platform on closed test track. MTU and NAV's proposed vehicle test fleet already have automated longitudinal vehicle control and, in certain instances, lateral as well through drive by wire (DBW) systems. For this project, the speed profile and lane utilization information will be displayed to the driver and control will be dedicated to the driver or the automated driving system depending on the details of the infrastructure, maneuver and number of vehicles involved. For this task, a demonstration of human driver's ability to follow speed profile and lane utilization as well as automated longitudinal control will be completed.

Start: 010/01/2021 Scheduled End: 12/31/2021 Percent Complete: 100%

- The task is complete.

Subtask 1.9.2 – MTU and NAV will integrate and demonstrate the ability to receive speed profile and lane utilization information real time and display the information to the driver. The ability to control the vehicle per speed profile and lane utilization via human driver and automated longitudinal control will be completed.

Start: 010/01/2021 Scheduled End: 03/31/2023 Percent Complete: 100%

- The task is complete.

Budget Period 2: Phase 2 – Implementation and Initial Validation

Task 2.1 – Cloud compute platform setup and optimization method verification:
Start: 01/01/2022 Scheduled End: 09/31/2022 Percent Complete: 100%

Subtask 2.1.1 – MTU will determine system communication latency of optimization algorithm(s) from vehicle to cloud and back to vehicle.
Start: 01/01/2022 Scheduled End: 09/30/2022 Percent Complete: 100%

- The task is complete.

Task 2.2 – Preliminary simulation and testing:
MTU and NAV with support from BW, AVL, TTS and ACM will conduct testing at the closed test track facility to perform initial testing of connectivity, automation and mixing of vehicles cohorts on intersections and highway infrastructure.
Start: 01/01/2022 Scheduled End: 09/30/2022 Percent Complete: 100%

Subtask 2.2.1 – MTU and NAV with support from BW, AVL, TTS and ACM will perform intersection analysis and testing.
Start: 01/01/2022 Scheduled End: 09/30/2022 Percent Complete: 100%

- The task is complete.

Subtask 2.2.2 – MTU and NAV with support from BW, AVL, TTS and ACM will perform highway analysis and testing.
Start: 01/01/2022 Scheduled End: 09/30/2022 Percent Complete: 100%

- The task is complete.

Task 2.3 – Vehicle dynamics assessment tool setup in vehicles:
Start: 10/01/2021 Scheduled End: 06/30/2023 Percent Complete: 100%
This task has been completed.

Subtask 2.3.1 – AVL with the support of MTU will set up instrumentation and sensors in vehicles to assess drive quality and perceived safety of vehicles in coordinated cohort maneuvers, particularly for automated driving scenarios.
Start: 10/01/2021 Scheduled End: 06/30/2023 Percent Complete: 100%

- This task is complete.

Budget Period 2: Phase 3 - Validation

Task 2.4 – Develop final simulation and test matrix:
Start: 04/01/2022 Scheduled End: 06/30/2023 Percent Complete: 100%

Subtask 2.4.1 – AVL in close cooperation with MTU, BW and NAV will develop final simulation and test matrix of infrastructure, and vehicle cohort composition and connectivity and automation configurations to fully demonstrate synergies of vehicle technologies and use of cloud-based cohort energy optimization algorithms.
Start: 04/01/2022 Scheduled End: 06/30/2022 Percent Complete: 100%

- This task is complete.

Task 2.5 – Test and demonstration of full matrix of infrastructure with mixed cohorts:
Start: 07/01/2022 Scheduled End: 03/31/2023 Percent Complete: 93%

Subtask 2.5.1 – MTU and NAV with support from BW, AVL, TTS and ACM will perform intersection testing at ACM's closed test track facility, single lane, signalized intersection, matrix of vehicles, vehicle attributes and connectivity and drive automation.

Start: 07/01/2022 Scheduled End: 03/31/2023 Percent Complete: 100%

- This task is complete.

Subtask 2.5.2 – MTU and NAV with support from BW, AVL, TTS and ACM will perform arterial testing at ACM's closed test track facility, multiple lanes and multiple signalized intersections, matrix of vehicles, vehicle attributes and connectivity and drive automation.
Start: 07/01/2022 Scheduled End: 03/31/2023 Percent Complete: 100%

- This task is complete.

Subtask 2.5.3 – MTU and NAV with support from BW, AVL, TTS and ACM will perform highway testing at ACM's closed test track facility, multiple lane, limited access highway loop, matrix of vehicles, vehicle attributes and connectivity and drive automation.
Start: 07/01/2022 Scheduled End: 03/31/2023 Percent Complete: 100%

- This task is complete.

Subtask 2.5.4 – MTU and NAV with support from BW, AVL and TTS will perform intersection testing with connectivity on public roads adjacent to closed test track facility utilizing cellular connectivity enabled EcoAND. Approach and departure speed profiles will be optimized using predicted SPaT communicated via cellular communication but be constrained to stochastic traffic conditions and presence of unconnected vehicles as possible cohort disruptors.
Start: 07/01/2022 Scheduled End: 03/31/2023 Percent Complete: 60%

- The team ran out of time to test real world configurations on AMC's highway loop during the March 2023 testing. Arterial roadways have been identified to emulate the SoS environment that are in southeast Michigan and in Oregon. Since there is no more track time left due funding, the team will create these scenarios in the SoS environment and test on a pseudo chassis dynamometer at Michigan Tech. The testing on dyno is similar to ORNL's CAV lab and will be equivalent to closed track testing. The method can be performed for multiple vehicles with only one physical vehicle installed on the dyno by performing the cohort in the loop testing sequentially. All dyno hardware and setup are already available and functional at Michigan Tech.
- This task was partially completed in Q11 and will be fully completed late 2023 or Q1 2024. As noted, this activity is internally funded and not with DOE funds.

