Energy Optimization of Light and Heavy Duty Vehicle Cohorts of Mixed Connectivity, Automation and Propulsion System Capabilities via Meshed Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) and Expanded Data

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2021 Vehicle Technologies Office Annual Merit Review

Project ID#: eems105
Pillar(s): CAVs, V2x, New Mobility Technologies

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Overview

Timeline

- Start Date: 10/1/2020
- End Date: 12/31/2022
- Duration: 27 months
- Percent Complete: 25%

Technical Barriers and Targets

- Recent R&D attention has been on automation & perception vs. connectivity – can connectivity synergize with automation to reduce energy consumption?
- Energy optimization of mixed vehicle cohorts with varying levels of automation and V2x connectivity has yet to be demonstrated on various infrastructures
- Develop a technology that achieves improved energy consumption beyond typical leader-follower CAV scenarios

Budget

- Total project funding
  - DOE share: $1,999,951
  - Prime share: $301,421
  - Contractors share: $1,698,530
- Funding for FY2021:
  - DOE share: $1,348,109

Partners

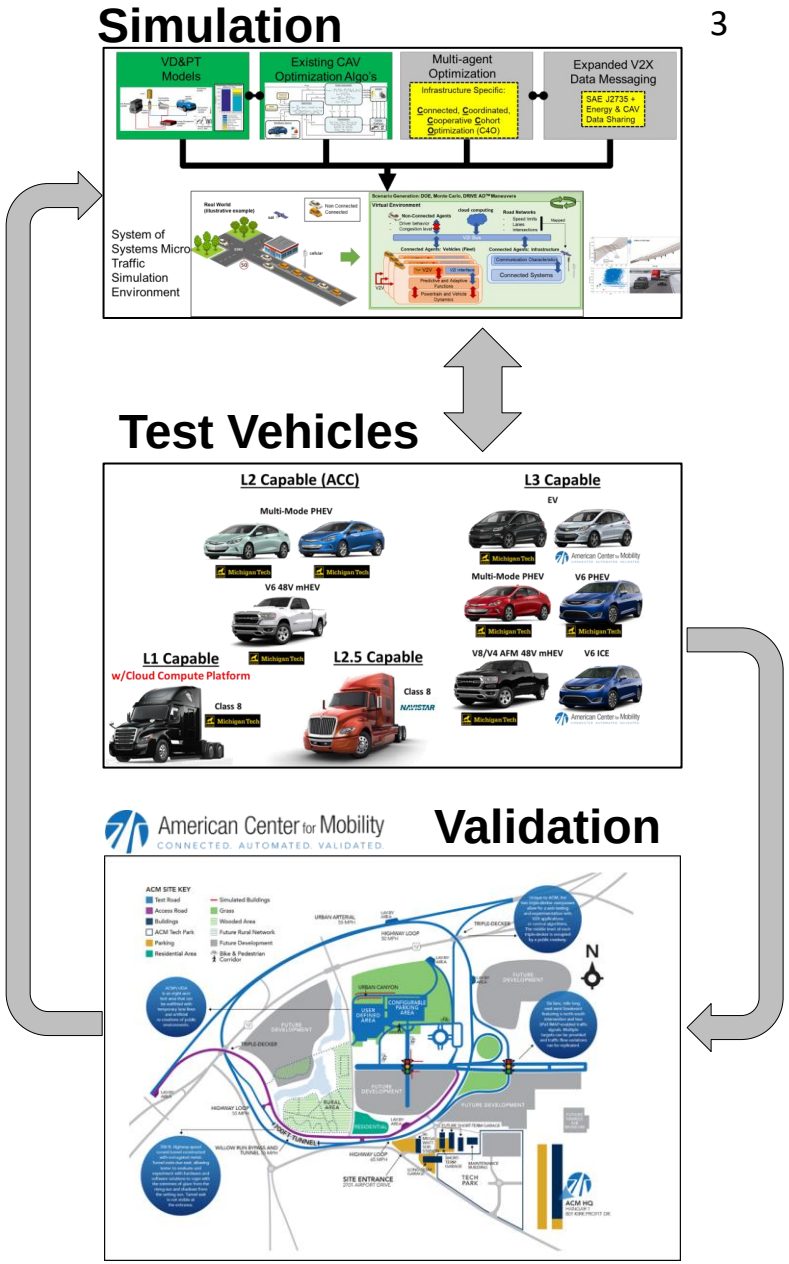
- American Center for Mobility (ACM)
- AVL Powertrain Engineering Inc. (AVL)
- Borg Warner Inc. (BW)
- Navistar (NAV)
- Traffic Technology Services (TTS)

