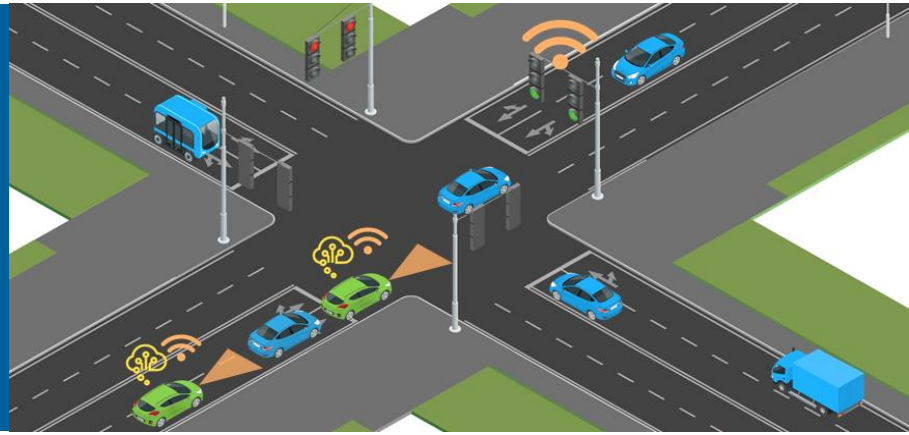
WWW.ANL.GOV/D3

ANL CORE TOOLS - HARDWARE

PROJECT ID# EEMS041



KEVIN STUTENBERG
Principal Investigator- VIL

MIKE DUOBA
Principal Investigator- Aero

2021 Vehicle Technology Office Annual Merit Review
June 22, 2021

Miriam Di Russo, Simeon Iliev, Trevor Crain, Priyash Misra
Center for Transportation Research

"This presentation does not contain any proprietary, confidential, or otherwise restricted information"

OVERVIEW

Timeline:

- Project Start Date – 10/1/2018
  - Task 1- Vehicle in the Loop (VIL)
  - Task 2- Aero
- Project End Date- 9/30/2021
- Percent Complete- 80%

EEMS Barriers Addressed:

1) Rapid evolution of vehicle technologies and services enabled by connectivity and automation
2) Accurately measuring the transportation system-wide energy impacts of connected and automated vehicles
3) Difficulty in sourcing empirical real-world data applicable to new mobility technologies such as connectivity and automation

Budget:

- FY21 Project Funding:
  - $750k: Vehicle-in-the-Loop (VIL)
  - $220k: Aero
- FY22 Project Funding: N/A

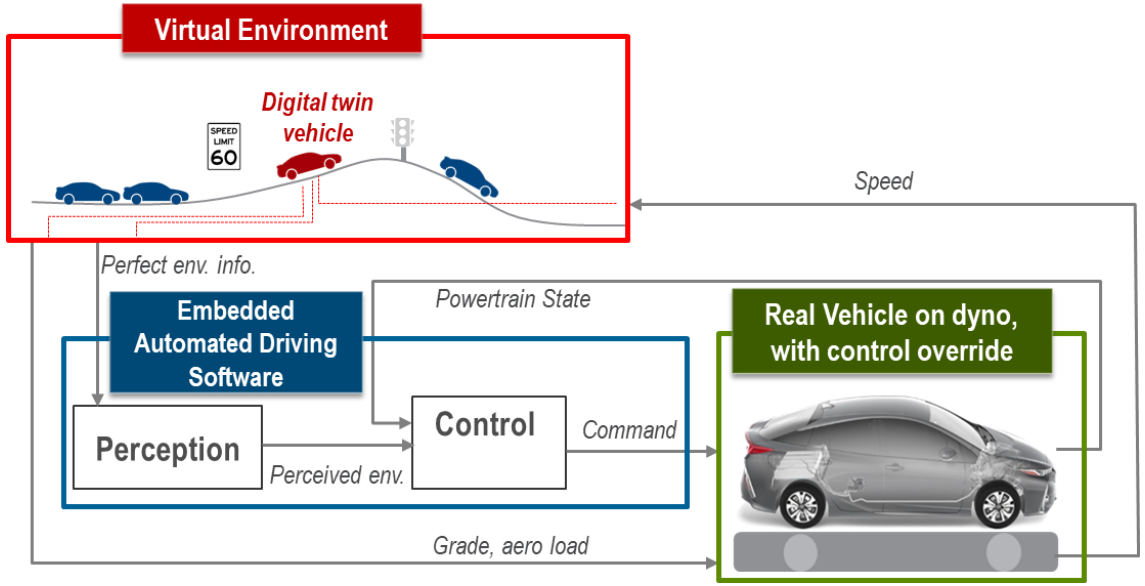
Collaborations / Partners:

- Ecocar Mobility Challenge
- ANL / DOE Vehicle Modeling & Control PI's
  - EEMS 094: ANL SMART 2.0- Controls
  - EEMS 089: ANL SMART 2.0- XIL workflows
- DOT NHTSA

OBJECTIVE/ RELEVANCE

Relevance:

Current methods of vehicle energy consumption measurement do not apply to connected and/or automated vehicle technologies-***advanced methods for experimentation are required*** to directly evaluate emerging mobility technologies and enable validation of DOE simulation efforts.



Objective:

Develop an experimental platform which can ***quantify vehicle-level energy use impacts of Connected and Automated Vehicles (CAVs)*** for use in model validation, data collection and direct analysis of future mobility technologies.