Subtask 2.5.5 – AVL with support from MTU, BW and NAV will perform simulation environment of full matrix of infrastructure and vehicle cohort from the test track experiments to illustrate co-simulation prediction capability.
Start: 07/01/2022 Scheduled End: 03/31/2023 Percent Complete: 100%

- This task is complete.

Subtask 2.5.6 – MTU and NAV with support from BW, AVL, TTS and ACM will perform integrated ACM drive cycle testing, includes all three infrastructures, tracking single CAV in and out of cohorts.
Start: 10/01/2022 Scheduled End: 03/31/2023 Percent Complete: 100%

- The team modified the design of the integrated drive cycle that will be performed on ACM tracks as well as discussed how to mechanize the drive cycle in concert with the test vehicles that will serve as connected cohorts during certain segments of the drive cycle. The drive cycle was homologated from test data from individual test runs for arterial, highway and intersection cohorts. All four light duty vehicles were tested on the drive cycle during March 2023.

- The integrated drive cycle was stitched together from the various infrastructure and cohort scenarios tested during March 2023 and the energy consumption results reported in the Q11 quarterly meeting.
- This task was completed Q11.

Task 2.6 – Assess drive quality, comfort, and perceived safety:
Start: 04/01/2023 Scheduled End: 06/30/2023 Percent Complete: 100%

Subtask 2.6.1 – MTU and AVL will assess drive quality, comfort, and perceived safety scoring of maneuvers from data collected using specialty test equipment in instrumented vehicles. Scores are based upon benchmarking testing and are on a relative scale. A score of 7 or above is required to pass the criteria for a given maneuver.
Start: 04/01/2023 Scheduled End: 06/30/2023 Percent Complete: 100%

- The team was able to post process all test vehicle data for drive quality and perceived safety from the March 2023 ACM trip. The scores were reviewed in the April and May 2023 monthly reviews with DOE staff.
- This task was completed in Q11.

Task 2.7 – Final results and assessment of simulation and vehicle fleet testing:
Start: 04/01/2023 Scheduled End: 06/30/2023 Percent Complete: 100%

Subtask 2.7.1 – MTU with support from AVL, BW, NAV, TTS, and ACM will report energy savings of full simulation and vehicle test matrix.
Start: 04/01/2023 Scheduled End: 06/30/2023 Percent Complete: 100%

- Results from SoS DoEx and vehicle testing at ACM were summarized in April and May DOE report outs as well as the 2023 AMR. The summary of the results is in this report.
- This task was completed in Q11.

Subtask 2.7.2 – MTU, AVL, BW, NAV and TTS will develop technology commercialization plan.
Start: 04/01/2023 Scheduled End: 06/30/2023 Percent Complete: 100%

- TTS has been in the process of commercializing C-V2x predicted SPaT and predicted intersection queuing with two OEM partners (confidential). This process began in the fall of 2022 and is ongoing with partnership agreements and technology maturation coupled with field testing underway in southeast Michigan.
- This task is complete regarding the project, TTS, AVL will continue to market technology developed to potential customers.

Project Approach and Outcomes

The project's main focus was on answering the question can connectivity synergize with automation to reduce energy consumption given that recent R&D attention has been near exclusively focused on automation and perception rather than connectivity. The team sought to explore coordinated behavior of non-homogeneous connected and automated vehicle cohorts, defined as a group of vehicles operating in close proximity on a given traffic infrastructure, and whether there exist a potential to reduce energy and improve transit throughput by leveraging the two technologies. The research thrust was then to develop a real-time, optimal predictive technology that achieves improved energy consumption while maintaining safety and driving comfort that goes beyond typical leader-follower for CAV cohort scenarios.

The virtual and physical test results coordinated, connected and automated cohorts relative to the project objectives in Table 1 are contained in Table 2. As noted, the number of simulations to develop energy reduction probability distribution functions increased through the project as high power compute clusters were leveraged with the mean value of energy savings falling within the projected goals for each infrastructure. Validation testing with the CAV test assets, performing scenarios extracted directly from the design of experiments (DoEx) proved to achieve energy reductions consistent with the simulations and again within the range of the goals of each infrastructure.

Table 2. Virtual and physical test results for the project by infrastructure. Compare to Table 1 for project objectives.

		Virtual SoS				Test Validation		
		Dec 2021	Jan 2023	April 2023	July 2023	Case 1	Case 2	Case 3
Single Intersection	# of Sims	972	51840	51840				
	Mean % Energy Savings	12.0%	7.8%	8.4%		2.8%	7.6%	
Arterial	# of Sims	2916	155520	155520	155520			
	Mean % Energy Savings	19.1%	15.8%	14.1%	17.6%	17.6%	14.7%	19.0%
Highway	# of Sims	180		46080	116302			
	Mean % Energy Savings	2.3%		4.6%	6.0%	10.9%		
Integrated Drive Cycle	Mean % Energy Savings				~ 17%	10.6%		

