Trevor Crain

Energy Consumption Testing of Connected and Automated Vehicle Technologies

Trevor Crain

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Per Reinhall, Chair

Alberto Aliseda

Robert B Darling

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Abstract

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Trevor Crain

Chair of the Supervisory Committee:

Professor Per Reinhall

Mechanical Engineering

This dissertation focuses on the development and implementation of methodologies and test systems to enable energy consumption testing of Connected and Automated Vehicle (CAV) technologies. The research in this work was conducted in environments spanning simulation, dynamometers, and test tracks using new methodologies capable of accommodating both production Advanced Driver Assistance System (ADAS) and prototype CAV features in a common test framework.

We initially developed and piloted this test framework to conduct energy consumption performance of a variety of prototype vehicles with CAV features designed by university teams in EcoCAR Advanced Vehicle Technology Competitions (AVTCs). AVTCs have a 35-year history of providing future automotive engineers with hands-on experience developing advanced vehicle technology in direct collaboration with industry, government, and academia [1]. The two latest competition iterations, the EcoCAR Mobility Challenge and EV Challenge, include the design, deployment, and testing of CAV hardware and software systems from the ground up. These

competitions tasked university teams with designing and implementing sensor systems, fusion algorithms, Vehicle-to-Everything (V2X) connectivity, and automated controls on a production vehicle platform throughout the course of each multi-year competition.

Our research team, with collaborators across the University of Washington (UW), Argonne National Laboratory, HORIBA Automotive, General Motors (GM), and other competition partners, designed and implemented this series of novel CAV energy testing methods and supporting hardware systems. While the motivation for this work was in support of AVTCs, the methods were also designed to enable flexible testing pathways capable of evaluating a wide variety of vehicles on common test scenarios and drive cycles. Methods demonstrated in this work fill a gap in current research activities by enabling tests that directly compare energy used by modern production ADAS-equipped vehicles with experimental connectivity and automation control features. This dissertation details these new CAV test methodologies, the development of test systems, and the implementation of pilot studies we deployed during university competitions to enable controlled, repeatable, and directly comparable energy testing of production ADAS and experimental CAV features. Both track testing and dynamometer energy results are presented based on testing we conducted at various industry test track facilities and Argonne's Advanced Mobility Technology Laboratory. Finally, we present our design for a novel flexible connected corridor test system that will be capable of representing a variety of real-world connected corridors and traffic scenarios in more controlled and repeatable test track settings.

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Chapter 1. Introduction

The breadth and depth of research on vehicle automation and connectivity has rapidly increased in recent years, with researchers across industry, government, and academia creating advanced vehicle capabilities that may fundamentally shape how society interacts with transportation. From Adaptive Cruise Control (ACC) and other Advanced Driver Assistance Systems (ADAS) to more experimental implementations of connectivity and automation, researchers and commercial entities are developing new technologies across the spectrum from passenger vehicles to commercial applications. Even commonly available features such as ACC may significantly alter the operation characteristics, speed profiles, and resulting vehicle energy consumption compared to traditional human-operated modes, while more experimental Connected and Automated Vehicle (CAV) features have the potential for greater energy impacts. Unfortunately, current regulatory fuel economy dynamometer testing procedures do not capture the energy impact of ADAS or CAV technologies [2]. Furthermore, there are no commonly accepted standard methods for evaluating ADAS or CAV features for energy consumption in either track or dynamometer environments. In order to directly compare different ADAS and CAV feature energy consumption in vehicles, we have developed new controlled and repeatable methodologies and test systems.

This work presents a foundational collection of test systems and methods developed by our research team to enable such energy evaluations, along with pilot testing we performed to evaluate CAV systems designed by the University of Washington (UW) and 10 other university teams during the Department of Energy (DOE) and Argonne National Laboratory’s EcoCAR Advanced Vehicle Technology Competitions (AVTCs). These competitions are designed to create a next-generation automotive workforce capable of engineering state-of-the-art new vehicles while also understanding and reducing the energy impacts of the CAV features they implement. In the most recent EcoCAR AVTCs, universities across North America have added electrified prototype drive systems and CAV technologies to production vehicles to minimize energy and environmental impacts.

As an Argonne National Laboratory (Argonne) competition organizer and University of Washington doctoral student, I spent many years working with researchers across Argonne, industry, and academia to create a variety of novel vehicle testing methodologies and test systems in support of AVTCs. We designed these methodologies and test systems to be flexible and expandable in nature, capable of testing a wide variety of production ADAS and prototype CAV features in track and dynamometer environments. In addition to the student competition use case, we designed the methods and test systems in this work to enable some of the first direct energy consumption comparison testing between production ADAS systems and more experimental CAV features operating on the same set of test scenarios. We then used these systems and methodologies to conduct energy comparison testing of a highly diverse fleet of test vehicles and CAV system implementations in the EcoCAR Mobility Challenge. This energy testing utilized a repeatable method consisting of multi-mile two-vehicle following maneuvers with an automated target vehicle and was performed across several automotive proving grounds. To ensure accuracy and repeatability of the target vehicle scenario replication, this work also presents our novel method for extending the J2951 dynamometer drive quality metric calculations [3] to be usable for track environments. Figure 1 provides an image of this energy testing in progress at a General Motors high speed circle track, where a university prototype CAV uses student-designed perception and control systems to follow a target vehicle test system we developed during this work.

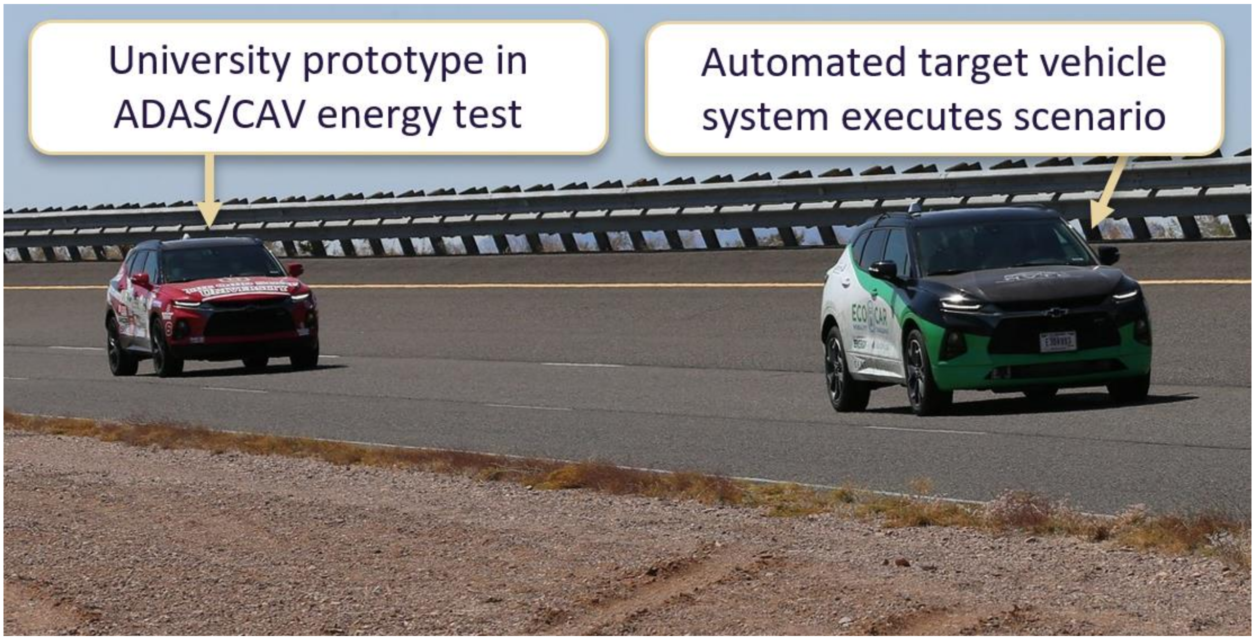


Figure 1. ADAS/CAV Longitudinal Energy Test in Progress

Once track testing was complete, we utilized the resulting vehicle data in a follow-up study to drive each of the university ACC cycles on a dynamometer using a common stock Chevrolet Blazer across all cycles. This process demonstrated a new method for combining both track and dynamometer testing to perform both realistic CAV trajectory assessments and use those trajectories to perform controlled dynamometer tests. The process first utilizes track testing to characterize longitudinal control behavior and then transforms those track-gathered velocity profiles into new CAV-specific dynamometer drive cycles for accurate and repeatable energy evaluations. We designed this track-to-dynamometer test method to extend outside of the AVTC prototype testing use case, as the inclusion of physical target vehicles on track would enable the same test sequence to be performed with production vehicles. Using this combined method, laboratory dynamometer energy testing can be performed that directly compares in-vehicle performance between multiple production or prototype ADAS/CAV features, without the need to directly inject sensor data that is unique to every vehicle make and model.

The final chapters propose novel methods and systems our research team designed to enable energy testing of CAVs operating in connected corridor environments. The eco approach and departure test methods from the EcoCAR Mobility Challenge are covered, along with our proposed design of a novel test system that combines automated target vehicles, multiple connected traffic lights, and simulated traffic to create a flexible and repeatable connected corridor energy test. This method could be used to overcome existing limitations at test tracks that only feature 1-2 sequential intersections. The proposed system enables an infinitely long connected corridor test with enough test miles to adequately evaluate energy usage and characterize control system behavior. It will be used in upcoming EcoCAR competitions and future Argonne CAV research activities.

Overall, this work details our novel test methodologies, systems, and pilot studies to evaluate energy consumption of CAV features in track and dynamometer environments. We deployed this research in support of AVTCs to evaluate university prototype vehicles, though they have also been designed for flexibility in evaluating a combination of production ADAS and experimental CAV features. By using physical target vehicles and traffic lights, these systems could enable some of the first direct comparisons of modern production ADAS features such as ACC with more experimental prototype CAV features in track and dynamometer testing environments. This capability would enable future studies to perform a fair evaluation of the potential benefits of connectivity and energy-optimized CAV controls in contrast to currently deployed stock systems.

1.1. Research Motivation

This dissertation is focused on research conducted as a doctoral student at the University of Washington and a CAVs Research Engineer at Argonne National Laboratory. The primary motivations for this work were to:

1. Enable DOE and Argonne's EcoCAR AVTCs to evaluate the energy consumption of experimental university-developed CAVs using fair and repeatable methods.
2. Leverage AVTCs to help UW, Argonne, and DOE better understand the energy impacts of CAV and ADAS features, including direct comparisons between test vehicles.

For over 35 years, AVTCs have been North America's premier training programs for advanced vehicle technologies where participants gain hands-on experience integrating the newest automotive technologies into production vehicle platforms [4]. Each competition series has had a unique focus, evolving in parallel with the automotive industry to provide our students with the most relevant vehicle technology experience. The EcoCAR Mobility Challenge was a significant advancement beyond EcoCAR 3 into CAV systems, where teams developed perception systems along with energy-optimized active longitudinal control features. This competition was the first AVTC to feature both connectivity and automation activities, where 11 university teams were tasked with implementing energy efficient connectivity and automation features onboard prototype hybrid vehicles [5]. To quantify efficiency and performance of university CAV implementations, it was necessary to develop novel methods and test systems that could support EcoCAR testing events while providing a foundation for addressing many existing challenges with testing CAVs in broader research and industry applications.

The research and methods in this work were founded upon energy consumption research conducted by Argonne over the last several decades. From investigating the energy impacts of new fuels and powertrain technology to leading the development of novel standards for testing energy and performance of hybrid and electric powertrains [6], Argonne scientists have developed and demonstrated new methodologies for capturing energy consumption and performance of many advanced vehicle technologies. These research activities have extended in recent years to develop capabilities for testing CAV features using controlled and repeatable methods [7] [8]. The activities in this dissertation were motivated by the need to create methods and test systems capable of supporting EcoCAR while also laying a foundation for broader and more standardized track and dynamometer ADAS/CAVs testing.

1.2. Dissertation Scope Definition

The field of ADAS/CAV research is both broad and complex, with focus areas spanning individual vehicles to entire transportation systems and applications ranging from micromobility and automated shuttles to privately-owned passenger vehicles, Medium-Duty (MD), and Heavy-Duty (HD) commercial applications. However, the scope of research in this dissertation is specifically constrained to the development of energy testing methods for assessing energy usage of passenger vehicles utilizing CAV and ADAS features. The methods could also be extended to MD and HD vehicles, though most studies in this work use cycles designed for passenger vehicle energy testing rather than commercial applications.

While this dissertation does not include transportation system-level technology impacts, Argonne performs extensive transportation research beyond the scope of this particular document. In the Transportation and Power Systems Division researchers investigate topics spanning micromobility, passenger, and MD and HD vehicle modes [9] [10]. Research groups work to understand CAV energy impacts at scales ranging from single vehicles of various levels of CAV and electrified powertrain implementation [7] to system-level transportation corridors [11]. Argonne researchers also extend this research to conduct mesoscopic analyses of entire geographic regions featuring millions of independent actors [12] [13]. AVTCs occupy a particular segment of this research portfolio, by providing hands-on experience developing single-vehicle CAV and powertrain technologies and guiding students as they refine them for both efficiency and consumer acceptability. The work is therefore constrained to the energy evaluation of single passenger vehicles. It is also focused on CAV energy reduction and decarbonization considerations rather than safety-oriented features such as automatic emergency braking.

The testing efforts in this work focus on the development and deployment of capabilities needed to perform direct comparisons of energy usage between vehicles using a variety of sensor systems, ADAS/CAV features, and electrified powertrains. While CAV simulation and modeling techniques are broadly discussed in this dissertation, our primary research emphasis is on testing these capabilities once they are deployed to vehicle platforms through test track and dynamometer evaluations.

1.3. Overview of Chapters

The systems described in this work have been designed and demonstrated through pilot implementations to provide a fair comparison between a diverse fleet of prototype hybrid vehicles with CAV features. As current research efforts do not traditionally perform comparative energy testing of a large fleet of vehicles equipped with both connectivity and automation technologies, it was necessary to develop specialized software, methodologies, and test systems capable of reliably evaluating EcoCAR vehicles. In doing so, we developed several novel capabilities and test methodologies that also address limitations identified in the current body of CAVs energy research. The following paragraphs provide an overview of each chapter.

Chapter 1. Introduction: Introduces readers to the overall document, including a succinct summary of existing CAV track and dynamometer vehicle testing research and limitations of existing methodologies. The goals and approach of the research in this work are described in detail, along with the specific research gaps and limitations this work addresses.

Chapter 2. CAV Energy Consumption and Testing Methods Review: Provides a foundational introduction to vehicle energy consumption and CAV operational concepts needed to understand the design and pilot testing of CAVs for energy consumption purposes. A review of CAVs energy testing research in dynamometer, track, and public roadway environments is presented.

Chapter 3. EcoCAR CAV Activities and University Designs: Introduces readers to the EcoCAR competition with a focus on the mobility challenge teams, activities, and propulsion system/CAV sensor and compute system implementations. The EcoCAR CAVs and energy consumption events are described along with the environments we used for testing these vehicles.

Chapter 4. ACC Energy Pilot Test using Network Guided Vehicle: Covers the design and implementation of an automated lead vehicle system to replay scenarios repeatably and accurately on track ahead of each vehicle under test. We collaborated with HORIBA Automotive to extend their DigiCAV Network Guided Vehicle platform [14] to be usable for multi-mile energy testing applications and traveled to their UK-based MIRA Technology Park [15] to perform a pilot demonstration of the system's capabilities. Material from this chapter was peer-reviewed, published, and presented at the 2020 IEEE 92nd Vehicular Technology Conference [16].

Chapter 5. Blazer Target Vehicle Software Development in HIL: Describes the MIL and HIL development we conducted to prepare the DigiCAV test system for integration into Argonne's Chevrolet Blazer platform, including setting up a flexible control hardware architecture to enable the Blazer to receive DigiCAV commands and provide feedback using a vehicle-agnostic CAN messaging structure. These MIL and HIL interface tests enabled a streamlined deployment process to the actual test vehicle. Material from this chapter was peer-reviewed, published, and presented at the 2020 IEEE 3rd Connected and Automated Vehicles Symposium [14].

Chapter 6. Lead Vehicle Track Testing and Accuracy Metrics: Provides details on our design and implementation of this Blazer-based target vehicle system and defines the experimental methodology used during EcoCAR Mobility Challenge Year Four competition. The Blazer automated target vehicle system was designed in collaboration between HORIBA Automotive and our research team to execute any longitudinal speed trace and test scenario in test track environments. This chapter also introduces a novel extension of the SAE J2951 [3] metrics beyond dynamometers to ADAS/CAV track testing applications, specifically to evaluate the control performance of target vehicles during multi-vehicle energy tests.

Chapter 7. University Fleet ACC Energy Track Testing Results: Covers the energy testing results from ACC energy consumption track experiments, where 11 university teams attempted to successfully follow behind the Argonne automated target vehicle while it executed urban and highway drive cycles. Seven teams were able to complete the ACC energy event with varying degrees of success. This chapter describes the calculation method we used for determining energy consumption of the University test vehicles along with energy results and ACC drive traces.

Chapter 8. Track-to-Dynamometer Methods for ADAS/CAV Energy Testing: Following the conclusion of the EcoCAR Mobility Challenge, a new dynamometer test method was designed and piloted that replicates track-based ACC and CAV velocity traces gathered from the experimental EcoCAR vehicles in more controlled dynamometer testing. Chapter 8 describes this track-to-dynamometer method and energy results from our multi-week research campaign testing Argonne's stock Chevrolet Blazer across all valid ACC drive traces gathered at the competition.

Chapter 9. Connected Intersection and Corridor Test Systems: Focuses on the connectivity aspects of the competition, where teams developed and tested capabilities for eco-approach and departure through a connected intersection based on Infrastructure-to-Vehicle (I2V) messaging from a portable connected traffic light. This chapter also introduces a proposal for our novel test system that combines methodologies and assets from preceding chapters into a flexible connected corridor test system capable of safe and controlled multi-mile energy testing with physical target vehicles and traffic lights.

Chapter 10. Future Work and Conclusions: Provides a direction for future work along with a summary of goals achieved and novel developments documented in this dissertation.

1.4. Review of CAVs Testing Research and EcoCAR Requirements

In preparation for developing the methods and test systems necessary for EcoCAR it was important to consult with experts in the field and review relevant energy testing activities for foundational understandings. After we conducted an extensive review of existing research and consulted with CAV and energy testing experts at Argonne, General Motors, HORIBA Automotive, other competition sponsors, and EcoCAR universities, it became apparent that we would need to expand upon existing CAV test methods to meet AVTC needs. This section provides an overview of specific requirements for EcoCAR CAV testing along with a summary of limitations with existing research on track and dynamometer CAV energy testing to give readers context for the overall research goals and activities. A more thorough discussion of track and dynamometer testing methodologies is presented in Chapter 2.

Of particular importance to this work is the applicability of methods for testing the different vehicle designs produced by EcoCAR university teams. The EcoCAR competition introduces several requirements that may not be present in other CAV research activities, with some of the following key considerations:

1. Methods must be capable of evaluating vehicle responses with sensor fusion systems included.
    a. In addition to implementing CAVs controls, teams also designed and deployed bespoke sensor systems through the addition of new radar, vision, and in some cases LIDAR sensors. Vehicles therefore must be evaluated using physical target vehicles and traffic lights to characterize the response of both sensor fusion and connectivity capabilities.
2. Energy tests must be able to be performed in track environments.

    a. Once vehicles are functional, vehicle testing events for each competition utilize General Motors proving grounds, where vehicles are also evaluated for non-automated energy consumption, performance, consumer appeal, and drive quality considerations.

    b. Dynamometer testing is also used as a development activity in AVTCs, but a ~1 week test event time constraint coupled with the sensor/powertrain diversity of the EcoCAR university vehicle fleet makes dyno testing all vehicle CAV features a significant challenge. Many of these vehicles also required a two-axle four-wheel-drive dynamometer due to electric motors on the rear axle.

3. Methods must accommodate both urban and highway speed driving over enough test miles to ensure hybrid powertrains can successfully charge sustain.

    a. Large High Voltage (HV) battery State of-Charge (SOC) fluctuations over a short section of driving could impact total fuel and electrical energy used. These SOC fluctuations are controlled for through SOC-correction, but ideally energy testing should occur over multiple test miles.

While the field of CAVs track and dynamometer energy testing research is currently somewhat limited, a significant body of research has been conducted to model and simulate the potential energy impacts of automated vehicles and V2X connectivity optimizations. DOE’s SMART Mobility Capstone Report thoroughly summarizes many of these efforts, including studies where consortium researchers “developed control algorithms for individual automated vehicles with intelligent powertrain and speed control. These algorithms can reduce energy/fuel consumption up to 15% alone, and up to 22% when integrated with Vehicle-to-Infrastructure communication of traffic signal information” [17]. While these technologies can potentially reduce the energy used compared to human operation, it is also possible that

ACC and CAV features could increase energy consumption, as researchers such as Mersky and Samaras [2] point out. With large energy usage and behavioral variations possible between different ACC implementations, new test methods and systems must be developed that enable real vehicles to be evaluated in controlled settings.

One common limitation of these simulations and testing activities is a lack of clarity and consistency for scenarios, test environments, and evaluation criteria. Traditional non-automated passenger vehicle energy testing generally uses a consistent set of drive cycles performed in dynamometer environments. This testing is tightly controlled for regulatory Corporate Average Fuel Economy (CAFE) and 5-cycle Environmental Protection Agency (EPA) label fuel economy testing, where vehicles drive a specific selection of longitudinal drive cycles in controlled thermal conditions with emissions instrumentation for calculating energy consumption results [18] [19]. These standards and dynamometer tests methods are described in more detail in Chapter 2. Unfortunately, no comparable energy testing standard exists for CAV technology [2] and the breadth of potential applications and operating environments makes it challenging to compare results from one study with another.

Very few of these investigations use production vehicle ACC/ADAS features as a baseline for comparison, with many researchers using models meant to mimic human behavior or a more generalized approximation of ACC behavior such as the Intelligent Driver Model [20]. Without direct comparison to production ADAS systems, it is difficult to quantify the energy saving potential of connectivity and automation optimized controls over highly refined production features that have been calibrated by Original Equipment Manufacturers (OEMs) such as General Motors with customer appeal in mind. Another area that most publications do not address is whether consumers would value or even utilize a vehicle’s automated features if its behavior differs too significantly from human driving. For example, it may be energy-optimal for an electrified vehicle to use advance knowledge of an imminent connected intersection traffic light phase change to red to begin braking early and recapture more energy, but to a customer (and surrounding traffic) that behavior may look like the vehicle erroneously slowing down. In Tang et al. [21], the authors account for rider comfort in the design of their algorithms and assessment criteria, but this paper was limited to simulations and the control features were not tested in vehicle at time of publication [21]. With large potential variations in both energy usage and vehicle trajectories between different ADAS and CAV implementations, new test methods must be developed to understand these systems as implemented in actual test vehicles with common production vehicle baselines.

Overall, there have been a number of publications and research efforts to investigate the energy impacts of CAVs. However, whether these investigations were conducted in simulation, dynamometer, track, or public roadway environments, more work remains to provide standard methodologies and scenarios that adequately assess the energy impacts of CAV features. Most researchers only compare a limited set of 1-3 test vehicles due to the challenge of developing CAV features across multiple research vehicles. Many of these research methods are incompatible with testing a fleet of >10 vehicles in AVTCs. From the industry side, many testing and evaluation activities are oriented towards evaluating safety and functionality of systems rather than energy testing [22]. The track-based testing activities that do exist for energy testing are generally limited based on physical constraints of the test tracks used and would not be applicable for testing production systems or EcoCAR vehicles that require physical targets.

A summary of select relevant studies that were referenced to draw these conclusions can be found in the following table. This summary is not meant to be exhaustive across all CAV simulation and testing research, but instead to provide a selection of studies that utilized test systems or methodologies that could be applied to energy evaluation of the EcoCAR test vehicles. The table also briefly describes limitations of each publication for the AVTC CAV testing context that would need to be addressed by our work in this dissertation.

Table 1. Selected CAV Energy Consumption Research Literature and Limitations

Reference	Objectives	Limitations
Mersky and Samaras (2016)	Proposed and simulated new AV test method, where AV follows target performing regulatory cycles to measure AV energy impacts [2]	Simulation only, specifics on methodology to determine cycles not provided.
Dvorkin et al. (2019)	Performed 2-vehicle ACC energy experiment where an ACC vehicle followed behind a human-driven target driving at steady state speeds and a highway cycle approximation [23]	Only approximate HWY trace driven, single test iteration. J2951 calcs used but focus on smoothness of follower rather than lead vehicle accuracy.
Prakash et al. (2016)	Proposed the use of a new regulatory cycle created based on a modeled vehicle following a hypothetical lead vehicle [24]	Using the same cycle for all test vehicles would not capture different trajectories from different ACC implementations. Simulation only.
He et al. (2019)	Reviewed ACC algorithms implemented by researchers on actual test vehicles [25]	Not intended to develop track methods, but rather review existing ACC algorithms on test vehicles. No energy analysis.
Y. Feng et al. (2018)	Utilized augmented reality on MCity test tracks to generate simulated background traffic that interacts with the subject vehicle in test [26]	No sustained high-speed driving due to track constraints, no physical targets used.
Fayazi, Vahidi, and Luckow (2019)	Utilized a vehicles CAVS approaching a pre-time traffic signal as a baseline test bed to benchmark their Mixed Integer Linear Program (MILP) based intersections controller [27]	Did not utilize real vehicles to simulate traffic nor real traffic signals, method not usable for sensor-integrated vehicles. Only single intersection.
Pourabdollah et al. (2017)	Performed energy analysis of Volvo test fleet operating using ACC on public roadways [28]	Public roadway testing eliminates possibility of direct comparison between test vehicles, traffic variable for each trip.
Schmied, Waschl, and del Re (2015)	Performed experiments of ACC vehicle with optimal controls following a target vehicle, found reduction of 15.8% energy between lead and follow vehicle [29]	Variety of arbitrary trajectories used for lead vehicle. Energy results not directly measured on both vehicles but rather modeled in HIL simulation.
Almannaa et al. (2019)	Conducted track testing of Eco-CACC algorithm with variety of participants at Virginia DOT's VTTI facility driving through an I2V intersection. [30]	Only a single intersection used with no physical or simulated traffic. No sustained higher-speed driving beyond intersection approach/departure.
Jeong et al. (2023)	Track-based evaluation of eco-driving control for EV platform following a simulated target vehicle conducted at American Center for Mobility [31]	Only simulated targets used, though method applicable to EcoCAR with addition of physical target vehicle.
Duoba and Canosa (2019)	Track-based measurement of road load changes experimentally determined for close-following vehicles [32]	Only steady-state driving used, results focused on road load impacts rather than direct energy measurements.
Ruan et al. (2022)	Tested real-time MPC control for car-following HEVs following target driving urban/highway cycles [33]	No vehicle testing used (HIL only), though method usable with EcoCAR vehicle through physical target system.
Tang et al. (2021)	Performed MIL simulations for CAV features optimized for both comfort and energy using on-road data for road and signal timing [21]	No vehicle testing used (MIL only), no lead vehicle, but example of multi-intersection sim using real roadway data.

Based on the limitations described in the table above, we concluded that our team must develop new test systems capable of multi-mile energy testing and the flexibility to be deployed at a variety of test tracks used by EcoCAR universities. The next section details research goals and activity areas for the work described in this dissertation and the specific limitations these goals and activities overcome.

1.5. Research Goals and Activity Areas

Each of the overarching research goals were established based on several critical requirements to meet the needs of both the EcoCAR Mobility Challenge and ensure applicability with research efforts beyond student competitions. The first table in this section describes each of the primary goals of our research activity, critical requirements, and relevant limitations of the current body of CAVs research that each goal addresses. These goals will be referenced throughout this work:

1. **Develop CAV Testing Pathways:** Design and refine test methodologies for energy evaluations of ADAS/CAV features in both dynamometer and test track environments.

2. **Implement CAV Test Systems:** Propose and implement flexible tools and test systems that enable Goal 1's track and dynamometer CAV energy testing pathways.

3. **Conduct University CAV Testing:** Utilize test systems and pathways to safely assess prototype CAV features developed by multiple university partners.

4. **Extend Systems to Broader CAV Research:** Demonstrate ways to extend these methods and systems beyond AVTCs towards standard tests of production and prototype ADAS/CAV systems.

The next table in this section provides critical requirements and relevant limitations of the current body of CAVs research that each goal addresses.

Table 2. Research Goals, Requirements, and Limitations Addressed

Goal	Requirements	Research Limitations Addressed
1. Develop CAV Testing Pathways: Design and refine test methodologies for energy evaluations of ACC/CAV features in both dynamometer and test track environments.	Methods shall be flexible enough for supporting tests of both stock and prototype ADAS and CAV features and must function at a variety of test tracks.	Current research methods restrict direct quantitative energy comparisons between production implementations of ACC and prototype CAV features.
2. Implement CAV Test Systems: Propose and deploy flexible tools and test systems to enable track-based CAV energy testing.	Systems must include guided target vehicles to mimic traffic ahead of vehicles under test to enable testing of both perception systems on longitudinal control algorithms.	Most guided target vehicles not designed for multi-mile scenario replication, guided soft target systems out of budget and may not function well on uneven circle track pavement at high speeds.
	Portable connected traffic light systems shall be developed that enable testing at a variety of test track environments without needing to use permanent intersection infrastructure.	Few commercially available test systems are deployable outside of a specific track and are designed for performing multi-mile energy tests in conjunction with more than two connected traffic lights.
3. Conduct University CAV Testing: Utilize tools and methods to safely assess prototype CAV features developed by multiple university partners.	Enable comparable energy evaluations across vehicles using different powertrain designs, sensor implementations, and longitudinal control strategies.	CAV research usually constrained to specific individual vehicles and tests are seldom run across many different vehicle designs.
	Enable testing of university-developed controls operating on Argonne test vehicles in dynamometer and track environments.	CAV test facilities exist that are usable by universities[34] [35] [36], but additional test systems needed for multi-mile energy testing at speeds above 65 mph for a wider variety of vehicles.
4. **Extend Systems to Broader CAV Research:** Demonstrate possible pathways for future standardized energy tests of production CAVs.	Methods and pathways shall have potential to be applicable for both current production systems and future vehicles with greater penetration of connectivity and higher levels of automation.	Existing regulatory testing does not assess CAV or ACC energy consumption and no consistent test methods are utilized for evaluating energy consumption of these technologies across industry, government, and academia.
	Methods must limit level of integration and test burden for each vehicle and be capable of fair energy comparison between difference vehicle designs.	

Once the overall goals of the work were outlined, we defined a research approach to ensure the methodologies, test systems, and pilot studies could be developed and implemented within the required competition timeframe. Table 3 provides an overview of research activities we performed to accomplish each of the primary goals, along with their link to relevant research goals. This table also provides a description of the progress made on each focus area and relevant manuscripts that have been published or are in preparation.

Table 3. Research Activities, Linked Goals, and Publication(s) Produced

Research Activity	Goals	Progress	Chapters and Publications
Propose and pilot a test methodology for track-based, repeatable ACC and CAV testing that can utilize both a physical target vehicle and simulated V2X elements	1, 2	Two-vehicle test method was piloted through collaborations with HORIBA MIRA at their test facility in Nuneaton, UK using their DigiCAV Network Guided Vehicle platform	Chapter 4. Published in IEEE VTC 2020 conference paper ***Modifying Network Guided Vehicle for Repeatable EcoCAR ACC Energy Testing*** [16]
Deploy test systems to use Chevrolet Blazer as a target vehicle through direct override of ACC system controls for accurate and repeatable scenario replication performance in EcoCAR testing	2, 3	Blazer vehicle system architectures were adapted for compatibility with HORIBA's DigiCAV software stack and Blazer controls and tuned for trace following accuracy	Chapter 5 and 6. Published in IEEE CAVS 2020 conference paper ***Prototyping EcoCAR Connected Vehicle Testing System Using DigiCAV Development Platform*** [14]
Adapt SAE J2951 dynamometer calculations to be applicable for new test methodologies, enabling assessments of trace replication accuracy for track target vehicles and dynamometer ACC/CAV trace replay	1, 3, 4	Novel track implementation of J2951 was utilized to assess EcoCAR testing target vehicle performance and in follow-up dynamometer ACC/CAV dynamometer testing	Chapter 4, 6, and 8. Used in ***Modifying Network Guided Vehicle for Repeatable EcoCAR ACC Energy Testing*** [16] and manuscripts in development [37] [38]
Utilize test methodology, target vehicle systems, and connected portable traffic lights to test multiple university prototypes for perception, connectivity, and energy consumption performance on track	2, 3	Conducted EcoCAR Mobility Challenge development activities and Year 4 competition with 11 university vehicles, including eco approach and departure and ACC-enabled energy consumption testing events	Chapter 6, 7, and 9. Manuscript **Track-based Energy Testing of Prototype Connected and Automated Hybrid Electric University Vehicles** [37] in development
Develop and pilot method for characterizing ADAS/CAV longitudinal behavior in track/simulation environments then replicating behavior in dynamometer-based energy testing. Potential future ADAS/CAV standardized test method	4	Method demonstrated on dynamometer using EcoCAR university ACC traces and stock Chevrolet Blazer as a common test platform. >40 test iterations over several weeks with direct energy comparison to standard cycles	Chapter 8. Manuscript ***Track-to-Dynamometer Methods for Repeatable ACC and CAV Energy Testing*** in development [38]
Develop methods and test systems for combining connected intersections and target vehicle into multi-mile connected corridor test system capable of emulating variety of scenarios and corridor designs	1, 2, 3, 4	Proposed test system with multiple C-V2X networked portable traffic lights and target vehicle to execute coordinated scenarios in a novel Flexible Connected Corridor (FlexCorridor) energy testing	Chapter 9. Manuscript **Design of a Track-based Flexible Connected Corridor Energy Testing System** in development [39]

Goal 1. Develop CAV Testing Pathways: Design and refine test methodologies for energy evaluations of ADAS/CAV features.

Goal 2. Implement CAV Test Systems: Propose and implement flexible tools and test systems that enable track/dynamometer CAV energy tests.

Goal 3. Conduct University CAV Testing: Utilize test systems and pathways to safely assess university prototype CAV features.

Goal 4. Extend to Broader CAV Research: Demonstrate methods extensions beyond AVTCs to broader ADAS/CAV test applications.

Chapter 2. CAV Energy Consumption and Testing Methods Review

Prior to presenting the specific methods and pilot studies our research team utilized for evaluating CAV energy usage, it is important to first introduce readers to fundamental concepts in vehicle energy testing and the current state of research into CAV energy impacts through vehicle-level testing activities. This chapter provides a background on energy testing methods and environments, followed by a literature review of testing activities in dynamometer and track environments. The chapter also includes updated content originally published in the introductory sections for ***Modifying Network Guided Vehicle for Repeatable EcoCAR ACC Energy Testing*** [16] and ***Prototyping EcoCAR Connected Vehicle Testing System Using DigiCAV Development Platform*** [14]***.*** This content has been edited and modified for inclusion in this chapter within the context of the overall dissertation.

2.1. Introduction to CAV and ADAS terminology and features

To understand CAVs energy testing and the pilot activities defined in this dissertation, readers should have a baseline understanding of terminology used in stock ADAS vehicles available to consumers along with more experimental CAV systems with more advanced automation or connectivity capabilities. This section will first introduce concepts and features related to control automation systems, followed by a brief overview of connectivity features and how they could impact future vehicle control responses and energy consumption results.

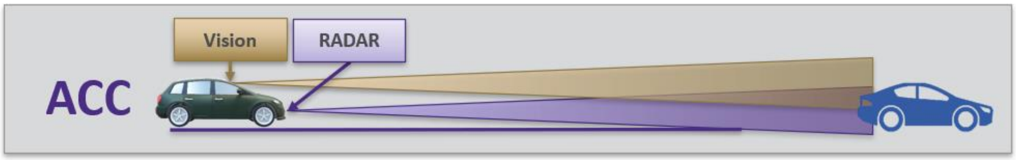
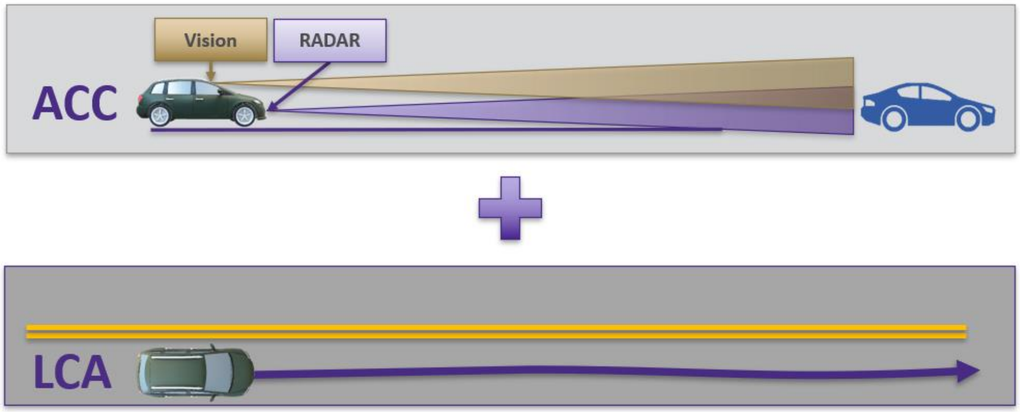
2.1.a. Automated Control Features and Terminology

Broadly speaking, automation or automated features refer to systems that use sensor inputs and compute systems to assess the surrounding environment and apply control inputs independently from the driver in order to perform dynamic driving tasks. These control inputs can be generally classified into the following three mechanisms, and may either fully replace driver inputs or be layered over the top of driver inputs:

- Longitudinal control
    - Controls the longitudinal (acceleration/braking) trajectory of the vehicle through either pedal actuation or direct requests to friction braking and propulsion systems.
- Lateral control
    - Controls the lateral trajectory (steering) of the vehicle through steering wheel torque application (or possibly also torque vectoring in rare cases).
- Propulsion system (or powertrain) control
    - Adjustment of propulsion system operation in reaction to upcoming conditions based on sensing system or connectivity inputs. For example, proactively cutting off fuel to an Internal Combustion Engine (ICE) in response to upcoming stopped traffic.

These control mechanisms are used in combined or independent fashion to enact features such as ACC or features that combine both lateral and longitudinal such as General Motors' Super Cruise [40] or Tesla's Autopilot and Full Self Driving [41]. Given the variability in naming and branding, it can be a challenge for consumers to understand or compare features across different OEMs. To address this challenge, organizations have attempted to establish common naming conventions for ADAS, automation, and connectivity capabilities. In the document Clearing the Confusion, a consortium of six organizations recommended the following universal terms and descriptions for ADAS features [42]. A selection of these terms and descriptions are displayed in Table 1, along with diagrams to illustrate an example implementation of each of the terms:

Table 4. Clearing the Confusion ADAS Feature Terminology

Adaptive Cruise Control (ACC)	"Cruise control that also assists with acceleration and/or braking to maintain a driver-selected gap to the vehicle in front. Some systems can come to a stop and continue while others cannot." 
Lane Keeping Assistance (LKA)	"Provides steering support to assist the driver in keeping the vehicle in the lane. The system reacts only when the vehicle approaches or crosses a lane line or road edge." 
Lane Centering Assistance (LCA)	"Provides steering support to assist the driver in continuously maintaining the vehicle at or near the center of the lane." 
Active Driving Assistance (ADA)	Provides steering and brake/acceleration support to the driver at the same time. The driver must constantly supervise this support feature and maintain responsibility for driving. 

As an example, General Motors Super Cruise [40] and Tesla Autopilot [41] are both forms of Active Driving Assistance (ADA) since they control both lateral and longitudinal controls. The specific behavior and functionality of ADA features will vary significantly between different manufacturers and models, and each vehicle may use a unique combination of vision, RADAR, LIDAR, and ultrasonic sensors to enact each feature.

2.1.b. SAE Taxonomy and Lack of Applicability to Prototype Vehicles

The Society for Automotive Engineers (SAE) has also developed the commonly used Levels of Automation [43] to describe vehicle automation capabilities. These levels span from Level 0, where features are limited to warnings or temporary actions such as automatic emergency braking, to level 5 where a manufacturer's vehicle can drive everywhere in all conditions fully autonomously without the need for operator takeover actions [43]. While SAE's terms can be useful when describing production or commercial-intent vehicle systems, they can be less applicable and often confusing when used in research papers as a shorthand way to describe prototype vehicle capabilities. Because the SAE taxonomy is focused primarily on expectations and capabilities of production vehicles driven by the general public, levels above SAE Level 2 are differentiated based on the expected level of driver attention, takeover time, and in what conditions and locations the feature can be operated [43]. For example, by certifying a vehicle feature as L3 instead of L2, such as BMW's DRIVE PILOT feature [38], a manufacturer is certifying that the feature will fully control the vehicle in certain conditions and environments and that constant driver supervision (and, therefore, rapid driver intervention) is unnecessary as the system will provide adequate time for drivers to re-engage attention, disengage automated systems, and retake control. In contrast, a L2 system requires that drivers constantly supervise the system operation and must always be ready to take over to maintain safety [43].

This operator-oriented taxonomy conflicts with the fact that most one-off research vehicles will **not** be regularly operated or ridden in by the public, and most developers of these systems are not certifying the system for operation in the broad set of environments a publicly available vehicle would experience. While a research group may demonstrate a “Level 4” feature implementation that can successfully avoid an intervention request in certain scenarios, that feature in most cases has not been tested to a degree that public consumers could regularly use it. These levels are therefore often not applicable in prototype vehicle settings and do not adequately describe research vehicle capabilities or functions unless the vehicle is intended for commercial use.

As an example, some EcoCAR Mobility Challenge and EV Challenge team vehicles were designed with multiple LIDARs, surround view radar systems, forward and surround camera systems, and vehicle features that could be used on an L3 or L4 vehicle **if it was refined to the point an entity could deliver it as a commercial product.** That consumer-oriented definition is not viable in most academia and lab settings and is often not applicable to the research being performed. In most research cases, the expectation of the system developer is that a safety driver will be constantly supervising operation and ready to take over at any moment. The research goal of many of these activities is to understand the operation and characteristics of vehicle behavior, rather than refine and test the system as a consumer-grade product to a point where they could certify the operation as L3 (driver will be given adequate time to take over but must do so when the feature requests) or L4 (will not require you to take over) rather than L2 (requires constant supervision). It is important that researchers in this field understand commonly used terminology such as the SAE levels along with their limitations to ensure accurate usage of the terms.

Now that readers understand different automation features and commonly used taxonomies for automated features, the following section describes wireless V2X connectivity features. These V2X features may provide significant impacts to automated feature behavior and have the potential to improve energy usage by extending environmental awareness beyond a single vehicle's onboard perception system.

2.1.c. Connected Vehicle and Infrastructure Features and Terminology

When using onboard sensing systems to detect surrounding roadway elements such as vehicles and traffic lights, an ego vehicle is limited to using vehicle positions and traffic lights within visual view of the collective sensor set. Connectivity presents the opportunity to augment a vehicle's on-board sensing capabilities by equipping other vehicles and stationary roadside infrastructure with the ability to send and receive messages wirelessly with any connected vehicle in range. These connectivity capabilities hold significant promise for improving both safety and energy consumption, as a vehicle could make more timely and informed decisions on trajectories using the information on upcoming traffic and signalized intersection behavior/layouts to augment its onboard perception detections.

Connectivity capabilities are enabled through hardware and software features deployed on vehicles, roadside infrastructure, transportation network operators, and other entities. At the most basic level, a vehicle would be equipped with connectivity hardware known as an onboard unit (OBU) programmed for transmitting messages to other roadway occupants using a standardized format such as the Basic Safety Message (BSM) defined by SAE in the J2735 V2X Communications Message Set Dictionary [44]. This BSM is one of many messages defined in that dictionary and includes location and trajectory information for a vehicle in a wireless format receivable by any entity with a compatible connection device. Vehicle-to-Vehicle (V2V) communication enables the sharing of BSMs and other standardized messages across hundreds of meters using point to point connections, or even longer distances using cellular signal towers [44]. This wireless sharing of information enables other vehicles to use V2V messages as inputs into onboard vehicle control algorithms, and roadside infrastructure to use more precise vehicle location and trajectory information for real-time traffic flow controls.