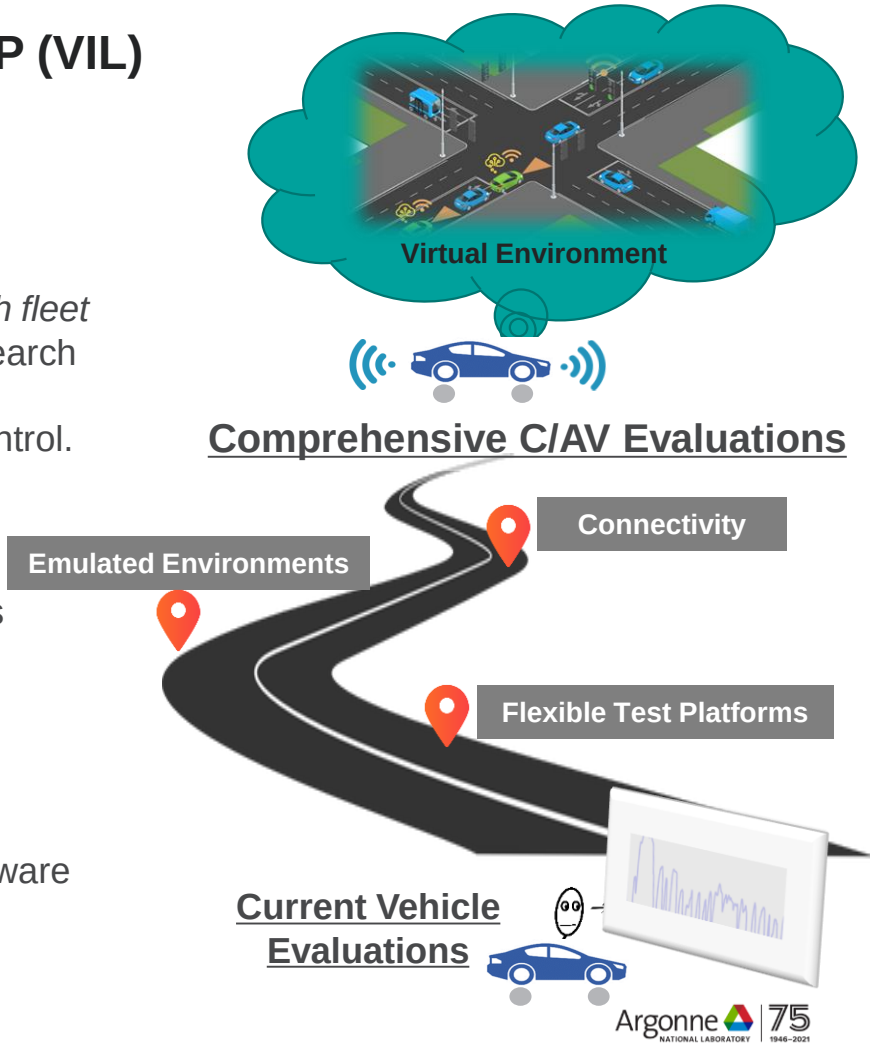
APPROACH: AMTL VEHICLE IN THE LOOP (VIL)

Accomplishing this goal requires development in three key areas:

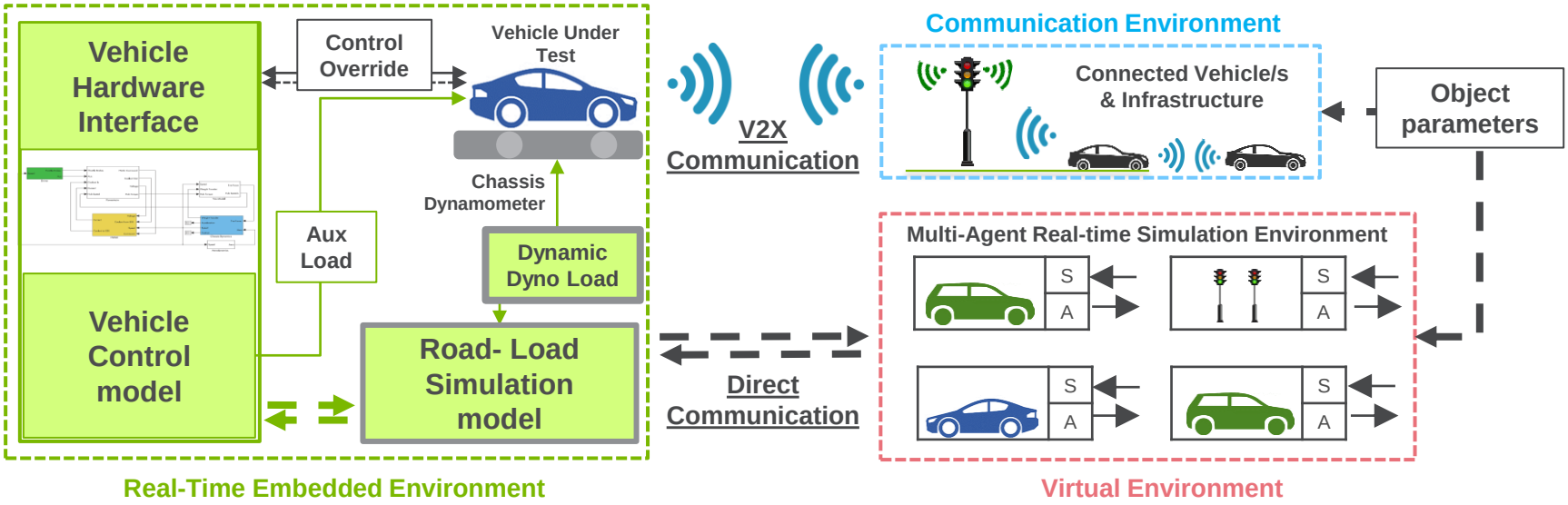
Flexible Test Platforms- *Develop a broad, flexible, research fleet*
- Enabling representative powertrain combinations for research of interest
- Enabling research-specific 'hooks' for vehicle-specific control.
- Integrate advanced instrumentation