The major approach to the project is depicted in Figure 1 that combines all elements of the project into one graphic. The graphic reads from left to right, with key hardware of 5 CAV test vehicles, connected infrastructure and a custom cellular based communication network. The 5 CAV test vehicles were procured from prior or existing DOE projects and required no additional hardware, only software and calibration. The connected infrastructure originates from TTS's cellular connectivity to traffic lights and the communication network links with the CAV's and TTS's SPaT data. All data then flows to the System of Systems (SoS) micro-traffic simulation environment that has vehicle-powertrain digital twins of the test CAV's and additional variants not available as test assets. Within the SoS are real-time optimization codes based upon neuroevolution that provide forward prediction horizon for CAV cohort coordination at signalized intersections, were single or multi-light and lane arterial infrastructure. Details of the AI based optimizations are found in [4 and 5]. The SoS environment is also set up with a DoEx configurator and couples to a Linux HPC for performing large batch simulations to generate many scenarios to extract validation test cases. Once suitable simulation test cases are selected, the scenarios are setup and overlaid on ACM's test tracks and the maneuver is choreographed and executed with the SoS essentially serving as a CAV hardware in the loop bench. Once complete, vehicle-powertrain is post processed for energy and dynamics as well as perceived safety and comfort using AVL's proprietary tools Cruise ADAS. Additional details of the SoS and constituent elements are shown in Figure 2 along with the entire system configured as an FMU to facilitate batch simulation. As will be discussed, 100,000 simulations scenarios for cohort coordination as unconnected or connected could be conducted within a couple days.

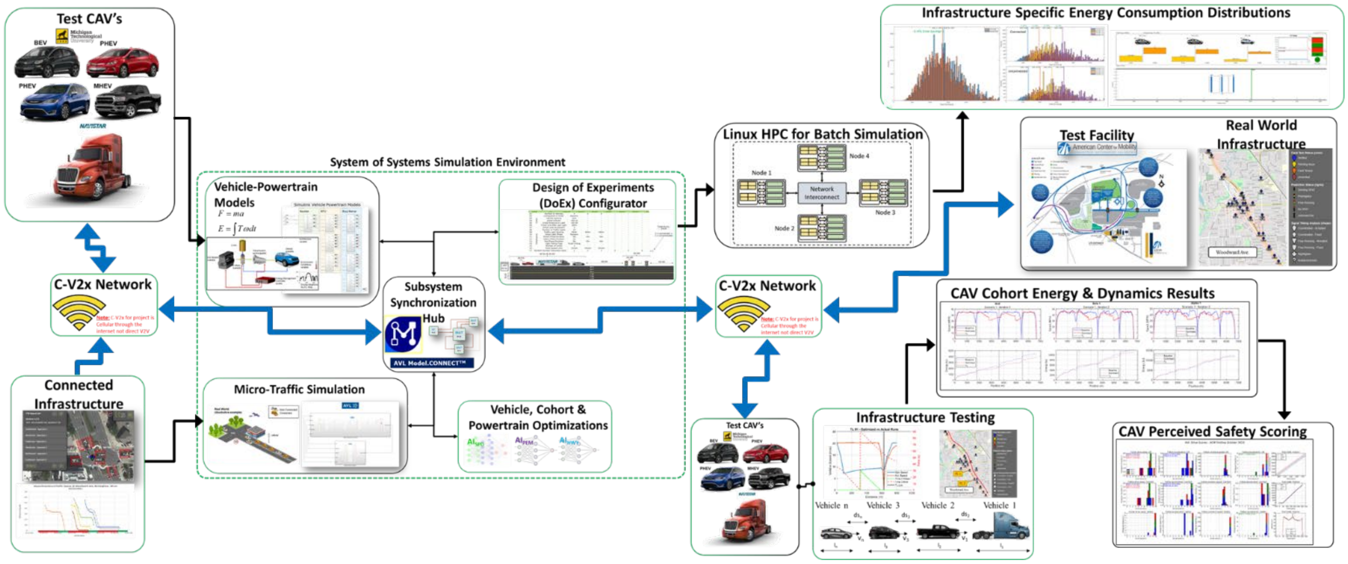

Figure 1. Coordinated automated driving of connected cohort project approach.