For an example of how this V2X communication could save energy, a vehicle in traffic on a highway would be regularly transmitting its current state via BSMs or additional messages usable by preceding vehicles farther back along a corridor. This information could enable a vehicle several hundred meters back to know that traffic is moving slowly or has come to a stop ahead, enabling an automated feature to begin braking proactively in advance of the stopped traffic. Without connectivity, the preceding vehicle would have only been able to sense 1-2 vehicles ahead and would have needed to brake more aggressively. Instead, the preceding vehicle can apply an optimal deceleration profile that does not require friction brakes, thereby recapturing more regenerative braking energy than possible during a hard stop event without connectivity. This example is just one of many proposed mechanisms for saving energy through connectivity, but without direct comparisons between ACC without connectivity and more advanced CAV implementations it is not possible to experimentally quantify how much energy could be saved.

Roadside infrastructure along highway corridors or at signalized intersections can also be equipped with connectivity capabilities through the use of Road-Side Units (RSUs) that operate similarly to vehicle OBUs but instead transmit information on stationary infrastructure. For signalized intersections, this connectivity capability can enable traffic controller systems for an intersection to transmit current signal phases (red, yellow, green lights etc.) for each lane, timing before upcoming signal changes, and intersection maps. These signals are transmitted through Signal Phase and Timing (SPaT) and MapData (MAP) messages defined in the J2735 Communications Message Set Dictionary [44]. These two messages are commonly transmitted by connected intersection to convey the current and future states of each signal along with geographic road information. MAP messages can be used to communicate to road users the geometry of roadways and most often the layout of particular intersections. These intersection layouts convey the lane geometries, shape and width of the lane, speed limit, allowed maneuvers, and which ingress or egress lanes they connect to [45]. They also locate all of this information using the World Geodetic System (WGS) 84 coordinate system and offsets to nodes included in the message. Readers may reference the Guidance Document for MAP Message Preparation created for the University of Virginia

Center for Transportation Studies [45] for a more thorough definitions of MAP data and instructions for defining a MAP message. This geometry information is then referred to within SPaT messages that define the current, future, and allowed phases (green, yellow, red, etc.) along with timing information for upcoming phase transitions for each lane of an intersection [45]. By combining these SPaT and MAP messages, an approaching vehicle could assess which ingress lane of an approaching intersection it currently occupies, what lanes and connected segments are available for egress from each ingress lane, what the current phase of each ingress lane is, and what the future phases and timings will be for transitions to occur.

A vehicle using an automated feature approaching a connected intersection or corridor with connectivity hardware could theoretically drive a smoother and potentially more efficient profile using this knowledge of current signal phase and the anticipated timing before the next phase transition to slow down proactively and maximize regenerative braking energy recovery. When approaching a red light with a known upcoming phase change to green, the automated feature could reduce speed in order to avoid coming to a complete stop before the impending change to green. The different V2V and I2V capabilities and the associated messages are summarized in the following figure:

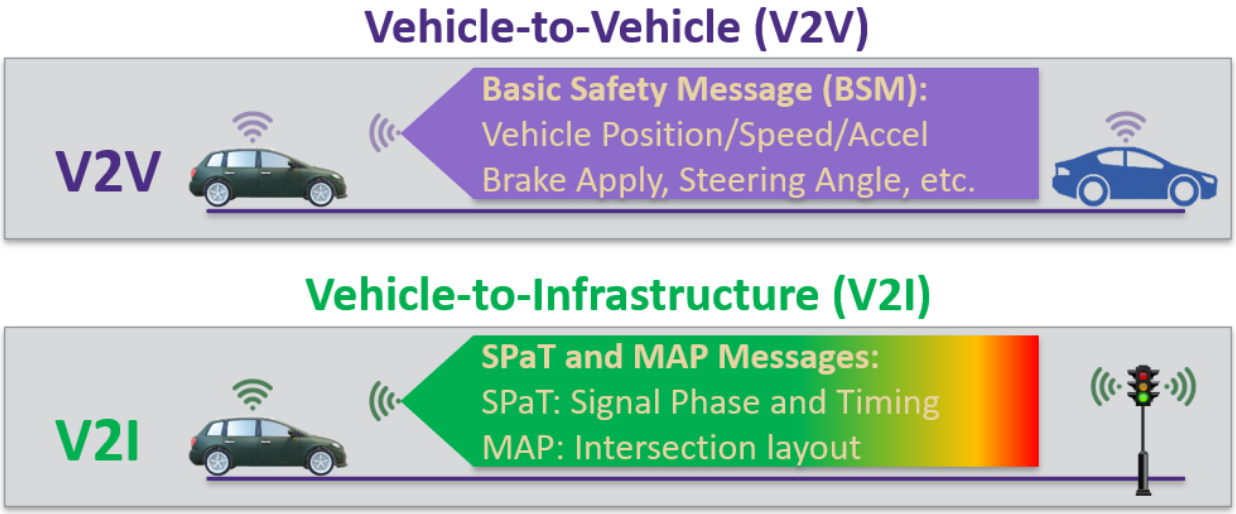


Figure 2. V2V and V2I Messages

Unfortunately, current production vehicles are not typically equipped with the required OBU hardware to transmit or receive V2X messages beyond select vehicles such as GM's 2017 Cadillac CTS [46]. To equip an experimental vehicle with DSRC communication capabilities generally requires adding additional DRSC radio hardware that is capable of sending messages using standardized messaging. In the EcoCAR Mobility Challenge, university teams used donated Cohda MK5 Dedicated Short Range Communications (DSRC) hardware (similar to those in the Cadillac CTS) to send and receive BSMs and SPaT/MAP messages. The more recent EcoCAR EV Challenge Competition has seen teams upgrade to using Cellular-V2X (C-V2X) radios that are capable of both point-to-point and cellular tower communication. This change was enacted in response to the Federal Communications Commission's reallocation of DSRC communication bandwidth [47] and approval of C-V2X deployments that effectively retired DSRC in favor of C-V2X. While C-V2X technology retains the message dictionary used by DSRC, several notable differences exist in possible transmission methods and the allocated frequency band of C-V2X. As described in Hajisami et al. [48], the newer C-V2X (also known as LTE-V2X) technology uses two interfaces for communication. Point-to-point communication similar to DSRC operation is still possible using what is known as the sidelink PC5 interface. This sidelink PC5 interface can operate without cellular coverage and enables low latency and safety critical communication directly between vehicles, infrastructure, and other road users [48]. In contrast, "the Uu interface exploits the existing LTE cellular and emerging 5G infrastructure to exchange data" [48].

Now that readers understand the different V2V and I2V messages and how they could be used, the next section describes various classes of cooperation that can be implemented between vehicles, traffic signals, and other connected actors.

2.1.d. Cooperative Driving Automation Features and Terminology

Beyond defining the basic V2X message dictionary, SAE has also published a Taxonomy and Definitions for Terms Related to Cooperative Driving Automation (CDA) for On-Road Motor Vehicles document [49] to define more advanced features that use coordinated control between vehicles and infrastructure. These features go beyond vehicles and infrastructure simply sharing their current trajectories and using V2X messages for their own independent control. Instead, CDA features vehicles and infrastructure that may share intent and future decision-making and may even conduct cooperative maneuvers. To enact CDA features, "Vehicles and infrastructure elements engaged in cooperative automation may share information, such as state (e.g., vehicle position, signal phase), intent (e.g., planned vehicle trajectory, signal timing), or seek agreement on a plan (e.g., coordinated merge). Cooperation among multiple participants and perspectives in traffic can improve safety, mobility, situational awareness, and operations" [49]. This document also defines various classes of cooperation and example features that could exist in the future using connectivity between vehicles, pedestrians, roadside infrastructure, and transportation network operators. Four specific CDA classes are defined by SAE in their taxonomy, with each progressive class increasing the amount of cooperation between vehicles and other actors [49]:

- Class A: Status-sharing. "Here I am and this is what I see."
- Class B: Intent-sharing. "This is what I plan to do."
- Class C: Agreement seeking. "Let's do this together."
- Class D: Prescriptive. "I will do as directed."

Most of the features from each of these classes exist purely in research applications and are not present on commercially available consumer vehicles. Several national laboratories including Argonne are actively developing capabilities in these different CDA classes to investigate energy consumption impacts of advanced features enabled by connectivity technology. While future transportation systems and user networks may have the ability to support many of these features, most current production vehicles and road systems are not equipped with hardware or features to enable any connectivity-enhanced automated control features capabilities. More research is needed to compare the specific energy impacts that connectivity features could save compared to more commercially available ACC or ADA features in use today. As described in later sections, much of the existing research investigating CDA feature energy impacts does not provide a direct comparison to modern production ADAS systems. Instead, the energy of vehicles using these features is often compared to human driver models and generally is not tested using methods enabling controlled and repeatable comparison of CDA, ACC, and human driving across a range of test vehicles. This dissertation addresses that limitation explicitly in future sections.

2.1.e. Mechanisms for CAV Features to Impact Energy

Regardless of the exact level of automation ascribed to a vehicle or automated feature, from an energy perspective these automated features can impact the overall efficiency of a transportation at several scales:

- Impacting the efficiency of a single vehicle
    - This work focuses specifically on single vehicle energy impacts and testing methods capable of assessing these in a controlled manner, with an initial emphasis on evaluating CAV longitudinal trajectories in dynamometer and track environments.
- Impacting the efficiency of groups of vehicles or the overall transportation system through traffic flow or routing adjustments
    - While out of scope for this dissertation, researchers in other works investigate considerations such as string instability of multiple sequential vehicles using ACC [50],

    - transportation corridor impacts, and other positive or negative impacts on energy that vehicles using automated features may have.

- Impacting the energy usage of a transportation system through driver behavior modifications and fleet impacts that change vehicle miles traveled for the system.
    - This topic is also out of scope for this work, though researchers on this dissertation committee and at a variety of institutions have investigated how automation may impact road vehicle energy consumption and greenhouse gas (GHG) emissions by causing changes in travel demand, vehicle design, operating profiles, and fuel choice [51].

The next section introduces readers to various methods of testing energy consumption of both automated and non-automated vehicles in environments spanning simulation, dynamometer, test tracks, and public roadways.

2.2. CAV and Energy Consumption Testing Methods Overview

From a regulatory perspective, vehicle fuel economy has been historically evaluated in the United States on chassis dynamometers using tightly regulated procedures and drive cycles defined by the US Department of Transportation's National Highway Traffic Safety Administration (NHTSA) and the EPA. Irene Barry's thesis succinctly describes the history of both NHTSA's CAFE Standards used for regulatory compliance and EPA's fuel economy labeling rules [52], and the full text final rule for CAFE and EPA fuel economy label testing can be accessed online [19] [18]. Testing efforts for both CAFE and fuel economy labeling utilizes chassis dynamometer testing, where each vehicle under test is driven on stationary metal rollers in front of a speed-controlled fan in an indoor temperature and humidity-controlled laboratory environment [53]. During these certification tests, the operator drives the vehicle over a prescribed second-by-second drive cycle with speeds, times, and shift points specified for each of the cycles. The FTP-75 and Highway Fuel Economy Test (HWFET) cycles are utilized for CAFE testing, with supplemental cycles known as the US06, SC03, and C-FTP used for 5-cycle EPA fuel economy label testing [54]. An image of Argonne personnel executing the FTP test can be seen in Figure 3. Figure 4 shows Argonne's 4WD dynamometer layout and measurement equipment.

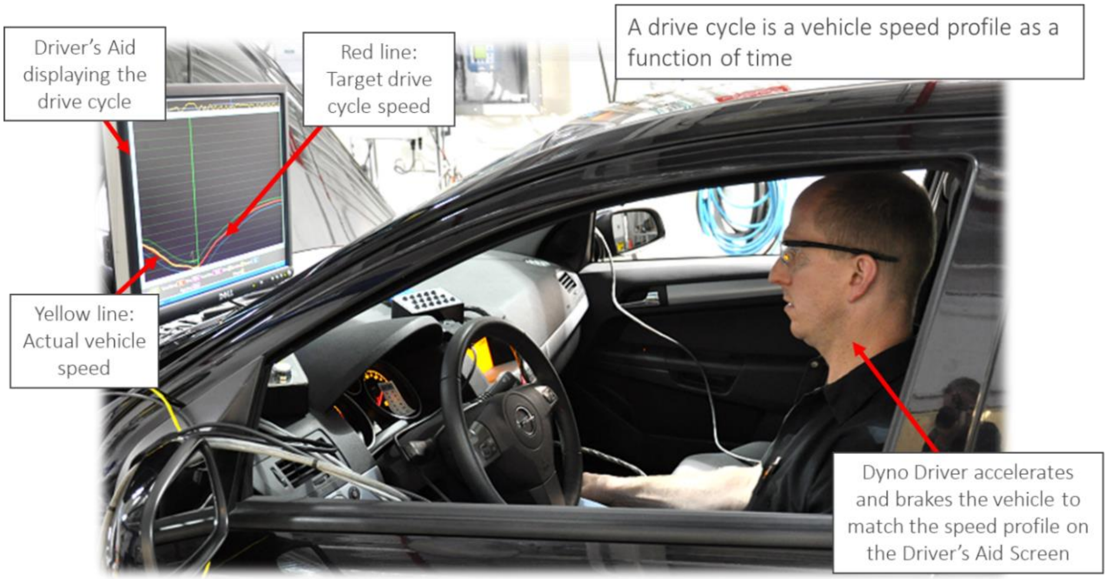


Figure 3. Argonne Dynamometer Testing Setup for Performing Regulatory Testing

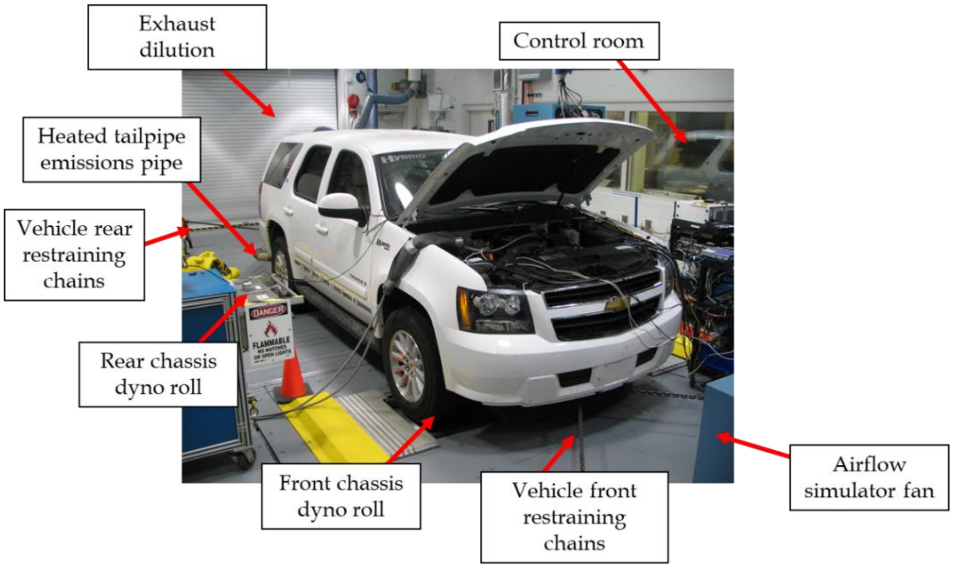


Figure 4. Argonne 4WD Chassis Dynamometer and Instrumentation

While these test procedures have historically been used for regulatory fuel economy testing, energy impacts of features such as ACC and other CAV technologies are not captured with the traditional methods [2]. The specified drive cycles capture driving characteristics presented by human-operated vehicle fleets. However, ACC and more advanced CAV features have the potential to dramatically alter vehicle drive profile characteristics compared to human operation, as the vehicle system's responses to traffic scenarios are significantly more consistent regardless of the specific person operating the vehicle and have the potential to be optimized for energy reduction using either onboard sensing or connectivity with other vehicles and roadside infrastructure. This optimized behavior would not be captured in CAFE or label 5-cycle testing since those tests require rigid adherence to the target traces.

Several researchers have proposed potential modifications to current regulatory testing in order to capture these energy consumption impacts of ACC and more advanced features. Mersky and Samaras [2] proposed adding new drive cycles to the legacy regulatory cycles, where vehicles under test would drive the resulting profiles from following a target vehicle driving the standard urban and highway cycles. They also performed simulations to show that these modified cycles could significantly impact fuel economy compared to traditional cycles [2].

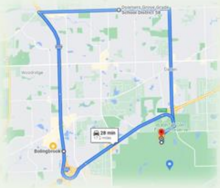
Prakash et al. [24] discussed the idea of a hypothetical lead vehicle trace, where a new drive trace could be created for a vehicle under test following a hypothetical lead vehicle[24]. In this case, they created a drive trace for the vehicle under test following a hypothetical lead vehicle by inverting the intelligent driver model developed by Treiber, Hennecke and Helbing [20]. In doing so, they predicted the speed of the vehicle under test and created a new cycle for ACC following [24]. However, this work was limited in suggesting that a generalized ACC drive cycle could apply across all vehicles.

Each vehicle with ADAS or CAV features may utilize different sensing, compute, and control algorithm implementations. The systems are calibrated and parameterized based on specific considerations for each manufacturer or research group in the case of prototype vehicles. With the advent of over the air updates, even a single vehicle's longitudinal velocity profile can vary drastically over the course of a year. For example, data collected by Argonne researchers on a Tesla Model 3 platform produced valuable results towards modeling the ACC behavior of that software build [55] However, Tesla software implementations are updated multiple times per year through Over-the-Air (OTA) updates and each update can significantly alter response characteristics of the same test vehicle. OTA updates will likely be a challenge for future standardization or regulation of ADAS and CAV feature energy testing.

Regardless of the specific energy testing method used, it will be necessary to move beyond traditional energy testing drive cycles to capture the energy impact of CAV and ADAS features. The concept of a vehicle under test following a target vehicle or driving through traffic lights was utilized heavily in the design of test methodologies in this dissertation and has been researched by Argonne and other parties in both dynamometer and test track environments. Mersky and Samaras [2] proposed such a test involving a target lead vehicle replicating drive traces and a follower vehicle under test operating using automation or ADAS features [2]. While the publication used only simulation and did not include vehicle testing, this method was used as a basis for the track testing that would be conducted in the EcoCAR mobility challenge.

The above images also highlight some fundamental challenges with using traditional dynamometer drive cycle testing to evaluate CAV and ADAS feature energy impacts. Many dynamometer test cells are fully enclosed on all four sides, and even those that reside in more open garages generally have an airflow fan directly in front of the vehicle under test along with walls or other obstructions in the immediate vicinity. Because CAV and ADAS systems drive the vehicle using sensor inputs to detect surrounding vehicles and objects, it is generally not possible to evaluate production automated control features in most dynamometer environments. In order to do so, it is necessary to feed simulated object or fused sensor data to production control systems and override any messages with detections from the surrounding dynamometer geometry. To accomplish this for a particular test vehicle, a research facility must have decoded information for the vehicle under test can networks and controller hardware capable of sitting in between sensors or ADAS controllers and the rest of the vehicle Electronic Control Modules (ECUs). Argonne has used a similar setup to evaluate production controls of a Prius Prime using this method, replacing all onboard sensor signals with simulated ones for a lead vehicle following certain scenarios.

Using a dynamometer to test stock implementations of automated controls is a significant challenge. These control features require a target vehicle to be detected using onboard sensors such as radar, vision, or LIDAR sensors that cannot operate in a closed test cell. It is therefore important to develop new methods for assessing energy consumption of ACC and CAV features in environments beyond chassis dynamometers. Argonne has been testing ACC and CAV technologies in a variety of environments in recent years, utilizing a combination of laboratory dynamometer, proving ground, and public roadway evaluations to assess energy usage of production and prototype CAV features [29]. Each of these environments has strengths and weaknesses for capturing distinct aspects of CAV technology, summarized in the following diagram:

Environment:	**Dynamometer**	**Dynamometer**	**Proving Ground (Test Tracks)**	**Public Roads**	**Public Roads**
Test Descriptions:	Certification Testing	Off-Cycle & CAV Testing	Cycle driving on circuits, intersections	On-Road Test Routes with test vehicles	Everyday driving, consumer fleets
Example images:					
Possible test types, traffic, routes, and environmental considerations:	● Regulatory drive cycles ● Single vehicle ● CAV features not tested ● Certification fuel ● 3 Temperatures: 20F, 72F and 95F	● Any drive cycles ● Single vehicle ● ACC w/ simulated cars ● Controlled temperature	● Any drive cycles/traffic ● Single/multi vehicle ● ACC w/ physical cars ● ACC w/ simulated cars ● Variable temperatures	● Real-world routes ● Variable Traffic ● ACC in real traffic ● Grade changes ● Range of climates	● Drive profiles/data are variable and uncontrolled ● Some insights from fleet-aggregated data
Possible Energy Measurement Methods:	● Lab fuel meters and engine CAN ● Full emissions bench ● Current/Voltage meters and battery CAN		● Compact fuel meters, engine CAN, gravimetric ● Portable Emissions Measurement Systems (PEMS) ● Current/Voltage meters and battery CAN		● Engine/battery CAN using cloud-based fleet data collection

Better measurement accuracy and repeatability

Worse accuracy and variability

Figure 5. Summary of Test Environments and Energy Measurement Methods Used by Argonne

Because the EcoCAR Mobility Challenge activities include development of custom sensor and control systems, our research team needed to create methodologies that could be used to test each of the university vehicles on a comparable basis in a test that could exercise sensing systems and longitudinal control algorithms while also evaluating their overall vehicle's energy results. This type of testing precluded dynamometer-based methods, since testing 11 different configurations of sensors and powertrains would not have been possible in a laboratory environment that required emulating each unique sensor configuration.

In past competitions, prototype university vehicles were assessed for energy consumption using manually driven longitudinal drive cycles on circuit-based proving ground test tracks [56]. However, due to the new EcoCAR competition's focus on energy impacts relating to CAV technology, we have now piloted novel track-based methods for assessing vehicle energy use in a controlled and repeatable manner while driving assistance and connectivity features are active. Ideally, modified versions of these test methods could also be applied towards assessing energy impacts of production vehicle driving control assistance features. While national laboratories, universities, and industry are actively researching CAV energy consumption, methods and test systems that could enable testing of vehicles using production driver assistance features such as ACC (particularly at high speeds for extended multi-mile drives) is fairly limited.

In the US DOT Meta-Analysis of Adaptive Cruise Control Applications, the reviewed studies demonstrated the potential for measurable changes to fuel consumption for both ACC and CACC systems [57] [29] [58] [28]. However, these results were based primarily on a combination of field tests and simulations and notably, "there were not any CACC-equipped passenger vehicles that were field-tested on freeways" [57]. Field operational tests such as these [29] [58] [28] are highly valuable for understanding in-use results from active driving assistance features. However, the data collected is sensitive to variations in traffic flow, route, operator control methods, and other variabilities. In a field operational test on public roadways, every test run across every vehicle tested is unique and unrepeatable in the same environment. A fair and direct energy consumption comparison between multiple test vehicles or even different test runs across the same roadway geometry with the same vehicle is not possible given that the traffic scenario perceived by the vehicle under test will be different for every run. This variation would even be present in the rare case that a target vehicle never changed lanes; while the traffic flow behavior could be similar (but could also vary significantly), the exact longitudinal trajectory of the target vehicle ahead would change in response to surrounding traffic.

Without some sort of repeatable test procedure in a more controlled environment, it is challenging to develop a comparison of the efficiency impacts from one vehicle's ACC system to those of a different model vehicle. In the article "Fuel economy testing of autonomous vehicles," the authors propose and simulate new methods for evaluating ACC energy consumption based on FTP-72 and HWFET drive cycles [2]. However, due to the prototype nature of university vehicles and lack of dynamometer test facilities for the competition it will be necessary to develop and execute novel track-based CAV energy measurement methods.

2.3. Conclusions and Current Vehicle Testing Research Limitations

Within the current body of vehicle testing research there exists several gaps and limitations for testing both prototype CAVs and production ADAS features. Our new test methods and systems developed in this work enable direct comparison on the same repeatable test between multiple CAVs and production ADAS features. The limitations spanning simulation, dynamometer, track, and public field testing are summarized as follows. Note that this list is not comprehensive but has been gathered from both the literature review and Argonne CAV research activities conducted across all three environments:

Table 5. Limitations of Testing ADAS and CAV in Various Environments

Environment	Limitations
Dynamometer	• Cannot test broad fleet of production ADAS without standardized object injection interface • Integration of each CAV into test system an arduous, multi-day or weeks long process even with highly refined XIL workflows • Even for previously tested cars, time for setup, debugging, teardown is significant (2 or more days depending on level of instrumentation) • Vehicle system faults are common, due to traction control, sensor diagnostics, etc. • Few facilities exist that can test CAVs, most (including Argonne) only have 1-2 chassis dynamometers equipped for testing.
Test Track	• Risks increased from dynamometer testing, though significantly lower than public roads • Few facilities have more than two sequential connected intersections, limiting applicability to energy testing • All instrumentation, including emissions and fuel measurement systems, must be carried onboard the test vehicle and powered (either through separate battery or drawing VUT energy) • Outdoor environmental factors (temperature, humidity, road surface) are more variable than dynamometer • Often challenging and expensive to purchase track time at closed courses.
Field Test on Public Roads	• Test runs are unrepeatable due to public roadway traffic • Large variations in travel time, VUT trajectory, lead vehicle behavior, and resultant energy consumption • Significantly increased risk to test operators and public road users. Systems must be heavily validated on closed courses prior to public tests • Outdoor environmental factors (temperature, humidity, road surface) are more variable than dynamometer

As shown in Table 5, there is no perfect environment for testing vehicles with ADAS or CAV features for energy consumption. AVTCs present a host of unique requirements that preclude methods used in most research activities. From the large volume of test vehicles to the test locations to the need to compare a variety of vehicle designs on the same track-based test, AVTC CAV testing requires an evolution of current methods and systems. However, these requirements are also relevant to enabling testing of production ADAS vehicles, providing a unique opportunity to advance the state of both experimental CAV and production ADAS energy testing research. The methods in this work are intentionally designed for applicability to both production and experimental vehicle applications.

Chapter 3. EcoCAR CAV Activities and University Designs

This chapter presents an overview of the EcoCAR Mobility Challenge competition, development timelines and approaches, and a selection of CAV system hardware architectures from participating teams. An overview of the latest competition, the EcoCAR EV Challenge, is also provided.

3.1. Introduction to EcoCAR Mobility Challenge and CAV Activities

The EcoCAR Mobility Challenge Competition took place over four academic years, from Fall of 2018 through May of 2022. During this time, 11 university teams from across North America designed and integrated prototype advanced electrified propulsion systems into a production 2019 Chevrolet Blazer while also implementing CAV technology. The original production vehicle delivered to teams was a conventional ICE platform. Teams were required to replace all stock powertrain components, including engine, fuel tank, and transmission components, with their own designs. They were also tasked with implementing a completely new set of CAV sensors and compute systems to replace the production ACC sensors and control features. Teams were responsible for designing their sensor system from the ground up, including selecting and mounting whichever sensors they deemed necessary based on simulations for field of view, detection ranges, and power consumption considerations. Competition organizers provided teams with significant latitude in selecting sensors, with some teams opting to add sensors beyond what was necessary for competition events in the interest of research or creating more accurate systems.

In AVTCs, universities follow a multi-year Vehicle Development Process (VDP) designed to emulate industry OEM programs. Unlike many other collegiate student competitions, AVTC students work with the same vehicle and overall design throughout the multi-year project. This approach is taken due to the complexity of working with production vehicle systems and ECUs along with providing experiential learning to students of more industry-relevant design timelines. In the Mobility Challenge, the original multi-year VDP consisted of the following focus areas each academic year:

- Year 1: Design, Simulation, and Component Selection:
    - Teams select the propulsion system components and CAV sensor and compute hardware. Teams receive vehicles after Y1 Competition design review.
- Year 2: Vehicle Build and Integration
    - Teams perform baseline testing of stock vehicle and ADAS systems, then remove stock propulsion system components before integrating CAV and propulsion system components. Basic safety and functionality tests of propulsion and longitudinal control capabilities are performed at Y2 competition.
- Year 3: Refinement of Propulsion System and Development of CAV Features
    - Teams demonstrate full functionality of powertrain systems and reliable performance of ADAS features and develop CAV V2X-augmented controls. Y3 competition includes basic CAV events to test V2V and V2I functionality and controls.
- Year 4: Optimization of CAV Features
    - Teams perform optimization of CAV feature operation for energy and performance, optimization of propulsion system operation and coordination with CAV features. Y4 Competition includes the full set of both CAV and Normal Driving Mode (NDM) non-automated vehicle tests.

This timeline can be seen in Figure 6, with each year consisting of a traditional university academic year spanning approximately September through May. The diagram also notates in blue the software development and testing timelines. AVTCs utilize a Model-Based Design (MBD) process for software development. Software is first developed on PCs using Model-in-the-Loop (MIL) tools such as Simulink and various vehicle powertrain and CAV design toolbox provided by The MathWorks. Teams then deploy software refined in MIL environments to rapid controls prototyping hardware targets such as MicroAutoBox II provided by dSPACE [59] and embedded Linux systems such as the IEI Tank-870-Q170 provided by Intel [60]. These hardware systems are tested in Hardware-in-the-Loop (HIL) environments, where a separate HIL component system is programmed to mimic vehicle responses. In an ideal HIL execution, the same software build could be transitioned from HIL to the next stage, in-vehicle testing, with minimal changes since the communication architecture and messaging would be identical. In practice, this parity between HIL and vehicle environments is nearly impossible for teams to achieve as they do not have access to a full GM vehicle model with identical CAN communications. However, this HIL testing is still invaluable for verifying CAN communication and testing diagnostics and basic operation prior to in-vehicle deployment.

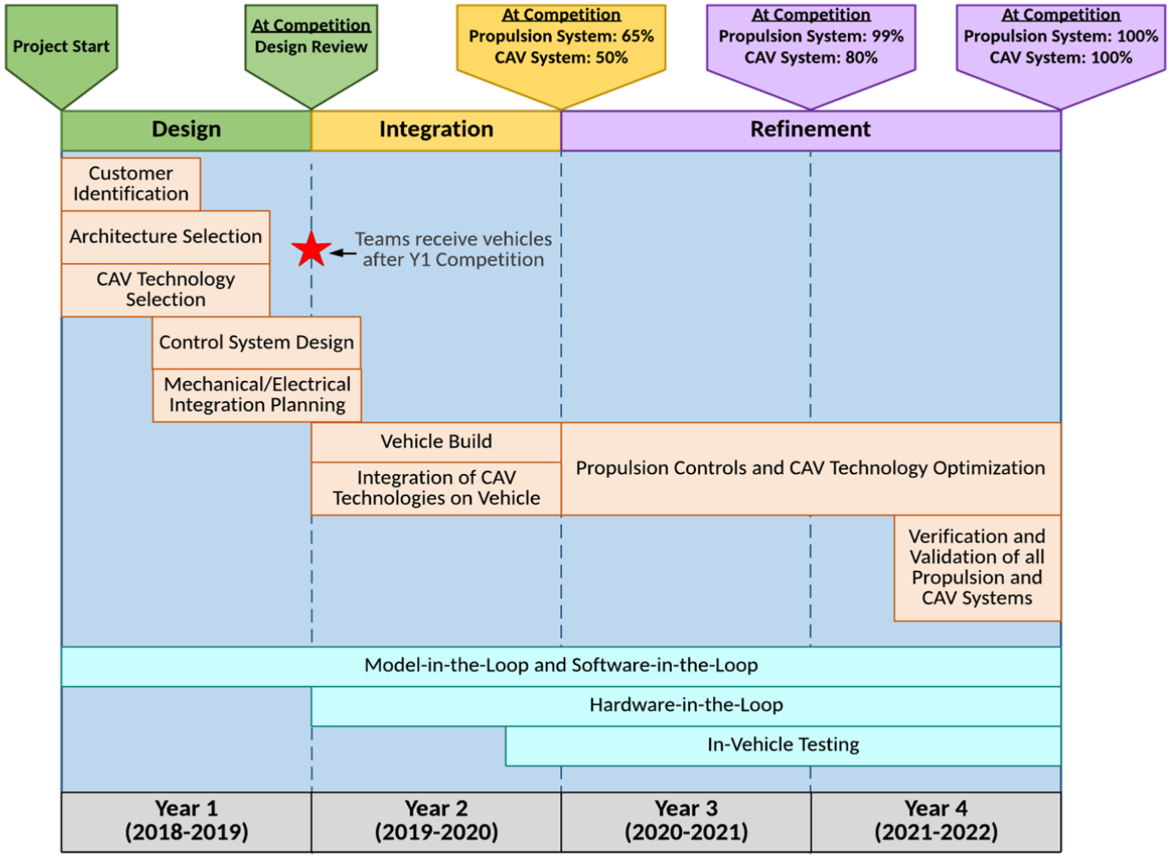


Figure 6: EcoCAR Mobility Challenge Vehicle Development Timeline

Readers should note that this competition occurred during the COVID-19 pandemic, which began impacting teams in Year 2 of the Mobility Challenge. As a result, the original timelines and expectations for teams were reduced. Both universities and organizers were resourceful in heavily pivoting to increase MIL and HIL activities that could enable virtual and remote development of software during this time, though overall vehicle testing and progress was still impacted. From a testing perspective, the competition testing in Year 2 and 3 was cancelled for safety reasons. Year 4 testing was conducted at a more limited scale with extensive social distancing and masking requirements in place. Because of these delays, some adjustments to the CAV testing were made to remove lateral control and V2V-augmented ACC testing in favor of single-vehicle ACC testing. ACC systems were still evaluated for energy consumption, along with functionality of V2I intersection navigation as described in later chapters.

The Mobility Challenge featured 11 participating universities, with teams selected through a competitive request for proposals process for participation in all four years of competition. These universities, their locations, and the abbreviations used in this dissertation are provided in Table 6.

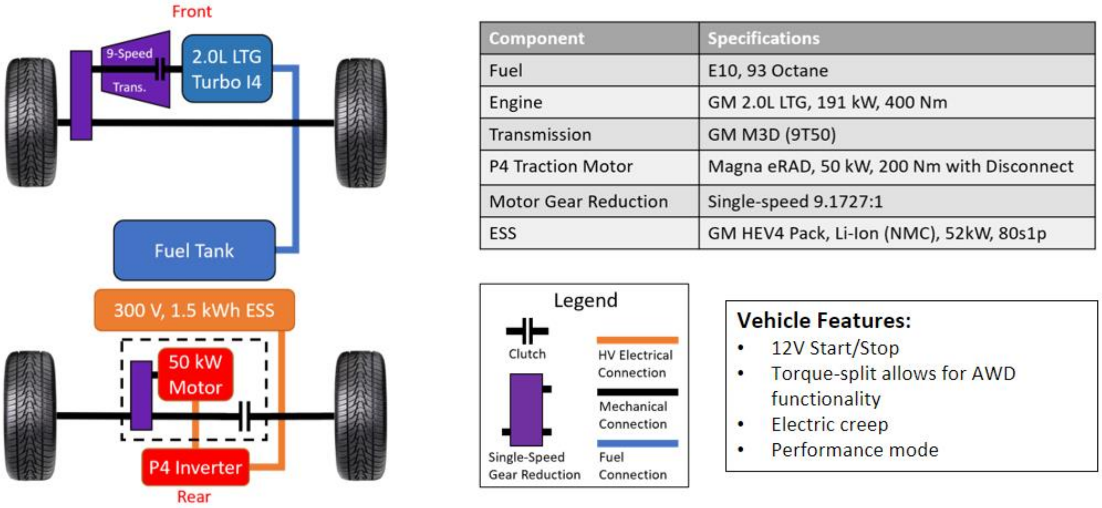
Table 6. EcoCAR Mobility Challenge University Teams

University Name	Location	Abbreviation
Embry Riddle Aeronautical University	Dayton, Florida	ERAU
Georgia Tech	Atlanta, Georgia	GT
McMaster University	Ontario, Canada	MAC
Mississippi State University	Starkville, Mississippi	MSU
Ohio State University	Columbus, Ohio	OSU
University of Alabama	Tuscaloosa, Alabama	UA
University of Tennessee, Knoxville	Knoxville, Tennessee	UT
University of Washington	Seattle, Washington	UW
University of Waterloo	Ontario, Canada	UWAFT
Virginia Tech	Blacksburg, Virginia	VT
West Virginia University	Morgantown, West Virginia	WVU

3.1.a. Mobility Challenge Propulsion Systems

While not the primary focus of this dissertation, powertrain integration and controls development are significant areas of emphasis for university teams and the components used provide helpful context to understand energy results. Readers should note that any energy results from university vehicles is impacted by both the powertrain design implemented by each school and the longitudinal control features. Because these propulsion systems are one-off prototype variants designed by universities, the resulting powertrain and trajectory controls do not reflect the same degree of refinement and consistency that a production system would exhibit. However, universities are also able to implement more experimental controls than publicly available production systems and have access to higher-powered and more flexible rapid prototyping controllers such as dSPACE's MicroAutoBox II's donated by the competition. While these prototype vehicles do not necessarily reflect production systems in terms of energy consumption performance, the diversity of design of both propulsion systems and CAV features provides a thorough pilot of energy testing methodologies that could eventually extend to production vehicle ADAS/CAV testing. Competitions also require more of a black-box fleet testing method than most one-off research projects, and the university vehicles must be fairly and consistently evaluated regardless of the specific sensor and powertrain design.

The university prototype powertrain implementations varied significantly across all teams in component choice, number and location of motors, and approach to energy management and torque distribution control algorithms. Each team was required to replace the stock engine and transmission, integrate a high voltage battery pack and at least one traction motor, and utilize rapid control development processes to achieve a functioning hybrid propulsion system. Universities implemented a range of configurations; in the case of UW, the team chose to use one of the donated GM engine/transmission pairings and augmented that with a 50 kW rear-axle traction drive motor shown in the following diagram:



Component	Specifications
Fuel	E10, 93 Octane
Engine	GM 2.0L LTG, 191 kW, 400 Nm
Transmission	GM M3D (9T50)
P4 Traction Motor	Magna eRAD, 50 kW, 200 Nm with Disconnect
Motor Gear Reduction	Single-speed 9.1727:1
ESS	GM HEV4 Pack, Li-Ion (NMC), 52kW, 80s1p

Vehicle Features:

- 12V Start/Stop
- Torque-split allows for AWD functionality
- Electric creep
- Performance mode

Figure 7. UW Mobility Challenge P4 Design

A summary of Mobility Challenge vehicle architectures and powertrain components is provided in the following table for reference. University teams were offered a selection of donated engines, transmissions, traction motors, and HV battery pack systems though they were also free to source their own components.

Table 7. EcoCAR Mobility Challenge Powertrain Architectures and Components

Team	Arch.	Fuel	Engine	Transmission	ESS	P4 Motor	P4 Motor Gearing	P0 Motor
Embry-Riddle (ERAU)	P0-P4	E10 (Regular)	GM 2.5L LCV I-4 (NA*, 148 kW)	GM M3D 9T50 (9-spd)	GM HEV4 Pack (296 Vnom, 52 kW, 1.5 kWh)	Magna eRAD (50 kW, 200 Nm)	9.17:1 Concentric Integrated Gearset	Denso ISG (32 kW)
Georgia Tech (GT)	P0-P4	E10 (Regular)	GM 2.5L LCV I-4 (NA*, 148 kW)	GM M3D 9T50 (9-spd)	GM HEV4 Pack (296 Vnom, 52 kW, 1.5 kWh)	Magna eRAD (50 kW, 200 Nm)	9.17:1 Concentric Integrated Gearset	Denso ISG (32 kW)
McMaster (MAC)	P4	E10 (Regular)	GM 1.5L LYX I-4 (Turbo, 126 kW)	GM M3U 9T45 (9-spd, ETRS†)	GM HEV4 Pack (296 Vnom, 52 kW, 1.5 kWh)	YASA-400 (70 kW, 250 Nm)	4.66:1 Gearbox (offset) + Axle Diff.	N/A
Mississippi State (MSU)	P4	E10 (Premium)	GM 2.0L LTG I-4 (Turbo, 191 kW)	GM M3D 9T50 (9-spd)	Custom HDS Pack‡ (346 Vnom, 90 kW, 3.5 kWh)	Cascadia Motion (85 kW, 330 Nm)	3.14:1 Custom Gear Reduction	N/A
Ohio State (OSU)	P0-P4	E10 (Premium)	GM 2.0L LTG I-4 (Turbo, 191 kW)	GM M3H 9T50 (9-spd, ETRS†)	Custom HDS Pack‡ (346 Vnom, 90 kW, 3.5 kWh)	Parker GVM210-100 (90 kW, 168 Nm)	8.28:1 BorgWarner eGearDrive	Denso ISG (32 kW)
Alabama (UA)	P4	E10 (Regular)	GM 1.5L LYX I-4 (Turbo, 126 kW)	GM M3U 9T45 (9-spd, ETRS†)	GM HEV4 Pack (296 Vnom, 52 kW, 1.5 kWh)	Parker GVM210-150J (50 kW, 266 Nm)	7.26:1 Planetary (in-line) + Axle Diff.	N/A
Tennessee (UT)	P4	E10 (Regular)	GM 2.5L LCV I-4 (NA*, 148 kW)	GM M3D 9T50 (9-spd)	A123 HEV Pack (320 Vnom, 105 kW, 4.5 kWh)	TM4 HSM60-MV255 (85 kW, 255 Nm)	3.45:1 Rear Axle Differential	N/A
Washington (UW)	P4	E10 (Premium)	GM 2.0L LTG I-4 (Turbo, 191 kW)	GM M3D 9T50 (9-spd)	GM HEV4 Pack (296 Vnom, 52 kW, 1.5 kWh)	Magna eRAD (50 kW, 200 Nm)	9.17:1 Concentric Integrated Gearset	N/A
Waterloo (UWAFT)	P4	E10 (Regular)	GM 2.5L LCV I-4 (NA*, 148 kW)	GM M3D 9T50 (9-spd)	Custom HDS Pack‡ (346 Vnom, 90 kW, 3.5 kWh)	AAM EDU4 (150 kW, 346 Nm)	9.04:1 Concentric Integrated Gearset	N/A
Virginia Tech (VT)	P4	E10 (Regular)	GM 2.5L LCV I-4 (NA*, 148 kW)	GM M3D 9T50 (9-spd)	Custom HDS Pack‡ (346 Vnom, 90 kW, 3.5 kWh)	PM eDrive (50 kW, 150 Nm)	10.0:1 Concentric Integrated Gearset	N/A
West Virginia (WVU)	P4	E10 (Regular)	GM 2.5L LCV I-4 (NA*, 148 kW)	GM M3D 9T50 (9-spd)	GM HEV4 Pack (296 Vnom, 52 kW, 1.5 kWh)	Magna eRAD (50 kW, 200 Nm)	9.17:1 Concentric Integrated Gearset	N/A

*NA: Naturally Aspirated
†ETRS: Electronic Transmission Range Selection
P0: HV Belted-alternator starter motor on ICE
P4: Rear-axle traction motor
P4-P4: Dual left/right uncoupled traction motors

3.1.b. Mobility Challenge CAV Activity Description

Mobility Challenge teams were tasked with designing CAV sensor and compute systems from the ground up, including replacing the functionality of stock radars and vision sensors. They were provided significant design freedom for architecting their system communication networks and chosen components, though all teams received software, sensors, and compute systems through donations from competition sponsors such as Intel, dSPACE, Bosch, and the MathWorks. Teams were challenged to implement V2X connectivity and longitudinal control features capable of operation in highway and urban environments. Each vehicle would be tested for its energy consumption and operational effectiveness through vehicle following and intersection navigation maneuvers. As this was the first AVTC to utilize automated controls and connectivity, teams were not expected to perform complex lateral maneuvers and the testing environments and scenarios were simplified. However, the test methods and systems we developed to support this university testing were intentionally designed to be expandable in future competitions.