Emulated Environment- *Enabling flexible test scenarios*
- Integration of common, highly leveraged, simulation tools easing collaboration with modeling and simulation efforts
- Flexible environment allowing 'swappable' mixture of simulation and hardware components

Connectivity- *Enabling wireless communication*
- Test platform and environment connectivity through hardware selected as desired by experimental objective



APPROACH: ADVANCED MOBILITY TECHNOLOGY LABORATORY (AMTL) VEHICLE IN THE LOOP (VIL)

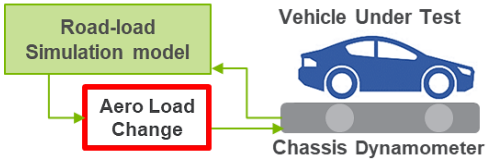


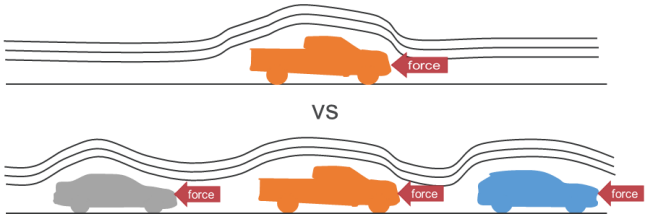
VIL is an intelligent/connected vehicle test platform that offers the following benefits:

- Flexibility- Variable powertrain (EV, Conv, …) / development - safe testing environment
- Precision and Repeatability- Controlled variation of specific test parameters
- Safety- Vehicle testing is in a stationary, controlled environment
- Portability- Following validation, hardware and control may travel with vehicle (e.g., track testing)

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APPROACH: CREATE A LOW-FIDELITY MODEL OF AV AERODYNAMIC LOAD CHANGES BASED ON EMPIRICAL DATA





Road load force from axle torque



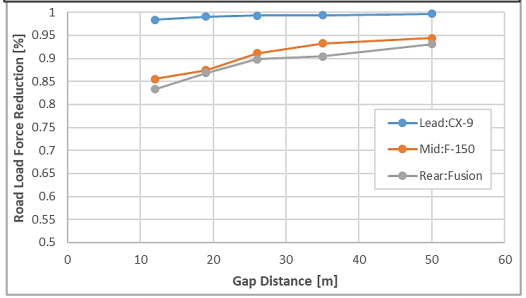
Autonomous Vehicle Driving Choices:

- Stay close: **lower drag**, higher traffic density
- Keep distance: smoother driving controls, efficiency

Limited Actual Data in Current Literature:

- CFD simulations
- Wind tunnels
- Out-of-date and sparse road data

Year 1&2: Method Produces Road Load Changes



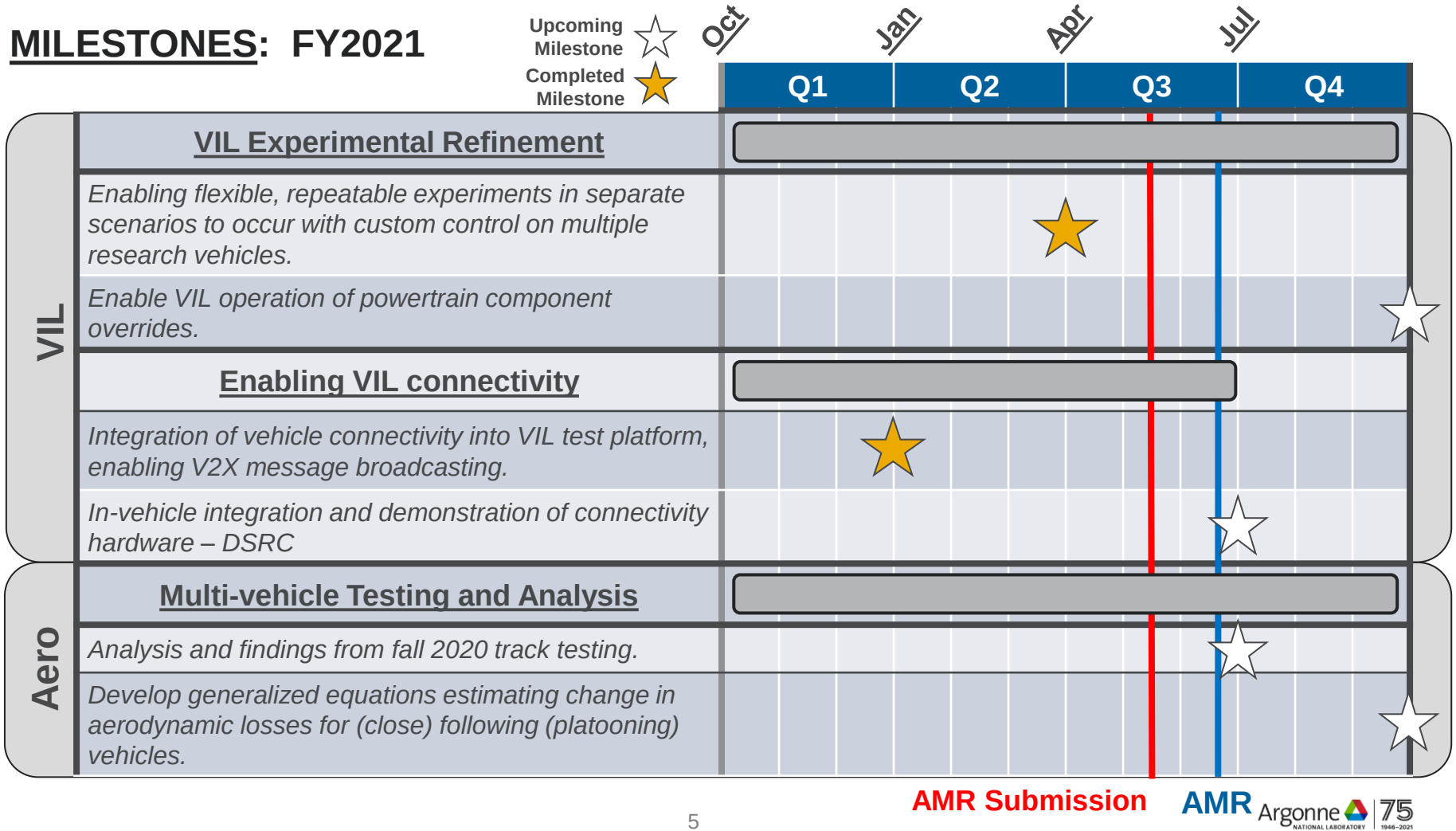
Project Vision:

- **Provide modelers empirical aerodynamic load changes with a set of equations:**
  - **Inputs: Speed, Gaps, Vehicle profiles**
  - **Output: Change in aerodynamic road load for each vehicle**



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MILESTONES: FY2021



ACCOMPLISHMENTS: ENABLING A COMPREHENSIVE RESEARCH FLEET

Goal: ***Expand research fleet by developing new methods for integrating instrumented research vehicle platforms.***

Two methods for controlling longitudinal dynamics:

Direct Override Method

- Controller overrides control command to ECU, object position, acceleration / torque, or powertrain command

Direct Actuator Method

- Controller generates pedal commands with the use of actuators (robot driver), simplifying vehicle integration
- Direct Actuator method **enables VIL testing of virtually any research vehicle**- following 'mapping' of pedal operation and integration of feedback signals

Methods complement each other to expand the fleet of vehicles, and enable varying levels of integrated control and vehicle portability

15 vehicles integrated (mapped or enabled) with either Direct Override or Direct Actuator method

Direct Override

Commands are issued at Middle-level controller layers

- ✓ Original sensors retained: no RT generation of physical stimuli
- ✓ Directly transferable to on-track/on-road testing (compact)
- ✓ Can be extended to include powertrain control
- ✗ Requires CAN override (time consuming)
- ✗ Varying applicability to all vehicles

Direct Actuator

Commands are issued at Low-level controller layer

- ✓ Does not require CAN override (time efficient)
- ✓ Calibration can avoid dyno specific issues (wheel slip)
- ✓ Leverages standard dyno testing data (accel/decel maps)
- ✗ Not portable for on-track/on-road testing
- ✗ Results accuracy depends on pedal maps and availability of vehicle communication signals

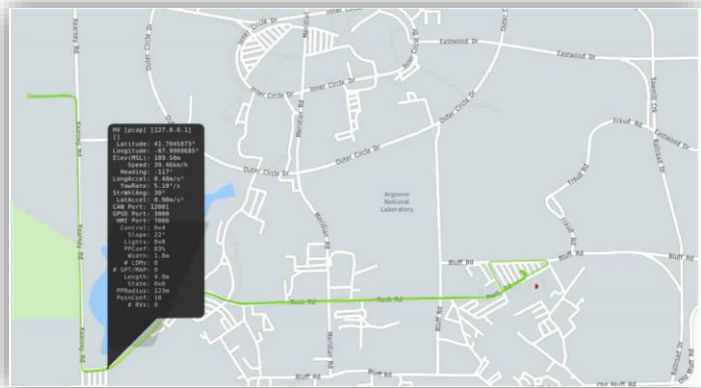
ACCOMPLISHMENTS: ECOCAR-VIL CAV TEST SYSTEMS DEVELOPMENT

Goal: ***Collaborate and align efforts between EcoCAR and AMTL to advance Vehicle-in-the-Loop experimental capabilities***



Objectives

- Capitalize on sponsor interest to collaboratively develop software and hardware solutions for novel CAVs testing
- Deploy flexible solutions to Argonne Chevrolet Blazer platform for use across EcoCAR and experimental efforts
- Enable future testing of OEM and prototype CAV control features in both track and dynamometer environments



Accomplishments

- Enabling Research Vehicles
  - Integrated Chevrolet Blazer as VIL platform with both direct actuator and direct override through ACC system
  - Performed energy use testing for model development and vehicle integration in SMART 2.0 ANL XIL workflow
- Connectivity
  - Integrated connectivity hardware from COHDA into experimental vehicles and testing platforms for use in lab and on-road.

ACCOMPLISHMENTS: ANL 'ANYTHING IN THE LOOP' XIL WORKFLOW

Goal: ***Enable experimental methods to develop and validate advanced vehicle controls within the SMART 2.0 workflow – enabling a smooth process for controls development and model validation.***