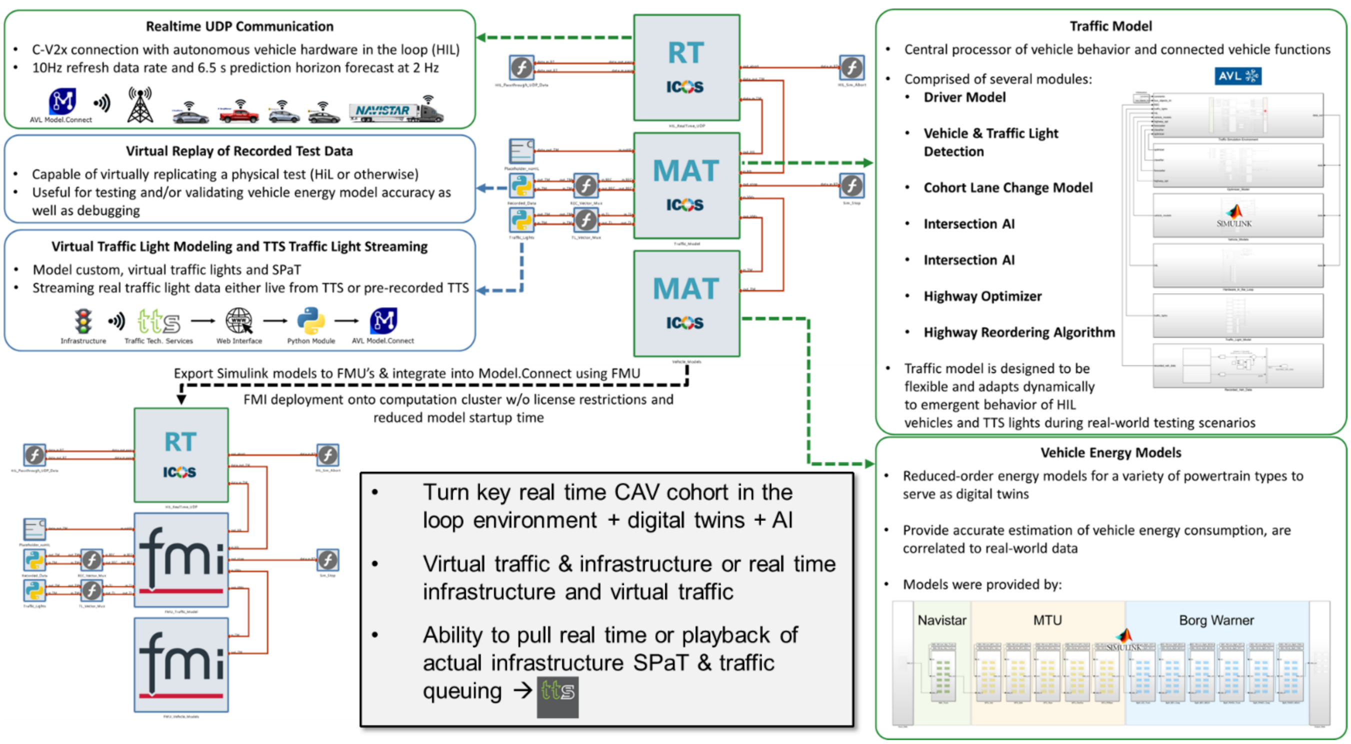

Figure 2. Details of the system of systems environment and constituent components, including FMU/FMI.

During the final quarter of the project, DoEx batch simulations were run with the SoS environment for single lane, single light intersection (SLSL), multi-lane, multi-light (MLML) arterial roadway with 10 lights and upwards of 8 km and limited access highway (LAH) infrastructures with unconnected cohorts and then with and connected, coordinated automated driving cohorts. The energy reduction probability distribution functions resulting are contained in Figure 3 showing mean savings of 8.4%, 14.1% and 4.6% respectively for SLSL, MLML arterial and LAH. From these simulations a few scenarios for validation testing with the CAV test vehicles were selected and testing conducted at ACM with the SoS and CV2x network governing and controlling the CAV's in real time.

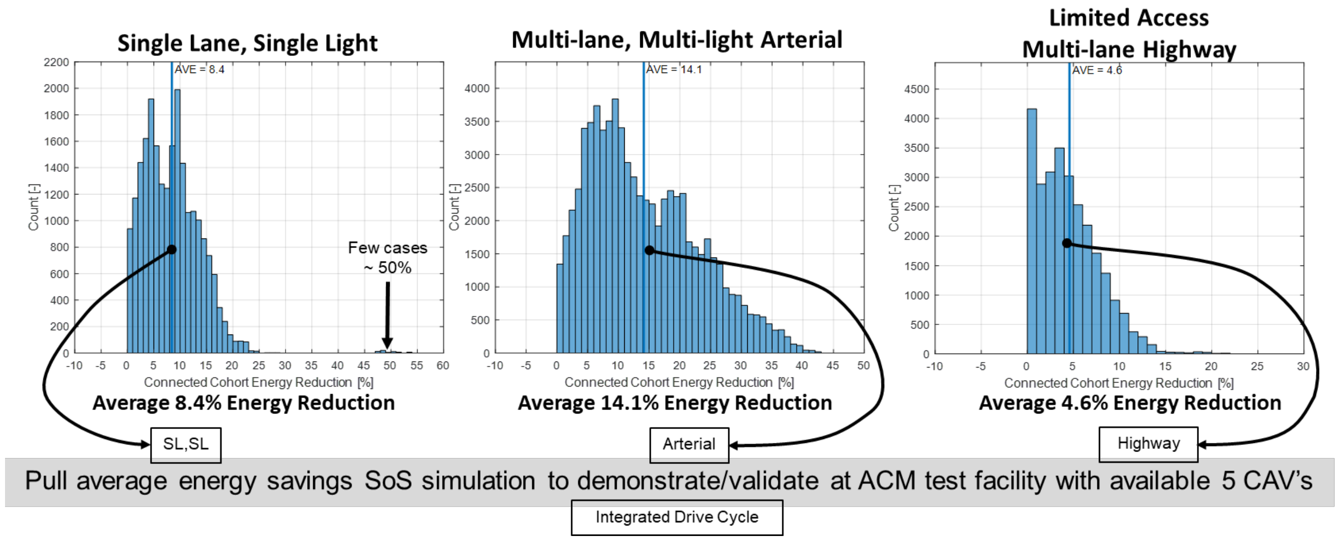

Figure 3. DoEx results of three infrastructures comparing unconnected vehicle cohorts to connected, coordinated and automated vehicle cohorts.

With the infrastructure scenarios selected, all 5 test CAV's were utilized for validation/correlation of the SoS DoEx simulations and to demonstrate how well the SoS worked as a real time CAV in the loop bench to optimize cohort dynamics and reduce energy consumption. Figure 4 contains images from testing at ACM in March 2023, which was the final vehicle testing for demonstration of the technology to DOE staff. A variety of scenarios and vehicles are shown. It should be noted that the highway loop of ACM was utilized to overlay the scenarios virtually with traffic lights only appearing virtually with no physical infrastructure.