While they were provided latitude and flexibility in their CAV system design and component selection, teams were required to comply with certain vehicle design requirements. One critical safety requirement prohibited teams from sending CAV commands directly from their CAV compute systems to powertrain components. Instead, we required that they send commands to the real-time propulsion system controller, which gatewayed those commands to the propulsion components. This restriction was done to ensure that CAN security and diagnostic features could always be performed on the more reliable real-time MicroAutoBox II system. It also allowed for CAV systems to be disabled through a physical switch until safety inspectors could perform static and dynamic checks that validated safe automated control feature operation. Most teams therefore had some commonalities in their overall CAV to propulsion system architecture, with a reference configuration shown Figure 8 from the EcoCAR competition rules [61]. While this configuration does not exactly match all university vehicle designs, it provides an example layout to understand the separation between CAV DSRC, sensor, and compute hardware and the rest of the propulsion system ECUs.

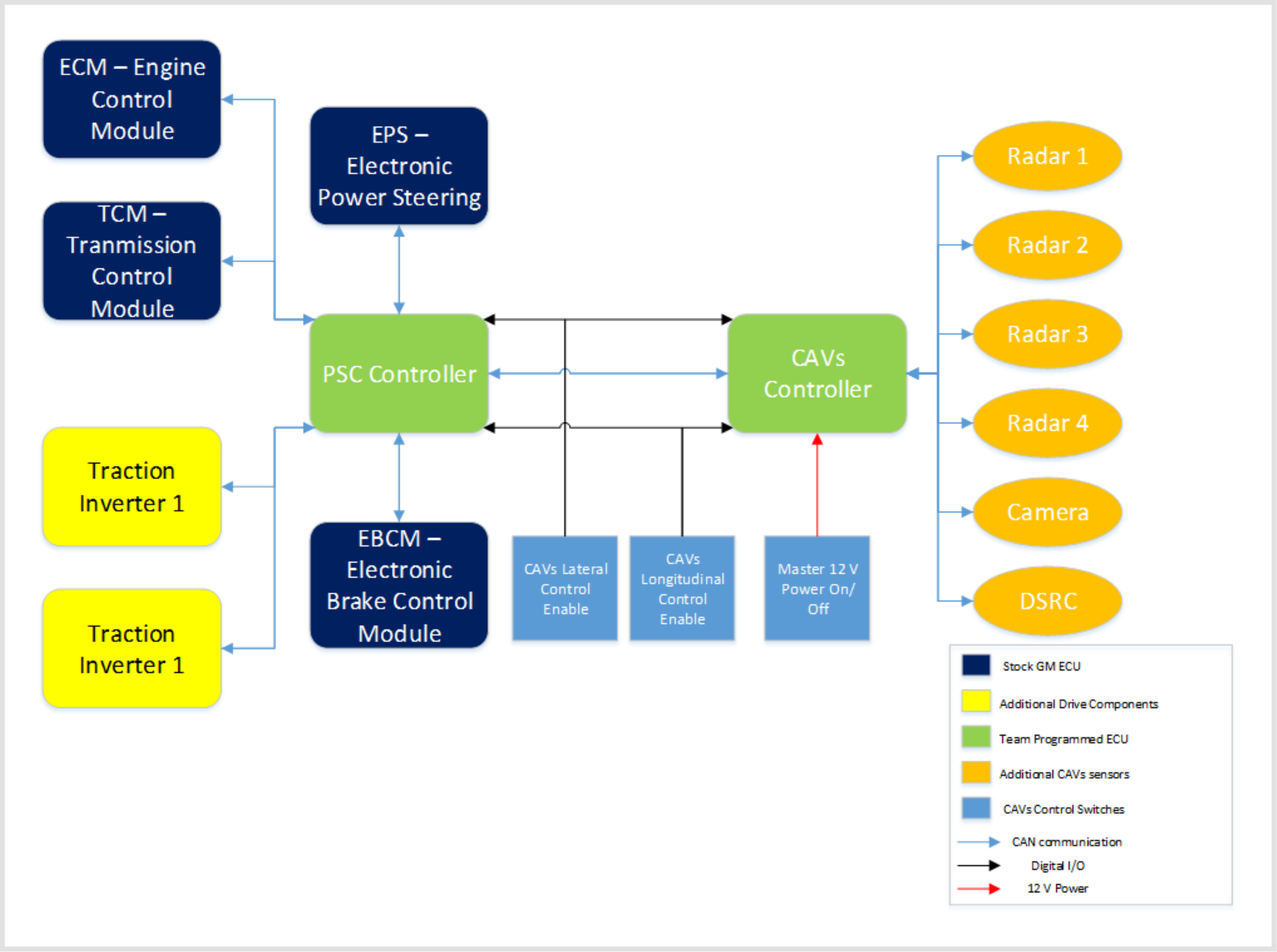


Figure 8: Example CAV Controller Architecture

A similar configuration was used for our Argonne and HORIBA-developed target vehicle test system described in later chapters, though for that application the primary goal was to repeatably drive a pre-established set of scenarios ahead of the university vehicles. It was also installed on a stock Chevrolet Blazer with an ICE propulsion system rather than the prototype hybrid systems used by teams. The work described in this dissertation focuses primarily on our development of the target vehicle test system and connected intersection/corridor test methods and systems. However, it is helpful to understand the context and design of the university vehicles and certain CAV system design requirements as these requirements impact the CAV energy measurements presented in Chapter 7.

In addition to vehicle design requirements, teams were subject to operational requirements in their CAV feature designs. For instance, the university vehicles were required to stay within a specified following distance constraint window behind any detected vehicles in their lane. This window included a minimum safety distance to minimize risk of collisions and give test operators adequate time to disengage the CAV feature if needed. The window also included a maximum following distance to ensure that university vehicles were not falling back so far that onboard sensors would be unable to reliably detect vehicles in competition track environments. The team developed this envelope conservatively for this first AVTC iteration, with a wide range of distances allowed to provide operational freedom to teams towards optimizing trajectories for energy. While the trajectories produced by teams may not directly reflect expected production performance, this wider envelope gave teams the opportunity to see what is both possible and optimal from an energy-saving perspective. The closest-allowable distance was established by Argonne's Energy Consumption Working Group, who analyzed on-road data from a variety of production AMTL vehicles and added a margin of safety to stopping distances and overall following distances versus speeds. A plot of this following distance constraint window can be seen in Figure 9.

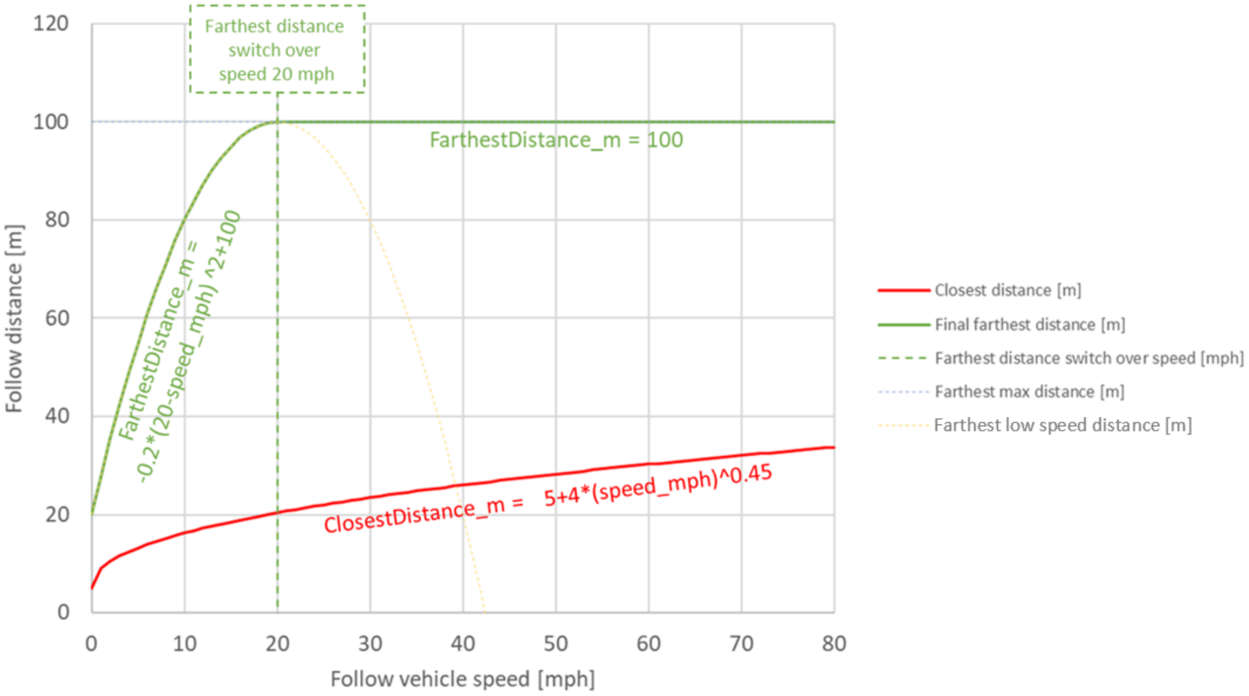


Figure 9. Following Distance Constraint Window for University CAV Systems

Over the course of the four-year competition, Mobility Challenge teams successfully developed a variety of diverse CAV features and powertrains. Their CAV systems varied in terms of sensor selections, modalities, placements, compute hardware, and algorithms utilized. At a minimum, they all utilized at least one forward-facing RADAR sensor, at least one forward-facing vision sensor, and at least one CAVs compute hardware system. Many teams went beyond that basic vision and radar sensor set, including one or multiple LIDAR solutions and additional RADAR units. While this greater sensor coverage went beyond what was required for success in the competition, it provided those teams with opportunities to learn additional sensor modalities and algorithms. Teams also utilized OxTS RT Range [62] systems during development and competition testing, enabling them to compare their sensor fusion system results with the RTK-corrected GPS serving as a “ground truth” verification. This OxTS system was also used during competition by our team to validate and evaluate their sensor system performance.

An image of some of the final university vehicles with CAV sensors installed can be seen in the following figure:

Figure 10. University CAV Prototypes in Year 4

From the above figure, readers may note a diversity in sensor system designs, with some teams electing to augment forward-facing radar and vision systems with one or multiple LIDAR sensors.

3.2. Evolution to the EcoCAR EV Challenge

After the conclusion of the Mobility Challenge in 2022, our Argonne team and headline sponsors DOE, GM, and The MathWorks designed and launched the current iteration of EcoCAR, the EcoCAR EV Challenge. The EV Challenge was designed in response to shifts in industry and government priorities towards more significant electrification. Students in this competition will start with a production EV platform, a 2022 Cadillac LYRIQ, and integrate new motor systems along with advanced CAV control capabilities. This competition features increased emphasis on connectivity technology, evolving beyond the more simplified ACC following and single intersection eco-approach and departure that was achieved in the Mobility Challenge. In EV Challenge, teams will utilize V2V, V2I, and longitudinal control capabilities along with the addition of lateral features to enact energy-optimized trajectory control in highly connected environments. The competition is intended to prepare university teams with advanced understanding of EV platforms while challenging them to advance the state connectivity and automation to drive progress throughout the automotive industry.

This increased emphasis on connectivity presents a significant challenge for Argonne and competition partners to provide test environments and methodologies able to fully exercise university CAV features. While some municipalities are beginning to deploy pilot connected corridors equipped with intersections or highway segments featuring RSU installations, these deployments are generally on publicly accessible roadways that are not suitable for controlled energy testing. As described in Chapter 2, the presence of traffic in test areas introduces variability between every single test run.

In addition, most track facilities are not yet equipped to conduct multi-mile, continuous energy testing of vehicles with both connectivity and automation features. Some partners such as TRC or Clemson have collaborated with Argonne research teams to perform connected vehicle energy testing [31]. However, most of these tests did not involve physical target vehicles on tracks capable of multi-mile driving at high speeds. Instead, an ego vehicle under test would receive virtual target vehicle trajectories through BSMs or other methods. EcoCAR EV Challenge vehicles would be capable of reacting to these simulated inputs in theory, but by limiting to only virtual targets there would be no characterization of perception system performance, time delays, or energy impacts.

While the test systems developed in the earlier chapters of this dissertation focus on vehicle following and single intersection capabilities, a novel combined test system is proposed in Chapter 9 that would enable this more advanced connected corridor testing. This system is designed for deployment at a wide variety of track facilities and is reconfigurable to support multiple real-world connected corridor geometries and SPaT/MAP transmissions in more controlled environments.

3.3. Chapter Conclusions

This chapter introduced the EcoCAR Mobility Challenge and EV Challenge competitions to provide context for the test methods and systems introduced in this dissertation. While much of this work focuses on Mobility Challenge test systems, methods and elements from these systems will be deployed in support of the EV Challenge as well as production ADAS and experimental CAV testing beyond student competitions. These competitions provide a unique opportunity to develop these new methods with a challengingly diverse set of potential test vehicles. The following chapters details the development of test methodologies, including target vehicle and connected intersections, along with pilot deployments of those approaches to test EcoCAR university vehicles. In the next chapter, a pilot method and target vehicle system is presented to enable longitudinal control feature energy testing.

Chapter 4. ACC Energy Pilot Test using Network Guided Vehicle

In this chapter, we present details on collaborative research performed with HORIBA Automotive to design and pilot a test method that enables controlled, repeatable track-based energy consumption testing of driver assistance features. The testing was performed at MIRA's proving ground facility in Nuneaton, UK, using their Network Guided Vehicle (NGV) connectivity and automation test platform. As described in Table 3, these activities are related to research **Goal 1. Developing CAV testing pathways** and **Goal 2: Implement CAV Test Systems**. Content from this chapter was published in the 2020 IEEE 92nd Vehicular Technology Conference paper Modifying Network Guided Vehicle for Repeatable EcoCAR ACC Energy Testing by Crain et al. [16]. Some minor modifications were implemented from the original text to avoid replication of content from earlier chapters and to accurately capture the work performed after manuscript publication.

4.1. Chapter Introduction

The study described in this chapter was our first pilot evaluation of the planned two-vehicle following CAV energy test designed for the EcoCAR Mobility Challenge. In past competitions, prototype university vehicles were assessed for energy consumption using manually driven longitudinal drive cycles on circuit-based proving ground test tracks [56], but the shift to CAV features in the Mobility Challenge drove the development of these new methods. As described in prior chapters, the EcoCAR vehicles are generally tested in track environments to accomplish testing of a fleet of up to 11 vehicles with diverse sensor and powertrain systems in a timespan that would otherwise require 6-7 dynamometers at one facility. While some increased variability is present in track environments due to the lack of a controlled laboratory setting, that decreased accuracy was deemed acceptable given that very few facilities exist to even test a fleet of vehicles this large in traditional non-automated energy testing. The CAV features in Mobility Challenge also introduced another limitation preventing dynamometer evaluations, namely the need to test the full spectrum of sensor performance, perception system accuracy, longitudinal control performance, and resulting vehicle efficiencies. We therefore decided to develop a new track-based method for energy testing that would enable energy performance evaluations of an entire fleet of up to 11 university vehicles using controlled and repeatable test systems.

This chapter presents our collaborative effort with HORIBA MIRA to propose and pilot a test method for controlled, repeatable track-based energy consumption testing of automated longitudinal control features. We performed this testing at MIRA's proving ground facility in Nuneaton, UK, using their NGV connectivity and automation test platform. The NGV served as a repeatable lead vehicle following prescribed drive traces around two different track circuits while the host vehicle under test, a Honda Civic with full speed range ACC, followed behind. We also utilized a novel track-based extension of SAE J2951 dynamometer drive quality metrics to quantify how repeatably and accurately the lead vehicle followed the trace. Additional details and methods for performing these calculations can be found in Chapter 6, as the original version of this conference publication focused primarily on the pilot test methodology.

The primary goal of this chapter is to introduce the reader to the test methodology, equipment set up, and process used as a foundation for future test activities. As the NGV was not easily transportable to the United States for EcoCAR testing, later chapters will describe the refinement and deployment of software from NGV's DigiCAV software stack to the EcoCAR Mobility Challenge Chevrolet Blazer target vehicle platform. The chapter also demonstrates that the methods we developed are usable with production ADAS systems, as we used a production Honda Civic with stock adaptive cruise control as the follower vehicle under test.

4.2. Test and Equipment Details

4.2.a. MIRA Network Guided Vehicle Development

In order to perform a repeatable evaluation of the host vehicle under test, it was necessary to implement a lead vehicle capable of using longitudinal control to execute a repeatable and accurate drive trace ahead of the host. MIRA engineers modified their Network Guided Vehicle (NGV) and DigiCAV Cooperative Driving Platform (CDP) [63] to operate the NGV as a semi-automated target vehicle during the tests.

The DigiCAV CDP and NGV were designed to enhance MIRA's capability in researching how connected infrastructure can help guide CAVs through the road network and to enable the next generation of CAV testing on a proving ground [63], [64]. When this work was originally performed, the NGV system ran on a modified Ford Mondeo designed to participate in a distributed VIL simulation using the DigiCAV CDP (see below). Through the DigiCAV CDP, the NGV engages in cooperative autonomy with a combination of simulated or real vehicles and CAVs.

Figure 11. NGV during test with display showing NGV position, path and real/virtual test participants

The NGV is a proving ground test platform and was not intended for public road use. It relies on high precision RTK-GPS to determine its position and requires the road network in its area of operations to be mapped. This iteration did not have extensive sensing capability and instead required the information about other objects in the operation area to be provided through the CDP.

For the purposes of this testing, MIRA engineers developed a drive cycle software tool to enable flexible and repeatable on-track replay of speed traces used in dynamometer-based US federal test procedures [65]. The software also enables the NGV to execute custom drive cycles, including simplified cycles or realistic scenario traces gathered during on-road testing. As seen in Figure 2, custom software replaces the path generator in the vehicle controller stack and controls the NGV to accurately follow the pre-defined drive cycle.

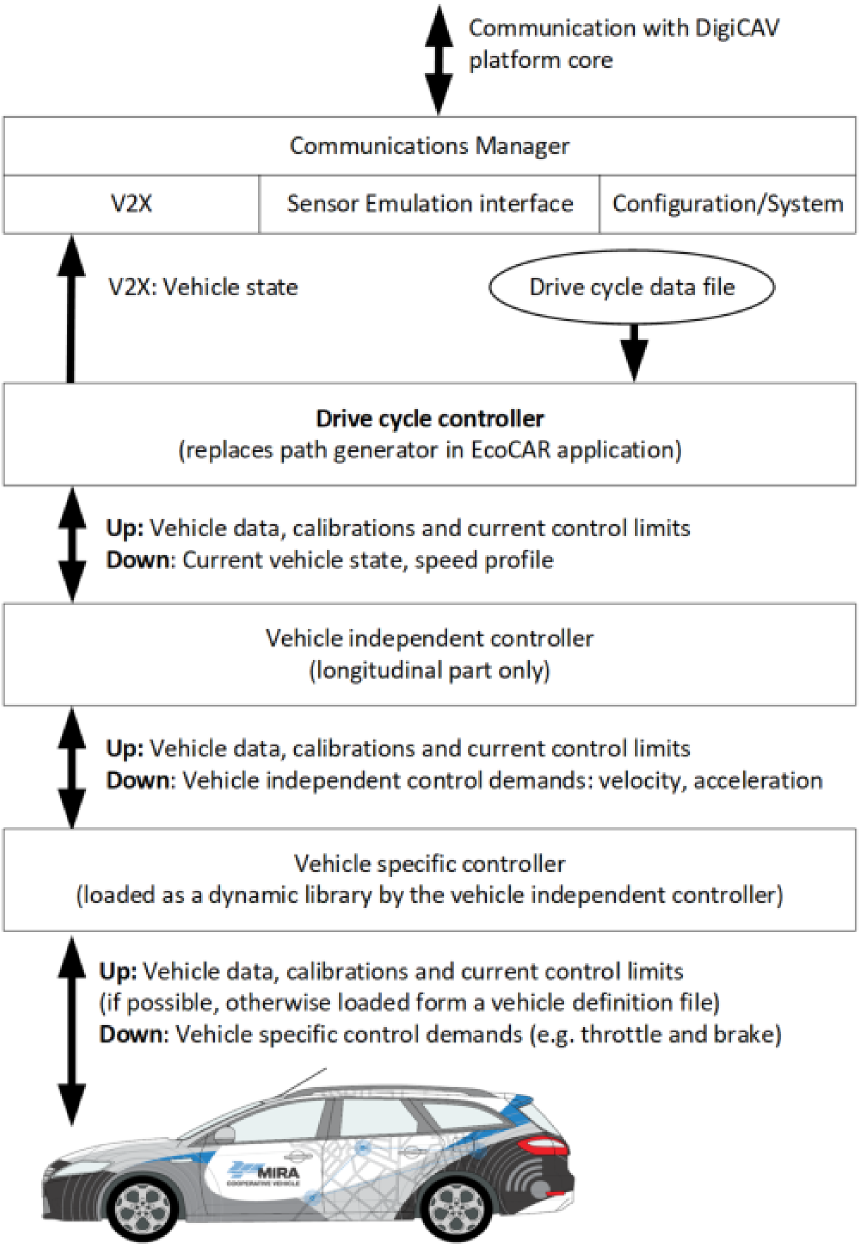


Figure 12. Structure of NGV controller in DigiCAV platform, modified to accept drive cycle stimulation

4.2.b. Track Description and Tests Performed

The automated energy testing described in this chapter was performed on the City Circuit and High Speed Circuit test tracks over the course of two days at the HORIBA MIRA Proving Ground, as seen in Figure 3.

The City Circuit was used for calibration and initial trials of lower speed cycles such as the Urban Dynamometer Driving Schedule (UDDS) [65]. This circuit is a safe, comprehensive and fully controllable 'cityscape' dedicated to the testing, validation and demonstration of intelligent vehicles and intelligent transportation systems in an urban and sub-urban environment. The circuit includes roadside architecture such as traffic signals and gantries plus a sophisticated range of real-time vehicle monitoring, modern communication technologies, private cellular networks, fully configurable wireless networks, and dedicated vehicle-to-vehicle communications.

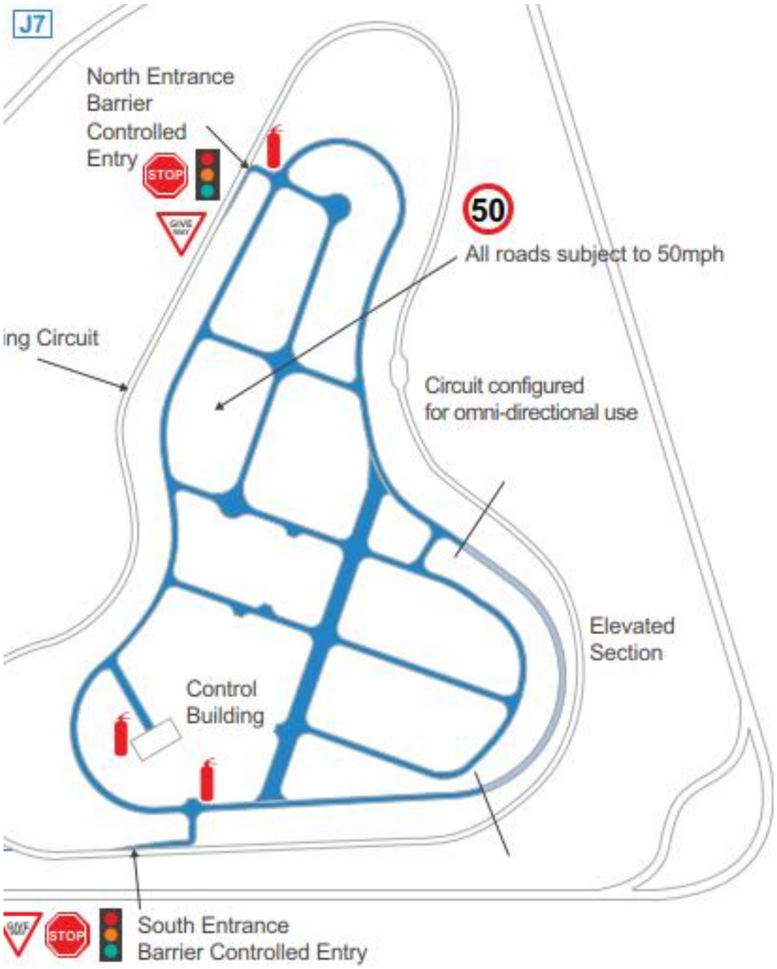


Figure 13. MIRA City Circuit Layout

The outer loop of this city circuit was utilized for all UDDS cycles described in this chapter. This loop did provide some limitations to allowable speeds due to its sharper curves and elevation changes, which occasionally made it difficult to keep the target vehicle in view of the host's sensors. The 50 mile-per-hour speed limit of the city circuit also made it necessary to alter the UDDS trace to remove hill two of the cycle. The High Speed Circuit was used to evaluate target and host performance on higher speed tests like the HWFET cycle [65]. This track was ideal for performing the type of energy testing described in this chapter, with shallow curves and higher-speed limits to enable faster cycles. However, due to other MIRA testing traffic it was only available on a very limited basis for the purposes of this chapter.

For the test itself, both vehicles were driven to either the City Circuit or High Speed Circuit (depending on the cycle), then prepped through several kilometers of driving prior to beginning testing. To prepare the follower vehicle for the test, both vehicles were driven up to the speed required to initiate the host vehicle's ACC system. At that point, ACC on the host vehicle was engaged and the set speed was manually set to 10 km/h greater than the top speed of the cycle. The NGV lead then decelerated to a stop.

To begin the test, the NGV initiated the requested cycle, and the operator of the host vehicle pressed the resume button, releasing the vehicle from a 'hold mode' as soon as acceleration of the lead vehicle was observed. The test was considered concluded once the host vehicle came to a stop behind the NGV at the end of the cycle. An image of the test vehicles on the High Speed Circuit can be seen in the following figure:

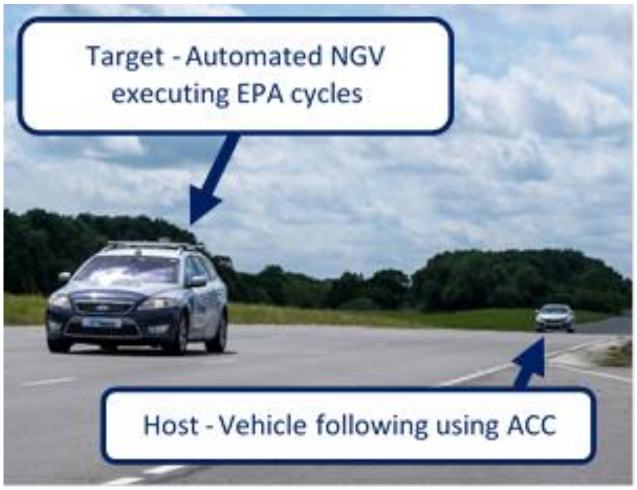


Figure 14. Host and target vehicle during HWFET on High-Speed Circuit

4.3. Results

Over the course of two days of testing at MIRA, several iterations of the UDDS cycle and one iteration of the HWFET cycle were successfully performed. A test was considered successful provided the NGV completed the entire cycle and a reasonable level of repeatability was achieved in the timing of resume functions on the host vehicle under test. Note that the host vehicle's stock ACC systems were not equipped to resume from a stop and required the operator to begin pressing the resume button repeatedly prior to the target NGV accelerating from a stop.

During the two-day test, we noted several limitations and challenges with the test procedure described. Some of the greatest challenges regarded controlling different variables for repeatability of the test method from test to test. All track-based testing is subject to a significantly higher degree of variability compared to dynamometer testing. In a track environment, temperature and humidity of the ambient air is uncontrollable and will always be a source of variation between days and even between individual tests depending on when they are run. In addition, operators of the vehicles must pay more attention to their surroundings than on a dynamometer and thus are more vulnerable to inconsistencies in the operation of the vehicle.

This variation was particularly noticeable in the timing of resuming ACC operation from a stop on the host vehicle. If the host driver actuated the resume function too early before host vehicle sensor systems perceived the NGV target accelerating away, the host would not accelerate as planned and the operator would need to press resume again. Alternatively, if even a slight delay happened prior to the operator pressing the resume button, the resulting host vehicle trace for that portion of the cycle exhibited higher accelerations, higher maximum speeds, and greater decelerations as it approached the target from behind at a greater rate.

Due to the pilot nature of this development activity, HORIBA researchers performed relatively limited calibration activities to enable the NGV to accurately follow higher speed drive traces needed for energy testing. Despite this limited calibration, the vehicle was able to execute drive traces with reasonable accuracy as seen in Figure 15 for the HwFET drive cycle.

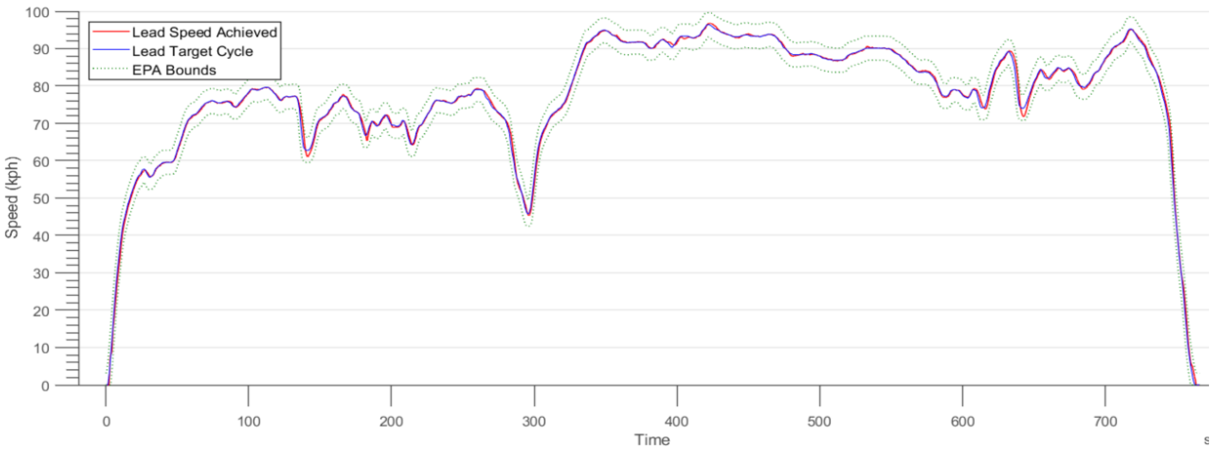


Figure 15. NGV trace achieved versus HwFET

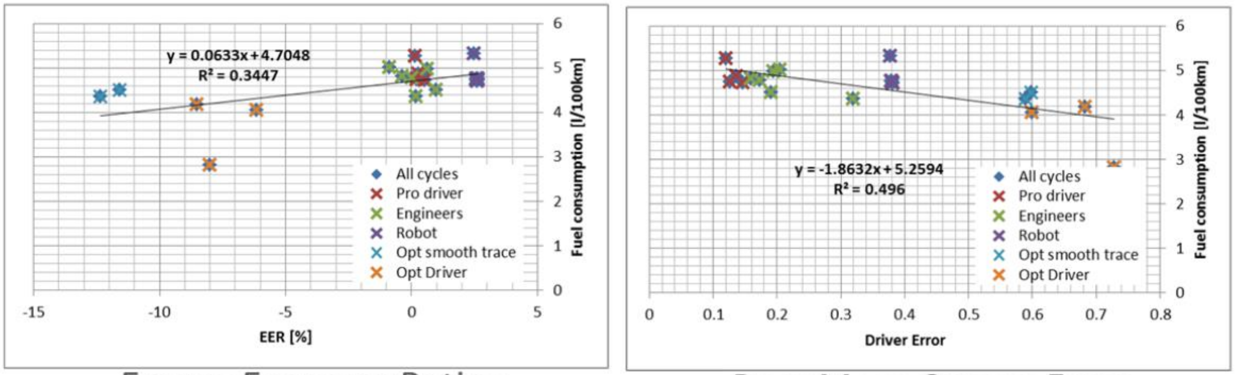
The figure above shows the trace achieved by the NGV over the HWFET cycle. For clarity the plot shows only the NGV lead speed achieved, the target cycle, and the bounds specified by EPA for dynamometer fuel economy testing [65]. There are some points of deviation, notably on harder deceleration events at approximately 140 and 630 seconds, but this particular iteration of the NGV controls was primarily calibrated in lower speed test conditions and was not purpose-built to follow higher-speed drive cycle traces.

Even with this rough calibration, the NGV achieved sufficiently high accuracy following the prescribed cycle for both the HWFET and UDDS. In order to quantify the accuracy of the NGV in following the prescribed trace, each of the successful cycles were analyzed using the SAE J2951 standard [3]. This standard was developed by Argonne personnel and industry partners for measuring the accuracy of trace following during a traditional dynamometer test [66]. However, the calculations also provide several useful parameters for measuring how accurately the NGV drove the target cycle on track. Our research team developed a method of extending this traditionally dynamometer-based calculation to be applicable using track-gathered data. Our J2951 metric calculation results for each of the cycles can be seen below.

Table 8. SAE J2951 results for NGV lead trace achieved

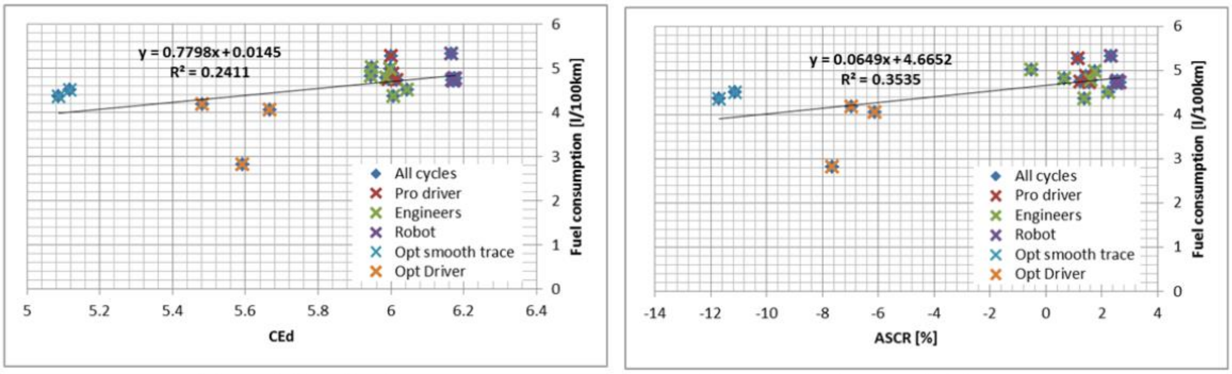
Cycle	Distance Rating (DR)	Energy Rating (ER)	Energy Economy Rating (EER)	Absolute Speed Change Rating (ASCR)	RMS Speed Error (RMSSE)
HWFET	0.06	0.34	0.28	5.74	0.59
UDDS 1	0.07	-0.34	-0.41	0.97	0.87
UDDS 2	0.08	-0.16	-0.24	0.97	0.87
UDDS 3	0.08	-0.61	-0.69	0.64	0.90
UDDS 4	0.08	-0.31	-0.39	0.82	0.90

Based on the results from this table, the NGV was reasonably accurate following the required drive trace as defined by SAE J2951. While these results for energy efficiency rating (EER) and RMS error are less accurate than those achieved with robot drivers in Argonne dynamometer testing in Figure 6 below [67], the testing performed in the figure was both completed in and optimized for a chassis dynamometer testing environment. In later evaluations, HORIBA MIRA and Argonne worked to refine both the repeatability and accuracy of the NGV software for on-track performance of the cycles needed for EcoCAR testing. The following plots show results from prior testing conducted on dynamometers at Argonne for comparison [66].



Energy Economy Rating

Root Mean Square Error



Total Cycle Energy

Absolute Speed Change Rating

Figure 16. SAE J2951 comparison performance of Argonne human and robot driver operators

These plots demonstrate the higher accuracy levels possible through highly trained human operators in the more controlled dynamometer environment. Argonne's robot driver systems have also been tuned specifically to follow certification cycles such as those used in this test method and were therefore able to achieve better performance. However, with additional calibration time it is likely that similar levels of accuracy could have been achieved with the NGV DigiCAV system.

Finally, it is beneficial to investigate the performance of the host vehicle under test during the cycles. Specifically, an excerpt of the HWFET cycle is shown in Figure 17 with the lead NGV trace achieved in red and the host Civic trace displayed in blue. The host vehicle data has been time shifted to align the first acceleration event with the NGV in order to compare the cycles followed by each vehicle.

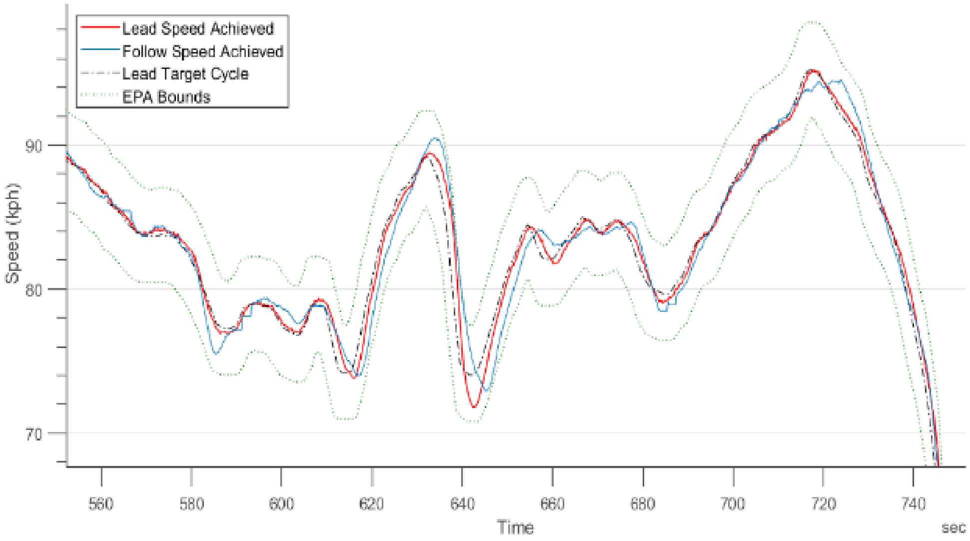


Figure 17. NGV trace achieved with host vehicle included on HWFET

The data displayed in Figure 17 show some portions of the host vehicle smoothing the achieved trace, such as during the small perturbations after 650 seconds. However, the host also encountered both overshoot and undershoot at various points in the HWFET cycle. Data for fuel usage was collected from the host vehicle using a combination of captured vehicle communication and a fuel flow meter installed in-line with the fuel line directly before the engine. Unfortunately, the results for fuel consumption were obfuscated by challenges which resulted in the inability of the device to be used as the primary measurement method. Most notably, over the course of the testing, consistent signal dropouts of the fuel flow meter signal were observed. These dropouts were likely caused by the low fuel flow volume compared to the prototype meter's designed flow rates, and future iterations of this meter corrected for this issue. Overall, it was difficult to demonstrate conclusive evidence of energy consumption impacts of ACC operation by the host vehicle given the small number of iterations of this cycle and the challenges present with the fuel flow meter. However, this testing was primarily designed to demonstrate the viability of the test method and develop a means of assessing the repeatability and accuracy of the drive trace followed by the NGV lead vehicle.

4.4. Chapter Conclusions

In this chapter, our new track-based energy testing method was demonstrated to be a viable method for assessing the energy consumption of an ACC vehicle following an automated target vehicle driving EPA drive traces. Results from our novel deployment of SAE J2951 metrics [3] to lead vehicle accuracy measures were presented showing acceptable performance for a pilot study. While no conclusive findings on fuel consumption were reported in this original publication due to an issue with the instrumentation that has since been corrected for, this outcome is an excellent demonstration of the challenges that come with energy testing in track and dynamometer environments. This is particularly true whenever a new method and instrumentation system is piloted, and many of the learnings from this pilot study informed later Mobility Challenge methodology development. Even with these challenges, the MIRA testing showed that this method could be used with production vehicle platforms in addition to university prototypes.

As described in Table 3, the research activities in this chapter link to **Goal 1. Developing CAV testing pathways**, and **Goal 2. Implementing CAV test systems**. With a proposed two-vehicle track ACC energy test method successfully piloted and foundations laid for future CAV test systems, the next chapter will describe the process to port the NGV DigiCAV control software in this study to a Chevrolet Blazer.

Chapter 5. Blazer Target Vehicle Software Development in HIL

This chapter describes our HIL-based development process used to prepare longitudinal control interfaces for Argonne's 2019 Chevrolet Blazer, in preparation for it to serve as a target vehicle ahead of EcoCAR Mobility Challenge university prototypes. Our team implemented a flexible controller architecture and HIL testing to deploy previously developed and validated software from the HORIBA MIRA pilot study, accelerating initial testing and calibrations of the control software for Blazer systems during the COVID-19 pandemic. Using these HIL test systems enabled our research team to perform remote calibration and functionality testing of the Blazer-specific DigiCAV controller implementation at a time when track-based testing was not possible. This chapter focuses on research **Goal 2: Implementing CAV Test Systems.**

Content from this chapter was published at the 2020 IEEE Connected and Automated Vehicle Symposium (IEEE CAVS 2020) under the title Prototyping EcoCAR Connected Vehicle Testing System Using DigiCAV Development Platform by Crain et al. [14]. Some modifications have been made to the original text to avoid replication of content and accurately capture the work performed after the original publication date.

5.1. Chapter Introduction

This chapter details the application of HORIBA MIRA's DigiCAV platform to the EcoCAR use case of developing test systems capable of evaluating CAV feature energy usage in proving ground environments. The DigiCAV platform is designed to enable users to develop and test CAVs and their subcomponents in a variety of simulated and real test environments [11].

In the prior chapter, a simplified version of the DigiCAV platform was used for deploying the Network Guided Vehicle to conduct a controlled two-vehicle ACC energy consumption test at the HORIBA MIRA proving ground in Nuneaton, UK. We performed this pilot testing to demonstrate the viability of conducting multi-vehicle ACC energy evaluations in the proving ground environment [12]. In the next phase of deployment, we extended the DigiCAV platform to use hardware and communication interfaces from Argonne's 2019 Chevrolet Blazer and performed initial calibration activities on target hardware using HIL test environments. The following sections describe the DigiCAV platform at a high level along with the EcoCAR-specific platform implementation.

5.2. DigiCAV Platform General Overview

The DigiCAV platform comprises a number of technologies designed to enable users to develop and test CAVs and their subcomponents in multiple test environments. These can be real, such as chassis dynamometers and proving grounds, virtual (using digital versions of real test tracks) or in mixed-reality approaches comprising both real and simulated environments [11]. DigiCAV aims to provide a set of interfaces to connect both physical and virtual elements (such as vehicles or individual CAV sensors) with the platform to enable co-simulation. These interfaces enable the use of simulation testing methods ranging from model and software to hardware and vehicle in-the-loop (MIL, SIL, HIL, VIL), providing support for a comprehensive range of test requirements.

The DigiCAV platform was still under development at time of publication. By collaborating with Argonne on the EcoCAR project, HORIBA MIRA was able to test a subset of the platform's capability in several real-life applications. The previous chapter's proving ground ACC testing [12] utilized a NGV to demonstrate precise automated vehicle control technology as well as the ability of the DigiCAV platform to facilitate interaction between real and simulated vehicles necessary for the EcoCAR project. The NGV is the evolution of the Network Assisted Vehicle described in a prior HORIBA MIRA publication [13].

One benefit of the DigiCAV platform is its ability to control and interact with a wide range of vehicles, from the smallest demonstration robots to the largest road vehicles. This flexibility comes from an architecture where most of the vehicle trajectory control is performed using a common set of vehicle-agnostic control algorithms. In this architecture, only the vehicle calibration and a single, low-level controller are specific to each physical vehicle. HORIBA MIRA can quickly produce this vehicle-specific controller for new test vehicle targets to achieve accurate trajectory control of new vehicle designs. Once developed and refined, this controller can be integrated into the rest of the DigiCAV architecture in a similar manner to installing a device driver on a computing platform. This capability allows DigiCAV to run a variety of different vehicles in its environment at the same time [11].