Relevance

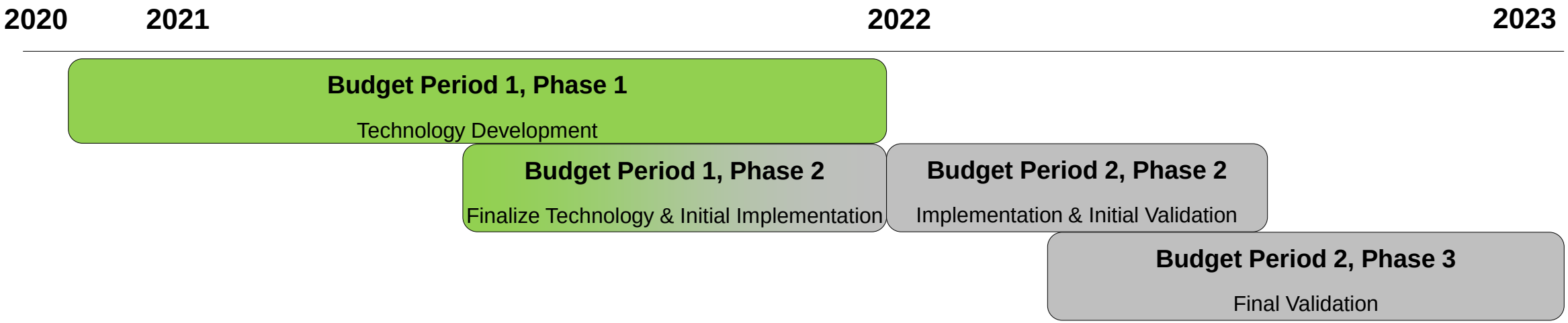
- Research, develop and validate ***vehicle connectivity & automation synergy to reduce energy consumption and improve mobility*** in transportation systems at multiple scales
- Alignment with EEMS strategic goals:
  - Leverage existing tools to create representative ***CAV energy modeling tools***
  - Demonstrate validated technology solutions that ***increase mobility energy productivity and/or reduce average energy consumption per mile***

Objectives

- Develop co-simulation environment to engineer improved energy consumption synergy on various infrastructure scales with mixed vehicle-propulsion, connectivity, drive automation technology levels
- Integrate expanded connectivity data sharing and link cloud based optimization into LD-HD CAV vehicle test fleet
- Validate models and demonstrate ***10-50% energy reductions at intersection, arterial roadway and limited access highway scenarios***
  - Closed test track facility and real world road testing