Figures 5 and 6 contain arterial roadway test results with description of correlation back to results from the SoS DoEx simulation. The arterial scenario in Figure 5 shows a 4 light duty cohort operating at 35 mph with a 10 km long, 10 traffic light roadway with two available lanes. The connected cohort is noted to pass the traffic maze with zero stops with stay together for the entire trip. The unconnected vehicles have 5 stops but maintain together. The testing produced an 18% energy reduction while the SoS simulation predicted 14%. The individual vehicle energy savings are also shown, with the Pacifica PHEV resulting in the highest savings at 27.8%, followed by the Bolt and Volt at roughly 15% and the Ram truck at 10.8%. The Ram truck only has a mild hybrid powertrain and only benefits during coast down and engine off during idle. Essentially the same narrative describes Figure 6 with the exception that the AI optimizer cannot prevent a stop at the 2nd traffic signal and the AI's classifier commands a connected cohort split at the 8th traffic signal for the CAV cohort.

Figure 4. Summary of CAV test vehicles and view of final demonstration testing at ACM in March of 2023 to conclude the project.

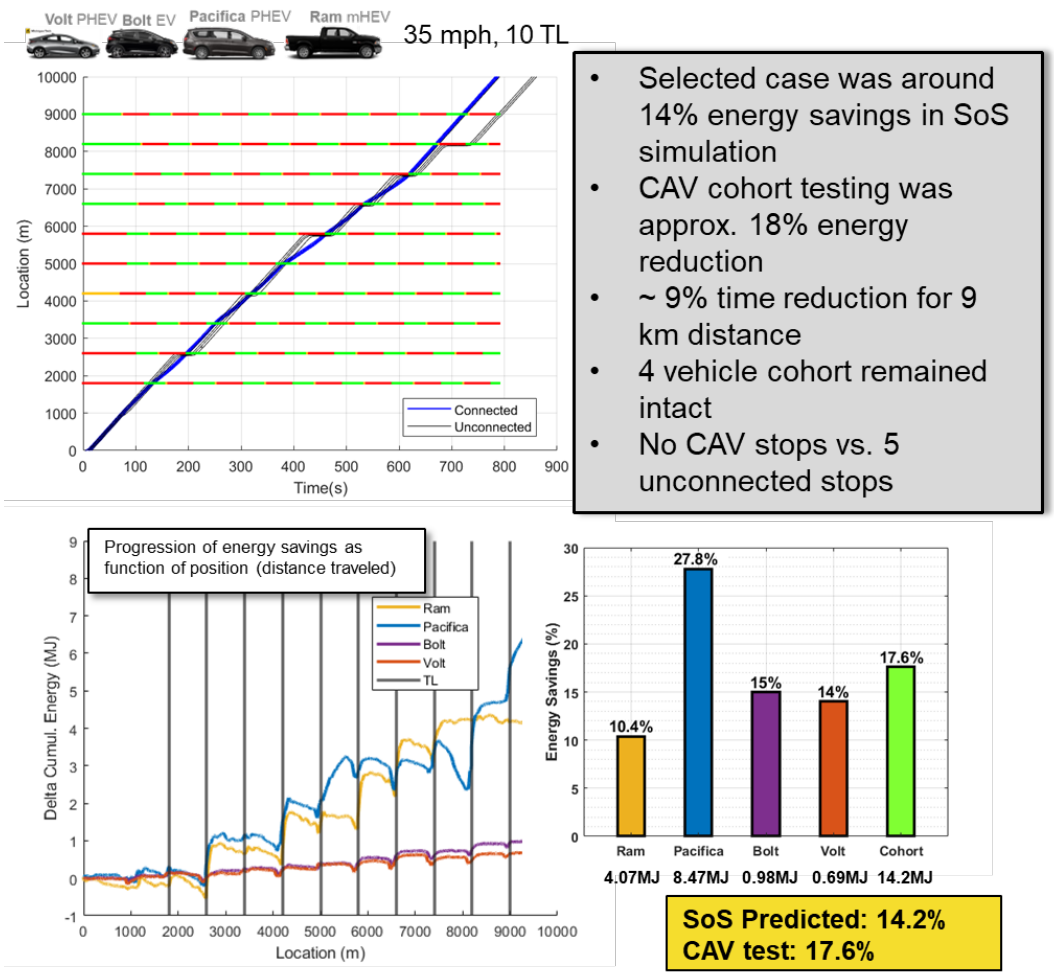

Figure 5. Arterial roadway at 35 mph, 10 km with 10 traffic lights showing connected coordinated cohort operation (blue) over unconnected vehicles (grey) and resulting energy savings. Simulation predicted 14.2% saving and testing produced 17.6%.