A similar distributed architecture was already in use by the Mobility Challenge teams (described in Chapter 3), where CAV perception and control algorithms were implemented on a ruggedized IEI TANK-870-Q170 compute system [60] before being passed to a dSPACE MicroAutoBox II 1401/1513 rapid prototyping controller [59] to translate those commands to the propulsion system. For our Argonne target vehicle, a modified implementation was used that had an IEI TANK running HORIBA's DigiCAV software stack and communicating with a Blazer-specific propulsion system gateway module developed in support of this research. This communication leveraged an existing CAN interface specification developed for teams that included longitudinal control messages in a vehicle-agnostic format, to be translated to Blazer-compatible longitudinal CAN commands.

Figure 1 showing this breakdown between system domains developed by each party. Additional details are described in the following section.

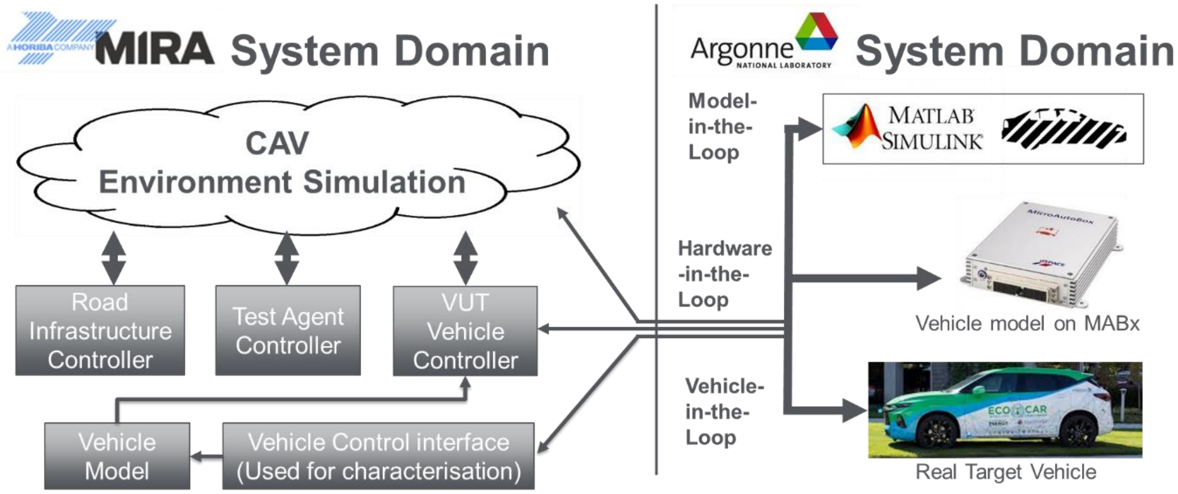


Figure 18. Breakdown of HORIBA MIRA and EcoCAR system domains

The figure above shows HORIBA MIRA's system domain on the left, which we collaborated on to calibrate based on Blazer control responses. We then worked with HORIBA to translate this software to the IEI TANK target hardware. On the right are the different environments our team used for development. We created a flexible model architecture in Simulink for MIL testing, converted it using dSPACE IO blocks to send and receive physical IO CAN messages defined for Blazer networks, created wire harnesses for interfacing with Blazer systems, and validated the overall system in-vehicle once MIL and HIL testing was complete.

5.3. EcoCAR Test Platform Design

In the EcoCAR test platform implementation, a Blazer owned by Argonne was the primary target vehicle for the majority of proving ground energy testing events. While the distributed nature of the DigiCAV platform system allows for different configurations, in this layout the Blazer provides the centralized location for running the DigiCAV platform. It housed all control hardware necessary for operating as a target vehicle, in addition to planned capabilities for simulating and transmitting V2X messages for additional vehicles and infrastructure.

The controller hardware architecture onboard the Blazer can be seen in Figure 2, along with descriptions of each element and high-level messaging content between modules.

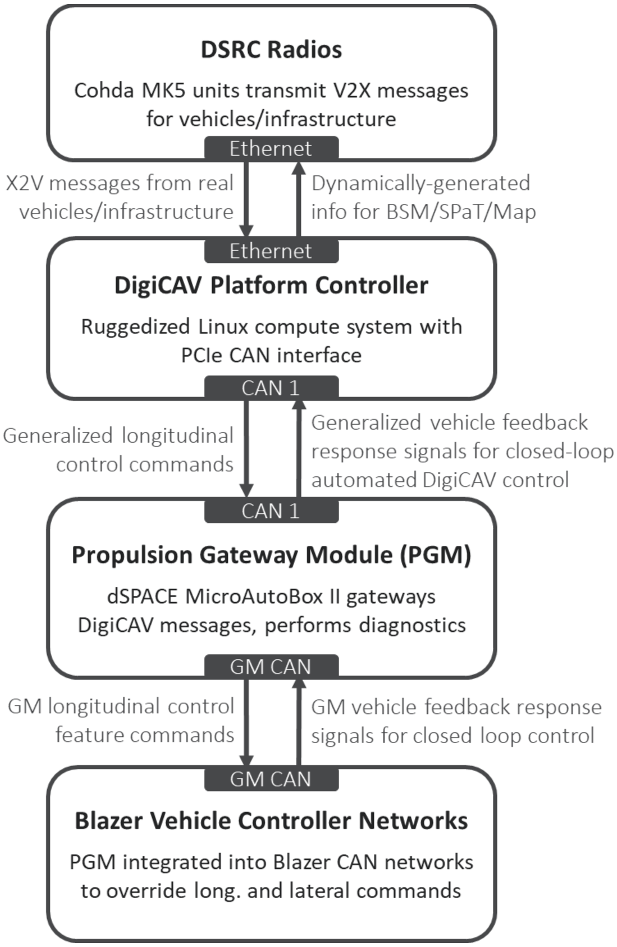


Figure 19. EcoCAR and DigiCAV Blazer Controller Architecture Diagram

As shown in the diagram, the DigiCAV platform ran on a ruggedized Linux compute system onboard the Blazer. The DigiCAV controller was connected via ethernet to a Cohda MK5 DSRC radio capable of operating as either OBUs for V2V transmission or RSUs if simulated infrastructure elements were required. While this feature was not utilized in the final competition testing, the capability was implemented in DigiCAV software to enable transmission of upcoming vehicle traffic ahead of the target using BSMs. The DigiCAV platform is capable of directly interfacing with vehicle CAN busses, though in this case for protection of proprietary data a Propulsion Gateway Module (PGM) MicroAutoBox II translated between generalized DigiCAV messages and those required by GM Blazer control modules. Longitudinal control was performed by overriding ACC system commands, and, if necessary, lateral control features could have been enabled by overriding automated steering commands on vehicle busses.

5.4. EcoCAR Testing Overview

This controller architecture allows for a wide variety of energy test methods and proving ground environments, where EcoCAR vehicles were tested through a combination of circuit-based medium and high-speed longitudinal drive cycle testing and more urban-focused intersection environments. While not fully utilized during official Mobility Challenge testing due to COVID-19 related delays, an example of a potential connectivity-augmented energy test method can be seen in Figure 3. The test would be executed on a circuit-based track such as the high-speed circle track facilities available at many proving grounds. In this configuration, the Blazer would act as a target vehicle in front of the prototype vehicle under test. It will follow drive cycles ahead of the vehicle under test in a repeatable and accurate manner, providing a controlled target vehicle for the CACC or ACC characterization of the test vehicle.

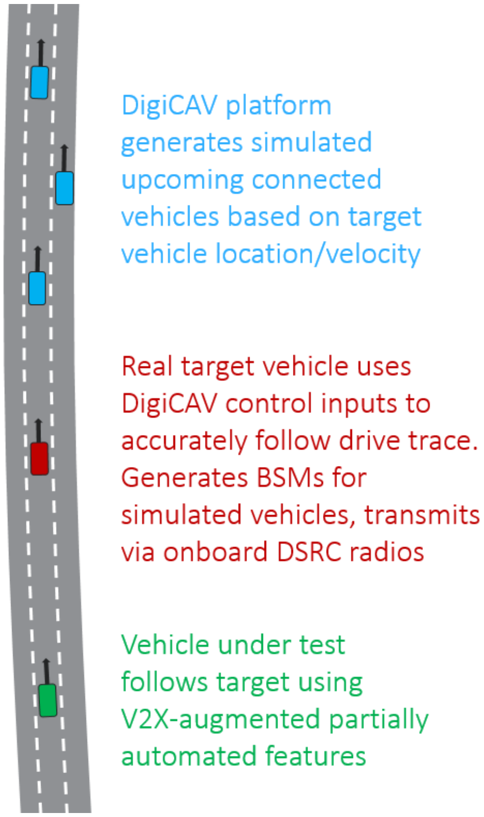


Figure 20. Planned test setup for EcoCAR connectivity-augmented ACC testing

Figure 20 also portrays the potential for DigiCAV-generated upcoming simulated vehicles based on the current target Blazer position and speed. Original event and system plans included the option for teams to potentially interact with the simulated vehicles and utilize this foresight of upcoming traffic behavior to smooth ACC trajectories and maximize regenerative braking of their prototype hybrid drive systems. However, due to COVID-19 delays in development both at Argonne and participating universities the final test only utilized the physical target vehicle trace following component. Future events in the EV Challenge will utilize this capability however, where the target vehicle software will be able to generate appropriate BSMs for each simulated vehicle and transmit these simulated vehicles back to vehicles under test using C-V2X Cohda MK5 hardware.

While this chapter's test system development focuses on utilizing two-vehicle proving ground test methodologies for ACC energy evaluation, later chapters include development of intersection-based connected urban corridor energy testing. In these future connected corridor evaluations, team vehicles would interact with physical and simulated target vehicles while traversing a series of connected intersections transmitting SPaT and MAP I2V communication. These urban connected corridor environments will challenge teams to utilize connectivity and onboard sensor measurements to maximize efficiency and user comfort while their prototype vehicles navigate the corridor with active driving assistance features.

5.5. Blazer-Specific Vehicle Interface Development

In order to deploy the Blazer as a real target vehicle in the DigiCAV platform, it was necessary to characterize the vehicle’s response to a set of pre-determined control inputs and calibrate a vehicle-specific Blazer controller interface. We originally planned to develop the Blazer longitudinal automation interface using a VIL approach at either a dynamometer or proving ground facility. This process would have required inducing a series of controlled acceleration and braking actuation profiles using the DigiCAV platform and calibrating the Blazer-specific controller based on the measured dynamic vehicle response. Unfortunately, the COVID-19 pandemic made it impossible to perform those trials due to facility access and international travel restrictions.

With access to the physical vehicle and testing facilities restricted, we instead decided to use a two-phased approach for developing the Blazer-specific interface. In the first phase (during the strictest lockdown period), we utilized a HIL setup to validate DigiCAV hardware interfaces while also enabling initial approximate calibration of the Blazer-specific controller parameters. The next chapter will describe the use of proving ground testing to refine those initial DigiCAV control parameters and optimize the real-world drive cycle following performance.

The HIL setup consisted of the Blazer DigiCAV and PGM controller hardware connected to an additional MicroAutoBox acting as a Blazer plant model; this plant model was designed to emulate the dynamic response of the Blazer to ACC inputs and utilized the same communication architecture and message structure as the Blazer. In this way, a relatively seamless transition between HIL bench and VIL environments was possible without large adjustments to CAN interface definitions on the DigiCAV or PGM controllers. The model was calibrated using existing vehicle data collected from on-road Blazer ACC system testing to create a vehicle dynamics model of sufficient fidelity for initial Blazer-specific controller development. A diagram of this modified HIL development setup can be found in Figure 19.

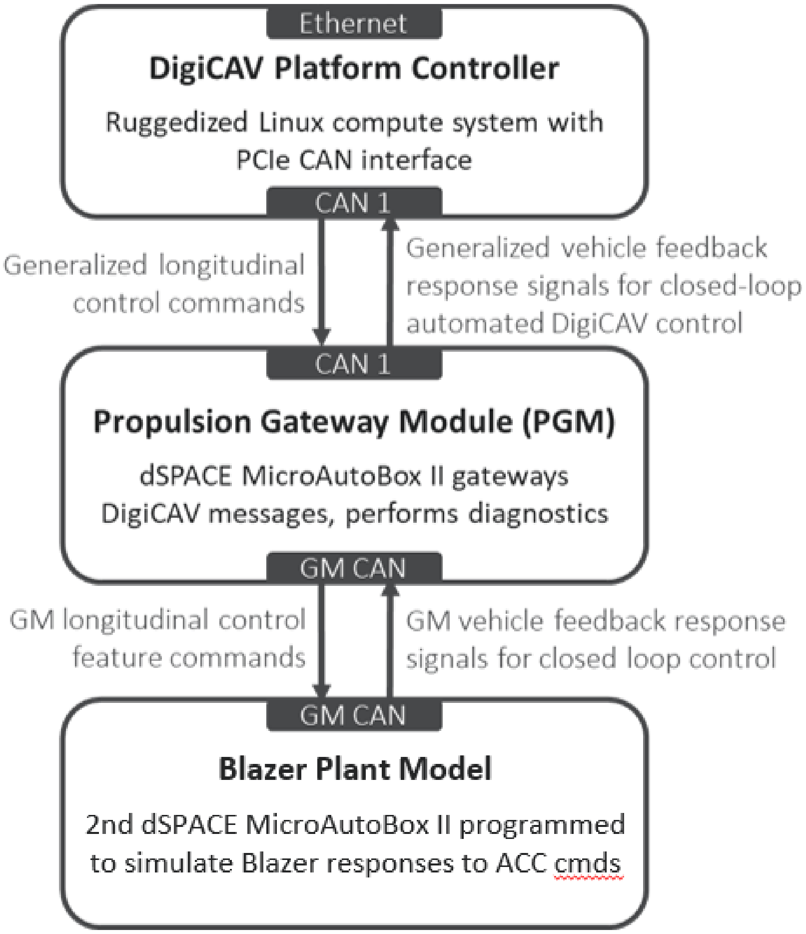


Figure 21. HIL Setup Used to Develop Target Vehicle Test System

In order to validate that calibration and HIL test setup, the DigiCAV system provided the same sequence of automated commands recorded from the on-road data. The open-loop response of the plant model was then compared to the vehicle dynamic response recorded on-road. This log data was recorded during in-field testing in dynamic traffic situations to capture the typical behavior of the stock ACC system. A more thorough characterization of the stock behavior was not possible given the barriers to in-field testing at that time, though the comparison still allowed for preliminary parameter calibration. A plot showing the resulting velocity traces is shown in Figure 22.

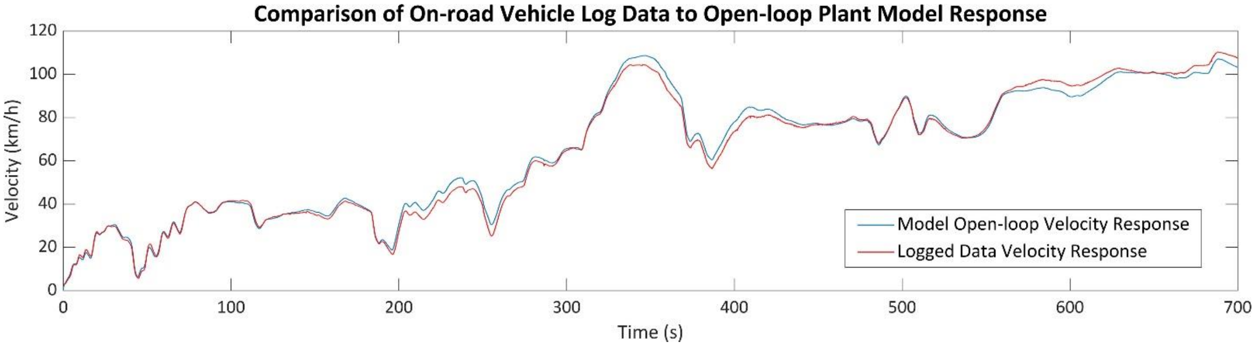


Figure 22. Model validation results from Blazer plant model responding to open-loop commands

It should be noted that this initial plant model was specifically designed for rough parameter calibration and thus did not represent the complex driveline dynamic behavior that would be necessary for a full controller calibration. The open loop plant model output did exhibit some variation from the logged data, but this is primarily due to the simplistic nature of the transfer function-based dynamics model. These differences were small enough in magnitude to enable initial parameterization of the Blazer-specific controller, provided additional calibrations were performed on the actual vehicle once vehicle testing facilities became accessible. In this next phase of development covered in Chapter 6, the HIL-validated DigiCAV and PGM system was be deployed for the originally planned VIL track testing activities.

As seen in Figure 22, these open-loop plant model response tests demonstrated similar behavior to results seen from actual on-road Blazer stock ACC system testing and validated the HIL-based test system for initial calibration and development activities.

5.6. Chapter Conclusions

The work from this chapter focused on research **Goal 2: Implementing CAV Test Systems**, using HIL-based rapid control prototyping development methods to accelerate deployment of target vehicle assets needed for Mobility Challenge tests. While HIL is commonly used in industry-based controls development, it is more traditionally used for creating and testing features intended for production vehicle controls rather than target vehicle test systems. This chapter's HIL testing and trans-continental collaboration during pandemic lockdowns was highly beneficial for quicker deployment of the system to the actual Blazer target vehicle once in-person research could resume.

With initial HIL-based interface testing complete and Blazer-specific controller development under way, the next phase of the process required proving ground evaluations of our Blazer target vehicle test system. These evaluations involved development trips to refine the operation of the Blazer over automated longitudinal cycles, characterize its accuracy and repeatability over a number of trials, and apply the methodology to evaluating a variety of stock ACC-equipped vehicles. This later testing demonstrated the viability of the Blazer lead vehicle system implementation while also providing a possible method for collecting stock ACC system data in a more controlled environment than public roads. Chapter 6 describes this in-vehicle deployment in greater detail along with performance measures to assess the accuracy of scenario replication by the Blazer target vehicle, followed by EcoCAR university vehicle energy testing results and discussion in Chapter 7.

Chapter 6. Lead Vehicle Track Testing and Accuracy Metrics

The next two chapters detail methodologies and pilot testing performed during the final year of the EcoCAR Mobility Challenge. These chapters present two sides of this testing: Chapter 6 focuses on the methodology and performance of the target vehicle using data from the EcoCAR ACC energy testing at GM's Desert Proving Ground, whereas Chapter 7 provides energy calculations and results from the university vehicles following behind the target vehicle. As described in Table 3, these activities are related to research **Goal 2: Implement CAV Test Systems** and **Goal 3: Conduct University CAV Testing**. Content from the next two chapters will be published in a manuscript currently in preparation, titled Track-based Energy Testing of Prototype Connected and Automated Hybrid Electric University Vehicles [37].

6.1. Chapter Introduction

Once the HIL-based development in Chapter 5 was completed, our next stage of deployment was to install and refine the HIL-tested target vehicle control system into the Chevrolet Blazer and use it to assess energy of the university prototype vehicles. This chapter discusses Blazer calibration and development activities and presents results of these accuracy calculations from all test runs at the Year 4 EcoCAR Mobility Challenge competition at the General Motors Desert Proving Grounds in Yuma, Arizona. To ensure that the competition provided a fair and repeatable comparison test between all vehicles under test, it was important to have a robust method for evaluating the performance of the test system itself.

6.2. Experiment Methodology and Test System Development

For the final year of the EcoCAR mobility challenge, we evaluated student vehicles over several events designed to exercise the sensor fusion, connectivity, and automated driving features developed by university teams. Student vehicles completed a variety of stationary and dynamic validation tests to ensure that both powertrain and could be tested safely in proving ground environments. Competition organizers verified various vehicle design requirements and validated basic longitudinal control and automated stopping capabilities in a highly controlled series of test maneuvers. Once these evaluations were passed, university vehicles were cleared to take part in two CAV events our team had designed:

- ACC Energy Consumption Evaluation:
    - Each student vehicle followed a competition-developed automated target vehicle as this lead vehicle replicated a city and highway drive cycle ahead of each university vehicle under test. The test was conducted at General Motors Desert Proving Ground's 3.5-mile circle track to enable continuous, multi-mile energy testing. We designed the event and target vehicle test systems to provide a fair comparison for ACC energy consumption across the variety of powertrain designs and sensor fusion/longitudinal control implementations.
- Connected Mobility Challenge:
    - Vehicles used automated longitudinal controls to drive through a portable intersection equipped with a physical traffic light accompanied with a DSRC roadside unit broadcasting SPaT and map signals. The experiment included a variety of light timings to test control system robustness. Details on the development and execution of this experiment will be provided in Chapter 9.

Pictures of each of these test methods are included in the figure below.

Figure 23. Connected Mobility Challenge Event (left) and ACC Energy Testing (right)

6.2.a. Methodology and test system development process

To develop the methodology for this testing procedure, Argonne convened a working group with representatives experienced in energy consumption testing, simulation, and analysis. Our research team led this working group of EcoCAR University faculty members, Argonne vehicle testing experts, and industry partners at General Motors, the MathWorks, and Horiba automotive to develop a methodology that would provide a fair comparison for ACC energy usage between each of the participating university vehicles.

Once the methodology was initially developed by our working group, we collaborated with HORIBA Automotive to create a flexible lead vehicle testing system capable of operating on a variety of test tracks. Throughout the EcoCAR mobility challenge competition, university vehicles were tested at several test facilities operated by industry partners General Motors and the Transportation Research Center (TRC) Inc. The research team worked with HORIBA to port their DigiCAV test system initially evaluated at their UK-based MIRA engineering center on their network guided vehicle [16] in order to run on Argonne's Chevrolet Blazer. After we achieved initial functionality at Argonne's closed roadway area, we further calibrated the system to achieve accurate trace following at TRC's Vehicle Dynamics Area [34] over the course of several development trips.

After validating the target vehicle and connected intersection system operation, teams were invited to participate in a Connected and Automated Vehicle Testing Event at TRC from October 11-15, 2021. In this development event, EcoCAR University teams attempted to participate in the two vehicle ACC energy test and drive through a connected intersection using automated longitudinal control. It is worth noting that this entire development process for Argonne, industry sponsors, and university teams took place during COVID-19 lockdowns throughout 2020-2022. Even with these challenges, many universities were able to develop functioning sensor fusion, ACC, and connected intersection longitudinal control algorithms prior to this TRC development workshop. At the workshop, university vehicle ACC capabilities were demonstrated and refined throughout the multi-day tests. The Blazer target vehicle was programmed to execute CAFE Urban and Highway cycles ahead of university vehicles, which followed behind using university-developed CAV systems. While energy was measured during this event, the primary goal was to provide teams with the opportunity to validate and refine the operation of their ACC controls in the same test they would experience later at the GM proving grounds for Year 4 Competition.

To operate the Blazer target vehicle, we mounted a touchscreen laptop (Microsoft Surface Pro 7+) securely in the lead vehicle and interfaced it with DigiCAV software running on the IEI TANK compute system as well as the dSPACE MicroAutoBox II. We created User Interfaces (UIs) to provide a simplified interface for selecting a drive cycle, preparing the DigiCAV system to start, then use dSPACE ControlDesk software to initiate start of test via a CAN message sent to the DigiCAV software. The UI used large buttons within reach of the driver while stationary and preparing for test. Once the vehicle was in motion, the operator could disengage and abort a test at will by using stock ACC disengagement methods such as pressing the brake pedal or cancel button on the steering wheel. As a secondary failsafe, an e-stop device was wired to the MicroAutoBox hardware and placed within easy reach of the operator. This e-stop would place the controller in sleep mode, ceasing all CAN traffic to GM busses and causing GM modules to detect a loss of communication with ADAS modules followed by automatic disengagement of the test system. Figure 24 shows an image of this target vehicle test setup during a run at the TRC development trip.

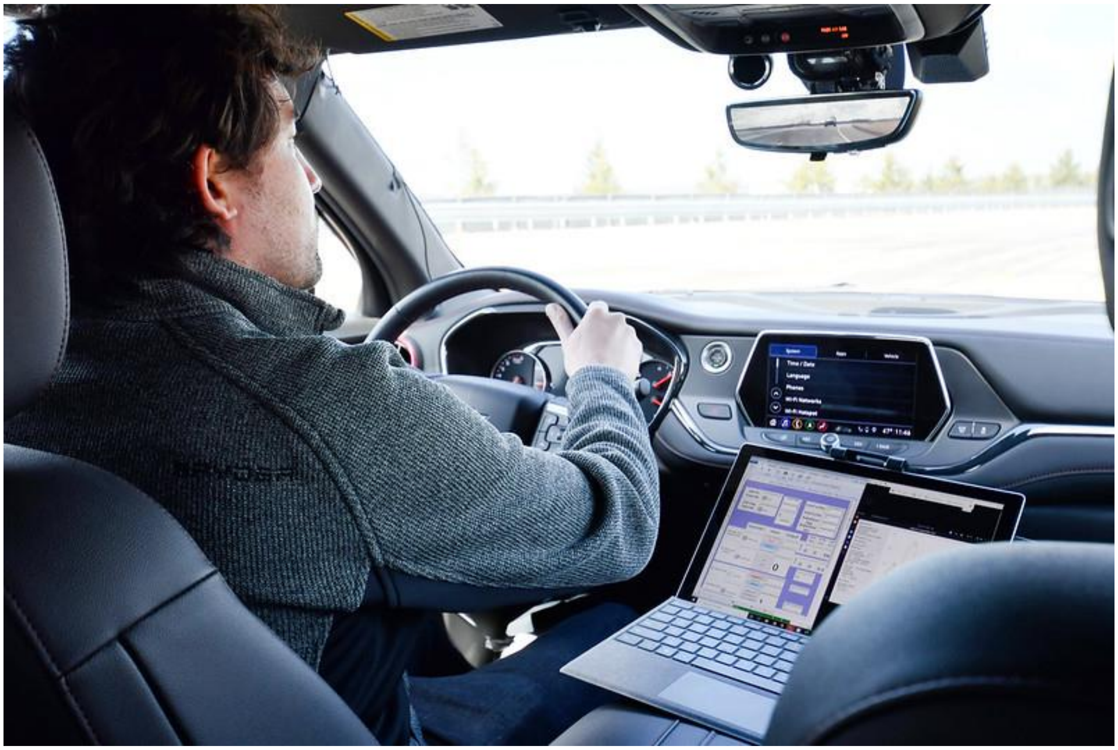


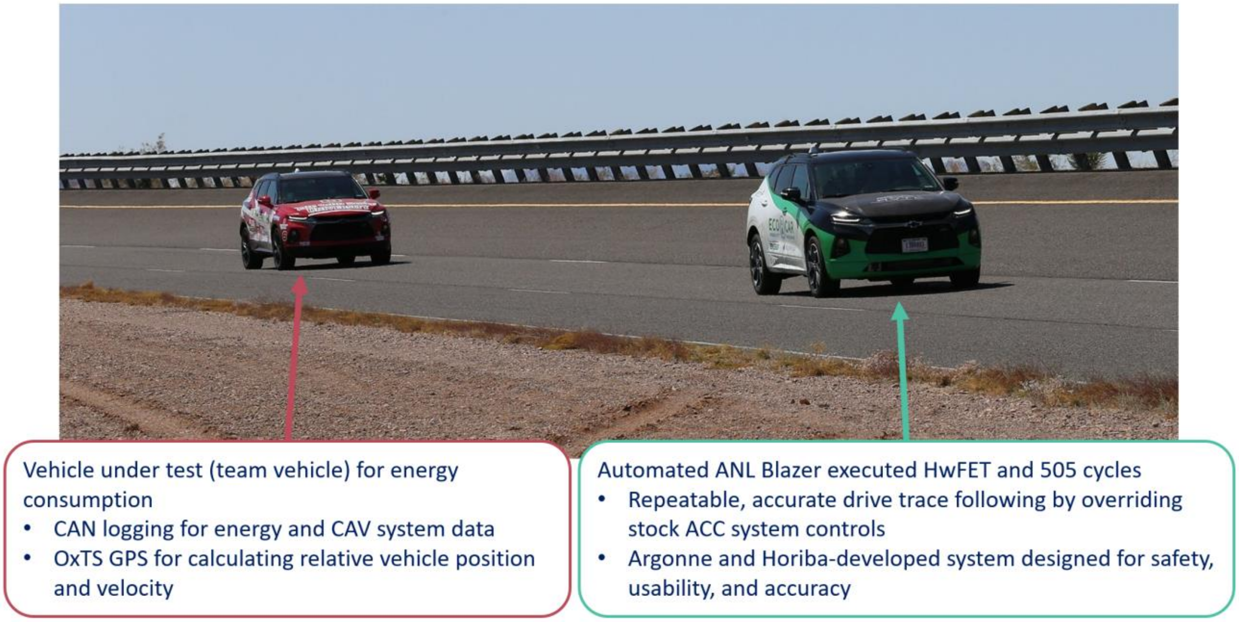
Figure 24. Lead vehicle conducting test with our experimental control interface

This TRC event was the first time university vehicles were tested for longitudinal control performance, as originally planned testing activities in Year 3 (2020-2021) of competition were cancelled due to COVID-19 travel and gathering restrictions. Despite pandemic-induced development delays at universities, several teams were able to demonstrate successful ACC following and intersection eco-approach and departure features at the TRC development trip. An image of one of the university vehicles following the Argonne target vehicle in an ACC energy test can be seen in Figure 25.

Figure 25. ACC Energy Test in progress at TRC dynamics pad with university vehicle ACC following

Following the conclusion of the TRC development trip, university teams continued refining their systems based on results from the initial TRC testing. Vehicles were then shipped to Yuma, AZ for the Year 4 Final Competition.

We performed this Year 4 Competition testing at the General Motors Desert Proving Ground in Yuma, Arizona over the course of 7 days in May 2022. With 11 different vehicle designs to test in a week, our team designed an energy testing event that could be conducted in proving ground environments, evaluated vehicles as a primarily closed system, and provided enough throughput to evaluate adaptive cruise control features for each of the vehicles from participating universities. An image of this test in progress at Year 4 Competition is shown in Figure 26, where a university vehicle under test follows behind the Argonne Target Blazer that we co-developed with HORIBA Automotive in the prior chapters.



Vehicle under test (team vehicle) for energy consumption
- CAN logging for energy and CAV system data
- OxTS GPS for calculating relative vehicle position and velocity

Automated ANL Blazer executed HwFET and 505 cycles
- Repeatable, accurate drive trace following by overriding stock ACC system controls
- Argonne and Horiba-developed system designed for safety, usability, and accuracy

Figure 26. ACC Energy Consumption Test in Progress with OSU Vehicle

The following figure depicts the circle track environment along with the road to and from the garage where universities were working on their vehicles and completing pre-flight safety and technical inspections.

Imagery ©2024 Airbus, CNES / Airbus, Landsat / Copernicus, Maxar Technologies, U.S. Geological Survey, Map data ©2024

Figure 27. Circle Track used for ACC Energy Testing and Route to/from Garage

In executing this testing, one critical requirement was for the target vehicle to replicate each test scenario profile accurately and repeatably. This method ensured that each university vehicle under test experienced as similar a test as possible for fair comparison between each vehicle. It is worth noting that the same methods and target vehicle system we used to evaluate the university vehicle platforms could also have been used to evaluate production ADAS vehicle implementations for a baseline comparison to energy-optimized longitudinal control features from teams. A production Blazer using stock ACC was used to verify this capability, though in this case the production vehicle was not instrumented for energy consumption measurements. Future studies will leverage these test methods to evaluate production controls on the same tests used for experimental CAVs controls.

6.3. Calculation Methods for Lead Vehicle Trace Following Results

In our proposed track-based testing method, the lead vehicle should follow a target trace as accurately and repeatably as possible to ensure that each vehicle under test experiences the same traffic scenario. Ideally, the lead vehicle would be controlled to minimize trace error and variation between each test iteration. In addition to subjective assessments of controller performance, objective measurements and calculations are beneficial for comparing the lead vehicle target velocity trace to the actual driven trace as measured during each test. Several key performance indicators were utilized to assess lead vehicle trace accuracy. As most automotive energy consumption testing utilizes dynamometer testing, recommended practices such as SAE J2951 Drive Quality Evaluation for Chassis Dynamometer Testing [3] and EPA-specified speed vs tolerance limitations [68] were originally designed to evaluate trace accuracy on dynamometer tests. However, with minor modifications we adapted many of these performance measures and calculation processes to track environments in order to assess how accurately the target vehicle replicates a drive cycle ahead of the vehicle under test.

6.3.a. Adapting SAE Dynamometer Metrics to Track Applications

In dynamometer testing, the dynamometer roll speed signal would be utilized to calculate SAE J2951 metrics. By using a consistent roll speed signal for J2951 calculations rather than vehicle-based speed signals, errors in a test vehicle's internal speed measurements do not impact the J2951 metrics. To adapt J2951 to this track application, however, the automated target vehicle's logging system would need to accurately record speed using an alternative signal since the dynamometer roll speed signal does not exist on track. The following alternative speed signal sources could be used in place of the traditional J2951 roll speed:

- Record internal stock speed measurements through CAN bus logging.
  - Wheel speed or vehicle speed could be utilized provided those messages are available on the CAN bus for logging and decoding and appropriately filtered.
  - Ideally, vehicle stock systems would be calibrated to a baseline dynamometer roll speed measurement during dynamometer testing prior to the track tests.
- Use GPS speed measurements via stock GPS systems or additional test equipment.
  - Systems should report GPS data with adequate frequency (≥10 Hz), as many off-the-shelf or stock vehicle GPS systems only report speed at 1 Hz and may not capture higher frequency deviations from the target trace.
  - Less accurate GPS devices may impact calculated J2951 metrics, ideally the lead vehicle would utilize an RTK system with base station connection covering the entire test track.

Regardless of the speed signal measurement method, replicating a drive cycle in track environments is challenging in comparison to dynamometer testing with the greater repeatability and controllability that a laboratory environment brings. In dynamometer testing, human drivers can focus solely on achieving the target trace through pedal actuation since steering the vehicle or avoiding vehicles and other track-based hazards is unnecessary. In contrast, even in a closed course circle track proving ground environment the lead vehicle driver must steer to keep centered in the lane, avoid other test vehicles on the track, and be ready at all times to take evasive action to avoid collisions with the following vehicle under test or any other hazards.

6.3.b. Selecting and Calculating Accuracy Metrics for Lead Vehicle

We used two primary resources for selecting and calculating accuracy metrics for the lead vehicle cycle following capability, EPA's 40 CFR Part 86 [68] and SAE J2951's recommended practice [3]. This section describes the metrics that were determined to be relevant for target vehicle cycle following accuracy in track environments. While the specific test conducted in this chapter only utilized City 505 and HwFET cycles, the metrics could be used for any cycle or traffic scenario driven by an automated lead vehicle. For example, if the lead vehicle were programmed to follow other common drive cycles or replicate the velocity trace driven by recorded traffic data, these metrics and calculation methods would still apply.

EPA's 40 CFR Part 86.115-78 provides upper and lower bounds that vehicles on a dynamometer must stay between for the test to be considered valid [18]. In the context of this track experiment, the lead vehicle is also attempting to replicate a specified drive cycle as closely and smoothly as possible to exercise the following vehicle under test ACC operation and energy consumption. It was decided to therefore enforce the requirement that the lead vehicle must, at a minimum, adhere to the EPA allowable range for dynamometer testing throughout the entirety of each test. This speed tolerance at any given point in the cycle is defined in 40 CFR based on a one second time window ahead of and behind each velocity vs. time point. Within this two second total window, the upper threshold is set at 2 mph above the maximum speed at any point and 2 mph below the minimum speed at any point (or 0 for cycle speeds at or below 2 mph). This threshold can be seen in the graphs from 40 CFR Part 86.115-78 [18]:

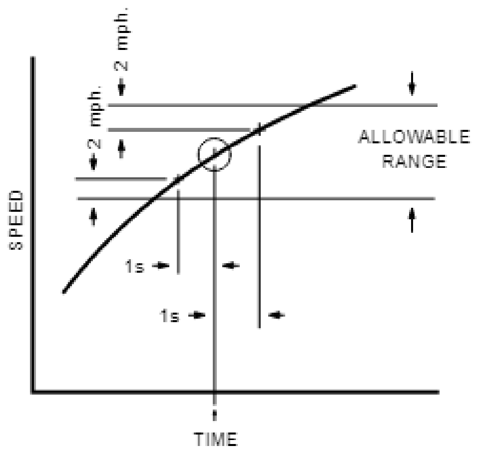


FIGURE B78-4a—DRIVERS TRACE, ALLOWABLE RANGE

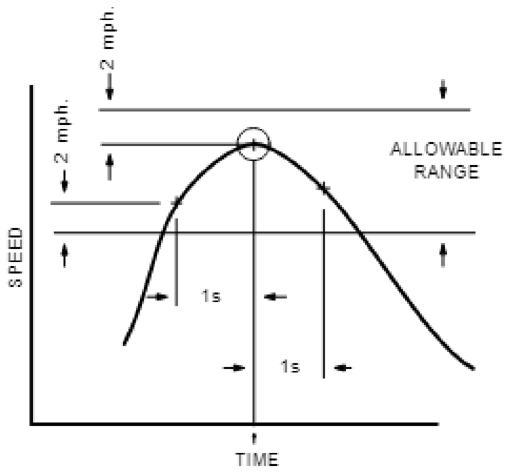


FIGURE B78-4b—DRIVERS TRACE, ALLOWABLE RANGE

Figure 28. EPA plots showing allowable ranges for cycle following

We modified MATLAB code provided in the SAE J2951 standard [3] to reflect the new track-based data sources, then used this script to calculate and plot EPA margins for a HWFET cycle. The results are shown in the following figures.

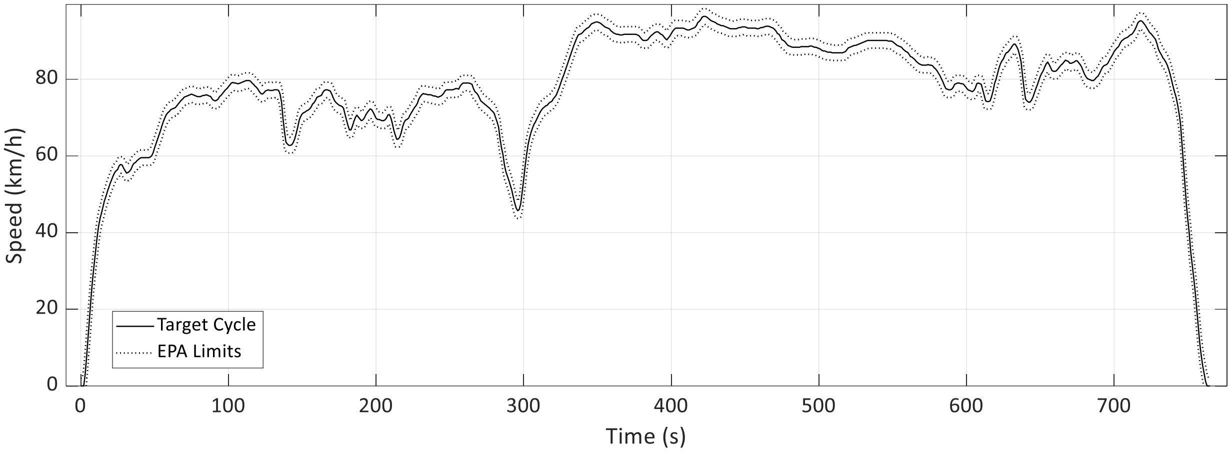


Figure 29. HwFET Cycle Speed vs. Time with EPA Upper and Lower Limits

In addition to the EPA speed tolerance limits, a set of overall numerical metrics for drive cycle following is defined in SAE J2951. This document provides metrics and calculation methods for assessing the accuracy of trace following for a vehicle under test during a dynamometer testing [3]. Certain metrics from J2951 are more relevant to the context of evaluating an automated lead vehicle for ACC track testing. Many of the primary metrics (such as the Energy Rating) in J2951 take into account the vehicle mass and road load coefficients in order to estimate the energy impacts of trace deviations on the vehicle under test [3]; in our application of multi-vehicle track testing however, the energy usage of the target vehicle that is attempting to accurately meet the trace does not matter because the method is only testing the follower vehicle's ACC system energy usage. The follower vehicle will therefore drive a completely new drive cycle based on its internal sensing and ACC control algorithms, so the calculations in this chapter will focus on metrics from J2951 that are independent from dynamometer coefficients and vehicle mass. These combined indicators are as follows:

Table 9. Summary of J2951 and EPA Margin Controller Performance Metrics

Performance Indicator	Short Name	Description	Units and Resolution
EPA Margins	EPA_M	Whether vehicle exceeded upper (EPA_{M+}) or lower (EPA_{M-}) bounds, defined by EPA as +2 mph above the maximum speed and -2 mph below the minimum speed over a 2 second centered time window for each data point.	None
Distance Rating	DR	The percent difference between the total distance driven by the lead vehicle and target cycle distance.	xx.xx %
Absolute Speed Change Rating	ASCR	The percentage difference between the discrete approximation for the integral of absolute magnitude of acceleration (ASC) for the driven and target traces. Provides an indicator of the "smoothness" of the driven trace relative to the scheduled trace. A driven trace that is "smoother" will have a lower ASC than the scheduled trace and so will result in a negative ASCR.	xx.xx %
Root Mean Squared Speed Error	RMSSE	Provides the driver’s performance in meeting the schedule speed trace throughout the test cycle in terms of the Root Mean Squared (RMS) Speed Error. The value is always a positive number with lower values (closer to zero) indicating better performance.	x.xx mph

The full calculation process for each of these metrics along with other details and example MATLAB code can be found in the J2951 documentation. For reference, however, the primary formulas used for calculating each of the above metrics are as follows. To adapt the J2951 calculations to this track application, the following modifications were made:

- Dynamometer roll speed becomes vehicle velocity measured either by GPS or on-board speed sensors with the same 0.5 s double moving average specified in the document.
- Target vehicle speed uses the original drive cycle trace the lead vehicle was attempting to replicate (including cases where non-standard drive cycles or traffic profiles are used).
    - Note: the J2951 usage of “target” does not translate well to the automated vehicle testing context of using physical target vehicles, since it was not designed for that application. In

J2951, “target vehicle speed” refers to the drive cycle the operator was attempting to drive.

6.3.c. Distance Rating (DR)

The distance rating is calculated by finding the percent difference between the total distance actually traveled by the target vehicle and the scheduled distance defined by the drive cycle trace the lead vehicle was attempting to replicate. This metric can be calculated using the standard formula from J2951 [3] shown below:

$$DR = \frac{D_D - D_T}{D_T} * 100 \tag{1}$$

- DR: Distance Rating
- D_D: Total distance driven by lead vehicle
- D_T: Scheduled drive cycle distance

6.3.d. Absolute Speed Change Rating (ASCR)

The absolute speed change rating is “an indicator of the ‘smoothness’ of the driven trace relative to the scheduled trace” as defined by J2951 and is “well-suited to quantifying small speed changes such as those that could come about from throttle perturbations [3]”. Cycles such as HwFET with longer periods of somewhat steady state speeds often resulted in higher ASCR values due to the automated system applying small positive and negative acceleration corrections (perturbations) to achieve the target speed.