EEMS089

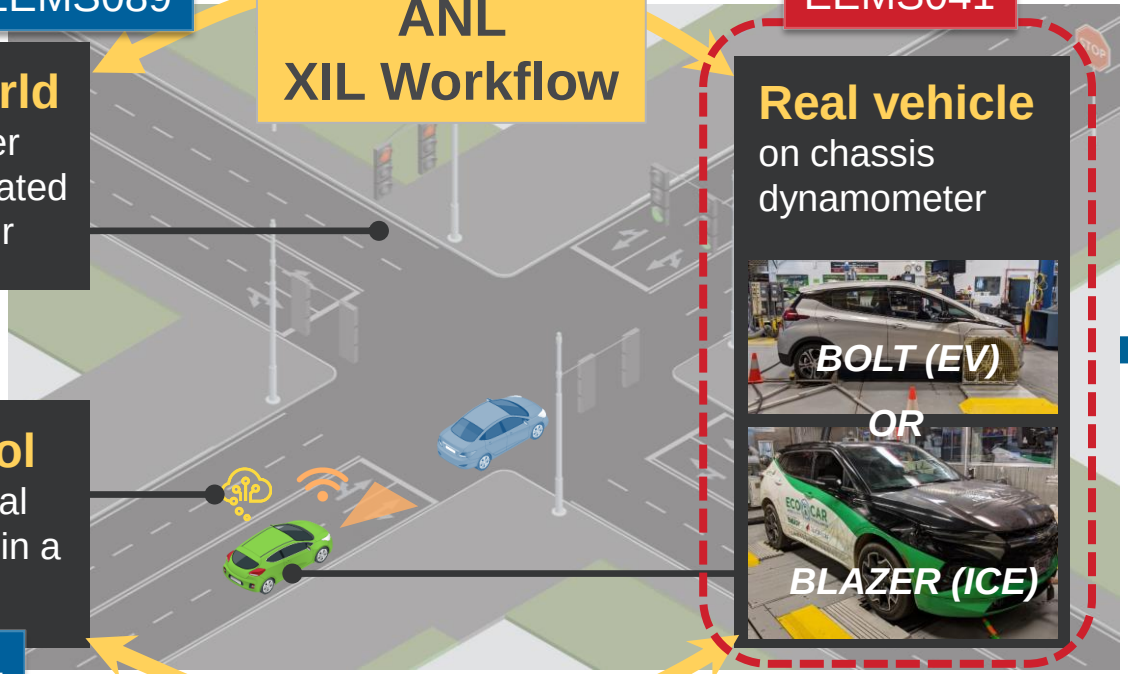
ANL XIL Workflow

EEMS041

Virtual World
Road and other vehicles simulated in RoadRunner

CAV Control
Controls the real vehicle driving in a virtual world

EEMS094

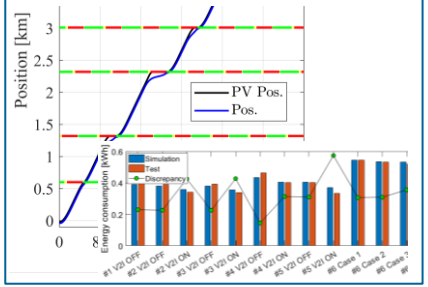


Real vehicle
on chassis dynamometer

OR

Results

- ✓ 22 scenarios, 63 tests (4-5 km each)
- ✓ Incl. V2I, multi-veh.
- ✓ Control functionality demonstrated
- ✓ Good match between XIL and 100% sim



Visit EEMS094 and EEMS089 for further details on this joint effort

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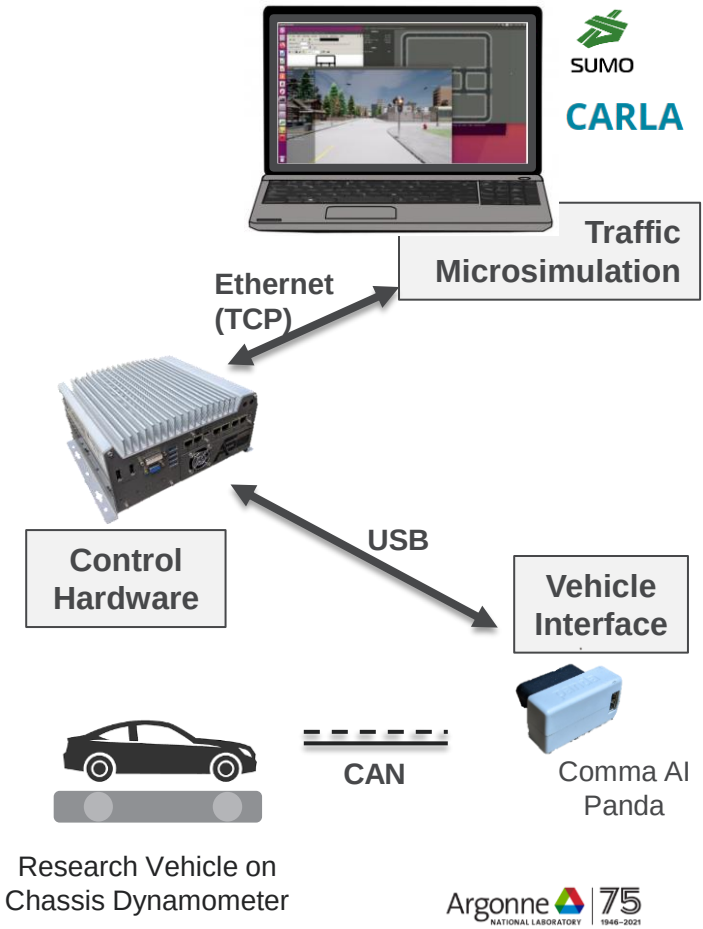
ACCOMPLISHMENTS: EXPANDING RESEARCH PLATFORMS AND ENVIRONMENTS WITH OPEN SOURCE

Goal: ***Leverage open-source developments to expand vehicle platforms and simulated environments***

Demonstrated 'proof of concept' Vehicle-in-the-Loop based on Open-Source software solutions.