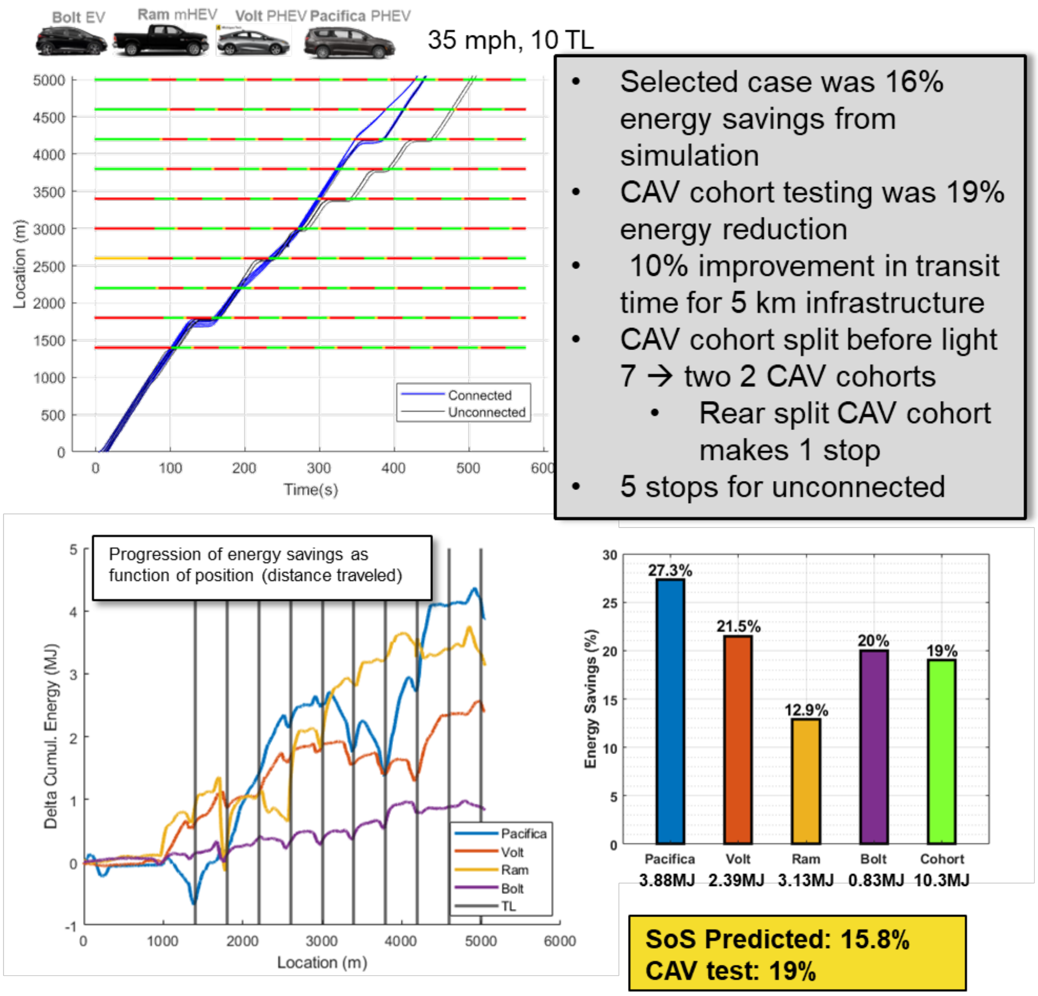

Figure 6. Arterial roadway at 35 mph, 5 km with 10 traffic lights showing connected coordinated cohort operation (blue) over unconnected vehicles (grey) and resulting energy savings. Simulation predicted 15.8% savings and testing produced 19%.

A limited access highway scenario used to validate the SoS simulation is shown in Figure 7 with the connected coordinated cohort being optimized for vehicle order and automated gap following. The unconnected case has the vehicle order indicated in the upper left of the figure with the AI based optimizer's configuration shown just below. The smaller, more energy efficient vehicles are placed in front to provide aerodynamic load reduction for the larger vehicles, netting an overall energy reduction for the cohort of 8.5% over a 20 km 45 mph, no stop drive. Although an energy increase (sacrifice) is paid by the Volt (-9.4%) and Bolt (-4.6%) the Ram and Pacifica reduce energy consumption such that the vehicle cohort has a net reduction in energy. This is an indicative finding of the DoEx scenarios simulated and illustrates that cooperative and coordinated driving can reduce energy consumption but can have a nonintuitive approach.

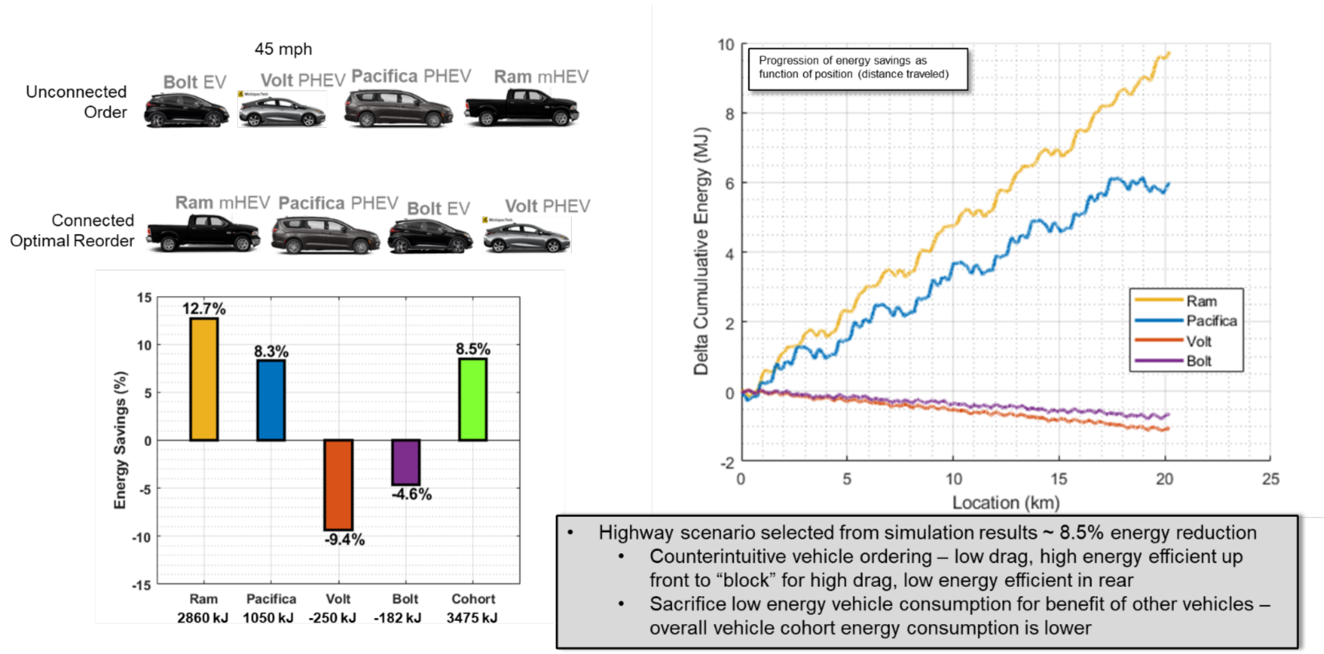

Figure 7. Limited access highway scenario at 45 mph and 20 km to validate SoS DoEx simulations tested at ACM in March 2023, comparing unconnected vehicles in order shown to connected vehicles running precise controlled gap and order indicated. Simulation predicted around 6% energy savings with 8.5% achieved in the test.