To calculate this metric, first the discrete approximation for the integral of the absolute magnitude of acceleration (or ASC) must be calculated using the following equations for ASC Speed Error for Driven and Target Traces [3]:

$$ASC_D = \Delta t \sum_{i=1}^{N} |a_{Di}|$$

(2)

$$ASC_T = \Delta t \sum_{i=1}^{N} |a_{Ti}|$$

Next, the Absolute Speed Change Rating can be calculated using the ASCR formula from J2951 [3]:

$$ASCR = \frac{ASC_D - ASC_T}{ASC_T} * 100 \tag{3}$$

The following terms are used in those equations, including our modifications to adapt these formulas to the lead vehicle track application:

- ASC_D: ASC for the driven trace (in this case by the lead vehicle)
- ASC_T: ASC for the intended target cycle trace (that the lead vehicle is attempting to replicate)
- Δt: sampling period (0.1 seconds for a 10 Hz datafile)
- a_{Di}: Central difference approximation of the driven vehicle acceleration (see J2951 for formula)
- a_{Ti}: Central difference approximation of the scheduled cycle acceleration
- N: Maximum number of data points
- i: data point index

6.3.e. Root Mean Squared Speed Error (RMSSE)

From J2951, "the RMSSE metric provides the driver's performance in meeting the schedule speed trace throughout the test cycle in terms of the Root Mean Squared (RMS) Speed Error [3]". In this case the driver was our automated lead vehicle control algorithm, but otherwise the same modifications defined above apply for calculating the final metric. The result should always be positive and lower values indicate better cycle following performance. The modified J2951 equation for calculating RMSSE [3] is shown as follows:

$$RMSSE = 2.237 * \sqrt{\frac{\sum_{i=1}^{N}(V_{Di} - V_{Ti})^2}{N}} \tag{4}$$

- $RMSSE$: Root Mean Squared Speed Error
- V_{Di}: Driven speed at point i
- V_{Ti}: Target speed at point i
- N: Number of total data points
- i: data point index

The J2951 document also provides data collected from a variety of vehicle test laboratories to provide context for the maximum and average capability ranges that test drivers in dynamometer environments were able to achieve. These values provide helpful context for assessing cycle following accuracy and dynamometer environments, though lower performance is expected when executing drive cycles in track environments with automated systems (instead of professional dynamometer drivers).

6.4. Experimental Results for Lead Vehicle

During the span of the EcoCAR Mobility Challenge Year 4 competition proving ground testing, seven different university vehicles completed both the highway and city ACC energy testing cycles at the General Motors Desert proving ground circle track. Argonne's Chevrolet Blazer lead vehicle executed the city and highway cycle ahead of each university vehicle under test, with 7 HwFET cycle and 7 City 505 cycle iterations. In this section the results are presented quantifying how accurately the Argonne lead vehicle followed each trace, followed by discussions and recommendations for future improvement of the test system.

6.4.a. Target Vehicle Cycle Following Accuracy Results

Throughout each test run, an OxTS RT Range unit installed in both university and Argonne Blazers recorded GPS speed. Using this speed signal and the target speed trace, we used the calculations defined above to assess whether the lead vehicle system stayed within EPA upper and lower speed bounds. The driven speed trace from each test run was used to calculate the selected J2951 metrics [3] and assess the lead vehicle system's accuracy and repeatability at driving tests cycles ahead of each vehicle under test. Plots of one of the city and highway tests can be seen in the following figures.

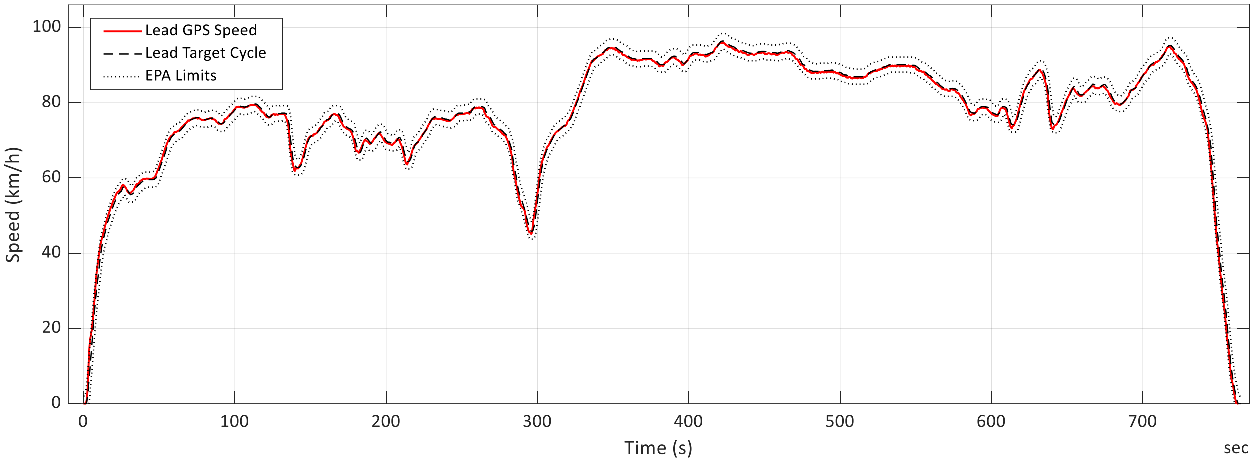


Figure 30. Lead Vehicle HwFET Target and Driven Cycles from EcoCAR Testing

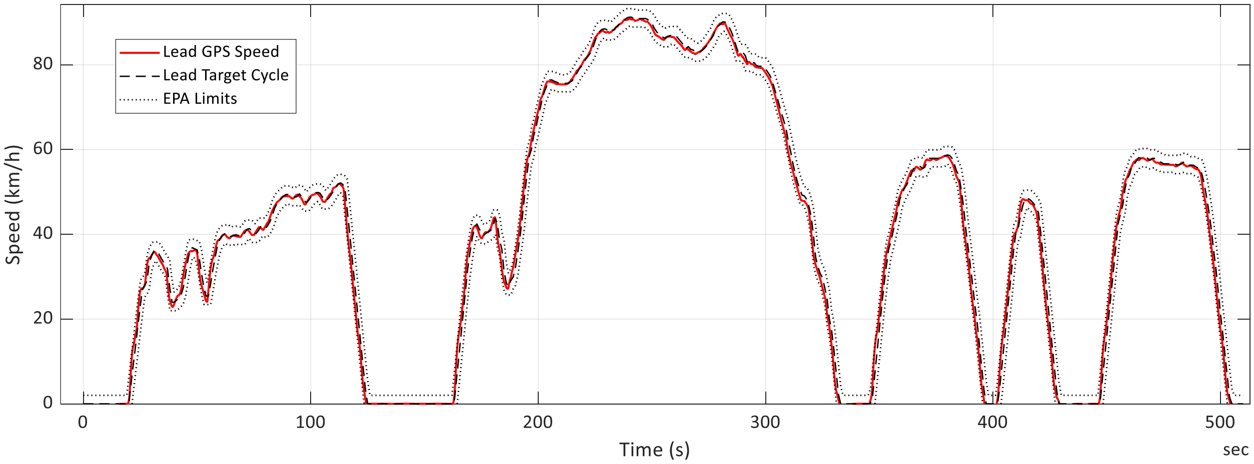


Figure 31. Lead Vehicle Urban 505 Target and Driven Cycles from EcoCAR Testing

As shown in these figures, the lead vehicle was able to complete both city and highway drive cycles and the resultant driven trace (in red) falls within the upper and lower thresholds specified by EPA. The lead vehicle successfully stayed within EPA margins for all tests apart from a single highway cycle iteration, where an initialization error in the controller caused enough deviation from the target trace to fall outside of those thresholds. While this error was unfortunate, the data from that run was still included as an example to show what J2951 metrics result from a test that exceeds EPA margins. For future experiments, the research team will develop a test post processing script that runs on the onboard controllers immediately after each run. This process improvement would enable operators to immediately see whether EPA margins or acceptable J2951 metrics were exceeded and prompt the operators to rerun the experiment if proper lead vehicle performance were not achieved.

Table 10 shows the results of our EPA margin calculations along with the calculated J2951 metrics to numerically assess the lead vehicle test system accuracy in achieving each target drive trace.

Table 10. SAE J2951 Results for Lead Trace Achieved

Vehicle Under Test (follow vehicle)	Drive Cycle	EPA Trace Miss?	Distance Rating (DR)	Absolute speed change rating (ASCR)	RMS Speed Error (RMSSE)
GT	HwFET	No	-0.48	4.37	0.40
MSU	HwFET	Yes	-0.46	4.66	1.04
OSU	HwFET	No	-0.39	5.42	0.43
UA	HwFET	No	-0.38	5.73	0.56
UT	HwFET	No	-0.35	6.55	0.58
VT	HwFET	No	-0.42	5.29	0.54
WVU	HwFET	No	-0.31	4.43	0.38
GT	City 505	No	-0.49	1.47	0.50
MSU	City 505	No	-0.47	1.29	0.71
OSU	City 505	No	-0.39	1.42	0.55
UA	City 505	No	-0.08	1.46	0.46
UT	City 505	No	0.08	1.26	0.49
VT	City 505	No	-0.24	1.15	0.48
WVU	City 505	No	-0.38	2.00	0.66

Our results from Table 10 demonstrate that the lead vehicle was able to operate within EPA bounds for the majority of the test runs and achieve reasonable results for J2951 metrics given the novel track-based nature of this test.

More testing and refinement of this system and future track testing systems will be necessary to determine what values for J2951 metrics should be deemed acceptable in this context. While SAE also presents some reference values for J2951 metric results gathered from different laboratories, the conditions these values were gathered under are significantly different from the implementation for track testing:

- For this track testing, the traces were driven by the DigiCAV automated cycle following system in a test track environment as opposed to professional human operators or pedal robots driving traditional dynamometer traces in tightly controlled laboratory conditions.
- The speed signal used for these track testing J2951 calculations utilized GPS speed rather than dynamometer roll speed. The measurement would have been more accurate with corrections from an RTK base station, but unfortunately there were none available for this specific test.
- The GPS speed must be time aligned with the target speed as closely as possible, with minor phase shifts between the target and driven traces significantly impacting J2951 metrics.
- The specific controller implementation used for this test was controlling the vehicle based on speed feedback signals sensed by the vehicle which could have some offset from GPS speed.

Because of these limitations and differences from laboratory dynamometer testing, lower accuracy values are expected compared to those that are achievable in traditional dynamometer testing. However, the track-based system was still able to follow the target trace and achieve reasonably accurate J2951 metric results when compared to those achieved by Argonne's robot driver [67]. As mentioned earlier in the chapter, we also tested the Argonne Blazer on the Advanced Mobility Technology Laboratory's 4WD chassis dynamometer using their robot driver test system. This testing included four iterations of drive traces collected from each university vehicle during their ACC test, along with a baseline test of HwFET, UDDS 505, and the full UDDS cycle. For comparison between track-based results with the prototype lead vehicle and dynamometer results with Argonne's more repeatable robot driver system, the table below displays the average J2951 metrics from each of the cycles along with individual cycles as well. As seen in the table, our track results gathered using Horiba DigiCAV control achieved relatively comparable results to Argonne's heavily-utilized robot driver system. The table also includes two entries from EPA's Test Car List for a 2019 Blazer with the same 3.6 L engine, though RMSSE and DR are not reported in that database [69]. These data were included to show that the Argonne Robot Driver achieved similar fuel economy results to EPA values. These combined results can be seen in the following table:

Table 11. Comparison of Track and Dynamometer J2951 Metrics and Fuel Economy Results

Vehicle Under Test and Driving Control System	*Drive Cycle*	*Environment*	*DR*	*ASCR*	*RMSSE*	*Fuel Economy (mpgge)*
Argonne Blazer (DigiCAV)	HwFET Average	Track	-0.39	5.30	0.48	NA
Argonne Blazer (Dynamometer Robot)	HwFET Average	Dynamometer	0.22	3.31	0.26	34.6
EPA Test Car Blazer	HwFET	Dynamometer	NA	3.15	NA	34.8
Argonne Blazer (DigiCAV)	City 505 Average	Track	-0.28	1.44	0.55	NA
Argonne Blazer (Robot)	City 505 Average	Dynamometer	0.29	-0.92	0.48	25.9
Argonne Blazer (Robot)	UDDS Full #1	Dynamometer	0.29	0.23	0.43	23.8
Argonne Blazer (Robot)	UDDS Full #2	Dynamometer	0.26	0.12	0.43	23.7
EPA Test Car Blazer	UDDS FTP-75	Dynamometer	NA	-0.72	NA	23.2

As shown in the table, in HwFET dynamometer testing the Argonne robot driver produced an average RMSSE of 0.26 compared to the track average of 0.48. For the city 505 cycle, the Argonne robot driver produced an average RMSSE of 0.48 compared to the track average of 0.55. Both systems exhibited similar magnitude of distance ratio values. Overall, these values show that the track-based test was able to achieve reasonably comparable results to testing in a highly controlled dynamometer environment with the Argonne robot driver test system. It should be noted that neither J2951 or EPA provide guidelines for what values should be considered acceptable for any of these metrics, even in the context of dynamometer testing alone [66].

6.5. Chapter Conclusions

This chapter provided an overview of the two primary CAV events in EcoCAR, the multi-mile ACC energy test and Connected Mobility Challenge (intersection navigation) events. Activities in this chapter are linked to **Goal 1: Develop CAV Testing Pathways, Goal 2: Implement CAV Test Systems,** and **Goal 3: Conduct University CAV Testing.**

Similar to Chapter 4, we extended the SAE J2951 metrics across all test runs to find quantitative performance measures for the target vehicle system's scenario replay. The EcoCAR pilot testing demonstrated that the test methods and systems are repeatable and capable of replicating the same test scenario for each follower vehicle under test. When using physical target vehicles to emulate traffic behavior, it is critical that each test be performed in a controlled and repeatable manner. This method would also apply to testing production ADAS systems, as demonstrated in Chapter 4, though in this case the methods were used at EcoCAR development events and Year 4 Competition.

The flexibility of the system was also shown through successful deployment at both TRC and GM Desert Proving Grounds, along with a high test volume of seven full ACC tests in less than one week of testing. This test time also included additional performance and safety events not described in this document. With a more focused CAV test activity, the primary limitation on the number of test runs would be the overall scenario length along with any warmup driving necessary for each vehicle under test. With the test method introduced and target vehicle performance measures quantified, the next chapter focuses on university energy results from the Year 4 testing at GM's Desert Proving Grounds Circle Track.

Chapter 7. University Fleet ACC Energy Track Testing Results

While the prior chapter focused on the experimental methodology and test system performance during ACC energy testing, this chapter provides the calculation methods and results for energy consumption from university vehicles during those same tests. This work is linked to **Goal 3: Conduct University CAV Testing.**

7.1. Energy Consumption Calculation from On-Road Data

The primary goal of this track-based test was to enable comparison of ACC system energy operation across multiple powertrain and CAV system designs from participating universities. While track testing is inherently less controllable and repeatable than laboratory dynamometer testing, the test design and other experimental controls were put into place to limit variation between teams as much as possible. The following section describes some of these controls along with the overall calculation process used to determine the SOC-corrected energy consumption of each of the university vehicles in the ACC energy testing event.

One common source of error and inconsistency in field or track testing is the choice of fuel used across all test vehicles. For fleet testing, it is generally impossible to control the fuel specifications across all vehicles in the data set as they refuel from standard gas stations without stringent controls or fuel properties testing in place. In contrast, for EcoCAR all experimental vehicles utilized certification E10 regular or premium fuel provided and tested by Gage Fuels for all properties necessary to calculate fuel consumption consistently regardless of which fuel was used.

In addition to using fuel with tested properties, the competition also requires that each university vehicle have a custom-designed, removable fuel tank to enable gravimetric assessments of fuel usage in addition to onboard fuel integration calculations performed by each Engine Control Module (ECM). While all universities utilized GM engine platforms, this ECM signal is likely to differ slightly from the gravimetric measurement. In order to calculate fuel mass from each university's ECM integrated fuel volume signal, prior to participating in the ACC energy testing event the vehicles were also tested on a Normal Driving Mode (NDM) energy testing event. This event also took place at the circle track but consisted of fully human-operated driving through a drive cycle defined by target speed signs, acceleration and braking zones, and stop/idle signs distributed around the track. EcoCAR has generally used the signage-based method for energy consumption as it allows drivers to focus on the roadway while still producing a relatively repeatable speed trace. Readers can reference a more detailed description of a similar test in the 2016 SAE Congress paper Application of Plug-in Hybrid Electric Vehicle (PHEV) Fractional Utility Factor Weighting to EcoCAR On-Road Emissions and Energy Consumption Testing [56]. A similar test method and the same test cycle was used for EcoCAR mobility challenge, with 3 notable differences:

- All vehicles in the mobility challenge were mild hybrids without a charge depleting mode so no utility factor calculations were necessary.
- Battery energy usage was calculated through onboard instrumentation rather than an instrumented Electric Vehicle Supply Equipment (EVSE).
- Emissions were not evaluated as a scored criterion, which eliminated the need for Portable Emissions Measurement Systems (PEMS) trailers.

University vehicle fuel tanks were weighed before and after participating in the NDM Event, both to provide a scored result for that event in addition to calculating a gravimetric correction factor for ECM integrated fuel measurements taken during the ACC energy test event. This gravimetric correction factor was applied to the results of the ACC energy testing event during the calculation process, defined within the competition's rules and event operations description documents [70] [61].

The following section describes the calculation process used for establishing the gravimetric correction factor and the overall vehicle fuel consumption for the ACC energy test event. These calculations were developed with support from Argonne researchers, General Motors event captains, and faculty advisors at participating universities.

7.1.a. Gravimetric Correction Factor and Fuel Volume Usage

The fuel used during the ACC Energy Consumption event was found by gravimetrically correcting the integrated ECM-measured fuel signal based on a gravimetric correction factor found based on the NDM Energy Consumption test results. To find this gravimetric correction factor, it was necessary to find both the gravimetric fuel mass and the ECM-measured fuel mass used during the NDM portion. The gravimetric fuel mass was found by subtracting the pre-test fuel tank mass from the post-test tank mass. To find the ECM-measured fuel mass, the ECM fuel flow signal was recorded throughout the NDM test, integrated to find fuel volume of the entire NDM drive, and then multiplied by the fuel density of whichever fuel the team used.

Once the ECM fuel mass and gravimetric fuel mass are calculated, the gravimetric correction factor is found by dividing the gravimetric fuel mass by the ECM fuel mass as shown in following equation:

$$GravCorrection = \frac{mass_{final} - \ mass_{init}}{\rho_{TestFuel} * \int FuelFlow_{ECM} \, dt} \tag{5}$$

Using the specific competition fuel density and energy content, the ECM-measured fuel volume of fuel used will be converted into an energy-equivalent volume of competition fuel used as shown below. Because each university was given the choice of "normal" or "premium" fuel, the fuel mass measured must be converted to an equivalent volume of baseline reference fuel using fuel properties from the normal or premium fuel that each team used. This calculation step is performed by using either the regular or premium octane fuel density ($\rho_{TestFuel}$) and Lower Heating Value ($LHV_{TestFuel}$) properties measured from each batch of test fuel. The $SpecificEnergy_{ref}$ of the common reference fuel used a competition-standard value of 32.3 kWh/gal [61].

$$FuelVolume_{Equiv} = \frac{GravCorrection * \rho_{TestFuel} * \int FuelFlow_{ECM}\, dt * \frac{LHV_{TestFuel}}{3600 * 1000}}{SpecificEnergy_{ref}} \tag{6}$$

This equation uses fuel volume in liters gasoline equivalent [Lge], mass is in grams [g], LHV (Lower Heating Value) is in [J/g] and specific energy of the competition reference is in kilowatt hours per gallon [kWh/gal]. The chemical properties for the specific fuels used at competition were taken from the fuel's specification sheet provided by the fuel provider based on their chemical analysis of those fuel batches.

7.1.b. Battery SOC Fuel correction calculation

To account for the electric energy used or generated throughout the test, an equivalent fuel volume corresponding to the net electricity was calculated by using a 25% fuel to electricity conversion efficiency. In the case of a perfectly charge sustaining test, this quantity will be zero. The fuel correction calculation based on net high voltage battery energy used over the cycle (BattCorr) is shown in the following equation:

$$FuelVolume_{BattCorr} = \frac{\frac{V_{ZC}}{3600 * 1000} * \int_{t_0}^{t_{end}} HVBatt_{current} dt}{0.25 * SpecificEnergy_{ref}} \tag{7}$$

This equation shows fuel volume is in liters gasoline equivalent [Lge], zero crossing voltage is in volts [V], high voltage battery current is in amperes [A], and specific energy of the competition reference is in kilowatt hours per gallon [kWh/gal]. Note that this correction is bidirectional depending on whether battery SOC increases or decreases in each test segment. If the powertrain charges the battery pack over the segment (i.e. charge gaining) the volume of fuel will be negative. If the powertrain discharges the battery pack over the segment (i.e. charge depleting) the volume of fuel will be positive.

7.1.c. Final charge-sustaining energy equivalent fuel consumption

Combining the above equations yields the final charge-sustaining equivalent of fuel volume used. The charge-sustaining energy equivalent fuel usage along with the distance driven over the event was used to calculate the final charge-sustaining energy-equivalent fuel consumption of the vehicle for the test as shown below.

$$FuelConsumption_{ChargeCorrEnergyEquiv} = \frac{FuelVolume_{UsedEquiv} + FuelVolume_{BattCorr}}{Distance} * 100 \qquad (8)$$

Fuel consumption is in liters gasoline equivalent per 100 kilometers [l/100km], fuel volume is in liters [l], and distance is in kilometers [km]. This calculation method was used for each energy consumption test run for each university team, resulting in a fuel consumption result that is comparable across all teams (regardless of their fuel type) as it uses a reference gasoline-equivalent consumption value. Note that all competition vehicles in this particular AVTC were mild hybrid architectures rather than plug-in hybrids with a Charge Depleting mode, so it was not necessary to find results in energy consumption format using concepts such as utility factor (as was done in prior competitions [56]).

7.2. Experimental results for University Vehicles Under Test

In total, seven different teams completed the driving portion of the event. This section provides results from the track-based ACC following test along with energy consumption results calculated using the prior method. A speed trace from one of the more natural-feeling university-developed ACC systems can be seen in Figure 32, which includes the original target HWFET cycle as a dotted black line, the achieved GPS speed trace driven by the automated target vehicle in red, the GPS speed from the university EcoCAR vehicle following with ACC in blue. For reference the plot also displays light dotted upper and lower thresholds for EPA ±2 mph trace limits, though those limits are only displayed to confirm proper HWFET replication by the automated lead vehicle. In contrast, university vehicles operating under ACC only needed to comply with a competition-mandated following distance constraint window described in Chapter 3. Those that deviated from this window received a reduction in overall competition points for the event.

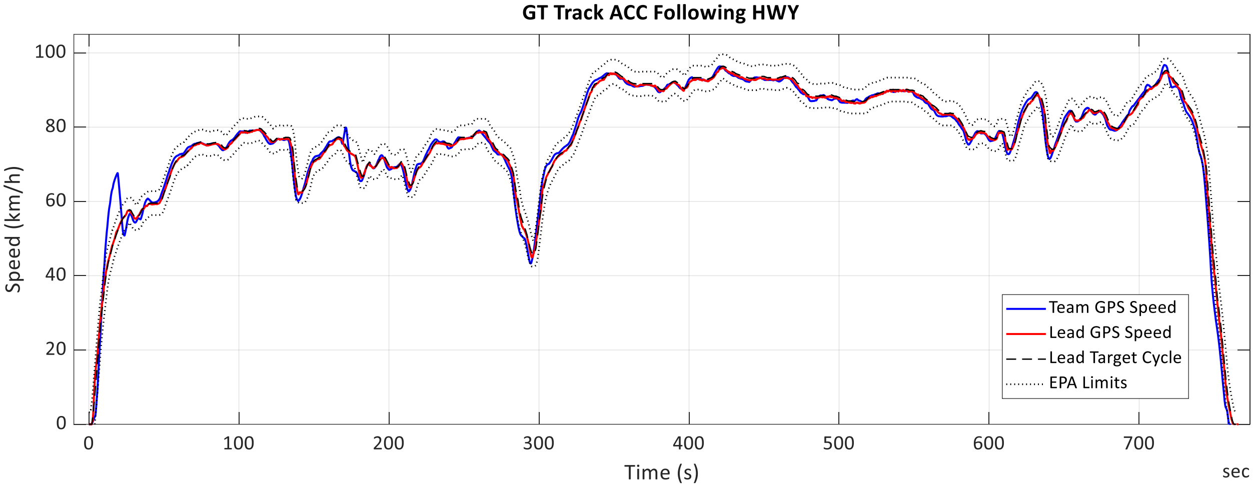


Figure 32. GT ACC Following HwFET Cycle on Track

As shown in the plot, the GT vehicle's ACC system matched speed with the automated target vehicle for most of the highway cycle apart from an initial overshoot on the first acceleration of the highway cycle. It is worth noting that the HWFET and UDDS cycles feature relatively mild positive and negative accelerations compared to other cycles, such as the US06 that were designed to supplement the UDDS and HwFET cycles to capture more aggressive driving.

Out of the seven vehicles that completed the ACC energy testing event, four vehicles stayed within the defined following distance constraint window the majority of the time. However, the results of this event also demonstrated that unexpected behavior can result from prototype vehicles being tested in environments beyond simulations or dynamometers due to unforeseen sensor fusion challenges. Due to delays introduced by the COVID-19 pandemic, this event was the first time many vehicle ACC systems were evaluated on track with physical targets.

As this event was the first time many vehicles demonstrated ACC system performance, due to issues with sensors on several of the university vehicles, some test runs resulted in erratic acceleration and deceleration characteristics throughout the test. If the vehicles drifted too far back from the lead vehicle, their sensor systems would lose the target vehicle or assign it to the wrong lane; the systems would then accelerate quickly to return to the set speed as if there was no lead vehicle present, then would slow dramatically once they approached the lead vehicle from behind. This behavior can be seen in the following plot, with large oscillatory speed variations from the target vehicle's trace.

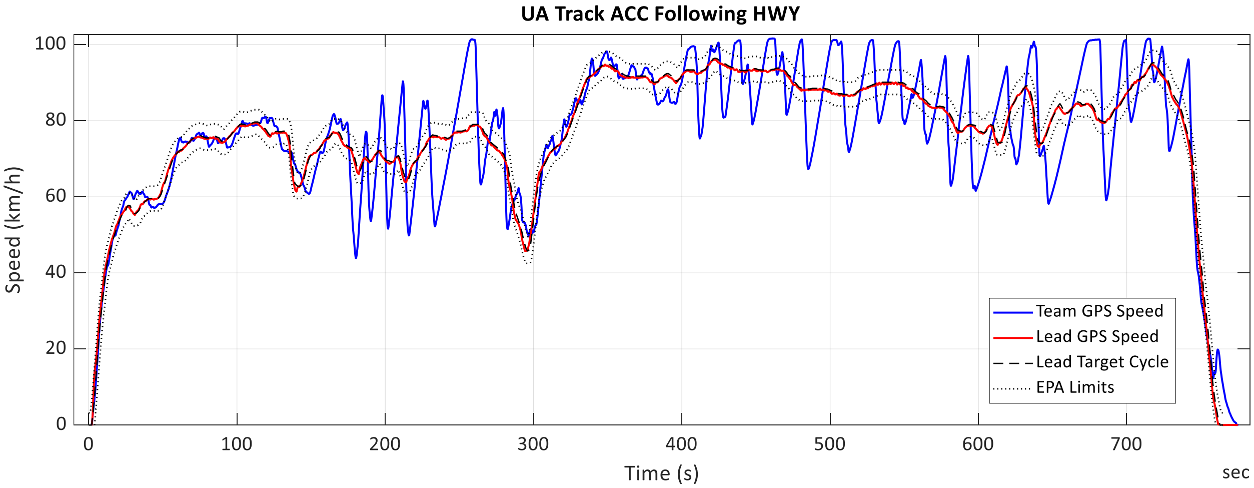


Figure 33. Oscillatory UA ACC due to sensor fusion challenge on circle track

The behavior was not unsafe due to using experienced vehicle operators that were trained to disengage the system if necessary. However, the resulting behavior would not be acceptable or usable for any normal consumer and was not the intended design of the vehicle. This dissertation will therefore focus primarily on vehicles that maintained detection of the lead vehicle throughout the majority of the test.

There were four tests meeting this criterion for each of the drive cycles, as seen in the following figures. Vehicles were tested over both a HwFET cycle and the first 505 seconds of the UDDS cycle. Due to event timing and the considerable number of potential vehicles to test in a short period of time it was decided to utilize the 505 second cycle rather than a full UDDS. While the Mobility Challenge Year 4 competition was limited to these two cycles, the test system could replay any potential drive traces or on-road scenario data through importing a properly formatted speed vs. time data file.

The results from this urban and highway portions of the test can be found in the following pages. Data from each vehicle was used to calculate final energy consumption results from each vehicle that participated in the test, though out of all seven results the four valid runs were for the GT, VT, MSU, and OSU university vehicles. The full set of results can be seen in Table 12.

Table 12. Energy Results from 2-Vehicle EcoCAR ACC Track Test

School	ACC 505 (Wh/km)	ACC HWFET (Wh/km)	Following Distance Constraint Window Adherence (%)
Georgia Tech (GT)	895	672	97
The Ohio State University (OSU)	1237	641	100
Virginia Tech (VT)	1040	719	94
Mississippi State University (MSU)	908	820	100
University of Tennessee (UT)	1528	1262	65
West Virginia University (WVU)	1135	1764	100
University of Alabama (UA)	1515	1618	84

As may be expected, teams with more oscillatory cycles saw significantly higher on-road energy consumption results. Readers should note, however, that powertrain components, operation characteristics, and control strategies also impacted energy consumption in conjunction with the ACC trajectory. For example, vehicles that used the larger capacity HDS battery with greater charge acceptance during regen braking may be less impacted by trace oscillations as the system could recapture some (but not all) of the braking energy during deceleration phases of oscillation. While production vehicles would not exhibit this degree of oscillation, some OEM ADAS features still present less-than ideal trajectories with mild oscillations. Further testing with production vehicles would be necessary to directly compare different ADAS feature performance.

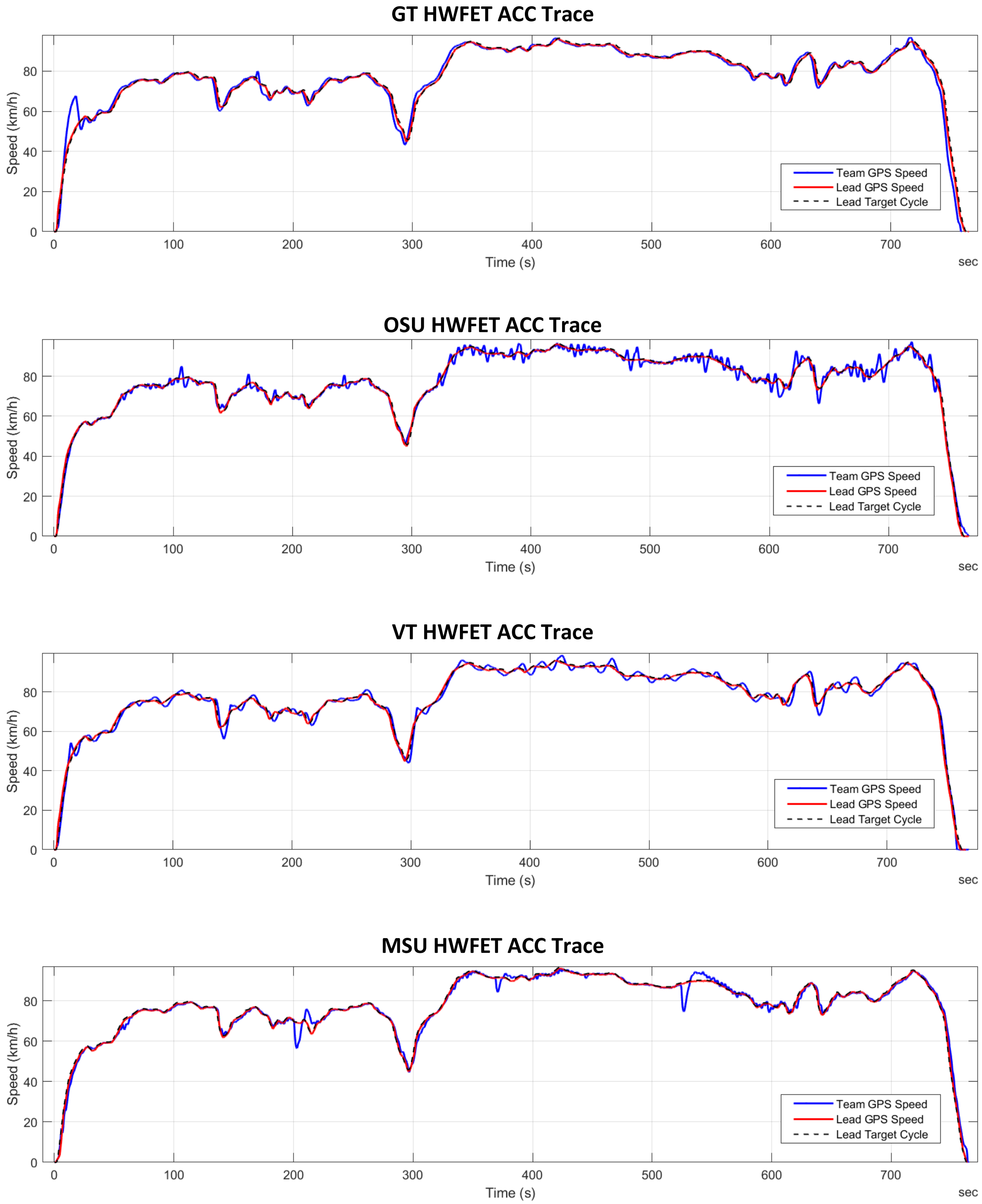
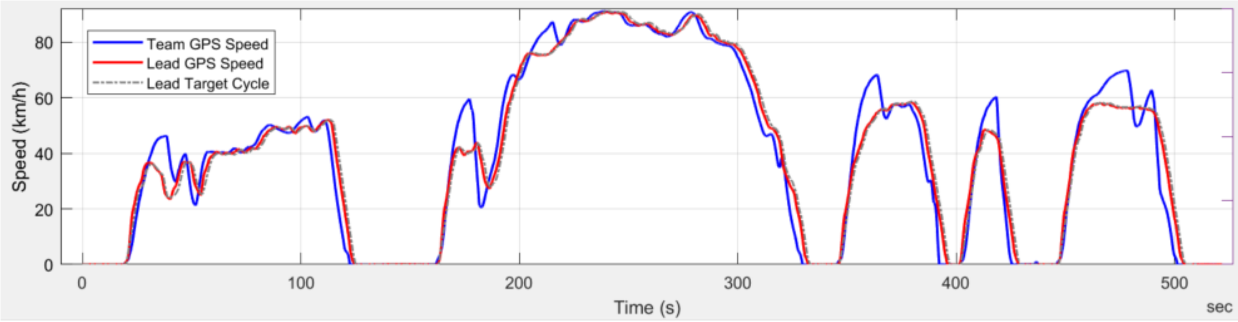


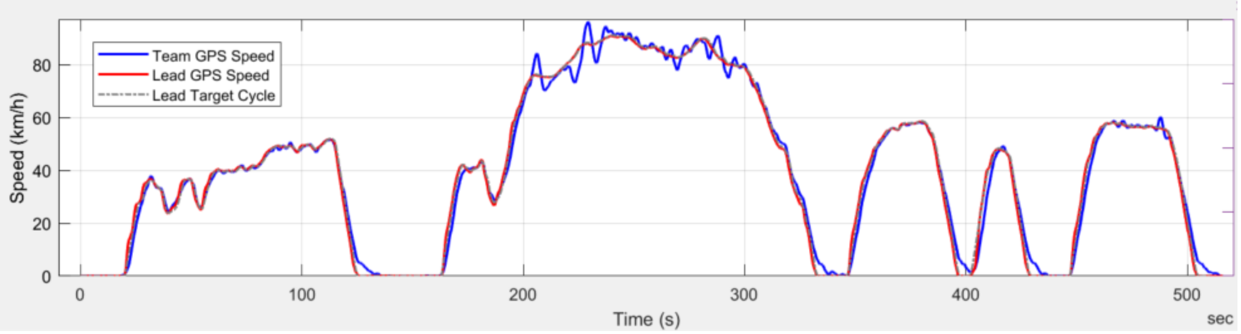
Figure 34. University Vehicle ACC Following HwFET Cycle on Track

The plots above demonstrate significantly different resulting trajectories from each of the University ACC implementations. The OSU vehicle presented higher frequency but lower amplitude oscillatory behavior. The GT system exhibited overshoot on the first acceleration as the VUT speed accelerated more aggressively to catch up to the Argonne target then had to slow significantly. Across all four vehicles there were areas for energy optimization, both in trajectory improvements and optimization of powertrain control strategies. However, the HwFET’s mild accelerations and somewhat steady speeds leave fewer opportunities for energy savings. A cycle with more braking events may present additional opportunities to use CAV controls to optimize vehicle following energy consumption. For example, the following plots show each vehicle under test following the target vehicle through the first 505 seconds of the UDDS cycle used in FTP-72 and FTP-75 testing.

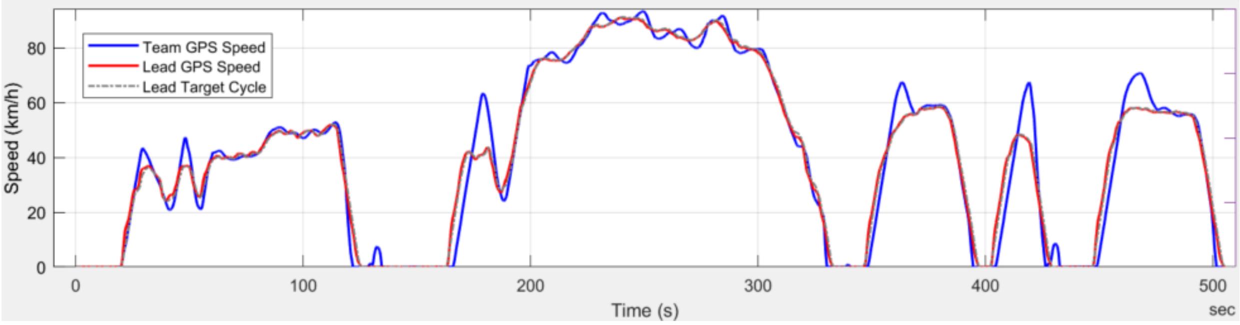
GT UDDS-505s Trace



OSU UDDS-505s Trace



VT UDDS-505s Trace



MSU UDDS-505s Trace

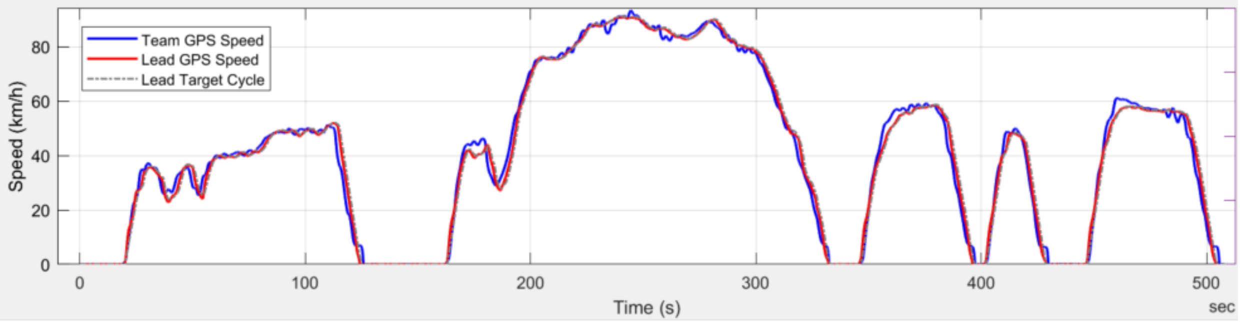


Figure 35. University Vehicle ACC Following UDDS-505s Cycle on Track

These urban cycle plots show greater trajectory variations, with more overshoot and reactionary braking on approaching target vehicle after acceleration events, such as those of the VT UDDS-505 plot. The MSU trace showed the closest adherence to the 505 trace, though this vehicle followed at a greater distance behind than the other three university prototypes and thus had more time to perform smaller trajectory adjustments. Overall, these university ACC track testing results show a wide variety of trajectories resulting from a simple goal – minimize energy consumed while still staying within the defined following distance constraint window. Teams used a variety of control algorithms and sensor systems to accomplish this task. These results also showed significant differences compared to some university dynamometer-based ACC development activities, demonstrating a potential need to conduct some track-based validation beyond just dynamometer ADAS and CAV test maneuvers.

7.3. Chapter Conclusions

In this chapter, energy consumption and trajectory results from Mobility Challenge Year 4 ACC testing were presented for all university prototype vehicles that completed the event. Seven universities completed the full test, with four of the universities able to reliably maintain detection of the Argonne Blazer target vehicle throughout the test. We found significant energy consumption variations across all of the teams, as is expected from such a diverse field of propulsion systems and automated control implementations. The lowest energy consumption across both urban 505 and HwFET vehicle-following tests was achieved by Georgia Tech, with 895 Wh/km on the 505 scenario and 672 Wh/km in the HwFET scenario. It should be noted that energy testing in track environments is subject to additional variabilities compared to laboratory dynamometer tests. Temperature and humidity vary throughout the day, and vehicles generally experienced higher temperatures in the Yuma desert environment near 100° F. Due to track time constraints and other testing event schedules, it was only possible to conduct a single iteration of each test. Multiple trials for each university team would have been preferable, though repeated runs were not feasible given time pressures.

Our research team and the universities learned a significant amount during the pilot testing process. One of the most prescient findings was that, when testing CAV systems for energy, it is necessary to perform a sensor validation check at every test track prior to starting the official test run. Metal guardrails, curved roadways, and sensor calibration or reliability challenges impacted many of the teams' sensor fusion performance. Though some teams performed dynamometer testing in preparation for the event, their system performance after shipping the vehicle to the GM proving ground differed significantly from operation in other environments. Overall, our Mobility Challenge track testing demonstrated both viability of the test method and the value of testing across MIL, HIL, VIL dynamometer, and in-vehicle track environments.

Chapter 8. Track-to-Dynamometer Methods for ADAS/CAV Energy Testing

In this chapter, a methodology will be proposed and piloted that enables dynamometer testing of ADAS and CAV longitudinal trajectories from both production and prototype systems. A key challenge of current ADAS/CAV energy testing is that no broadly accepted test procedures exist that are capable of side-by-side energy comparisons of different production ADAS systems. There is also no way to compare experimental CAV controls with baseline production ADAS systems to quantify the improvements that connectivity and energy-optimized controls may introduce. This novel proposed testing pathway could overcome these key limitations through a track-to-dynamometer energy evaluation of ADAS and more advanced CAV systems. The contents of this chapter will be published in a manuscript currently in preparation, titled **Track-to-Dynamometer Methods for Repeatable ADAS and CAV Energy Testing** [38].

8.1. Chapter Introduction

As standalone test environments, dynamometer and track testing offer different benefits and drawbacks. While dynamometers are the current standard method for evaluating general vehicle energy consumption [53], there is no commonly accepted pathway to conducting similarly standardized tests of ADAS on production vehicles nor is there a way to extend those methods to CAV features. This chapter proposes several methods for overcoming that challenge, including:

1. A two-step track-to-dynamometer test pathway that uses track testing to characterize ADAS/CAV longitudinal trajectories followed by replication of those trajectories on dynamometer.

2. A modified method that characterizes trajectories using MIL simulation based on manufacturer-provided or separately generated ADAS models instead of track testing.

3. A theoretical standardized interface implemented by OEMs in future production vehicles that enables direct injection of sensor detections or fused target data.

On dynamometers, production ADAS features are not currently testable unless researchers have unique interface intervention capabilities such as overriding objects from every sensor. For a given ADAS-equipped vehicle, it is theoretically possible to establish a method for generating a repeatable target vehicle profile ahead of the vehicle on dynamometer through sensor system interventions. However, each manufacturer and potential vehicle under test has a different sensor set, a highly proprietary CAN messaging architecture and message composition, traction control and other diagnostic triggers that may disable ADAS, and other unique considerations. To extend methods used by Argonne and other entities on one vehicle to the broader fleet of ADAS production systems is an unapproachable task. Instead, new methods proposed in this chapter enable broader and more standardized methods for production vehicle ADAS and experimental CAV feature evaluations without the need for extensive development work with every potential test vehicle.

In this pilot study, ACC operation data will be gathered in track environments where it is possible to capture ACC system performance while following a repeatable lead vehicle designed to replay traffic scenarios ahead of the vehicle under test. This method is well-suited to capture the entire system response of a vehicle under test without requiring extensive modifications to the control system and can be used on a variety of proving ground test tracks across both prototype and production ACC/CAV implementations. However, this method is less repeatable from an energy consumption perspective, since the humidity, temperature, and other factors are uncontrollable in a test track environment. Dynamometers, on the other hand, are well-suited for repeatable energy consumption testing but production vehicles do not currently have any sort of standardized interface to emulate behavior of automated controls that would be present on the road.