- Process overview
  - SUMO produced traffic simulation
  - CARLA driving simulator provided visual environment
  - comma.ai openpilot (modified branch) created vehicle interface
- Preliminary Proof of Concept (POC) testing
  - 2017 Toyota Prius Prime on chassis dynamometer
  - Software modifications to openpilot for dyno use
    - Steering response required simulation
    - openpilot status checks differ from on-road

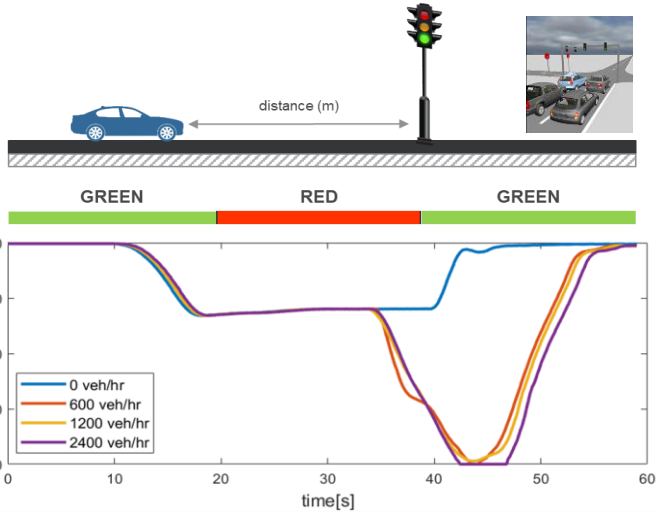
Successful proof of concept experimentation conducted



ACCOMPLISHMENTS: DIRECT MICROSIMULATION TESTING RESULTS

Goal: ***Demonstrate traffic microsimulation (Aimsun) integration into VIL environment and assess real vehicle operations in virtual multi-vehicle scenarios***

- **Test Objective :** Understand the energy benefits of published eco-driving algorithms in a scenario with traffic disturbance
- **Test Scenarios:**
  - 2017 Toyota Prius Prime with direct control override
  - 1 km straight road with single intersection
  - Four traffic congestion levels (0, 600, 1200, 2400 veh/hr)
- **Test Highlights**
  - Traffic's stochastic nature has an impact on overall vehicle energy consumption
    - Real-world traffic affects the expected eco-approach benefits
    - Important to evaluate optimization approaches in real-world conditions
  - Energy Consumption increases as traffic becomes more congested (up to 30%)



Traffic Condition	Traffic Density	Energy Consumption [Wh]	Difference from "Ideal" Eco-Approach [%]	90% Confidence Interval
No Traffic	0 veh/hr	47.82	-	0.64
Low Traffic	600 veh/hr	64.29	(+34.44)	0.38
Moderate Traffic	1200 veh/hr	58.48	(+22.29)	1.91
Heavy Traffic	2400 veh/hr	58.52	(+22.37)	0.41

Results published in SAE Technical Paper 2021-01-0112

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ACCOMPLISHMENTS: REAL-TIME COLLABORATIVE FACILITY TESTING

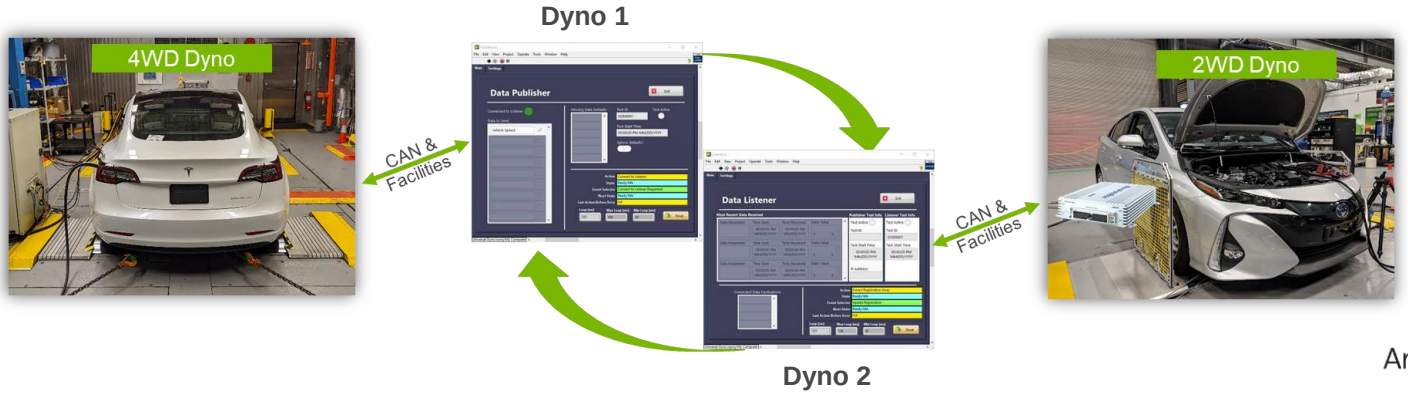
Goal: ***Develop communication backbone for collaborative vehicle testing across facilities***

Expand VIL capabilities for real-time testing across multiple facilities

- Enable joint human driven and CAV experimentation in shared scenarios
- Develop standardized communication interface
- Leverages existing facilities instrumentation for precise vehicle energy characterization

Accomplishments:

- Integrated method for data transmission/reception within laboratory DAQs
- Developed vehicle controller interface to distribute data between vehicle and facilities
- Further testing is planned for collaborative dynamometer operation with longitudinal control use-case



ACCOMPLISHMENTS: AERO

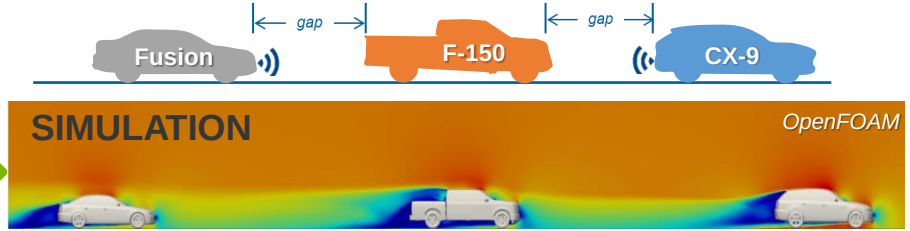
Goal:
1) Upgrade DAQ and control system for final data collection
2) Use CFD analysis to inform track testing

1) Improvements for Mass Data Collection



- Heads-up touchscreen controls
- One operator/driver (covid restrictions)
- Switched to Delphi ESR radar (from optical sensor)
- Higher precision GPS speed/location sensor