Milestones



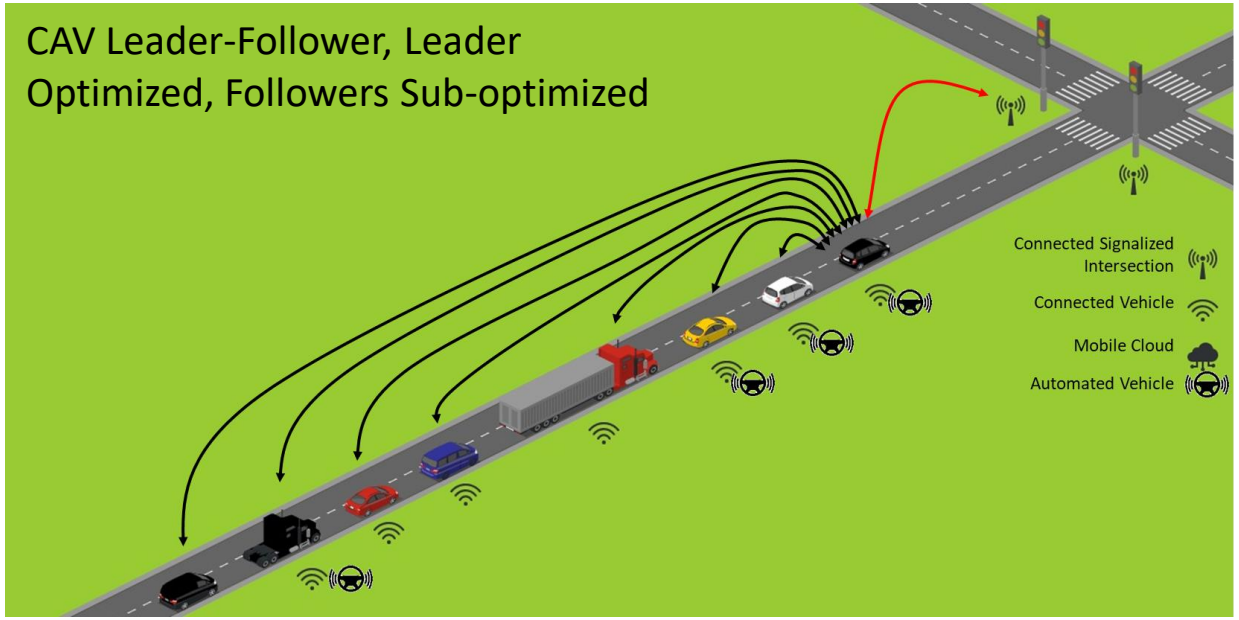
Month/Year	Description of Milestone or Go/No-Go Decision	Status
December 2020	ACM infrastructure drive cycles and routes developed	In progress
March 2021	Initial matrix of vehicle and propulsion system combinations formulated	Complete
June 2021	Cloud optimization algorithm(s) developed	On schedule
June 2021	Matrix of vehicle and propulsion system combinations developed	On schedule
September 2021	Baseline testing for vehicle cohort energy consumption completed	On schedule
September 2021	Simulation environment with optimal cohort predictions fully integrated	On schedule
December 2021	Vehicle fleet connectivity setups verified and operational	On schedule
December 2021	**G/NG**: Simulation readiness for mixed CAV cohort optimization	On schedule

Approach
Example Single Lane Signalized Intersection

Current Scenario

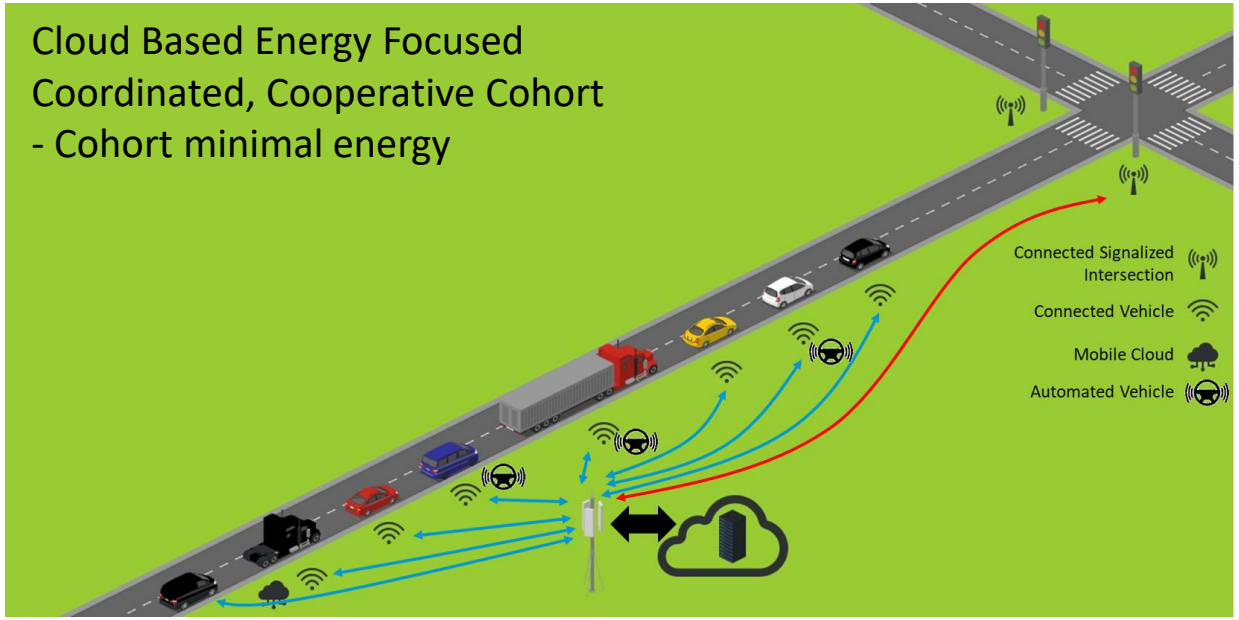
- Sub-optimal leader-follower CAV scenario
  - Lead vehicle optimizes selfishly
  - Follower vehicles constrained