This methodology and pilot study demonstrates an alternative method of energy testing that uses both track and dynamometer environments in a two-stage test suited for capturing both prototype and production system performance and behavior while generating repeatable and accurate energy consumption results. In the first stage, vehicles would be tested in track environments using similar methods to the EcoCAR Mobility Challenge, with potential editions of connected traffic lights or simulated upcoming connected vehicles. The results from this test can then be used to generate an ACC-specific drive trace for each test vehicle or control implementation. That drive trace could then be performed using standard accelerator and brake pedal controls or robot driver systems on dynamometers with the same test vehicle, so that longitudinal control system behavior of stock and prototype systems can be emulated in dynamometer environments without needing a pre-determined manufacturer interface for direct injection of simulated sensor data.

8.2. Methods for Dynamometer Testing CAV Features

There are several methods for dynamometer testing automated longitudinal control features. In traditional dynamometer testing, drive cycles consisting of velocity profiles over time are driven by either a human operator or robot driver. These drive cycles have been defined over the years by EPA or other entities in order to emulate human-driven operation of varying intensities. Unfortunately, these traditional cycles do not adequately capture or represent the types of velocity profiles that may be seen by an automated longitudinal control algorithm acting in response to surrounding traffic elements. There is also no widely applicable automated longitudinal control cycle that could apply across different manufacturers and models since each system will respond very differently to a particular traffic scenario. Each vehicle with ADAS or CAV features utilizes different sensing, compute, and control algorithm implementations and the systems are calibrated and parameterized based on specific considerations for each manufacturer or research group in the case of prototype vehicles. With the advent of over the air updates, even a single vehicle's longitudinal velocity profile can vary drastically over the course of a year.

Based on these limitations, it is necessary to develop new methods beyond traditional drive cycle testing for evaluating the energy consumption of both prototype and production CAV features. Ideally, these methods and any required test systems would be designed with flexibility in mind so that they could not only be applicable to the development of prototype controls what could also be utilized to evaluate production implementations of longitudinal control.

There are several potential approaches to evaluating ADAS/CAVs features on dynamometer environments, which we broadly summarize in Table 13:

Table 13. Various ADAS/CAV dynamometer evaluation approaches

Method	Description	Limitations
Generalized ACC Drive Trace Testing	Create a new drive cycle or cycles that represent general ACC system behavior across all vehicles and test each vehicle using this new cycle(s) with the traditional human or robot operator following the new traces	Not specific to any specific control implementation. Unlikely to accurately represent actual behavior of each test vehicle.
Closed-loop Longitudinal Control Testing	Closed-loop testing of the automated control system on dynamometer by injecting target vehicle information and potentially connected infrastructure information in a way that the vehicle longitudinal controls operate the same as they would in roadway environments.	Not possible without intimate knowledge of vehicle CAN messaging or prototype controller implementations. Each new test vehicle requires significant engineering efforts.
Vehicle-specific ACC Drive Trace Generation and Testing	Develop a drive trace unique to each vehicle or control implementation that represents the velocity trace that would result from a vehicle following a target vehicle using either track or simulation methods. Replicate trace on dynamometer using human or robot driver.	Speed trace replication does not include look-ahead powertrain control and sensor/compute loads may differ from track methods.

8.2.a. Approach 1: Generalized ADAS Drive Cycle Method

Approach one has been proposed in various publications such as Prakash et al. [24], where a new trace could be generated that would represent generalized ACC system behavior across all ADAS-equipped vehicles when following a target vehicle that is driving the EPA drive cycles. However, as previously described, this approach has significant fundamental limitations that may prevent it from accurately representing system behavior the variations in ACC system behavior across different makes and models of vehicles. This approach also does not capture any potential benefits or impacts a manufacturer or research laboratory may implement using connectivity, nor longitudinal controls designed to maximize efficiency. It does have the benefit of providing the lowest test burden addition from a manufacturer perspective. However, applying the same generalized ACC cycle across all new vehicles would not capture any vehicle-specific impacts of connectivity or automation implementations implemented by various manufacturers. Failing to capture these differences in vehicle-specific ADAS trajectories would not only introduce a non-representative energy test, but also fail to incentivize the development and refinement and implementation of these features in consumer vehicles.

8.2.b. Approach 2: Closed-loop Longitudinal Control Testing Using Real-time Interfaces

The second approach is currently the most widely used method for researchers to evaluate energy impacts of prototype longitudinal control algorithms. Argonne and the Department of Energy have devoted significant resources to design and build core tools and capabilities for both developing CAV control algorithms and testing those features using real test vehicles in dynamometer environments. For example, Argonne's Vehicle Mobility Systems department has developed a Simulink-based software called RoadRunner that supports closed loop ADAS and CAV testing in MIL, HIL, and dynamometer environments. This software is designed for researchers to develop energy-efficient vehicle and powertrain controls, and our research team has collaborated with Vehicle and Mobility Systems to perform closed-loop testing with the Chevrolet Blazer and other vehicle platforms.

There are several potential actuation mechanisms for commanding vehicles during this closed-loop CAV control testing, described as follows:

- **Robot driver control**
    - Actuation of vehicle accelerator and brake pedals with linear actuators systems or other methods.
    - Significantly lower threshold required for understanding vehicle systems and communication networks. Requires mapping of pedal position to vehicle response characteristics.
- **Torque and/or acceleration command direct override**
    - Control hardware replaces stock can commands traditionally sent by the ADAS system with new torque or acceleration requests to the stock vehicle systems.
    - Method requires proprietary knowledge of vehicle hardware, software, and functionality to intercept and replace the correct can signals while avoiding inducing any communication faults.
- **Stock sensor override**
    - Control hardware replaces all sensor detections and/or fused objects on vehicle CAN or other communication networks with a target vehicle
    - Method requires proprietary knowledge of CAN communication AND accurate simulation of sensor performance characteristics.
- **Standardized dedicated test interface**
    - This method would require manufacturers to include a standardized test interface into production vehicles, enabling direct injection of target locations and trajectories using a standardized format.
    - This capability is not currently present on production vehicles, though a pilot implementation will be used in the EcoCAR EV Challenge CAV dynamometer testing.

Each of these mechanisms for enabling closed-loop real-time CAV or ADAS feature controls on dynamometers has unique benefits, drawbacks, and challenges. While robot drivers provide the lowest challenge for integration and knowledge of vehicle CAN communication, this method of control has slightly longer response times due to the linear actuators needing to move and press on the physical pedals.

Direct CAN overrides, in contrast, are sent over vehicle communication busses and are carried out as quickly as the vehicle is able to. However, this method requires decoding proprietary CAN messaging or working directly with OEMs to perform the overrides.

The third option is overriding sensor detections upstream as opposed to the downstream torque or acceleration commands. This method enables characterization of production ADAS system performance but may be the most challenging to execute as vehicle sensor systems become more complex. For example, modern vehicles may feature multiple vision sensors, RADARs, and in some cases LIDAR sensors. To perform this type of testing, it is necessary to either emulate the raw sensor data stream or override the resolved target objects on CAN (if they are present on CAN at all). When performing testing beyond overriding CAN-based objects, it is also necessary to use a 3D simulation environment to produce realistic camera and LIDAR data streams.

The final option is not currently possible with production vehicles, though Argonne and our research team have already piloted a vehicle-agnostic standard hardware and messaging interface for use on our XIL dynamometer test capable vehicles. We expanded upon the CAN-based CAV command interface used by EcoCAR teams and the Argonne target Blazer to develop this interface, which can be used with either ethernet or CAN-based communication. We call this flexible anything-in-the-loop interface our FlexIL interface, and it is used for simulation PCs or other controllers to send vehicle-agnostic commands to an XIL-integrated vehicle in our dynamometer test cell. We are currently expanding this interface to include fused object trajectories, for use in upcoming CAV dynamometer testing in later years of the EV Challenge competition. This generalized CAV test interface is also being used as a basis to define potential production vehicle standard test interfaces that could be integrated into future OEM vehicles. It would enable researchers or regulators to inject standardized and vehicle-agnostic scenario data or targets and force the test vehicle to ignore the real sensor information in favor of targets from this test interface.

While closed-loop testing has many benefits from a research perspective, one common challenge across all four methods is that they are usually not currently usable across a broad fleet of test vehicles and production ADAS systems. Argonne operates a significant number of vehicle platforms that have been integrated and developed to enable this type of closed-loop testing. However, currently there are few vehicles enabled for sensor object injection and those use more simplified RADAR and vision detections with objects available on CAN. Every one of these vehicles takes a significant amount of development time to enable closed loop control testing, including weeks or months of dynamometer troubleshooting even with OEM support.

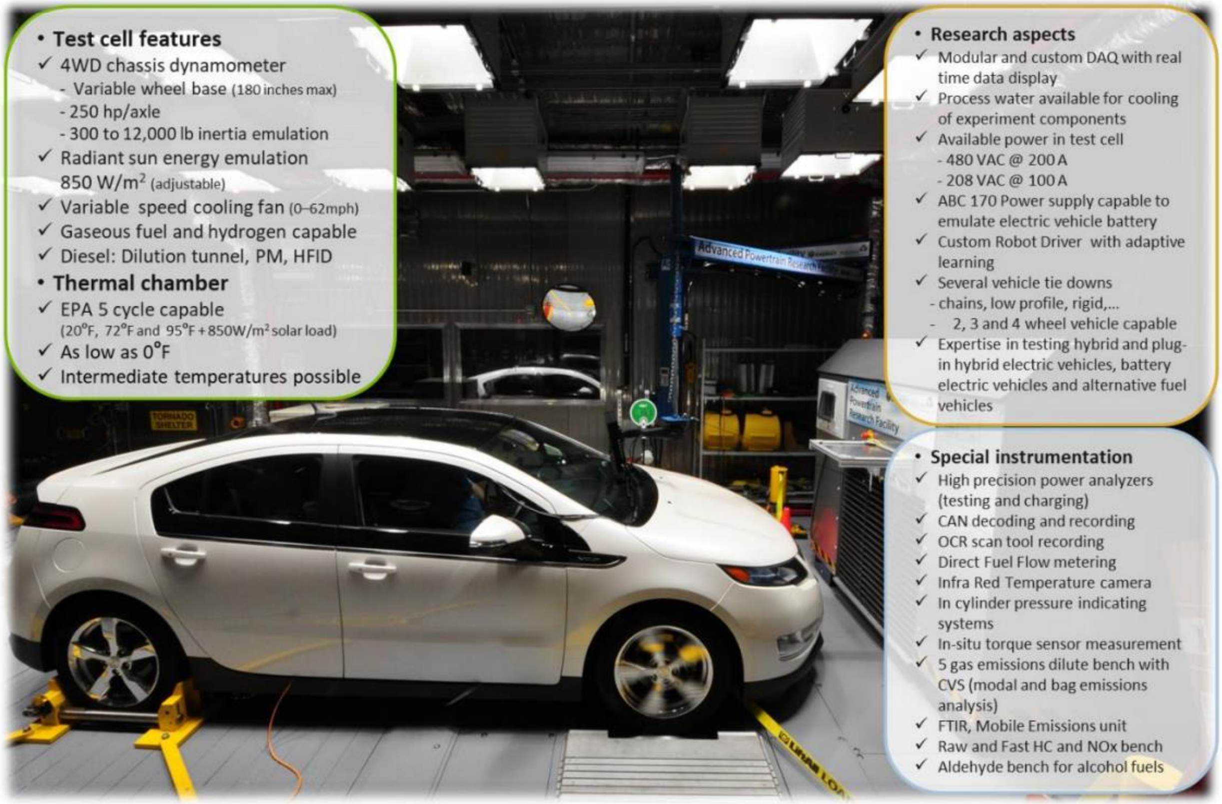
These limitations prevent larger-scale testing of many production ADAS systems, preventing researchers from evaluating production ADAS systems in tests that directly compare operation on the same set of scenarios. To overcome those limitations, we propose a third option that enables broader test fleets of ADAS vehicles and experimental prototypes to be directly compared. This chapter focuses on this third option, where track or simulation results produce a drive cycle specific to each test vehicle or CAV feature implementation. This drive cycle can then be used on dynamometers to achieve accurate and repeatable laboratory testing using track-validated ADAS system characterization.

8.3. Argonne Vehicle Testing Facilities

This study was performed at Argonne National Laboratory's Advanced Mobility Technology Laboratory (AMTL) at the 4WD chassis dynamometer test cell. AMTL's dynamometer facilities have been designed and customized to enable accurate and flexible testing of a broad selection of vehicle technologies, from advanced and electrified powertrains to connected and automated vehicle features. AMTL also operates a 2WD dynamometer with much of the same instrumentation and Data Acquisition (DAQ) equipment. This section summarizes content covered in greater detail by Stutenberg et al. [66], with a focus on relevant elements of the 4WD dynamometer test cell, instrumentation, and DAQ system used for this testing.

The 4WD test facility has been equipped with instrumentation for precisely testing a broad array of powertrains, from traditional emissions and fuel measurement devices to power analyzers for hybrid and electric powertrains. The facility is also equipped to evaluate hydrogen-fueled vehicles. Argonne also operates a custom DAQ system that serves as a centralized test control setup in addition to logging and time-aligning data from each vehicle under test, the dynamometer, emissions and fuel/electricity measurement instrumentation.

The DAQ system is also capable of multiple methods of controlling a vehicle during testing. For tests where one of the Argonne operators is actuating pedals, the DAQ displays the target and achieved drive trace on a screen suspended in front of the vehicle windshield. Argonne researchers also implemented custom-built robot driver actuators for tests where a human operator is unnecessary. The following figures provide a summary of the overall capabilities of the 4WD test cell and DAQ systems [66].

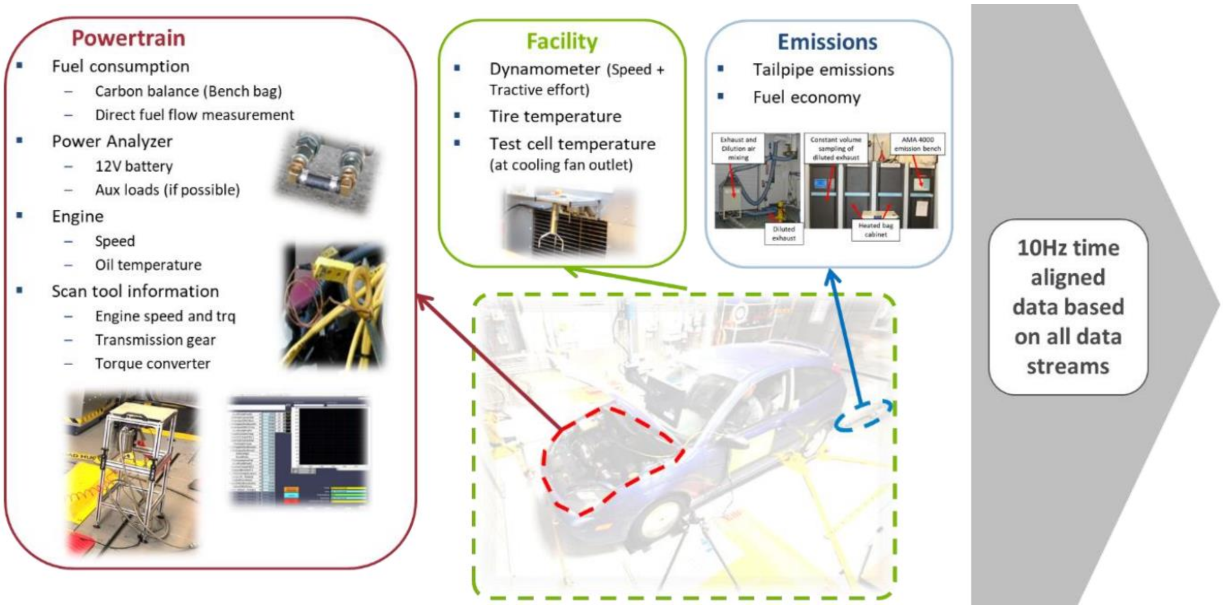


- **Test cell features**
  - ✓ 4WD chassis dynamometer
    - Variable wheel base (180 inches max)
    - 250 hp/axle
    - 300 to 12,000 lb inertia emulation
  - ✓ Radiant sun energy emulation 850 W/m^2 (adjustable)
  - ✓ Variable speed cooling fan (0–62mph)
  - ✓ Gaseous fuel and hydrogen capable
  - ✓ Diesel: Dilution tunnel, PM, HFID
- **Thermal chamber**
  - ✓ EPA 5 cycle capable (20°F, 72°F and 95°F + 850W/m^2 solar load)
  - ✓ As low as 0°F
  - ✓ Intermediate temperatures possible

- **Research aspects**
  - ✓ Modular and custom DAQ with real time data display
  - ✓ Process water available for cooling of experiment components
  - ✓ Available power in test cell
    - 480 VAC @ 200 A
    - 208 VAC @ 100 A
  - ✓ ABC 170 Power supply capable to emulate electric vehicle battery
  - ✓ Custom Robot Driver with adaptive learning
  - ✓ Several vehicle tie downs
    - chains, low profile, rigid,...
    - 2, 3 and 4 wheel vehicle capable
  - ✓ Expertise in testing hybrid and plug-in hybrid electric vehicles, battery electric vehicles and alternative fuel vehicles

- **Special instrumentation**
  - ✓ High precision power analyzers (testing and charging)
  - ✓ CAN decoding and recording
  - ✓ OCR scan tool recording
  - ✓ Direct Fuel Flow metering
  - ✓ Infra Red Temperature camera
  - ✓ In cylinder pressure indicating systems
  - ✓ In-situ torque sensor measurement
  - ✓ 5 gas emissions dilute bench with CVS (modal and bag emissions analysis)
  - ✓ FTIR, Mobile Emissions unit
  - ✓ Raw and Fast HC and NOx bench
  - ✓ Aldehyde bench for alcohol fuels

Figure 36. 4WD Test Cell Features Overview



Powertrain
- Fuel consumption
  - Carbon balance (Bench bag)
  - Direct fuel flow measurement
- Power Analyzer
  - 12V battery
  - Aux loads (if possible)
- Engine
  - Speed
  - Oil temperature
- Scan tool information
  - Engine speed and trq
  - Transmission gear
  - Torque converter

Facility
- Dynamometer (Speed + Tractive effort)
- Tire temperature
- Test cell temperature (at cooling fan outlet)

Emissions
- Tailpipe emissions
- Fuel economy

10Hz time aligned data based on all data streams

Figure 37. Overview of Instrumentation and DAQ Time Alignment

These facilities were used in a follow-up study to the EcoCAR track testing in order to demonstrate a new method for combining track testing for ACC and sensor system behavior characterization with dynamometer testing to achieve a more controlled and repeatable measurement for energy consumption in laboratory conditions.

8.4. Pilot Study Performed with Argonne Blazer

The proposed methodology was outside of the original definition of EcoCAR competition activities, so it was not possible to utilize each of the university vehicles in dynamometer testing. However, the stock Argonne Blazer was used to drive each of the valid ACC drive traces gathered during EcoCAR year for competition, achieving energy results across four different ACC implementations on a common and consistent stock Blazer test platform. This testing was performed on the Argonne 4WD chassis dynamometer with energy data gathered using laboratory fuel flow meters. In addition to energy calculations, the SAE J2951 Drive quality evaluation metrics were calculated for each test to assess repeatability and accuracy of the Argonne robot driver system in following the ACC traces from each team. An image of the Blazer installed on the Argonne four-wheel-drive dynamometer can be seen in the following figure:

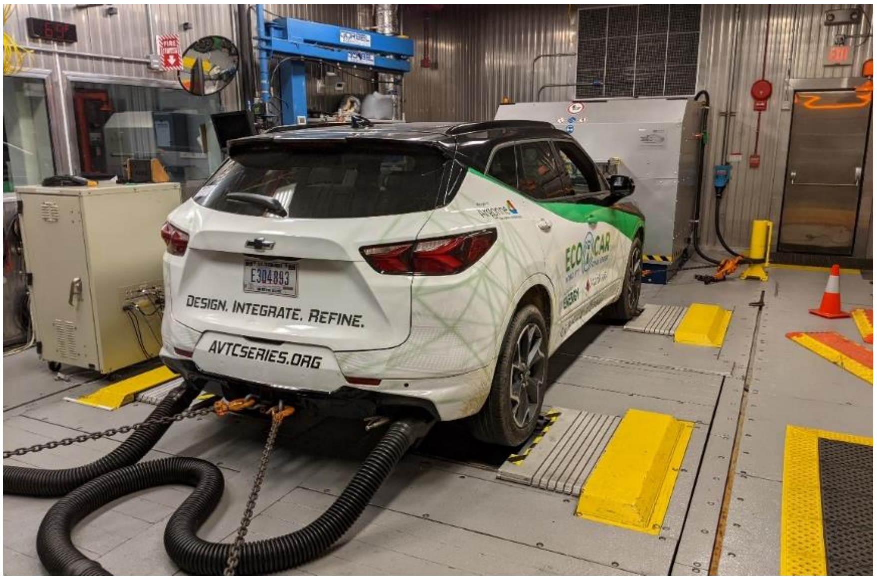


Figure 38. Argonne Blazer Setup on 4WD Chassis Dynamometer for University ACC Cycle Testing

Argonne's robot driver system was set up and calibrated to Blazer vehicle responses in order to accurately drive each of the ACC traces. This system uses analog inputs to control two linear actuators for the accelerator and brake pedal, with Argonne's dynamometer data acquisition and control systems performing closed loop control based on vehicle speed feedback. The control software for this system is built into AMTL's custom DACs system, and includes tunable features such as lookahead, gain scheduling, and active feedforward learning so the system can be calibrated to accurately perform certification cycles or other specialized tests. The different components of this robot driver system can be found in Figure 39 [66].

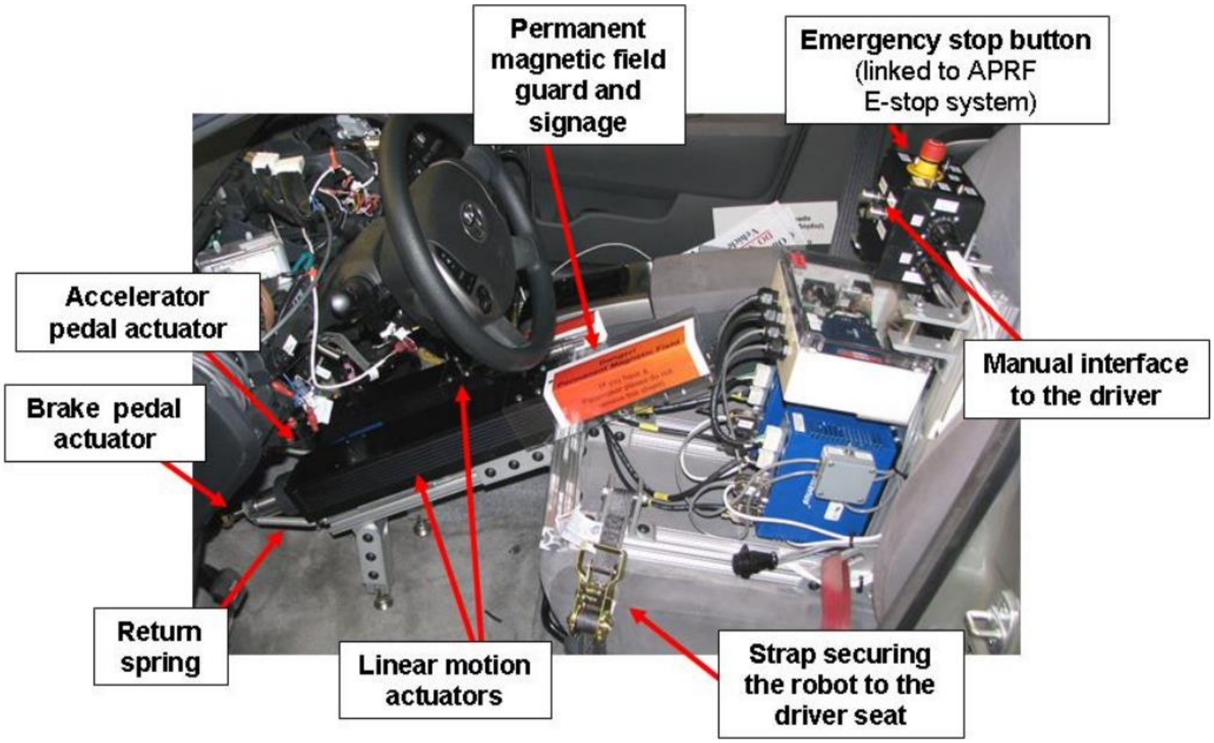


Figure 39. Argonne Custom Robot Driver Components

For the testing described in this study, the robot driver system was installed in the Blazer as seen in Figure 40. Once installed, the system was calibrated to the Blazer's dynamic responses by Argonne technicians for accurate and repeatable trace following. This testing presented a particular challenge in calibrating the system to follow the ACC traces collected from track testing, as these traces exhibit higher frequency oscillatory behavior compared to traditional certification drive cycles. This challenge is described in greater detail in the results section.

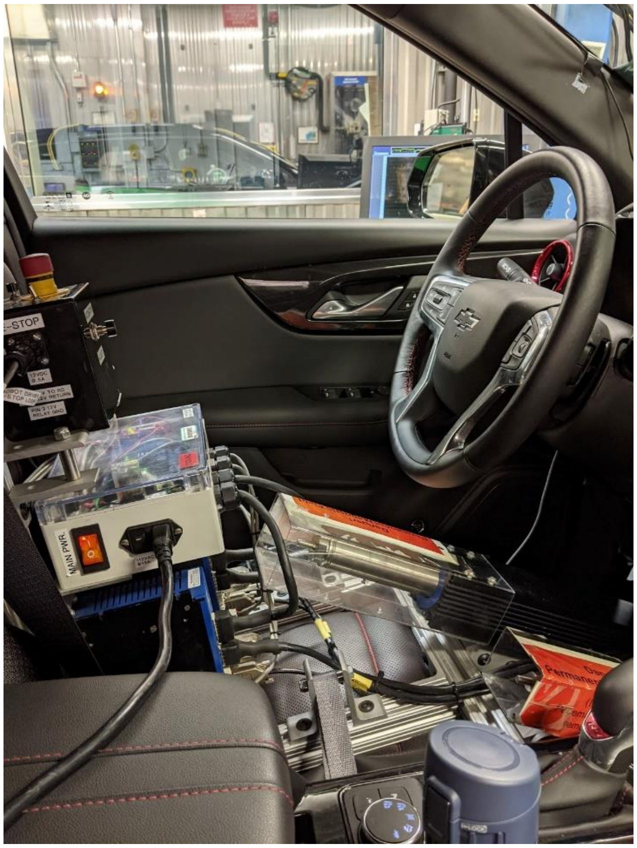


Figure 40. Robot Driver Installed in Argonne Blazer for Replicating On-track ACC Traces

As part of the standard Argonne test preparation, the Blazer was "soaked" at the same ambient temperature for 12 hours prior to the start of each test day. Before any fuel economy measurement tests were conducted each day, or if the vehicle sat idle for an extended period of time, the powertrain was warmed up by driving minimum of 2 back-to-back highway cycles. Achieving a steady state thermal condition in the vehicle with warm powertrain components prior to energy consumption testing is critical to ensuring that each test run could be compared to others, as cooler components generally exhibit higher friction and greater efficiency losses than those that are adequately warmed up through prep cycles.

The test vehicle was filled with EPA Tier II test fuel with tested fuel properties to ensure that measured fuel volumes and mass could be converted to fuel economy in miles per gallon gasoline equivalent. Fuel flow within the AMTL testing facilities may be measured in several different ways including:

1. Carbon balance fuel economy results from the emissions bench (bag and modal)
2. Volumetric fuel flow measurement
3. Mass fuel flow measurement

As described in the technical report, “each data stream provides unique benefits and levels of accuracy, dependent on specific testing and powertrain configurations. Due to this, the exact method of fuel flow instrumentation is vehicle dependent, and the vehicle specific report should be referenced for measurement points and routing [66].” While certification fuel economy testing measures fuel usage using the first method [71], both modal and bag-based measurements do not capture highly transient changes in fuel consumption and smooth out those peaks along with introducing a transient delay as the exhaust travels through the collection pipes [66]. Because of those challenges, for this experiment we desired a more dynamic measurement with less instrumentation and decided to utilize both volumetric and mass fuel flow measurements available through AMTL instrumentation. To take these measurements, our research team rerouted the Blazer’s fuel line in between the vehicle tank and fuel rail into the instrumentation system shown in Figure 41 [66].

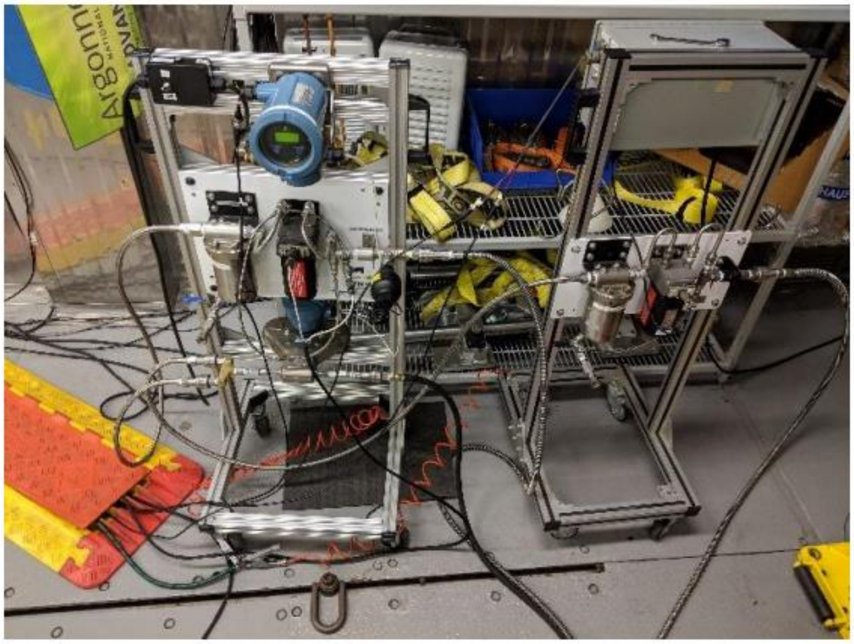


Figure 41. Direct Fuel Flow Measurement Coriolis and Fuel Scale Instruments

The figure shows a volumetric fuel flow measurement system (Re-Sol RS840-060), which uses a positive displacement flow meter to capture the volumetric flow rate of fuel and can measure flow rates ranging from 0.3 to 60 L per hour with an accuracy of ±0.36% of the full-scale reading. This system provides a digital frequency output f that is proportional to the flow in liters/hour according to:

$$FuelFlow = f * 3.6/K_d \tag{9}$$

Where K_d is the digital calibration factor in pulses/cm supplied by the manufacturer. Gravimetric measurements were conducted using a micro motion Coriolis flow meter shown in Figure 41, which has a nominal flow rate of 25.97 g/s and an accuracy of ±0.1% of reading [66]. The calculations in this chapter were performed using the volumetric fuel flow signal, though the mass flow results were also recorded for comparison.

8.5. Test Approach and Preparation

The methodologies proposed in this chapter are intended to show the viability of our novel multi-environment approach to testing and comparing energy consumption of different vehicles or control implementations using automated control features. These methods are intended to augment, rather than replace, existing closed-loop evaluations conducted by Argonne and other entities with methods that can be used across a broader fleet of both production and prototype test vehicles.

The general approach for our method is to first generate a vehicle-specific drive trace that accurately represents the behavior of an ADAS or CAV feature then perform that trace in more accurate laboratory dynamometer conditions. This speed vs. time trace would represent the resulting longitudinal trajectory a particular ADAS/CAV feature would produce when the vehicle under test follows a target vehicle or participates in a traffic scenario. Instead of the generalized ACC trace described earlier with the inherent limitations, this vehicle-specific trace would instead accurately represent each feature's behavior and enable direct comparison between different vehicle designs or CAV control implementations.

There are multiple potential pathways to generate this vehicle-specific ADAS/CAV drive trace. The method our team used in designing this particular set of experiments was a novel track-to-dynamometer pathway, where data from track testing is used to generate the vehicle-specific ADAS/CAV cycle. Either physical target vehicles or simulated ones could be used on track to gather this data, though by using physical targets it becomes possible to test production vehicles on the same test. The speed and time data from this testing would then be executed as a dynamometer drive cycle, eliminating the need for ADAS-specific instrumentation in the laboratory. Alternatively, a MIL-based approach could be used if an OEM has access to models with high enough vehicle powertrain and ADAS behavior fidelity to accurately represent realistic ADAS/CAV behavior. An image of our two CAV test pathways is shown in Figure 42, along with the traditional Argonne XIL method in Pathway 3.

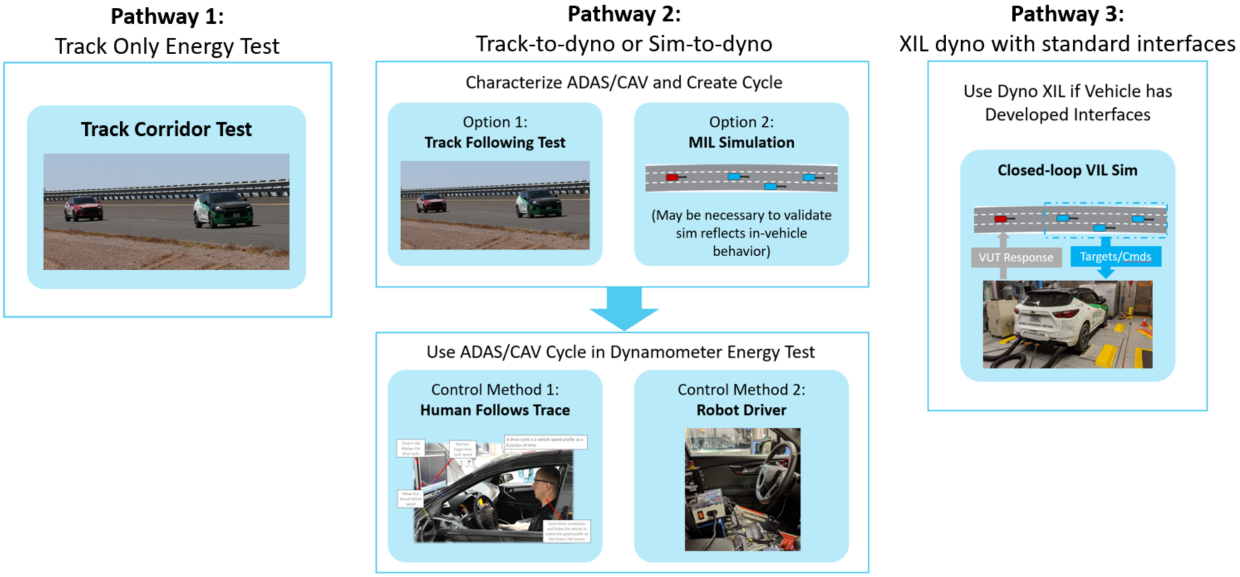


Figure 42. Flows for Multi-environment Automated Cycle Testing

For this pilot version of the study, the track-based method was used to gather University ACC drive traces and generate a series of ADAS/CAV traces. Each trace was then tested with the Argonne stock Blazer as a baseline using the Robot Driver method of control. While the ideal test pilot would have used each university vehicle to execute the corresponding ACC trace, by performing each trace on a common production vehicle this test demonstrated that different ACC traces may impact energy consumption compared to standard (non-ACC) drive cycles. Future testing would be required to evaluate whether production systems have similarly significant variations, as the university traces are likely more oscillatory and less refined than most production vehicle ACC and ADA features.

8.6. Results from ACC Trace Replication Testing

We tested the production Chevrolet Blazer over a period of several weeks, with four iterations each of the University ACC traces and baseline traces of the standard FTP, 505, and HwFET drive cycles. In addition to the university ACC traces gathered from university track data, several tests were run using standard (non-ACC) UDDS, UDDS 505, and HwFET drive cycles for a baseline energy and J2951 metric comparison between the traditional cycle and the ACC following cycle. The following plots display comparisons between the original track-based speed traces in black and the actual dynamometer roll speed achieved during the test in red.

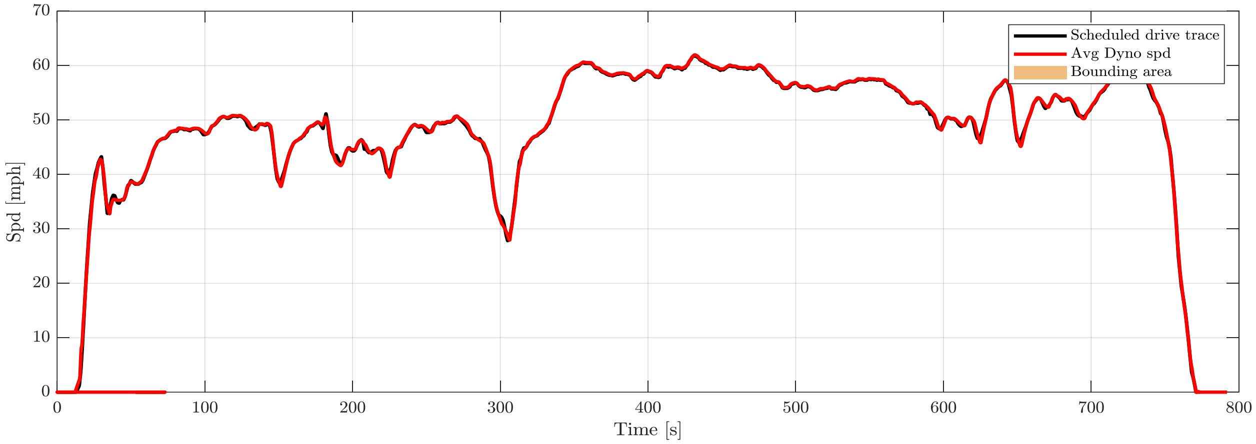


Figure 43. ACC Highway Track Trace vs. Dynamometer Robot Driver Execution

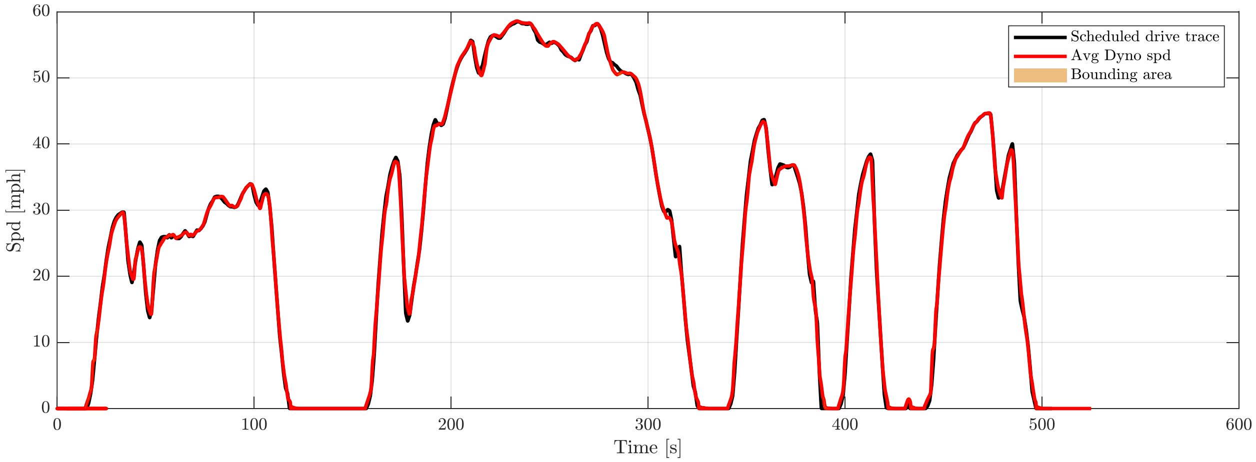


Figure 44. ACC UDDS 505 Track Trace vs. Dynamometer Robot Driver Execution

As these tests were run using the AMTL robot driver system, some deviations were expected given the oscillatory nature of several of the university ACC following traces. However, the system was able to stay within required EPA margins for all tests.

The following graphs show results comparing each university ACC trace following a lead vehicle executing each standard trace with a comparison to the standard versions of each cycle. Interestingly, the university vehicles traces generally resulted in worse fuel consumption compared to the standard traces. While the Argonne Blazer is not directly representative of their hybrid drive system implementations, this shows that depending on how ACC controls are implemented they may result in worse energy consumption than a vehicle driving standard regulation cycles. The full set of energy consumption and J2951 results from this testing can be found in Appendix 2: Data from ACC Dyno Trace Testing.