2) CFD Collaboration with OEM



- All three test vehicles modeled in OpenFOAM CFD
- Experiments were rerun in simulation
  - *Loads match except for pickup truck*
  - *More truck experiments for a closer look*
- Simulation complements experiment design
  - *Simulation has low accuracy at larger gaps*
  - *Simulation supports with small gaps(safety limit)*

Test Plan: 10 days at test track for mass data collection in May, June, July, August:

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RESPONSES TO REVIEWER COMMENTS: FY2020

- *….if there is no standard method for CAVs, then how does the work extend? The reviewer would like the team to explain further and in greater detail in future documentation.*

Response: The processes developed from this effort can enable testing in these unique areas which can directly support the development of standards. Note- researchers on this project are currently involved with other standard development activities through EEMS096 and ELT273. Future collaborations on XIL experimental activities with governmental agencies and industrial partners is under discussion.

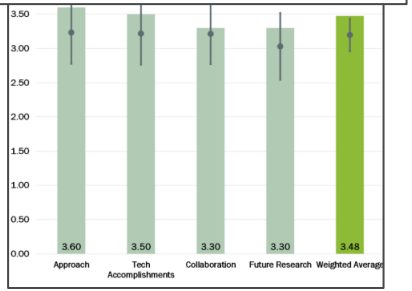
- *Collaboration exists, but it is still unclear who would be the transition partners*

Response: This research effort focuses on developing the core capabilities needed for experimental evaluation of C / AV technologies. These developments have enabled other research efforts, within the SMART 2.0 consortium research, as well as other collaborative proposals currently under review.

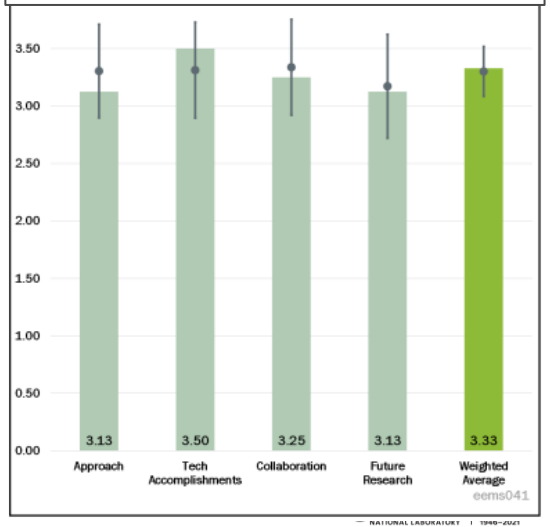
- *The current work appears to meet DOE objectives. For this to remain the case in the future as the project nears completion, the researchers will need to distill and generalize the findings in a useful and actionable way. Otherwise, it will primarily end up as an academic exercise.*

Response: This research effort has now been leveraged for use in multiple other efforts within SMART 2.0, enabling experimental testing to provide insight as well as direct validation of developments in advanced control.

FY2019 Review Results



FY2020 Project Review Results



COORDINATION: EXISTING COLLABORATIONS WITH OTHER INSTITUTIONS

DOE National Laboratory Partners:

- **Ecocar Mobility Challenge**
- DOE SMART Research Efforts
  - EEMS 094: ANL SMART 2.0- Controls
  - EEMS 089: ANL SMART 2.0- XIL workflows

Outside Partners / Collaborators:

- US DOT- NHTSA
  - Research vehicles and equipment support, XIL effort
- Universities
  - Illinois Institute of Technology (Graduate student support)
- FOA applications (multiple- under review as of AMR submission)
- DOE Researcher & publicly available vehicle data
  - www.anl.gov/d3
  - DOE Livewire data platform

REMAINING CHALLENGES AND BARRIERS FOR THIS PROJECT

Vehicle-In-the-Loop

- Development of unique testing methods for implemented research platforms requires refinement. ***No standard method for energy use evaluation of CAV technologies exists***
- New instrumentation and vehicles require unique developments to integrate.
- Advancing vehicle sensing and cybersecurity measures will make direct control overrides increasingly challenging
- Consistent realistic representation of vehicle loading requires real-world testing, data collection, and analysis for quantification and model development
- *Though progress continues, experimental operations were, and continue to be, impacted by the COVID-19 pandemic and safeguards established to ensure safe operations*

Aero

- The COVID-19 pandemic put preferred, nearby test locations out of business, while travel restrictions limited alternate locations
- Chosen track is smaller, so it will be challenging to collect sufficient quantities of steady-state data for the generic platoon load model

PROPOSED FUTURE WORK FOR THIS PROJECT

Vehicle-In-the-Loop

- Development of testing methodologies with VIL environment
- Extension of vehicle-centric Vehicle-in-the-Loop testing environment
  - Expansion of vehicle connectivity into simulated environment
  - Development of standardized communication interface for simplified test vehicle and instrumentation integration
  - Development of Driver-in-the-Loop experimental methods.
  - MD/ HD experimentation, similar workflow- different facilities and vehicles
- Expansion of vehicle fleet to enable research into advanced powertrains
  - Variation in both manufacturer and powertrain architecture (conv / HEV / EV)
- Development of models for generalized lateral loading impacts (think aero - but turning)

Aero

- Compare with on-road testing to validate “in-use driving”
- Develop methods for longer platoons (>3 vehicles)

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

SUMMARY

Relevance

- Innovative methods of experimentation are required to accurately quantify the energy impacts of future automotive technologies.

Approach

- Development of a vehicle-centric testing environment for unique research and model validation of Connected and Automated Vehicle (CAV) technologies.
- Quantification of aerodynamic road-load impact of platooning through direct measurement.