  Connectivity & automation not synergized



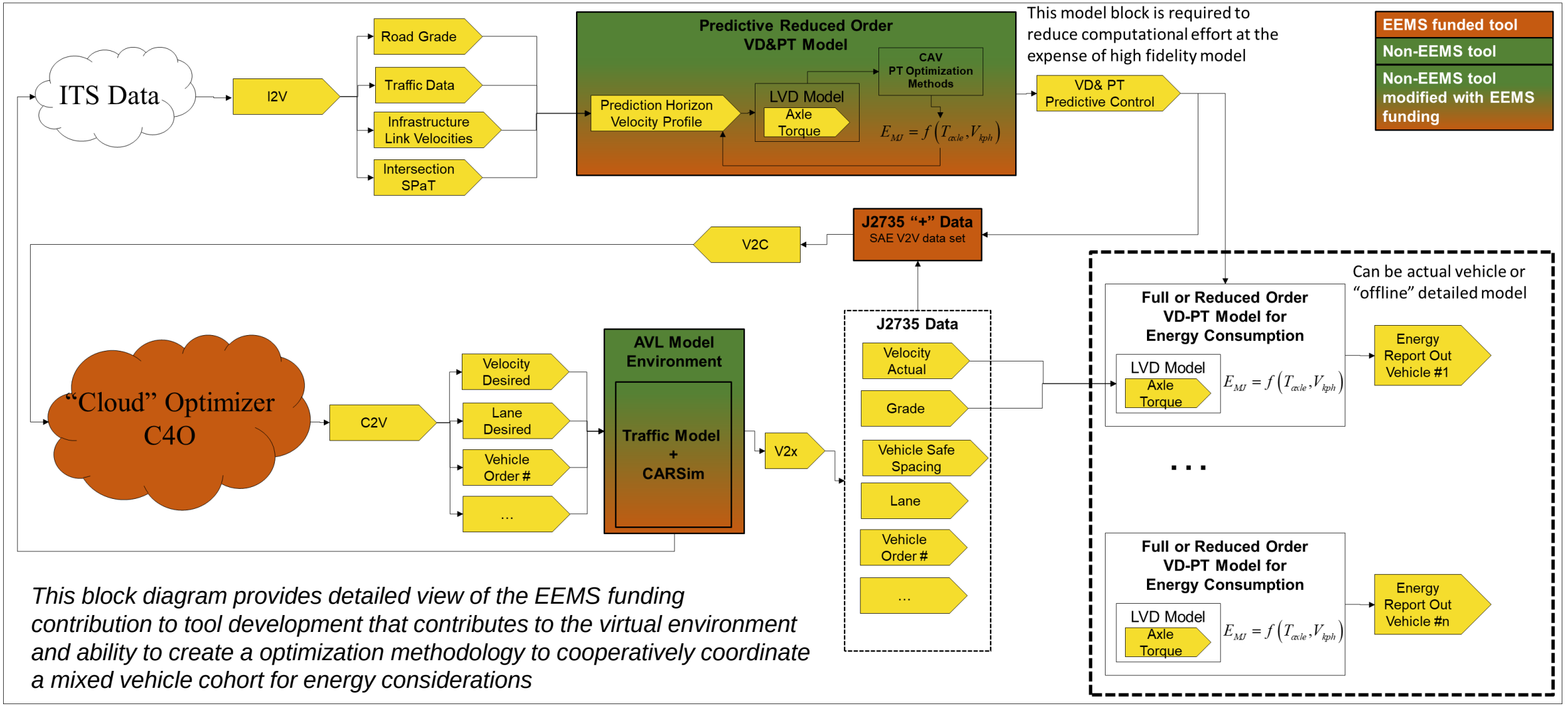
Proposed Technology

- Expanded V2x to include energy & CAV data
- Cloud based cohort optimization algorithm coordinates for reduced energy ***
- Connectivity & automation synergized



*** could be centralized or decentralized – for purposes of demonstration and simplification, team is aiming for centralized approach

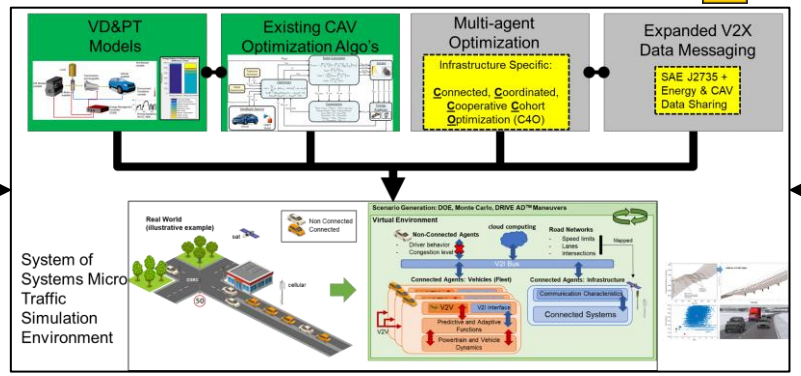
Technology Development Focus - Block Diagram