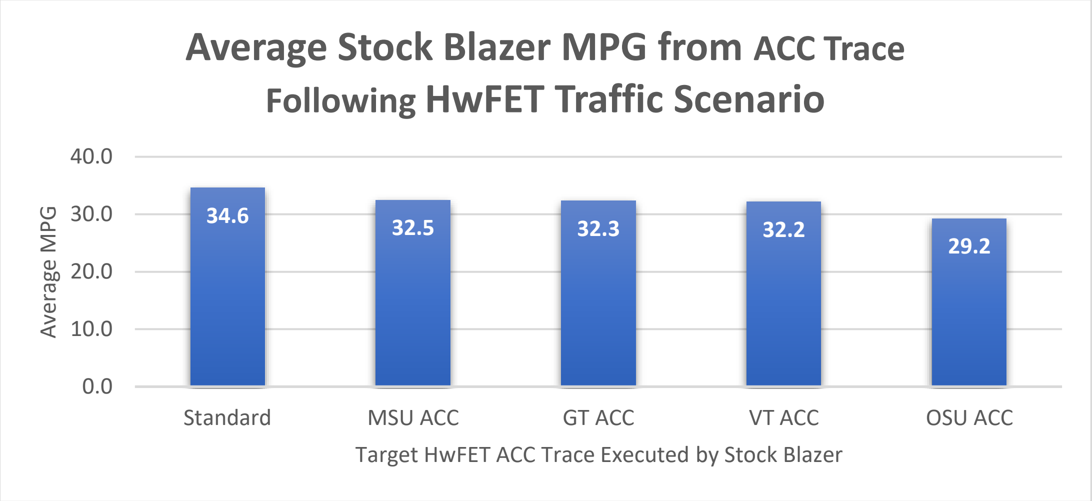


Figure 45. HwFET ACC Trace Results from Stock Blazer Executing Traditional and ACC Traces

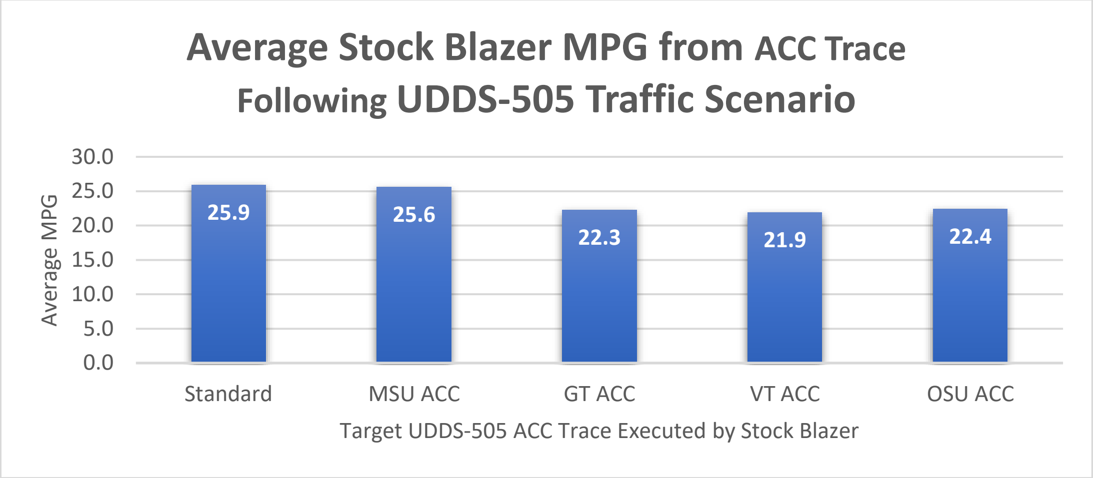


Figure 46. 505 ACC Trace Results from Stock Blazer Executing Traditional and ACC Traces

Table 14. Average MPG and SAE J2951 Metrics across four test iterations

Drive Cycle	MPG Avg.	DR Avg	ER Avg.	EER Avg.	ASCR Avg.	RMSSE Avg.
HwFET: Standard	34.6	0.22	0.34	0.13	3.31	0.26
HwFET: VT ACC	32.2	0.20	-1.69	-1.92	-0.02	0.34
HwFET: GT ACC	32.3	0.20	-1.68	-1.91	-0.55	0.32
HwFET: OSU ACC	29.2	0.04	-21.67	-27.71	-24.39	0.55
UDDS 505: Standard	25.9	0.29	-0.69	-0.98	-0.92	0.48
UDDS 505: MSU ACC	25.6	0.25	-6.29	-6.99	-4.50	0.51
UDDS 505: VT ACC	21.9	0.15	-2.66	-2.88	-2.73	0.59
UDDS 505: GT ACC	22.3	0.13	-2.09	-2.26	-2.09	0.59
UDDS 505: OSU ACC	22.4	0.11	-10.56	-11.93	-6.73	0.50
UDDS Full: Standard	23.7	0.28	0.46	0.19	0.18	0.43

The results in the table above highlight an interesting consideration that arises when replicating ACC traces on dynamometer. Specifically, the robot driver system tended to significantly smooth out ACC velocity traces with significant oscillatory characteristics. Argonne's robot driver system control algorithms were originally developed to follow standard drive traces with few or minor oscillations. In fuel economy testing, a robot driver system (and human operators) can significantly impact the resultant fuel economy by attempting to follow target traces too aggressively. Unless the system is a risk of violating the EPA thresholds, it is generally preferable to tip out of the accelerator pedal and coast back to the target trace speed rather than applying the brake pedal and inducing further energy losses with either friction brakes or electric regen braking conversion inefficiencies. In contrast, the ACC drive traces had greater high-frequency oscillations than standard drive cycles and the robot driver system tended to dampen out these oscillations during the study. The J2951 metrics from the OSU ACC cycles demonstrate this behavior most clearly, with the highway-following cycle tests averaging ASCR of -24.39 and ER of -21.67 compared to the standard HwFET following test that achieved 3.31 ASCR and 0.34 ER. These significantly negative values indicate excessive smoothing of the driven ACC trace versus target trace gathered on track, along with likely reduced energy used. Interestingly, the RMSSE metrics for these OSU ACC traces did not show as large a discrepancy. They were higher than the normal highway cycle tests at 0.55 for OSU ACC vs. 0.26 for standard, but those values are similar in magnitude to the 505 results. The dampening of oscillations can be seen in the following figure:

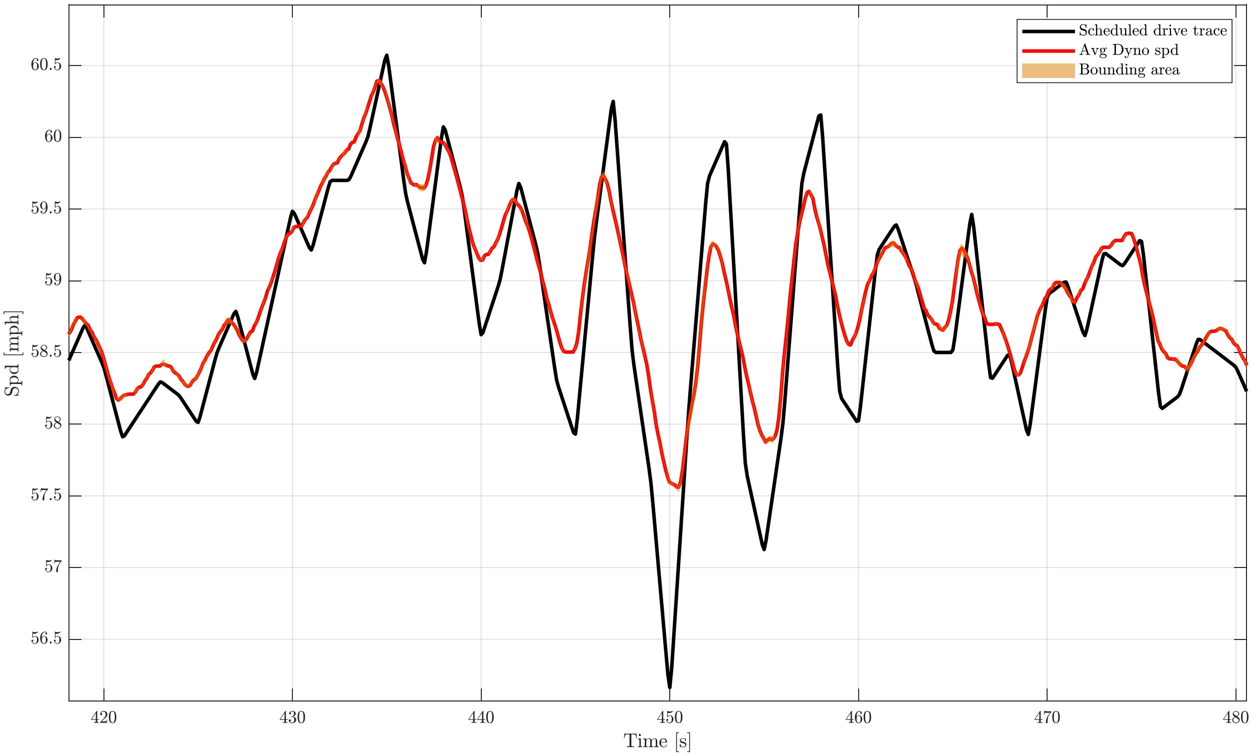


Figure 47. OSU ACC Trace with Driven vs. Target Oscillation Smoothing

Overall, this outcome demonstrates the need to calculate and consider each of the J2951 metrics when executing these type of ACC trace following tests. The smoothing effect also highlights the need for control system development and calibration time in order to most accurately conduct this test method using systems traditionally used for standard energy testing. Future studies will include production ACC system behavior alongside prototype implementations to provide a more realistic baseline to current industry state-of-the-art. It is likely that production versions of ACC systems may not exhibit this large a degree of oscillation, though even a reduced magnitude of oscillations and overshoot resulting from production ACC systems following a target vehicle would still impact energy consumption and should therefore be accounted for in representative dynamometer testing.

8.7. Chapter Conclusions

In this chapter, we developed and piloted a new method for track-to-dynamometer testing that enables a broader selection of both production ADAS and experimental CAV features to be tested in more controlled dynamometer environments. This new method overcomes certain challenges with testing production ADAS systems in indoor dynamometer environments. In order for researchers to conduct production ADAS system energy testing, it would be necessary to either override sensor inputs or have an accurate representation of the system performance in a particular scenario. While overriding sensors is possible for certain platforms and has successfully been done by Argonne and other research institutions [8], it is not possible to perform this work across a broad selection of production vehicles as every make and model uses different sensors, communication network architectures, and secure CAN messages.

As one possible alternative method, we proposed and piloted a pathway that uses methods from the Mobility Challenge to gather track-based ACC/CAV system trajectories and then replicate those trajectories in more controlled dynamometer settings. While the method was initially piloted using EcoCAR university traces, the same pathway could be used to gather ACC trajectory data from production vehicles and then test those trajectories with each vehicle in a dynamometer environment. The results from this study showed that certain challenges remain with this method, in particular it may be necessary to develop robot driver control algorithms that produce less smoothing of drive traces. However, this pilot testing implementation demonstrated that the method is viable, enables repeatable energy testing of ADAS and CAV features, and avoids the extensive development work required for closed-loop testing. This closed-loop testing is still necessary for the development of new CAV control features, but the track-to-dynamometer method we have developed expands the scope of testable vehicles to include additional production platforms.

Chapter 9. Connected Intersection and Corridor Test Systems

This chapter focuses on methods and test systems for evaluating CAV control responses to connected intersections and corridors. An overview of the EcoCAR Mobility Challenge testing is provided as an example of a single intersection test that all operational Mobility Challenge vehicles took part in. A novel evolution of the Mobility Challenge assets is proposed that implements a reconfigurable flexible connected corridor test system (FlexCorridor). The system will be capable of testing both CAV and production ADAS systems in the same connected corridor scenarios. It will be created by combining multiple sequential portable connected intersections or RSUs with automated target vehicle(s) to replay a synchronized traffic scenario. Content from this chapter will be published in an upcoming manuscript in preparation, **Design of a Track-based Flexible Connected Corridor Energy Testing System** [39] and is linked to all four primary research goals.

9.1. Chapter Introduction

The EcoCAR Mobility Challenge and EV Challenge competitions have challenged teams with using connectivity information from traffic and stationary roadside infrastructure to implement energy-optimized automated control features. To support fair comparisons between different university vehicles in these connected environments, test systems that can execute repeatable scenarios with each vehicle under test must be used. Ideally, these scenarios and test systems could also be used without modification to evaluate production ADAS features as an automated, but unconnected, baseline comparison. In the first section, readers will be introduced to the single intersection single vehicle test used in the Mobility Challenge and the first iteration of a portable intersection test asset.

The following section will present a proposed expansion of that test setup to combine multiple intersections and at least one physical target vehicle capable of executing a controlled and repeatable traffic scenario. The combined multi-intersection system will be capable of representing a variety of real-world or theoretical connected corridor geometries and SPaT/MAP messages. This FlexCorridor test system has been designed with a number of use cases in mind, from AVTC applications to production ADAS characterizations.

CAV energy optimization in connected environments is a common topic of research, with investigations into energy impacts of performing maneuvers such as eco-approach and departure through single or multiple intersections. MIL environments provide the opportunity to evaluate experimental CAV controls in safe and accessible virtual intersections or connected corridors without the need to pay for track or dynamometer testing time. In State-Constrained Optimal Solutions for Safe Eco-Approach and Departure at Signalized Intersections, Argonne's Han, Karbowski, and Rousseau [72] provide fundamental methods for efficiently passing through connected intersections with simulated energy results across several real-world routes. This MIL research has been extended in recent years to VIL dynamometer evaluations using several research vehicles integrated into Argonne's XIL CAV research systems [73]. These dynamometer-based methods are critical to enabling the development of experimental CAV control features. However, current methods have not been used to perform comparison testing between larger fleets of >10 experimental vehicles in a short time as is necessary for AVTCs. These methods have also not yet been extended to enable production vehicle tests in connected corridors other than proposed track-to-dynamometer methods in earlier chapters.

Despite the growing body of research simulating CAV optimized controls, comparatively few entities have implemented these features using real test vehicles on dynamometer, track, or public roadway tests with real or virtual connected intersections. In Jeong et al. 2023 [74], Argonne and Clemson collaborated to conduct VIL track testing of energy optimized controls with Eco-approach and departure through connected intersections. However, this research was performed using only virtual intersections and vehicle traffic and was not performed on a broad fleet of test vehicles [74]. Other researchers such as Almannaa et al. [30] have evaluated operation of test vehicles through single intersections. This study was performed with a broad selection of drivers operating one test vehicle at Virginia Department of Transportation's Virginia Smart Road at VTTI. Their single intersection test method was similar to the Mobility Challenge testing though they used permanent connected intersections and public participants. It also highlights several challenges in capturing consistent energy impacts over such a short distance, even with just one heavily-instrumented test vehicle. In this case, challenges with onboard instrumentation resulted in researchers using vehicle powertrain modeling to estimate energy use. Even with this modeling-reliant approach, there were significant variations in fuel usage across all test runs [30].

While these research activities provide a positive foundation for connected intersection and corridor research, to meet the requirements for AVTC testing it was necessary to introduce new methods and test systems that are flexible, portable, and capable of evaluating larger and diverse fleets of CAVs. To adequately quantify the benefits that connectivity can provide over just single vehicle automation, these systems and methods would ideally be capable of direct comparison testing to non-connected production ADAS systems. The first step of creating these new flexible and portable connected intersection/corridor test systems was performed for the final year of the Mobility Challenge.

9.2. EcoCAR Mobility Challenge Connected Intersection Testing

In the EcoCAR Mobility Challenge, teams implemented Eco-approach and departure algorithms for longitudinally driving through a connected intersection. Teams developed the capability to transmit BSMs from their test vehicles, receive I2V information from a connected intersection, and use that connectivity to drive with longitudinal automation through the connected intersection. The university vehicles would be tested using connected intersection events at TRC and GM proving grounds during the final year of the Mobility Challenge. This event was designed primarily as a functionality test rather than an energy evaluation, as it is difficult to achieve repeatable energy test results from a single intersection approach and departure. Instead, the test activity was meant to evaluate the robustness and performance of the team connectivity and longitudinal control algorithms and ensure that vehicles could successfully navigate variety of scenarios with different signal phase and timing implementations.

To test University vehicle Eco-approach and Departure capabilities, it was necessary to develop a connected intersection test system that was portable and deployable at both TRC and GM proving grounds. While certain V2X connected test track facilities such as the American Center for Mobility and TRC feature permanently installed four-way connected intersections [36], systems developed for AVTCs must be portable and deployable across several sponsored track facilities over the course of a single competition. Participating teams also needed a method to test and refine their algorithms at test areas near their university, as most schools do not have dedicated test facilities with connected intersections. Because of these multiple required testing locations, Argonne and Cohda collaborated to implement RSU and OBU software and hardware systems that could be used regardless of their physical location. The systems could be run without a physical traffic signal at universities, where teams ran experiments in closed course test areas with their Blazers equipped with OBUs and stationary laptops connected to RSUs. These stationary systems simulated SPaT information and transmitted using standard DSRC protocols. Examples of university testing from Ohio State [75] and Georgia Tech [75] can be found in Figure 48.

```
Blazer [127.0.0.1]
[]
 Latitude: 40.0030724°
Longitude: -83.0438032°
Elev(MSL): 213.00m
    Speed: 35.00km/h
  Heading: -178°
LongAccel: 0.00m/s²
  YawRate: -0.44°/s
StrWhlAng: -2°
 LatAccel: -0.87m/s²
CAN Port: 12001
GPSD Port: 3000
 HMI Port: 7000
```

```
RSU [192.168.2.77]
[]
 Latitude: 40.0023030°
Longitude: -83.0436950°
Elev(MSL): 213.00m
    Speed: 0.00km/h
  Heading: 105°
LongAccel: 0.00m/s²
  YawRate: 0.00°/s
StrWhlAng: 0°
 LatAccel: 0.00m/s²
GPSD Port: 3001
 HMI Port: 7001
```

```
blazer [127.0.0.1]
[]
 Latitude: 34.1030758°
Longitude: -84.1352350°
Elev(MSL): 327.00m
    Speed: 20.00km/h
  Heading: -156°
LongAccel: 0.00m/s²
  YawRate: 16.01°/s
StrWhlAng: 100°
 LatAccel: 1.55m/s²
CAN Port: 12001
GPSD Port: 3000
      Fix: 3
 HMI Port: 7000
     # Tx: 3477
     Sync: 1
     # Rx: 281
```

Figure 48. University Closed-course Virtual Connected Intersection Testing

Universities across the Mobility Challenge used similar test setups at closed courses available for development activities. While this testing was beneficial for initial debugging purposes, it did not include physical traffic lights detectable by vision systems. To add physical traffic lights, TRC and Argonne collaboratively developed a single intersection system using portable traffic signal assets. For the TRC testing, this system used a construction zone traffic light combined with a Cohda MK5, laptop and solar panel with batteries. For better portability when shipping the system to GM for Year 4 Competition, the system implemented was a single traffic light mounted on a pole with a laptop with control hardware to actuate each of the signal lamps. These two traffic light systems can be seen in the following figure.

Figure 49. Construction zone signal system at TRC (left) and smaller single signal at GM (right)

For both test systems, the research team set up the Cohda MK5 radio to enable flexible configuration of SPaT map information to evaluate a variety of timing sequences. Custom software was also developed to enable the radio to begin each pre-determined sequencing precisely when an approaching vehicle reached a set distance. This capability used university vehicle BSMs to assess when they had passed a set location on approach, triggering the system to initiate light sequencing and SPaT/MAP transmission. This triggered start ensured that the various SPaT sequences would be executed the same way for each university vehicle to increase test-to-test repeatability.

9.2.a. Connected Mobility Challenge Intersection Test Methodology

At TRC and GM, teams took part in a closed course test where their prototype Blazers attempted to navigate a signalized connected intersection with real-time SPaT and MAP information. The following section presents an abbreviated version of the requirements and event description provided to teams in our event operations description document [76].

Vehicles were expected to successfully interpret SPaT and MAP data and use it during Eco-approach and departure testing as a real-time control system input. For example, if the expected phase on arrival at the intersection stop line was red, vehicles were required to stop safely before the stop line before waiting until the phase turns green to resume driving through the intersection. If the expected phase on arrival at the stop line was green, vehicles were expected to drive through the intersection without stopping. Teams were also instructed to never exceed the speed limit during the drive throughout the test.

For the Mobility Challenge's single connected intersection test, vehicles were taken through a series of tests with a variety of SPaT timings meant to evaluate the robustness and capabilities of each vehicle's longitudinal Eco-approach and departure algorithms. Because this initial pilot test was performed primarily as a functionality test rather than an energy evaluation, no physical target vehicles were used during any of the scenarios. It is worth noting that this type of test is likely not representative of most real-world connected intersections, where vehicles would be restricted from freely choosing optimal trajectories due to other roadway occupants such as vehicles and pedestrians. However, as an initial demonstration it provided teams with an adequate testing experience to demonstrate automated controls with connected infrastructure inputs. A top-down view of the GM test track layout can be seen in Figure 50.

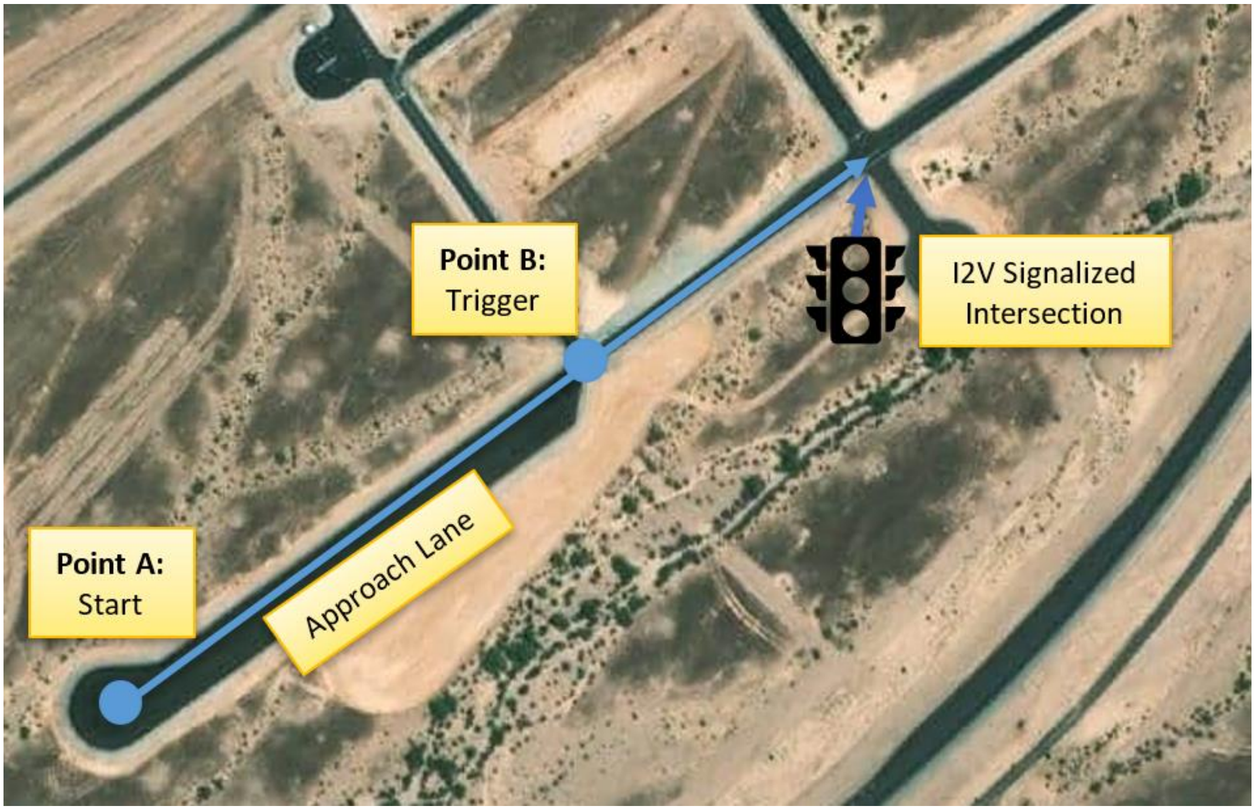


Figure 50. Mobility Challenge Connected Intersection GM Test Track Layout

Prior to each test, the university vehicles were required to complete a series of static evaluations and a dynamic On-road Safety Evaluation to ensure that they could be safely operated in the test. Organizers also verified that the vehicle's DSRC OBUs could successfully transmit BSMs and receive I2V information correctly.

Once a university's vehicle successfully completed this process, it was driven to the test track location. The following procedure was used to test each university vehicle:

1. Pull vehicle to Start position at Point A and wait for test to begin.
2. Once the test begins, accelerate to 30 mph and engage longitudinal control before reaching Trigger Point B.
3. On reaching Point B, the vehicle shall receive SPaT and MAP messages from the intersection.

4. The vehicle then performs the required actions, depending on the current light timing:
    a. If the expected phase on arrival at the stop line was red, the vehicle should stop safely before the stop line. The vehicle must wait till the phase turns green before accelerating through the intersection.
    b. If the expected phase on arrival at stop line is green, the vehicle must drive through the intersection without stopping. The vehicle may never exceed the speed limit during the drive though a green light.
5. Once the vehicle crosses the intersection, the test run was considered complete and the driver shall apply manual brakes.
6. The operator shall then drive back to the starting point.
7. This overall process was then repeated for all five scenarios.

Test vehicles were given freedom to choose an optimal approach and departure trajectory for energy optimization, though they were only assessed on the ability to navigate the intersection safely. The SPaT for this event followed a conventional Red->Green->Yellow->Red cycle. After passing the trigger point, any of the three phases could have been transmitted as the initial phase. After that point, the next phase in the cycle would use the conventional cycle as mentioned earlier.

The distance between Start and Trigger points was approximately 250 m, enough to reach the required speed and engage longitudinal control. The distance between Trigger point B and the intersection stop line was approximately 160 m. While this 160 m distance at which vehicles initially received SPaT and MAP messages was likely shorter than a real-world RSU would be capable of transmitting, for simplicity and track geometry constraints these distances were deemed adequate for initial testing.

Overall, each university vehicle was able to participate in the single intersection evaluation. This activity served to introduce students to connected intersection Eco-approach and departure concepts while also creating a key foundation for future test systems. The next section describes how assets covered previously in this work will be combined to create a method for controlled connected corridor testing of multiple traffic lights and target vehicles.

9.3. FlexCorridor: Combining Test Assets to Create Connected Corridors

The next generation of CAVs testing will require more advanced capabilities to adequately measure energy consumption impacts of CAVs features. The previously described test methods included only a single intersection or a car following maneuver without physical traffic lights. Organizations including Argonne and EcoCAR universities in the new EV Challenge are now developing vehicles with the ability to use sensor systems to follow vehicles, longitudinally control themselves through a series of intersections, and, in some cases, perform cooperative driving maneuvers with intersections and other test vehicles.

This next generation of research vehicles will need to be tested alongside production vehicles as an additional baseline beyond the typical human-driven comparison case, which necessitates the development of a new test system capable of overcoming limitations at existing testing facilities and supporting a broad array of upcoming CAVs research. This chapter presents a new test system in development that combines several portable connected intersections with a synchronized connected lead vehicle to create a broad array of traffic scenarios and CAVs testing maneuvers specifically designed for evaluating energy consumption.

9.3.a. Connected Corridor Energy Consumption Track Testing Requirements

While a number of track testing facilities have advanced connected infrastructure capabilities including physical or virtual connected intersections, many of these permanent infrastructure elements have been designed for safety and functionality testing of CAVs and are less applicable for energy consumption. Ideally, a CAVs energy consumption test facility with connected infrastructure would be capable of the following:

- Multiple miles of continuous driving at speeds above 65 mph.
- Multiple sequential intersections.
- Reconfigurable intersection locations and spacing between traffic lights.
- Synchronized and customizable light sequencing triggerable at start of test.
- C-V2X roadside units rather than DSRC to comply with new federal requirements.
- Physical traffic lights and target vehicle(s) capable of being detected by sensor systems.

These features are specifically beneficial for energy testing for a variety of reasons. With multiple miles of continuous driving at sustained higher speeds, energy tests can be conducted which are more comparable to traditional drive cycles used in energy consumption research and federal test procedures. For example, even the lower speed urban UDDS cycle has top speeds of 56.7 mph and a total distance of 7.5 miles [77]. HWFET and US06 cycles have maximum speeds of 60 mph and 80 mph and would be conducted over a track distance of 10.26 and 8.01 miles [77]. It is not a critical requirement that all track tests be conducted at these distances or speed ranges, but energy testing results obtained from lower speed tests across very short distances may overinflate differences between various control implementations or test vehicles and lack test-to-test repeatability.

Conducting energy tests over multiple test miles has several benefits from a testing perspective. The additional test miles equate to more fuel and electricity usage in the case of hybrid/electric vehicles, which can dampen the impact of error introduced by transient effects in powertrain and vehicle operation characteristics. For example, the energy results from a vehicle driving through only one connected intersection may show a significant energy savings between two different control implementations. However, such testing does not include sustained driving at steady state speeds, which would significantly reduce the overall effects of energy saved from a single Eco-approach and departure event. In addition, a control algorithm tuned for a specific intersection may not exhibit a similar level of robustness or energy savings when tested across multiple intersection layouts and geometries. A system with reconfigurable spacing could therefore better evaluate the robustness and energy impacts of test vehicles across multiple urban corridor implementations.

Synchronized and reconfigurable intersection light timing would also be beneficial for energy testing, as any test conducted through multiple signalized intersections should ideally exhibit a similar behavior across all test vehicles and repetitions. The one caveat to this statement would be tests featuring intersections and vehicles with bidirectional communication, where approaching connected vehicles may be able to trigger different light sequences for maximum energy savings. However, such capabilities may see a reduced impact when implemented in more realistic traffic contexts. Traffic flows approaching intersections from multiple directions and corridors of synchronized intersections may often make it infeasible for a single vehicle to dramatically impact SPaT sequencing without detrimental impacts on the surrounding traffic. More research must be done to understand the limitations of control based on bidirectional communication between vehicles and intersections.

Finally, connected intersections and participating test vehicles must be equipped with C-V2X technology, updated from the legacy DSRC systems that are being phased out in compliance with new federal rules [47]. C-V2X technology promises both benefits and drawbacks from the previous DSRC approach, though in the context of energy testing rather than safety there are a number of potential benefits that C-V2X technology may provide. Provided a test track has the proper cellular data coverage, experiments could utilize cell tower information or data transmission to synchronize test start between all connected intersections and test vehicles. Time-stamped test data can also be collected at each intersection and onboard each test vehicle and saved with synchronized data streams using cloud-based logging systems.

The use of physical intersections, traffic lights, and target vehicles is not a necessity for all CAV testing activities, as many prototype systems can be set up with interfaces and override functionalities to respond to I2V signals without visual confirmation from sensors. While highly beneficial for CAV controls testing and development, track tests that only use virtual traffic lights and test vehicles such as those described in Jeong et al. 2023 [74] limit the experiments to vehicles that feature experimental control and the ability to ignore onboard perception in favor of the wireless messages.

With a test system of physical target vehicles and traffic lights, a stock vehicle using production ACC could be used as a baseline for comparison to other prototype control implementations in the same study. In addition, for research vehicles such as those developed by EcoCAR universities in the mobility challenge it is necessary to characterize the vehicle in a way that includes the sensing, sensor fusion, powertrain controls, and longitudinal controls. Without physical targets to accompany the X2V signals, the testing would not characterize the performance of sensor fusion systems and would also not assess the energy impacts of time delays and relative position/velocity/acceleration measurements induced by these systems. Such delays and inaccuracies could have a significant impact on overall energy consumption, as they could result in more oscillatory behavior, overshooting the target gap on approach to lead vehicles, and later braking initiation which could increase engine runtime for conventional vehicles and friction brake usage for electrified powertrains.

Most existing test facilities are not equipped to meet these ideal capabilities, as a primary focus for CAVs test track areas has historically been functionality and safety evaluations such as those defined in the NHTSA or European New Car Assessment Program (NCAP) [78]. Many of these research facilities equipped for CAV testing such as those at the Transportation Research Center [34] or the American Center for Mobility [36] have 1-2 connected intersections equipped with traffic signals capable of I2V transmission of SPaT and map information. While these locations feature a high degree of customizability and are beneficial for single intersection safety testing, there is no permanent infrastructure or track areas for the intended multi-mile corridor testing necessary for EcoCAR.

9.3.b. Proposed Design of Flexible Connected Corridor System

The aforementioned limitations of existing test facilities require the development of a new test system that can support track-based evaluations of CAVs using a flexible system deployable at any proving ground or test track. This section details a proposed design for a combined system of both automated target vehicles and multiple connected traffic lights capable of enacting a simulated traffic scenario with vehicles under test ranging from production ACC systems to prototype experimental vehicles with connectivity-optimized longitudinal control. The system was designed with several considerations in mind:

- Enable deployment at any test facility with an extended straightaway or circle track.
- Make traffic light systems portable, customizable, and synchronizable.
- Enable a combined test with synchronized physical target vehicle and corridor of multiple physical connected traffic lights.
- Minimize system costs to enable a greater number of sequential traffic lights.
- Enable connected corridor testing with a large number of sequential traffic lights and test miles.

- Enable both high-speed highway testing and urban corridor testing using the same test system.

With those considerations in mind, the test systems and capabilities described in preceding chapters were used to design the following flexible connected corridor (FlexCorridor) test system that combines an automated lead vehicle, simulated upcoming traffic with real C-V2X BSMs, and multiple connected and synchronized traffic lights. This combined system is shown in Figure 51.

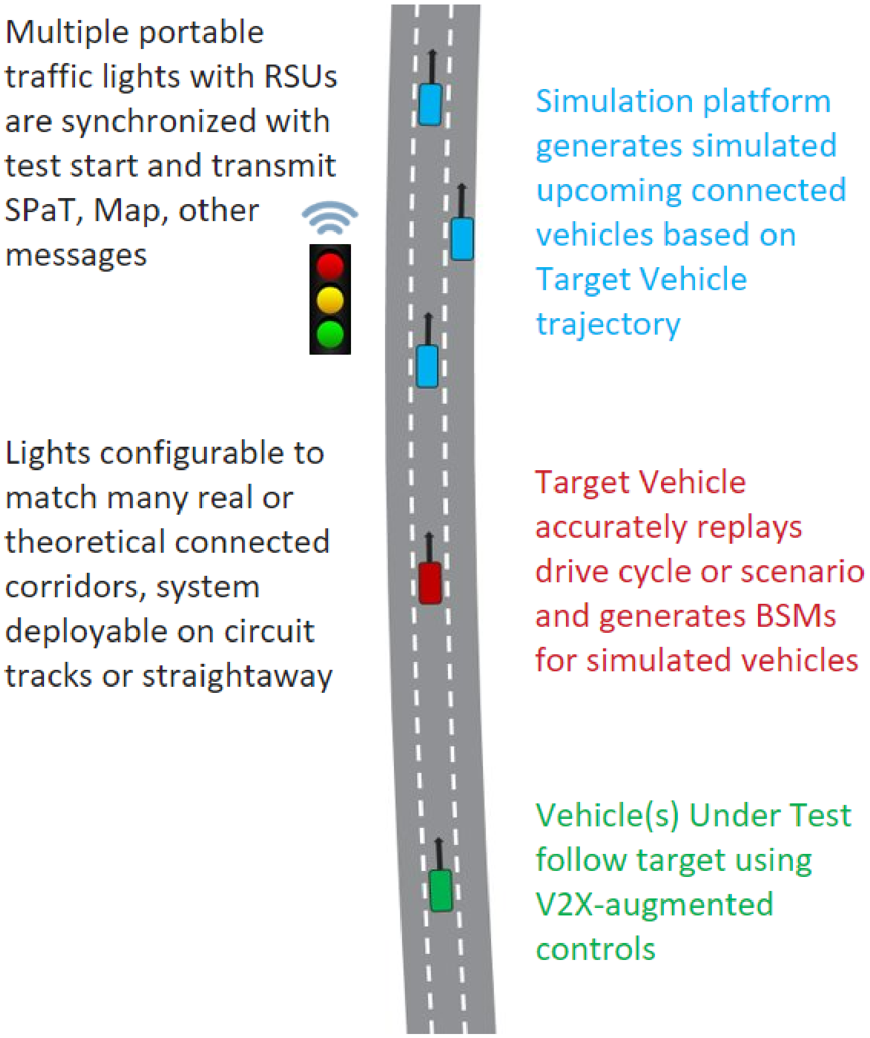


Figure 51. Flexible Connected Corridor (FlexCorridor) Test System

The intent of this system is to maximize flexibility in terms of deployment locations, types of testable vehicles, possible traffic scenarios, and traffic light geometries and behavior. The system will be designed for deployment at a wide variety of test tracks (including both circle tracks and straightaways), utilize portable battery-powered traffic lights with highly customizable RSUs, and will be able to support both EcoCAR testing and future CAVs research at a variety of test facilities. The following sections define the target vehicle and traffic signal hardware and software that will be utilized in the FlexCorridor system.

9.3.c. Target Vehicle and Connected Traffic Signal Development

The proposed system will utilize the same Cadillac LYRIQ model used by universities in the current EcoCAR EV challenge AVTC as a physical target vehicle. This vehicle was selected to be one of the next vehicles integrated into Argonne's xIL workflow [73] and utilizes General Motors' Ultium EV powertrain and infrastructure along with SAE Level II SuperCruise capable of hands-free operation in certain freeway environments [40]. For the purposes of the FlexCorridor system, the longitudinal controls on the LYRIQ will be overridden with new torque inputs to follow drive cycles or test scenarios (similar to the Blazer in earlier chapters). This vehicle will likely present a greater degree of controllability due to the faster response rate of the fully electric powertrain, which should enable increased cycle following accuracy and better SAE J2951 metric results.

The following instrumentation will be installed on the LYRIQ lead vehicle platform synchronization with connected traffic lights, GPS localization, and longitudinal control overrides:

- OxTS RT range RTK-enabled GPS system with 0.02 m longitudinal range accuracy, 0.02 km/h relative velocity accuracy relative to the proceeding vehicle under test, in addition to providing localization and speed real-time data to the longitudinal controller [62].
- Cohda MK6 OBU with customizable software to enable transmission of BSM for itself and simulated upcoming traffic [79].

- Speedgoat baseline M real-time controller hardware for overriding torque command messages on vehicle can networks [80].

- dSPACE Autera compute system for sensing location of follow vehicles and assessing adherence to distance and velocity constraints [81].

- Simulation PC with touchscreen interface for operator HMI and execution of DigiCAV or other simulation software to enable LYRIQ to act as either the lead vehicle in a flex corridor test or an ego vehicle for baseline evaluations.

- DataSpeed intelligent power distribution system (iPDS) for power distribution and energy monitoring of low-voltage additional components listed above [82].

These hardware systems are shown in the diagram below in the green box and will be integrated into the LYRIQ in following configuration. The vehicle and traffic signals below the green box represent elements outside the target vehicle, in this case a university CAV or other vehicle under test following behind the target and the series of connected FlexCorridor Connected Traffic Signals (FlexSignals) that we are developing:

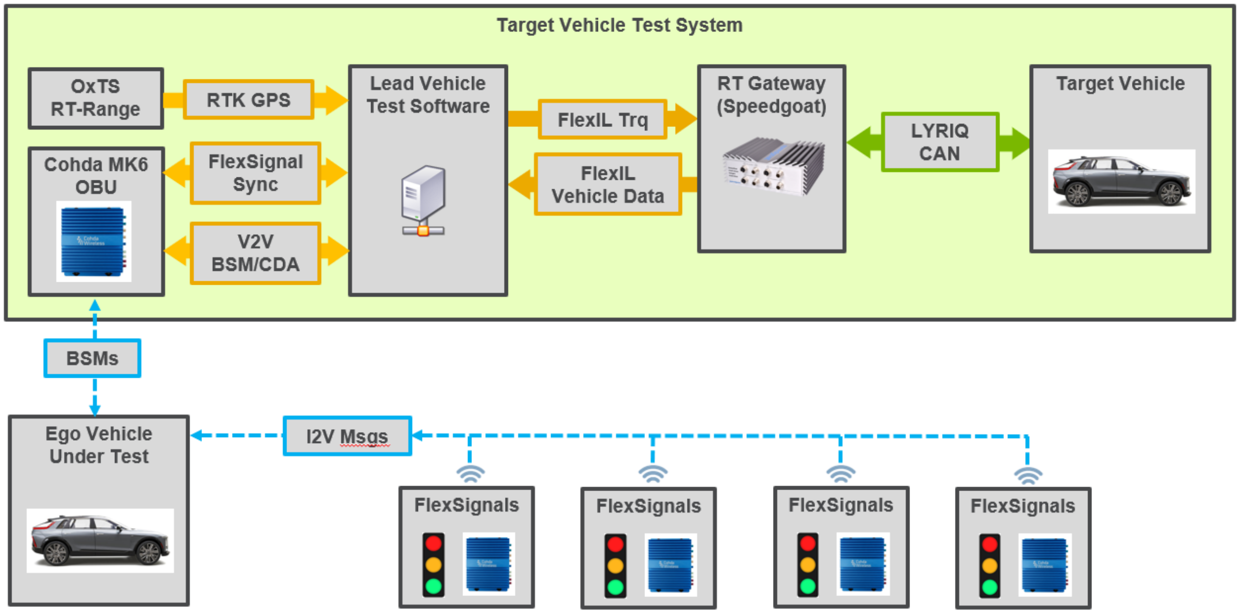
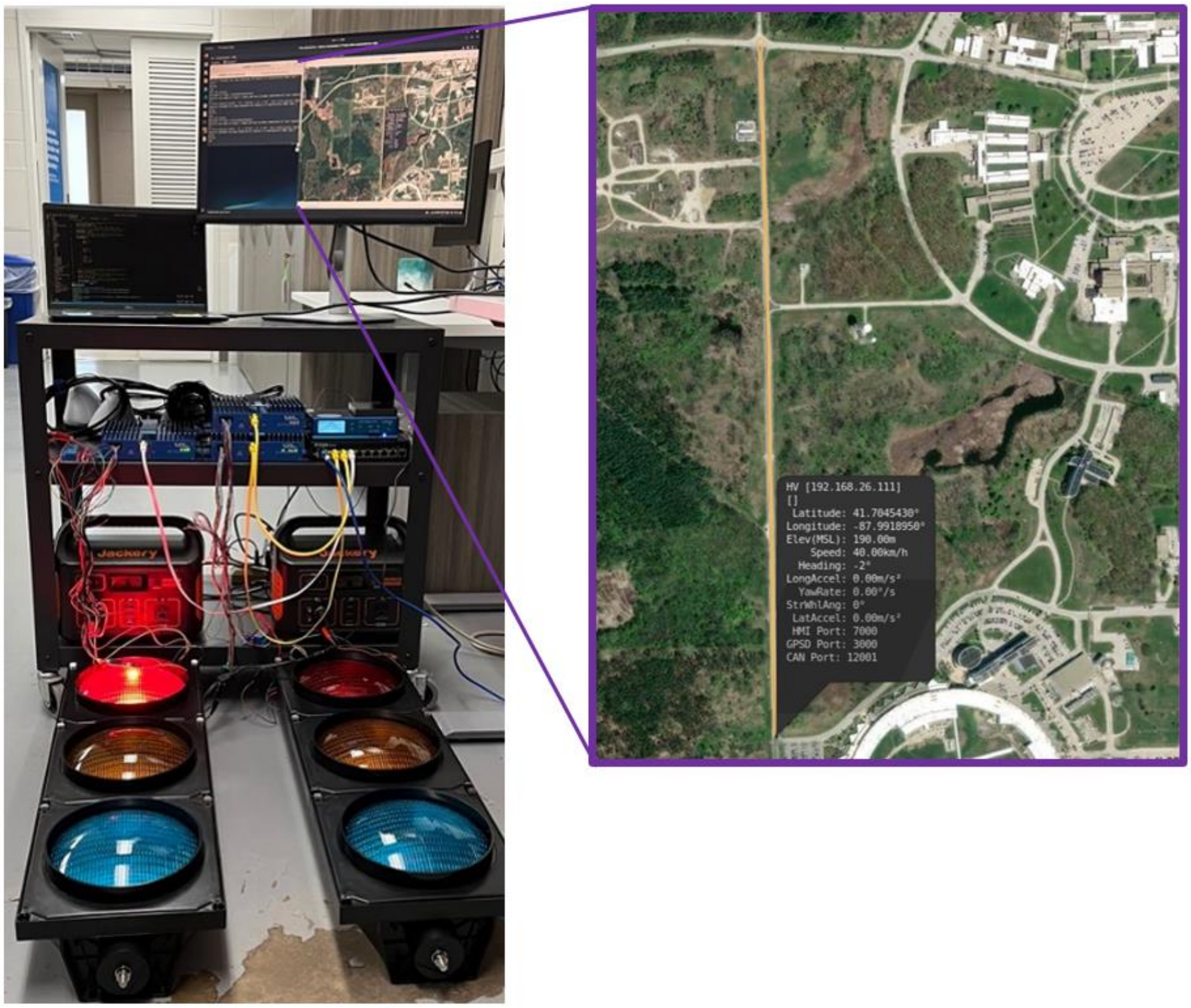


Figure 52. FlexCorridor Target Vehicle and Traffic Signal Messaging

The FlexIL CAV control interface that is used for Argonne test vehicles has been implemented for the LYRIQ platform. This interface uses a similar interface to the Blazer but instead of CAN leverages ethernet-based UDP messages for commands and vehicle response messages.

Our team's Principal CAV Research Engineer Priyash Misra is leading the development of the portable connected traffic signal system, and his team has achieved successful synchronized operation of multiple lights and target vehicles in HIL and track environments. An image of the HIL test setup can be seen in the following figure.



```
HV [192.168.26.111]
[]
 Latitude: 41.7045430°
Longitude: -87.9918950°
Elev(MSL): 190.00m
    Speed: 40.00km/h
  Heading: -2°
LongAccel: 0.00m/s²
  YawRate: 0.00°/s
StrWhlAng: 0°
 LatAccel: 0.00m/s²
 HMI Port: 7000
GPSD Port: 3000
CAN Port: 12001
```

Figure 53. HIL Testing of Connected Traffic Lights

In the next phase of development, we will implement a test central coordination system onboard the LYRIQ that will control the target vehicle, synchronize traffic lights to begin sequencing at start of test, simulate or replay upcoming traffic trajectories, and transmit BSMs for those simulated target vehicles. Figure 54 shows how this Test Central Coordinator will send torque requests to the LYRIQ Realtime Gateway module, which then uses CAN-based override requests to make the target LYRIQ recreate the desired traffic scenario ahead of vehicles under test.