The last infrastructure considered for the project was an integrated drive cycle of approximately 20 km that includes the previous three infrastructures set up for optimization. The integrated drive cycle considers a single selfish vehicle that comes into and out of operation with other CAV's to form a cohort. The setup of the integrated drive cycle and details around the infrastructure segments are shown in Figure 8 while Figure 9 reports the results out for each of the 4 light duty CAV test vehicles. The comparison is the unconnected vehicle traversing the drive cycle with no connected information or operation as a cooperative, coordinated cohort, vs. operation with connectivity, automation and coordination with other CAV's as a cohort. Energy savings on an individual vehicle and as a cohort basis are contained in Figure 9, showing the ability to achieve savings of between 10% to nearly 17% depending on specific details. This result matched the anticipated savings desired in Table 1 and is a good results and demonstration of the technology's potential.

URBAN Startup	Single Lane, Multi-Light Traffic	Highway Infrastructure	Multi-Lane, Multi-Light Traffic	URBAN Destination
• Each vehicle starts its trip in an urban setting • Characterized by slow downs and stop signs	• Vehicles enter single lane road with multiple traffic lights • No Lane changes • Approach speed optimization	• Enters limited access highway • Drive at Speed Limit • Optimal vehicle ordering for max aero benefit	• Multiple lane road with multiple traffic lights • Lane changes allowed • Approach speed optimization	• Final destination in an urban setting • Characterized by slow downs and stop signs

- Unconnected Case: 4 Ego vehicles passing through different traffic infrastructures without coordination
- Connected Case: Coordinated vehicle cohort behavior to minimize energy consumption on different infrastructures

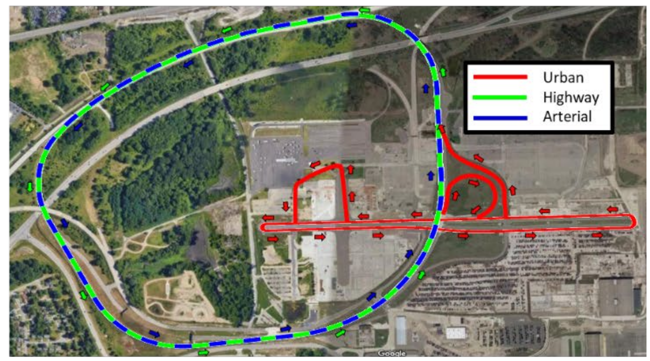

Figure 8. Integrated drive cycle setup on ACM test tracks and details of setup for each segment, tested March 2023.

Combined Energy Savings on all Infrastructure

Vehicle	Connected Infrastructure Savings (%)	Combined Savings (%)
Ram	12.69%	10.30%
Pacifica	12.97%	10.74%
Volt	16.66%	11.71%
Bolt	12.01%	10.04%

- 10.60% Total Energy Savings from all 4 vehicles on all infrastructure
- No connected test case in Urban setting

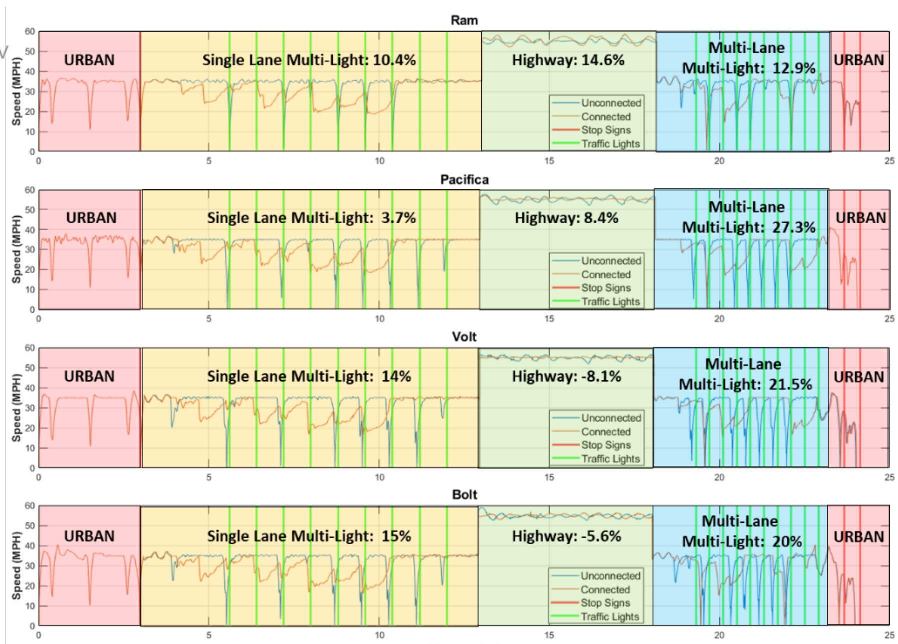

Figure 9. Integrated drive cycle energy reduction results for testing at ACM in March 2023, show comparison on unconnected to connected vehicle velocity profiles.