Highlighted Accomplishments

- VIL- Expansion of research vehicle fleet through direct actuator overrides
- VIL- Integration of VIL with ANL 'Anything in the Loop' (XIL) workflow enables direct, automated pathway from simulation to experimentation
- Aero – Redesign of DAQ completed for greater amount of data collection with less staff



QUESTIONS?

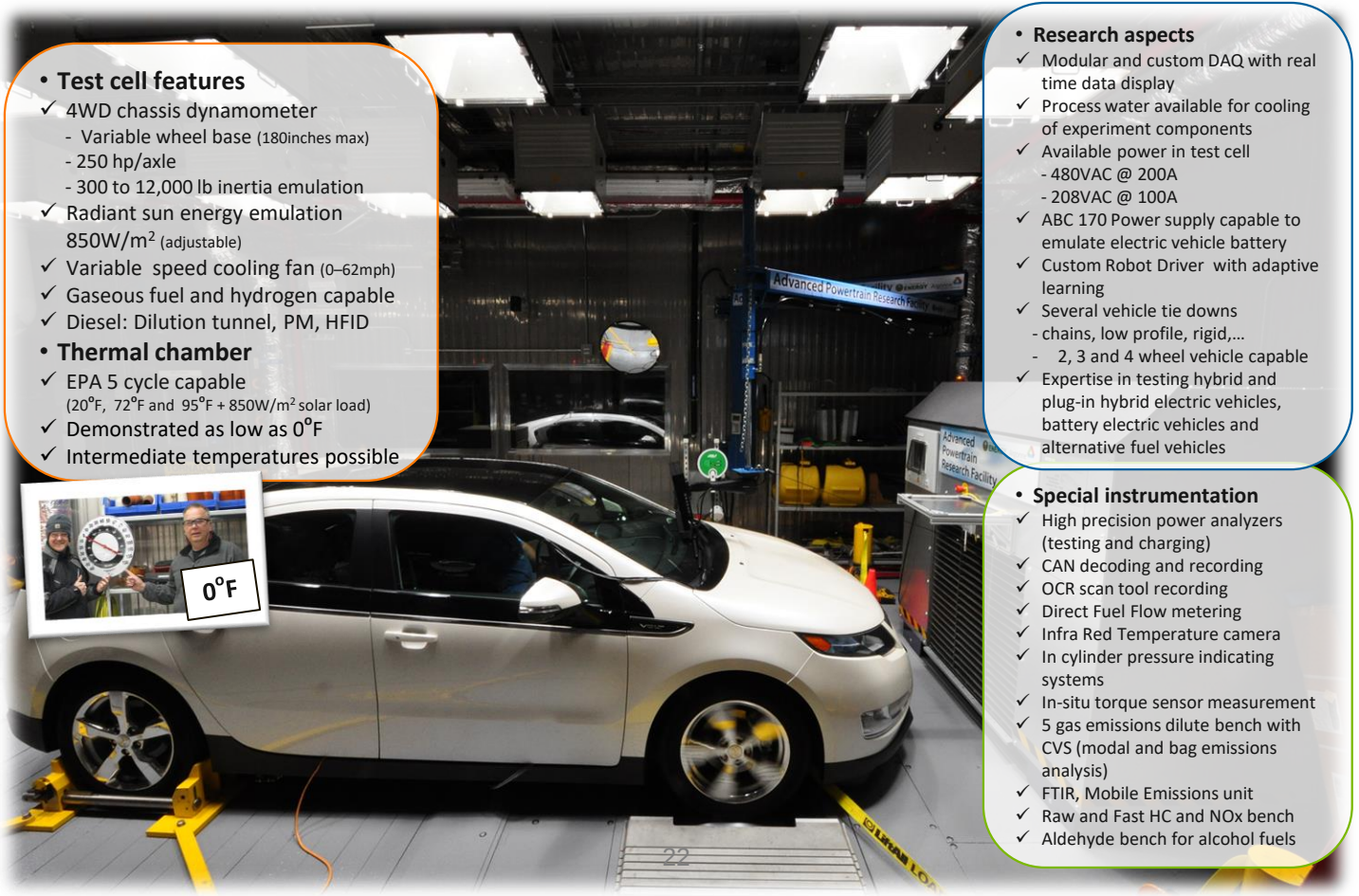


TECHNICAL BACK-UP SLIDES

U.S. DEPARTMENT OF ENERGY
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ADVANCE MOBILITY TECHNOLOGY LABORATORY
4WD CHASSIS DYNAMOMETER THERMAL TEST CELL



- **Test cell features**
  - ✓ 4WD chassis dynamometer
    - Variable wheel base (180inches max)
    - 250 hp/axle
    - 300 to 12,000 lb inertia emulation
  - ✓ Radiant sun energy emulation 850W/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)
  - ✓ Demonstrated 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
    - 480VAC @ 200A
    - 208VAC @ 100A
  - ✓ 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

ADVANCED MOBILITY TECHNOLOGY LABORATORY
2WD CHASSIS DYNAMOMETER



- **Test cell features**
  - ✓ 2WD Light Duty / Medium Duty chassis dynamometer
    - 300 hp
    - 300 to 14,000 lb inertia emulation
    - 10,000 lb max weight driven axle
  - ✓ Multiple cooling fans available
  - ✓ Vehicle lift (max 10,000 lb)
  - ✓ Remotely located control room with conference area

- **Research aspects**
  - ✓ Modular and custom DAQ with real time data display
  - ✓ Flexible to adopt any drive cycle
  - ✓ Available power in test cell
    - 480VAC @ 200A & 100A
    - 208VAC @ 50A, 30A & 20A x3
  - ✓ ABC 170 power supply capable to emulate electric vehicle battery
  - ✓ Custom Robot Driver with adaptive learning
  - ✓ 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
  - ✓ SEMTECH-DS (Mobile Emissions unit) with AVL DVE mass flow sensor

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