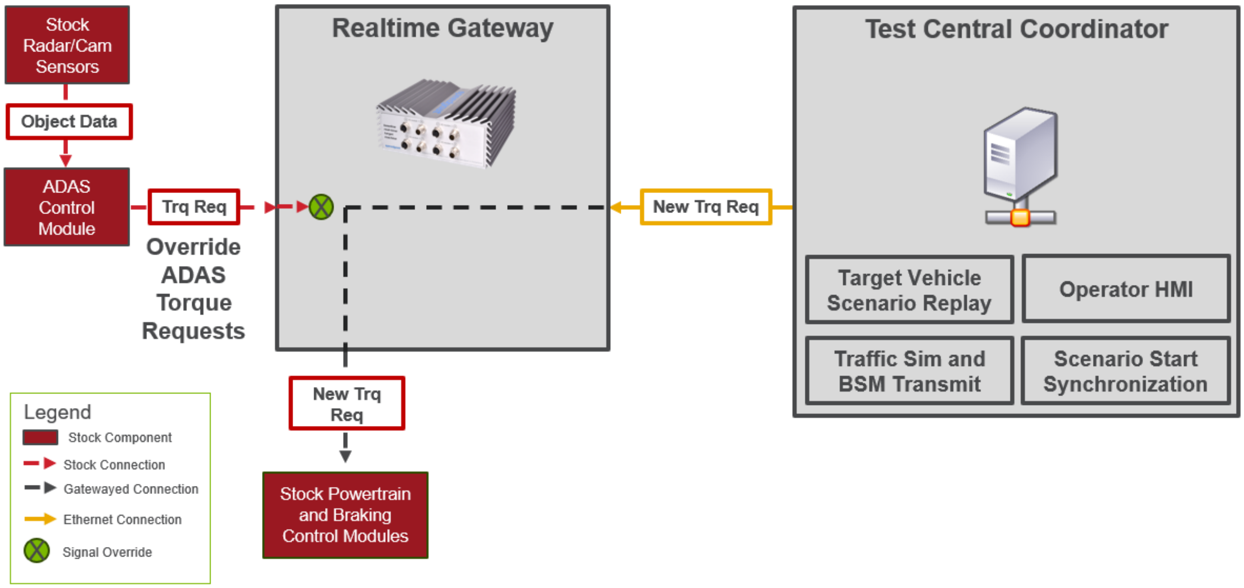


Figure 54. Target Vehicle Architecture for Torque Override

To implement this LYRIQ-based target vehicle system, our team is currently working towards implementing longitudinal override commands for the Cadillac LYRIQ in both dynamometer and test track environments. This process is initially being conducted on Argonne's four-wheel-drive dynamometer, with additional follow-up testing to be conducted on closed roads in the near future. We have successfully established longitudinal torque command authority and friction brake command overrides, and in future months will be developing the same capabilities utilized on the 2019 Chevrolet Blazer target vehicles system. An image of the LYRIQ under development is shown below.

Figure 55. Cadillac LYRIQ Installed on Argonne 4WD Chassis Dynamometer

In the next phase of piloting the system we will test the LYRIQ controls in closed roadway environments, then demonstrate a pilot scenario on Argonne closed roadways. The system will be used for Year 3 and Year 4 Competition testing events in May 2025 and 2026.

9.4. Chapter Conclusions

In this chapter, we presented an overview of the single connected intersection testing conducted in the Mobility Challenge as a precursor to connected corridor energy testing in the upcoming EV Challenge. Our research team has begun developing both the Cadillac LYRIQ target vehicle test system and a series of portable connected traffic lights deployable at any track facility. These assets will be combined to create a novel FlexCorridor test system that we have designed to enable controlled and repeatable track testing of real-world connected corridor designs. By using portable traffic lights, the system can be reconfigured for a variety of distances between intersections. Our research team has begun working towards networking these traffic lights using C-V2X technology to enable a synchronized test execution across all lights and the LYRIQ target vehicle that will drive ahead of vehicles under test.

The development of this FlexCorridor system was intended to support not only EcoCAR advanced vehicle competitions, but also future experimentation and research studies involving connected vehicle applications. The goal of this development activity is to design and implement a test system capable of flexible experimentation across a broad array of connectivity and automation feature implementation and refinement levels. The FlexCorridor system will be refined in the coming months, with pilot demonstrations scheduled for September 2024 on Argonne closed roadway areas.

Chapter 10. Future Work and Conclusions

This dissertation has detailed our development and execution of an array of test methodologies, systems and pilot implementations for evaluating the energy consumption of CAV and ADAS features. The following chapter describes a summary of the research presented in this dissertation, outlines future work we will conduct in support of energy testing for CAV technologies, and presents our overall conclusions.

10.1. Summary of Goals, Outcomes, and Advancements

Our research and development work documented in this dissertation has expanded the current scope of CAVs and ADAS testing across track and dynamometer environments, while also enabling testing of current and future CAV platforms in AVTCs and beyond. These research activities were targeted towards four primary goals: developing CAV testing pathways, implementing CAV Test Systems, conducting university CAV testing, and extending these systems to broader ADAS and CAV energy research.

For the first research goal, developing CAV testing pathways, we set out to design and refine new test methodologies for energy evaluations of ACC/CAV features in both dynamometer and test track environments. These CAV and ADAS energy testing methods were developed to meet AVTC's unique requirements while also providing maximum flexibility, from the type and volume of vehicles that can be tested to the track environments that can now be utilized. Notably, controlled and repeatable test methods for CAV feature energy consumption were developed to enable multi-mile testing with target vehicles replaying traffic scenarios. Our research team also refined portable connected intersection test methods to be triggerable on vehicle approach, improving repeatability of tests. We introduced a new multi-environment approach for energy testing that uses track-gathered trajectory data to create vehicle-specific CAV and ADAS drive cycles, enabling follow-up dynamometer testing without the need for significant manufacturer-specific knowledge. Finally, we began combining many track testing assets into a novel approach to enable multi-mile repeatable connected corridor testing with target vehicles and portable intersections.

To meet the goal of implementing CAV test systems, our team developed a number of assets and test systems that enabled goal 1's track and dynamometer CAV energy testing pathways. We collaborated with HORIBA to add multi-mile energy testing capabilities to their DigiCAV software stack, piloted a multi-vehicle ACC energy test method at their test facility, then used those learnings to create a controlled and repeatable Chevrolet Blazer target vehicle system. This system was calibrated and refined through several development trips to the TRC Proving Ground before usage to test a fleet of university prototypes at the EcoCAR Mobility Challenge Year 4 Competition. To measure the system's capability to perform scenarios and drive cycles accurately on track, we extended the SAE J2951 metrics to the new application of assessing several performance indicators of the target vehicle in track environments. The Blazer target vehicle achieved SAE J2951 root mean squared speed error track results of 0.55 mph for HwFET and 0.48 for urban 505 drive cycles despite limited calibration time due to COVID-19 impact. Our team also developed DSRC and C-V2X portable connected intersection assets that could be deployed at any track facility.

These developments culminated in accomplishing goal 3, conducting university CAV testing. We implemented the aforementioned methodologies and test systems to conduct a large-scale evaluation of EcoCAR Mobility Challenge vehicles at the General Motors Desert Proving Ground, testing a fleet of 11 experimental prototype vehicles with hybrid propulsion systems and CAV features designed by universities across North America. On the ACC energy test event, Georgia Tech's vehicle achieved an energy consumption of 672 Wh/km for HwFET following and 895 Wh/km for urban 505 following maneuvers. Seven universities completed the ACC energy testing event with four valid test runs. Teams also participated in a Connected Mobility Challenge I2V intersection navigation event, where our test systems enabled an eco-approach and departure test using portable intersections.

In order to accomplish the final goal, extending these test systems to broader CAV and ADAS testing applications, we validated with production Honda Civic and Chevrolet Blazer ACC systems that the test methods could be used for energy testing production ADAS systems in the same tests as experimental CAVs. We also piloted a method to perform follow-up dynamometer testing of vehicle-specific ACC trajectories in more controlled dynamometer tests with the stock Chevrolet Blazer, replicating ACC traces collected from four universities during a multi-week testing campaign. This testing was primarily done to demonstrate that the method is usable for production vehicles, though follow-up testing is recommended to characterize several production vehicle ACC systems and test those same vehicles on dynamometer.

In Chapter 9, we combined several foundational assets and methodologies to propose a novel Flexible Connected Corridor test system (FlexCorridor), which uses physical target vehicles and multiple low-cost connected traffic lights to enable track-based testing of real-world connected corridor layouts. This system overcomes several critical limitations with existing track facilities. It enables multi-mile testing through connected corridor environments at a variety of potential track facilities that may not have permanent V2X systems in place, while also avoiding the uncontrolled and more hazardous field testing environment of public roadway connected corridors.

The following table presents a summary of these research goals, along with the key contributions our research and development efforts produced. It should be noted that the activities described in this dissertation were only possible through an immense collaboration between the University of Washington, Argonne National Laboratory researchers, AVTC sponsors, and perhaps most importantly, the tireless efforts of our EcoCAR university students and faculty to create the vehicles for our systems to test.

Table 15. Research Goals, Requirements, and Key Contributions

Goal	Requirements	Key Contributions
1. Develop CAV Testing Pathways: Design and refine test methodologies for energy evaluations of ACC/CAV features in both dynamometer and test track environments.	Methods shall be flexible enough for supporting tests of both stock and prototype ADAS and CAV features and must function at a variety of test tracks.	Developed multiple energy testing methodologies and demonstrated viability through pilot studies, including track-based ACC and Eco-approach testing and dynamometer methods compatible with production ACC vehicles.
2. Implement CAV Test Systems: Propose and deploy flexible tools and test systems to enable track-based CAV energy testing	Systems must include guided target vehicles to mimic traffic ahead of vehicles under test to enable testing of both perception systems on longitudinal control algorithms.	Designed and implemented target vehicle test system along with key performance indicators for controlled and repeatable track-based multi-mile CAV algorithm testing.
	Portable connected traffic light systems shall be developed that enable testing at a variety of test track environments without needing to use permanent intersection infrastructure.	Deployed portable connected traffic light system and designed future system enabling multi-mile testing of CAVs in reconfigurable connected corridors.
3. Conduct University CAV Testing: Utilize tools and methods to safely assess prototype CAV features developed by multiple university partners.	Enable comparable energy evaluations across vehicles using different powertrain designs, sensor implementations, and longitudinal control strategies	Tested university vehicles in track environments using test systems, used methods that enabled direct comparison of sensor performance and energy usage between diverse array of vehicles. Used cycle data to demonstrate novel method to replicate track traces on dynamometers.
	Enable testing of university-developed controls operating on Argonne test vehicles in dynamometer and track environments.	
4. **Extend Systems to Broader CAV Research:** Demonstrate possible pathways for future standardized energy tests of production CAVs	Methods and pathways shall have potential to be applicable for both current production systems and future vehicles with greater penetration of connectivity and higher levels of automation	Designed combination target vehicle and connected traffic light system (FlexCorridor) that could perform direct comparisons testing between production systems and prototype implementations. Showed method for multi-environment energy testing (track/simulation -> dynamometer) that is usable with broad array of production/prototype vehicles.
	Methods must limit level of integration and test burden for each vehicle and be capable of fair energy comparison between difference vehicle designs	

10.2. Future Work

While the vehicles tested in this dissertation were primarily prototype vehicles or production systems executing experimental controls, in future research activities the methods will be used to evaluate energy consumption of a broader selection of university and production vehicles over a comprehensive set of scenarios. To perform this research, the target vehicle and traffic light test systems will be combined to enable connected corridor evaluations consisting of multiple sequential test miles following target vehicles through physical and reconfigurable intersections. This FlexCorridor system will be developed in the coming years in order to test the more advanced capabilities of university vehicles in the EcoCAR EV challenge. Students will participate in events that test their energy consumption over these multi-mile connected corridor events in addition to their ability to perform both lateral and longitudinal maneuvers through urban grids of connected traffic lights. Finally, the dynamometer methods described in Chapter 8 will be used to obtain a more accurate assessment of each university vehicle's energy consumption in dynamometer environments.

While this testing is valuable for university research applications, the methods and test systems piloted in this dissertation could provide just as much value as a foundation towards standardized energy testing for ADAS and CAVs features using methods that enable direct comparison between different vehicles and control implementations. By using physical vehicles and traffic lights, most production ACC or higher SAE level systems could be evaluated alongside controls developed by national laboratories and universities to provide a fair comparison between different implementations of automated controls. The research team is currently planning to utilize these test systems for performing such investigations, providing a clearer picture of the degree of difference advanced connectivity-augmented features could provide in direct comparison to unconnected production features on current state-of-the-art test vehicles.

10.3. Conclusions

Overall, our research contributes significantly to the field of automotive engineering by introducing several flexible and expandable ADAS and CAV energy testing methodologies. The methods and test systems we developed and demonstrated successfully supported testing a diverse fleet of experimental university prototypes in the Mobility Challenge, while also enabling direct comparisons between production ADAS systems and advanced CAV feature implementations. 11 university vehicles and two production platforms were tested throughout the research presented in this work. New dynamometer testing pathways were developed and piloted to transform ACC trajectories gathered on track into drive cycles usable in dynamometer testing. This method will support future dyno testing of 13 different university prototypes in the EV challenge and create a pathway for testing a broader set of production ADAS.

The assets and methods developed in this work also laid a foundation for conducting controlled and repeatable multi-mile connected corridor testing in the upcoming EV Challenge vehicle tests. Our novel FlexCorridor test system will enable Argonne researchers to set up a variety of real-world connected corridor layouts and traffic scenarios. The system is designed for portability and flexibility, with portable intersections and an automated target vehicle that can operate at a variety of high-speed circuit test tracks. By using real targets rather than virtual, the system can also be used to conduct direct comparison testing between production ADAS systems operating on the same corridor to quantify the energy saving potential of connectivity over ACC and other features.

In future research activities, our team will pilot the FlexCorridor test system at a variety of proving grounds with both production ADAS and experimental CAV features developed by Argonne and universities. We will also be refining many of the interfaces and methodologies proposed in this work into standardized CAV and ADAS energy testing methods for future usage with production vehicle platforms.

Chapter 11. Bibliography

[1] "Advanced Vehicle Technology Competitions (AVTC)." Accessed: May 22, 2023. [Online]. Available: https://avtcseries.org/

[2] A. C. Mersky and C. Samaras, "Fuel economy testing of autonomous vehicles," *Transp. Res. Part C Emerg. Technol.*, vol. 65, pp. 31–48, Apr. 2016, doi: 10.1016/j.trc.2016.01.001.

[3] L. D. V. Performance and E. M. Committee, *SAE J2951 Drive Quality Evaluation for Chassis Dynamometer Testing*. 2014. doi: https://doi.org/10.4271/J2951_201401.

[4] "AVTC's History," Advanced Vehicle Technology Competitions. Accessed: Jan. 27, 2024. [Online]. Available: https://avtcseries.org/about-avtc/avtcs-history/

[5] "EcoCAR Mobility Challenge – Advanced Vehicle Technology Competitions." Accessed: May 22, 2023. [Online]. Available: https://avtcseries.org/about-avtc/past-competitions/ecocar-mobility-challenge/

[6] "Advanced Mobility Technology Laboratory | Argonne National Laboratory." Accessed: May 22, 2023. [Online]. Available: https://www.anl.gov/taps/reference/advanced-mobility-technology-laboratory

[7] J. Jeong *et al.*, "Vehicle-In-The-Loop Workflow for the Evaluation of Energy-Efficient Automated Driving Controls in Real Vehicles," presented at the WCX SAE World Congress Experience, Mar. 2022, pp. 2022-01–0420. doi: 10.4271/2022-01-0420.

[8] M. Di Russo, S. Iliev, K. M. Stutenberg, J. Ku, and E. Rask, "Experimental Evaluation of Longitudinal Control for Automated Vehicles through Vehicle-in-the-Loop Testing," presented at the WCX SAE World Congress Experience, Apr. 2020, pp. 2020-01–0714. doi: 10.4271/2020-01-0714.

[9] N. Kim, D. Karbowski, and A. Rousseau, "Validating Heavy-Duty Vehicle Models Using a Platooning Scenario," in *SAE Technical Paper 2019-01-1248*, SAE International, Apr. 2019. doi: 10.4271/2019-01-1248.

[10] N. Kim, D. Karbowski, J. Jeong, and A. Rousseau, "Simulation of Heavy-Duty Vehicles in Platooning Scenarios," in *21st International Conference on Intelligent Transportation Systems (ITSC)*, Maui, Hawaii, Nov. 2018, pp. 1604–1610. doi: 10.1109/ITSC.2018.8569275.

[11] J. Jeong, N. Kim, D. Karbowski, and A. Rousseau, "Implementation of Model Predictive Control into Closed-Loop Micro-Traffic Simulation for Connected Automated Vehicle," in *9th IFAC International Symposium on Advances in Automotive Control*, Orleans, France, Jun. 2019, pp. 224–230. doi: https://doi.org/10.1016/j.ifacol.2019.09.036.

[12] J. Auld, M. Hope, H. Ley, V. Sokolov, B. Xu, and K. Zhang, "POLARIS: Agent-based modeling framework development and implementation for integrated travel demand and network and operations simulations," *Transp. Res. Part C Emerg. Technol.*, vol. 64, pp. 101–116, Mar. 2016, doi: 10.1016/j.trc.2015.07.017.

[13] A. Moawad *et al.*, "A Deep Learning Approach for Macroscopic Energy Consumption Prediction with Microscopic Quality for Electric Vehicles," *ArXiv211112861 Cs*, Nov. 2021, Accessed: Dec. 10, 2021. [Online]. Available: https://anl.box.com/s/fsexy08ee86c5r5l4pv9fglxt0dignjc

[14] T. Crain, P. Jaworski, I. Kyriakopoulos, R. Blachford, and B. C. Fabien, "Prototyping EcoCAR Connected Vehicle Testing System Using DigiCAV Development Platform," in *2020 IEEE 3rd Connected and Automated Vehicles Symposium (CAVS)*, Victoria, BC, Canada: IEEE, Nov. 2020, pp. 1–5. doi: 10.1109/CAVS51000.2020.9334669.

[15] "HORIBA MIRA Technology Park." Accessed: Jan. 27, 2024. [Online]. Available: https://www.miratechnologypark.com/r-d-facilities

[16] T. Crain, P. Jaworski, K. Stutenberg, M. Di Russo, and B. C. Fabien, "Modifying Network Guided Vehicle for Repeatable EcoCAR ACC Energy Testing," in *2020 IEEE 92nd Vehicular Technology Conference (VTC2020-Fall)*, Victoria, BC, Canada: IEEE, Nov. 2020, pp. 1–5. doi: 10.1109/VTC2020-Fall49728.2020.9348807.

[17] E. Rask *et al.*, "SMART Mobility. Connected and Automated Vehicles Capstone Report," DOE/EE--2064, 1656706, 8261, Jul. 2020. doi: 10.2172/1656706.

[18] "Final Rule for Revisions and Additions to Motor Vehicle Fuel Economy Label | US EPA." Accessed: May 23, 2023. [Online]. Available: https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-revisions-and-additions-motor-vehicle-fuel

[19] "Corporate Average Fuel Economy (CAFE) Standards | US Department of Transportation." Accessed: May 23, 2023. [Online]. Available: https://www.transportation.gov/mission/sustainability/corporate-average-fuel-economy-cafe-standards

[20] M. Treiber, A. Hennecke, and D. Helbing, "Congested Traffic States in Empirical Observations and Microscopic Simulations," arXiv.org. Accessed: Jan. 01, 2024. [Online]. Available: https://arxiv.org/abs/cond-mat/0002177v2

[21] "Improving Ride Comfort and Fuel Economy of Connected Hybrid Electric Vehicles Based on Traffic Signals and Real Road Information | IEEE Journals & Magazine | IEEE Xplore." Accessed: Apr. 27, 2024. [Online]. Available: https://ieeexplore.ieee.org/document/9367002

[22] K. D. Kusano, J. M. Scanlon, and Y.-H. Chen, "Comparison of Waymo Rider-Only Crash Data to Human Benchmarks at 7.1 Million Miles".

[23] W. Dvorkin, J. King, M. Gray, and S. Jao, "Determining the Greenhouse Gas Emissions Benefit of an Adaptive Cruise Control System Using Real-World Driving Data," presented at the WCX SAE World Congress Experience, Apr. 2019, pp. 2019-01–0310. doi: 10.4271/2019-01-0310.

[24] N. Prakash, A. G. Stefanopoulou, A. J. Moskalik, and M. J. Brusstar, "Use of the hypothetical lead (HL) vehicle trace: A new method for evaluating fuel consumption in automated driving," in *2016 American Control Conference (ACC)*, Jul. 2016, pp. 3486–3491. doi: 10.1109/ACC.2016.7525453.

[25] Y. He *et al.*, "Adaptive Cruise Control Strategies Implemented on Experimental Vehicles: A Review," *IFAC-Pap.*, vol. 52, no. 5, pp. 21–27, Jan. 2019, doi: 10.1016/j.ifacol.2019.09.004.

[26] Y. Feng, C. Yu, S. Xu, H. X. Liu, and H. Peng, "An Augmented Reality Environment for Connected and Automated Vehicle Testing and Evaluation," in *2018 IEEE Intelligent Vehicles Symposium (IV)*, Jun. 2018, pp. 1549–1554. doi: 10.1109/IVS.2018.8500545.

[27] S. A. Fayazi, A. Vahidi, and A. Luckow, "A Vehicle-in-the-Loop (VIL) verification of an all-autonomous intersection control scheme," *Transp. Res. Part C Emerg. Technol.*, vol. 107, pp. 193–210, Oct. 2019, doi: 10.1016/j.trc.2019.07.027.

[28] M. Pourabdollah, E. Bjärkvik, F. Fürer, B. Lindenberg, and K. Burgdorf, "Fuel economy assessment of semi-autonomous vehicles using measured data," in *2017 IEEE Transportation Electrification Conference and Expo (ITEC)*, Jun. 2017, pp. 761–766. doi: 10.1109/ITEC.2017.7993365.

[29] R. Schmied, H. Waschl, and L. del Re, "Extension and experimental validation of fuel efficient predictive adaptive cruise control," in *2015 American Control Conference (ACC)*, Jul. 2015, pp. 4753–4758. doi: 10.1109/ACC.2015.7172078.

[30] M. H. Almannaa, H. Chen, H. A. Rakha, A. Loulizi, and I. El-Shawarby, "Field implementation and testing of an automated eco-cooperative adaptive cruise control system in the vicinity of signalized intersections," *Transp. Res. Part Transp. Environ.*, vol. 67, pp. 244–262, Feb. 2019, doi: 10.1016/j.trd.2018.11.019.

[31] J. Jeong, A. B. Dudekula, E. Kandaswamy, D. Karbowski, J. Han, and J. Naber, “On-Track Demonstration of Automated Eco-Driving Control for an Electric Vehicle,” presented at the WCX SAE World Congress Experience, Detroit, Michigan, United States, Apr. 2023, pp. 2023-01–0221. doi: 10.4271/2023-01-0221.

[32] M. Duoba and A. Fernandez Canosa, “On-Track Measurement of Road Load Changes in Two Close-Following Vehicles: Methods and Results,” presented at the WCX SAE World Congress Experience, Apr. 2019, pp. 2019-01–0755. doi: 10.4271/2019-01-0755.

[33] S. Ruan, Y. Ma, N. Yang, C. Xiang, and X. Li, “Real-time energy-saving control for HEVs in car-following scenario with a double explicit MPC approach,” *Energy*, vol. 247, p. 123265, May 2022, doi: 10.1016/j.energy.2022.123265.

[34] “Ohio | TRC.” Accessed: May 24, 2023. [Online]. Available: https://www.trcpg.com/tour/ohio/

[35] “Mcity 2.0 - Mcity.” Accessed: May 24, 2023. [Online]. Available: https://mcity.umich.edu/our-work/mcity-test-facility/mcity-2/

[36] “Home - American Center for Mobility.” Accessed: May 24, 2023. [Online]. Available: https://acmwillowrun.org/

[37] T. Crain *et al.*, “Track-based Energy Testing of Prototype Connected and Automated Hybrid Electric University Vehicles,” *Manuscr. Prep.*, 2024.

[38] T. Crain *et al.*, “Track-to-Dynamometer Methods for Repeatable ADAS and CAV Energy Testing,” *Manuscr. Prep.*, 2024.

[39] T. Crain, P. Misra, N. Goberville, D. Ord, and P. Reinhall, “Design of a Track-based Flexible Connected Corridor Energy Testing System,” *Manuscr. Prep.*, 2024.

[40] A. J. Leslie, R. J. Kiefer, C. A. Flannagan, B. A. Schoettle, and S. H. Owen, “Analysis of Field Effects Associated with the GM Super Cruise System”.

[41] R. Chen and H. Mao, “The Impact of Autopilot on Tesla,” *BCP Bus. Manag.*, vol. 31, pp. 89–95, Nov. 2022, doi: 10.54691/bcpbm.v31i.2540.

[42] “Clearing the Confusion: Recommended Common Naming for Advanced Driver Assistance Technologies,” CR Advocacy. Accessed: May 13, 2023. [Online]. Available: https://advocacy.consumerreports.org/research/advanced-driver-assistance-systems-standard-nomenclature/

[43] On-Road Automated Driving (ORAD) committee, “Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles,” SAE International. doi: 10.4271/J3016_202104.

[44] V2X Core Technical Committee, “V2X Communications Message Set Dictionary,” SAE International. doi: 10.4271/J2735_202007.

[45] “Guidance Document for MAP Message Preparation.” Athey Creek Consultants, LLC and Synesis Partners, LLC, Jun. 2023. Accessed: May 05, 2024. [Online]. Available: https://engineering.virginia.edu/sites/default/files/Connected-Vehicle-PFS/Resources/MAP%20Guidance%20Document%20-%20Revision%202_06232023.pdf

[46] tim@envyus.com.au, “Cohda Wireless is Proud to Supply V2X Technology for the Recently Launched Cadillac CTS,” Cohda Wireless. Accessed: Apr. 21, 2024. [Online]. Available: https://www.cohdawireless.com/cohda-wireless-is-proud-to-supply-v2x-technology-for-the-recently-launched-cadillac-cts/

[47] “Federal Communications Commission Order on Reconsideration.” Accessed: Apr. 21, 2024. [Online]. Available: https://docs.fcc.gov/public/attachments/DA-23-343A1.pdf

[48] A. Hajisami, J. Lansford, A. Dingankar, and J. Misener, “A Tutorial on the LTE-V2X Direct Communication,” *IEEE Open J. Veh. Technol.*, vol. 3, pp. 388–398, 2022, doi: 10.1109/OJVT.2022.3201432.

[49] C. D. A. Committee, “Taxonomy and Definitions for Terms Related to Cooperative Driving Automation for On-Road Motor Vehicles.” SAE International, 2021. [Online]. Available: https://doi.org/10.4271/J3216_202107

[50] B. Ciuffo *et al.*, “Requiem on the positive effects of commercial adaptive cruise control on motorway traffic and recommendations for future automated driving systems,” *Transp. Res. Part C Emerg. Technol.*, vol. 130, p. 103305, Sep. 2021, doi: 10.1016/j.trc.2021.103305.

[51] Z. Wadud, D. MacKenzie, and P. Leiby, “Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles,” *Transp. Res. Part Policy Pract.*, vol. 86, pp. 1–18, Apr. 2016, doi: 10.1016/j.tra.2015.12.001.

[52] I. Barry, “The Effects of Driving Style and Vehicle Performance on the Real-World Fuel Consumption of U.S. Light-Duty Vehicles,” 2010.

[53] E. DOE, “How Vehicles Are Tested.” Accessed: May 23, 2023. [Online]. Available: https://www.fueleconomy.gov/feg/how_tested.shtml

[54] S. C. Davis and R. G. Boundy, “Transportation Energy Data Book: Edition 40”.

[55] M. Duoba, T. V. Baby, J. P. Gonzalez, and B. HomChaudhuri, “On-road testing to characterize speed-following behavior in production automated vehicles,” SAE International, Warrendale, PA, SAE Technical Paper 2024-01–1963, Apr. 2024. Accessed: Feb. 04, 2024. [Online]. Available: https://www.sae.org/publications/technical-papers/content/2024-01-1963/

[56] T. Crain, T. Gorgia, and R. J. Alley, “Application of PHEV Fractional Utility Factor Weighting to EcoCAR On-Road Emissions and Energy Consumption Testing,” presented at the SAE 2016 World Congress and Exhibition, Apr. 2016, pp. 2016-01–1180. doi: 10.4271/2016-01-1180.

[57] A. Eilbert, I. Berg, and S. B. Smith, “Meta-Analysis of Adaptive Cruise Control Applications: Operational and Environmental Benefits,” p. 29.

[58] S. Vasebi, Y. M. Hayeri, C. Samaras, and C. Hendrickson, “Low-Level Automated Light-Duty Vehicle Technologies Provide Opportunities to Reduce Fuel Consumption,” *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2672, no. 24, pp. 60–74, Dec. 2018, doi: 10.1177/0361198118796401.

[59] “MicroAutoBox II,” dSPACE Inc. Accessed: Apr. 29, 2024. [Online]. Available: https://www.dspace.com/en/inc/home/products/hw/micautob/microautobox2.cfm

[60] “IEI TANK-870-Q170 Series Embedded System User Manual.” IEI Integration Corp., Jul. 13, 2018.

[61] “EcoCAR Mobility Challenge - Non Year Specific Rules Rev. P.” Argonne National Laboratory, Apr. 29, 2022.

[62] “RT-Range Datasheet,” OxTS.com. Accessed: Jan. 20, 2024. [Online]. Available: https://www.oxts.com/wp-content/uploads/2021/06/RT-Range_Datasheet_210630-1.pdf

[63] T. Edwards, J. Moore, M. Loukadaki, and P. Jaworski, “A network assisted vehicle for ADAS and ITS testing,” in *2011 14th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, Washington, DC, USA: IEEE, Oct. 2011, pp. 681–685. doi: 10.1109/ITSC.2011.6083085.

[64] I. Kyriakopoulos, P. Jaworski, and S. Kanarachos, “DigiCAV project: Exploring a Test-Driven Approach in the Development of Connected and Autonomous Vehicles,” in *2019 IEEE International Conference on Connected Vehicles and Expo (ICCVE)*, Graz, Austria: IEEE, Nov. 2019, pp. 1–6. doi: 10.1109/ICCVE45908.2019.8965026.

[65] “Federal Register :: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule.” Accessed: May 13, 2023. [Online]. Available: https://www.federalregister.gov/documents/2010/05/07/2010-8159/light-duty-vehicle-greenhouse-gas-emission-standards-and-corporate-average-fuel-economy-standards

[66] K. Stutenberg, H. Lohse-Busch, M. Duoba, S. Iliev, F. Jehlik, and M. Di Russo, “An Overview of Argonne’s Advanced Mobility Technology Laboratory Vehicle Systems Instrumentation and Evaluation Methodology,” ANL-21/36, 1814503, 167512, Apr. 2021. doi: 10.2172/1814503.

[67] M. Duoba, H. Lohse Busch, K. Stutenberg, and E. Rask, “HEV, PHEV, EV Test Standard Development and Validation.” DOE Hydrogen Program and Vehicle Technologies Annual Merit Review, May 13, 2013. [Online]. Available: https://www.energy.gov/eere/vehicles/articles/hev-phev-ev-test-standard-development-and-validation

[68] *Passenger Automobile Average Fuel Economy Standards - 49 CFR Part 531*. Accessed: May 23, 2023. [Online]. Available: https://www.ecfr.gov/current/title-49/subtitle-B/chapter-V/part-531?toc=1

[69] O. US EPA, “Data on Cars used for Testing Fuel Economy.” Accessed: Jan. 15, 2024. [Online]. Available: https://www.epa.gov/compliance-and-fuel-economy-data/data-cars-used-testing-fuel-economy

[70] T. Crain, “EcoCAR Mobility Challenge - Y4 Energy Consumption EOD Rev B.” Argonne National Laboratory, Apr. 29, 2022.

[71] “Exhaust Sample Analysis,” Code of Federal Regulations. Accessed: Jan. 14, 2024. [Online]. Available: https://www.govinfo.gov/content/pkg/CFR-2015-title40-vol30/xml/CFR-2015-title40-vol30-part600.xml#seqnum600.112-08

[72] J. Han, D. Karbowski, and A. Rousseau, “State-constrained optimal solutions for safe eco-approach and departure at signalized intersections,” in *ASME 2020 Dynamic Systems and Control Conference*, Pittsburgh, Pennsylvania, USA, Oct. 2020. doi: 10.1115/DSCC2020-3150.

[73] J. Jeong *et al.*, “Vehicle-in-the-loop workflow for the evaluation of energy-efficient automated driving controls in real vehicles,” in *SAE Technical Paper 2022-01-0420*, SAE International, Apr. 2022. doi: 10.4271/2022-01-0420.

[74] J. Jeong, A. B. Dudekula, E. Kandaswamy, D. Karbowski, J. Han, and J. Naber, “On-Track Demonstration of Automated Eco-Driving Control for an Electric Vehicle,” in *SAE Technical Paper*, Apr. 2023. doi: https://doi.org/10.4271/2023-01-0221.

[75] N. Hummel and B. Zhao, “EcoCAR Mobility Challenge: Georgia Tech Year 4 CAV Presentation,” May 18, 2022.

[76] P. Misra, “EcoCAR Mobility Challenge - Y4 Connected Mobility Challenge EOD.” Argonne National Laboratory, Apr. 29, 2022.

[77] “Emission Test Cycles.” Accessed: Jan. 22, 2024. [Online]. Available: https://dieselnet.com/standards/cycles/index.php

[78] “National Highway Traffic Safety Administration New Car Assessment Program,” NHTSA, Fed. Regist., Vol. 87 No. 46, Mar. 2022.

[79] “Product Brief: MK6-OBU,” Cohda Wireless. Accessed: Jan. 20, 2024. [Online]. Available: https://www.cohdawireless.com/wp-content/uploads/2022/08/CW_Product-Brief-sheet-MK6-OBU.pdf

[80] “Baseline real-time target machine | Speedgoat.” Accessed: Jan. 20, 2024. [Online]. Available: https://www.speedgoat.com/products-services/real-time-target-machines/baseline-real-time-target-machine

[81] “dSPACE AUTERA,” dSPACE Inc. Accessed: Jan. 20, 2024. [Online]. Available: https://www.dspace.com/en/inc/home/products/hw/autera.cfm

[82] “Power Integration Solutions and Services | Dataspeed.” Accessed: Jan. 20, 2024. [Online]. Available: https://www.dataspeedinc.com/vehicle-integrations/power-integration/

Chapter 12. Appendices

12.1. Appendix 1: Abbreviations and Terminology

Table 16. List of Abbreviations

Abbreviation	Terminology
4WD	Four Wheel Drive (2-roll chassis dyno)
ACC	Adaptive Cruise Control
ADA	Active Driving Assistance
ADAS	Advanced Driver Assistance System
AMTL	Advanced Mobility Technology Laboratory
Argonne	Argonne National Laboratory
ASCR	Absolute Speed Change Rating
AVTCs	Advanced Vehicle Technology Competitions
BSM	Basic Safety Message (V2X message)
CACC	Cooperative Adaptive Cruise Control
CAFE	Corporate Average Fuel Economy
CAN	Controller Area Network
CAV	Connected and Automated Vehicle
CDA	Cooperative Driving Automation
CDA	Cooperative Driving Automation
CDP	Cooperative Driving Platform
C-V2X	Cellular-V2X or LTE-V2X
DAQ	Data Acquisition
DOE	Department of Energy
DOT	Department of Transportation
DR	Distance Rating (J2951 metric)
DSRC	Dedicated Short Range Communications
dyno	dynamometer
ECM	Engine Control Module
ECUs	Electronic Control Modules
EPA	United States Environmental Protection Agency
EPAM	EPA Margins
ERAU	Embry Riddle Aeronautical University
EV	Electric Vehicle

EVSE	Electric Vehicle Supply Equipment
FlexCorridor	flexible connected corridor
FlexCorridor	flexible connected corridor
GPS	Global Positioning System
GT	Georgia Tech
HIL	Hardware-in-the-Loop (development environment)
HIL	Hardware-in-the-Loop
HwFET	Highway Fuel Economy Test (drive cycle)
ICE	Internal Combustion Engine
IEEE	Institute of Electrical and Electronics Engineers
J2951	SAE J2951 Drive Quality Evaluation for Chassis Dynamometer Testing
kW	kilowatt
L1-L5	SAE Level of Automation 1-5
LCA	Lane Centering Assistance
LHV	Lower Heating Value
LIDAR	Light Detection and Ranging (sensor type)
LKA	Lane Keeping Assistance
MAC	McMaster University
MAP	MapData (V2X message)
MIL	Model-in-the-Loop (development environment)
MIL	Model-in-the-Loop
MPC	Model Predictive Control
MSU	Mississippi State University
NA	Naturally Aspirated (engine)
NCAP	New Car Assessment Program
NDM	Normal Driving Mode (non-automated operation)
NGV	Network Guided Vehicle (HORIBA MIRA target vehicle)
NHTSA	National Highway Traffic Safety Administration
OBU	Original Equipment Manufacturers (GM, etc.)
OEM	On-board Unit (DSRC or C-V2X hardware)
OSU	The Ohio State University
OTA	Over-the-Air (vehicle software updates)
PC5	C-V2X sidelink PC5 point-to-point interface
PEMS	Portable Emissions Measurement Systems
PGM	Propulsion Gateway Module (ECU)
PHEV	Plug-in Hybrid Electric Vehicle
RADAR	Radio Detecting and Ranging (sensor type)
RMSSE	Root Mean Squared Speed Error (J2951 metric)

RSUs	Road-Side Units (DSRC or C-V2X hardware)
RTK	Real-Time Kinematic (base station corrected GPS)
SAE	Society for Automotive Engineers
SPaT	Signal Phase and Timing (V2X message)
TRC	The Transportation Research Center (proving ground)
UA	University of Alabama
UDDS	Urban Dynamometer Driving Schedule (drive cycle)
UT	University of Tennessee, Knoxville
Uu	C-V2X Uu cellular interface
UW	University of Washington
UW	University of Washington
UWAFT	University of Waterloo Alternative Fuels Team
V2V	Vehicle-to-Vehicle (development environment)
V2X	Vehicle-to-Everything (connectivity)
VIL	Vehicle-in-the-Loop (development environment)
VT	Virginia Tech
VTTI	Virginia Tech Transportation Institute
WGS	World Geodetic System
WVU	West Virginia University
XIL	Anything-in-the-Loop (development environment)

12.2. Appendix 2: Data from ACC Dyno Trace Testing

The following table provides the full set of data collected at Argonne AMTL. These data were gathered by executing ACC velocity traces gathered at the Mobility Challenge Year 4 competition using AMTL robot driver systems on a production Chevrolet Blazer. The Cycle Type column describes whether each trace was a traditional drive cycle such as the UDDS 505 or HwFET, or alternatively an ACC trace collected from a university vehicle following that drive trace. In addition to the university ACC traces, several tests were run using UDDS, UDDS 505, and HwFET drive cycles for a direct comparison between the traditional cycle and the ACC following cycle.

Table 17. Data from Argonne ACC Dynamometer Testing

Cycle Type	Test Name	DR	ER	EER	ASCR	RMS SE	Grams of Fuel	MPGe
Standard (No ACC)	UDDS 505s Standard 1	0.22	-0.68	-0.91	-0.90	0.42	379.9	26.0
Standard (No ACC)	UDDS 505s Standard 2	0.20	-0.63	-0.84	-0.92	0.41	379.5	25.9
Standard (No ACC)	UDDS 505s Standard 3	0.49	-0.65	-1.15	-0.80	0.67	381.2	25.8
Standard (No ACC)	UDDS 505s Standard 4	0.23	-0.80	-1.04	-1.04	0.42	381.3	25.8
Standard (No ACC)	HwFET Standard 1	0.21	0.14	-0.07	3.59	0.27	830.1	33.6
Standard (No ACC)	HwFET Standard 2	0.22	0.42	0.21	3.33	0.27	799.3	34.9
Standard (No ACC)	HwFET Standard 3	0.22	0.44	0.21	3.12	0.26	799.5	34.9
Standard (No ACC)	HwFET Standard 4	0.22	0.38	0.16	3.20	0.26	800.4	34.9
Standard (No ACC)	UDDS Full Standard 1	0.29	0.50	0.21	0.23	0.43	862.1	23.8
Standard (No ACC)	UDDS Full Standard 2	0.26	0.42	0.16	0.12	0.43	863.0	23.7
Track ACC Replay	HwFET MSU ACC 1	0.20	-5.74	-6.31	-7.88	0.36	875.1	32.3
Track ACC Replay	HwFET MSU ACC 2	0.21	-5.86	-6.45	-8.85	0.36	863.9	32.7
Track ACC Replay	HwFET MSU ACC 3	0.21	-5.67	-6.23	-7.94	0.37	871.3	32.4
Track ACC Replay	HwFET MSU ACC 4	0.21	-5.71	-6.28	-8.26	0.37	869.4	32.5
Track ACC Replay	UDDS 505s MSU ACC 1	0.25	-6.32	-7.01	-4.51	0.51	386.9	25.7
Track ACC Replay	UDDS 505s MSU ACC 2	0.26	-6.32	-7.02	-4.49	0.52	393.8	25.3
Track ACC Replay	UDDS 505s MSU ACC 3	0.25	-6.44	-7.15	-4.70	0.51	388.1	25.7
Track ACC Replay	UDDS 505s MSU ACC 4	0.25	-6.10	-6.77	-4.32	0.52	389.8	25.6
Track ACC Replay	HwFET VT ACC 1	0.19	-1.68	-1.90	0.13	0.35	887.4	31.9
Track ACC Replay	HwFET VT ACC 2	0.20	-1.61	-1.84	0.02	0.34	879.0	32.2
Track ACC Replay	HwFET VT ACC 3	0.20	-1.70	-1.93	-0.08	0.34	878.7	32.2
Track ACC Replay	HwFET VT ACC 4	0.20	-1.77	-2.00	-0.16	0.34	876.4	32.3
Track ACC Replay	UDDS 505s VT ACC 1	0.16	-2.57	-2.81	-2.64	0.59	456.4	22.0
Track ACC Replay	UDDS 505s VT ACC 2	0.14	-2.71	-2.93	-2.79	0.58	460.2	21.8
Track ACC Replay	UDDS 505s VT ACC 3	0.15	-2.70	-2.93	-2.65	0.59	457.8	21.9
Track ACC Replay	UDDS 505s VT ACC 4	0.14	-2.66	-2.88	-2.86	0.59	462.3	21.8
Track ACC Replay	HwFET GT ACC 1	0.20	-1.64	-1.87	-0.31	0.33	873.3	32.9
Track ACC Replay	HwFET GT ACC 2	0.20	-1.71	-1.95	-0.59	0.32	896.2	32.0
Track ACC Replay	HwFET GT ACC 3	0.20	-1.69	-1.92	-0.62	0.32	890.0	32.2
Track ACC Replay	HwFET GT ACC 4	0.20	-1.67	-1.89	-0.66	0.32	889.1	32.2
Track ACC Replay	UDDS 505s GT ACC 1	0.13	-2.13	-2.31	-2.06	0.59	452.2	22.4
Track ACC Replay	UDDS 505s GT ACC 2	0.11	-2.18	-2.34	-2.23	0.59	451.3	22.5
Track ACC Replay	UDDS 505s GT ACC 3	0.13	-2.03	-2.21	-2.08	0.60	459.5	22.1
Track ACC Replay	UDDS 505s GT ACC 4	0.14	-2.00	-2.18	-1.98	0.59	460.2	22.1
Track ACC Replay	HwFET OSU ACC 1	0.04	-21.63	-27.65	-24.28	0.56	979.5	29.0
Track ACC Replay	HwFET OSU ACC 2	0.04	-21.64	-27.67	-24.42	0.56	968.9	29.3
Track ACC Replay	HwFET OSU ACC 3	0.05	-21.68	-27.75	-24.39	0.55	966.6	29.3
Track ACC Replay	HwFET OSU ACC 4	0.04	-21.71	-27.79	-24.46	0.55	966.7	29.3

Track ACC Replay	UDDS 505s OSU ACC 1	0.12	-10.83	-12.28	-6.83	0.50	445.8	22.5
Track ACC Replay	UDDS 505s OSU ACC 2	0.09	-10.48	-11.81	-6.74	0.50	443.6	22.6
Track ACC Replay	UDDS 505s OSU ACC 3	0.11	-10.39	-11.72	-6.63	0.50	452.4	22.1
Track ACC Replay	UDDS 505s OSU ACC 4	0.12	-10.52	-11.89	-6.73	0.50	446.2	22.4