Project Outputs

Outputs from the project are listed in the categories that follow:

A. Journal Articles – Published

1. F. Jacquelin et al., "Connected and Autonomous Vehicle Cohort Speed Control Optimization via Neuroevolution," in IEEE Access, vol. 10, pp. 97794-97801, 2022, doi: 10.1109/ACCESS.2022.3206364.
2. Jacquelin, F., Bae, J., Chen, B., Robinette, D., Santhosh, P., Kraemer, T., Henderson, B., "Real Time Predictive and Adaptive Hybrid Powertrain Control Development via Neuroevolution," Vehicles 2022, 4, pp. 942-956, https://doi.org/10.3390/vehicles404005.
3. Jacquelin F, Bae J, Chen B, Robinette D. Neuroevolution Application to Collaborative and Heuristics-Based Connected and Autonomous Vehicle Cohort Simulation at Uncontrolled Intersection. Eng. 2023; 4(2):1320-1336. https://doi.org/10.3390/eng4020077.

B. *Conference Papers – Published*
   1. Ma, J., Bauer, T., Ova, K., Hatcher, K. et al., "Deliver Signal Phase and Timing (SPAT) for Energy Optimization of Vehicle Cohort Via Cloud-Computing and LTE Communications," SAE Technical Paper 2023-01-0717, 2023, https://doi.org/10.4271/2023-01-0717.

C. *University PhD Dissertations – Published*
   1. Jacquelin, Frédéric F., "Neuroevolution and Machine Learning Research Applied to Connected Automated Vehicle and Powertrain Control", Open Access Dissertation, Michigan Technological University, 2023. https://doi.org/10.37099/mtu.dc.etdr/1578

Project outputs that are under development, in progress or under review are listed in the categories that follow:

A. *Journal Articles*
   1. Journal TBD – Validation of Coordinated Automated Driving on Non-homogenous Connected Vehicle Cohorts on Arterial Infrastructure – anticipated Q1 2024
   2. Journal TBD – Artificial Intelligence Based Energy Optimization for Non-homogenous Connected Vehicle Cohorts on Limited Access Highways - anticipated Q1 2024
   3. Journal TBD – Synergy of Artificial Intelligence Based Predictive Behavior for Connected Vehicle Dynamics and Powertrain Energy Consumption – anticipated Q2 2024
   4. Journal TBD – Enhanced Predictive Cooperative Adaptive Cruise Control for Vehicle Gap Following Utilizing C-V2x and Machine Learning – anticipated Q2 2024
   5. Journal TBD – Effect of Coordinated Automated Driving of Connected Vehicle Cohort Energy Consumption on Arterial Roadways with Actuated Traffic Lights – anticipated Q2 2024

B. *Conference Papers*
   1. 2024 SAE Word Congress Experience – "A System of Systems Approach to Model in the Loop for Cooperative Automated Cohort Driving on Connected Arterial Infrastructure"

C. *University PhD Dissertations*
   1. Coordinated Automated Driving via Cellular V2x Vehicle and Powertrain Energy Reduction – Pruthwiraj Santhosh – anticipated April 2024.

Acknowledgements

The project PI would like to acknowledge the combined team of Michigan Technological University (MTU), AVL Mobility Technologies Inc. (AVL), Borg Warner (BW), Traffic Technology Services Inc. (TTS), American Center for Mobility (ACM) and Navistar (NAV) for their close cooperation, resource sharing and collaborative efforts. The entire project team would also like to thank DOE for their time and commitment to the project, in particular, Erin Boyd, Danielle Chou (now DOT) and Daniel Nardozzi.

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2. A. Vahidi and A. Sciarretta, "Energy Saving Potentials of Connected and Automated Vehicles," Transportation Research Part C: Emerging Technologies, vol. 95, pp. 822-843, 2018.

3. F. Zhang, X., Hu, R. Langari and D., Cao, "Energy Management Strategies of Connected HEVs and PHEVs: Recent Progress and Outlook," Progress in Energy and Combustion Science vol. 73, pp. 235–256, 2019.

4. F. Jacquelin et al., "Connected and Autonomous Vehicle Cohort Speed Control Optimization via Neuroevolution," in IEEE Access, vol. 10, pp. 97794-97801, 2022, doi: 10.1109/ACCESS.2022.3206364.

5. Jacquelin, F., Bae, J., Chen, B., Robinette, D., Santhosh, P., Kraemer, T., Henderson, B., "Real Time Predictive and Adaptive Hybrid Powertrain Control Development via Neuroevolution," Vehicles 2022, 4, pp. 942-956, https://doi.org/10.3390/vehicles404005.

Project Impact/Takeaway:

- Connectivity data does not include vehicle energy consumption behavior and characteristics, representing an opportunity to expand data sharing streams to improve cohort coordination through centralized or de-centralized energy minimization strategies.
- Paradigm shift from leader-follower behavior of CAV's to energy based coordination via connected cloud cohort energy optimization method. Modeling and vehicle test work will serve to develop multi-agent optimization algorithms for application to LD, HD or mixed cohort operation and future commercialization efforts.

Key Deliverables/Accomplishments:

- Mixed vehicle cohort coordination, leveraging expanded connectivity and cloud coordination for 10-50% cohort energy reductions on various infrastructure scales.
- Demonstrations of LD & HD in mixed vehicle cohorts with matrix of CAV capability for assessment to properly synergize connectivity and drive automation technologies for energy savings.