This block diagram provides detailed view of the EEMS funding contribution to tool development that contributes to the virtual environment and ability to create a optimization methodology to cooperatively coordinate a mixed vehicle cohort for energy considerations

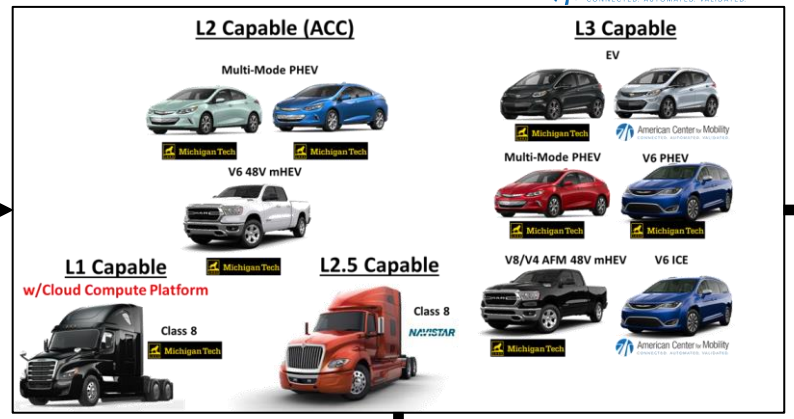
Approach: Overview

Simulation



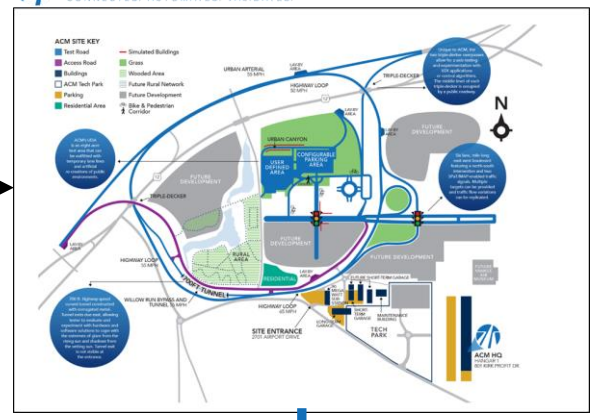
- Micro traffic model
- CAV and nonCAV agents
- Configurable connectivity data bus
- Environment visualization
- Selfish CAV and CAV cohort optimization

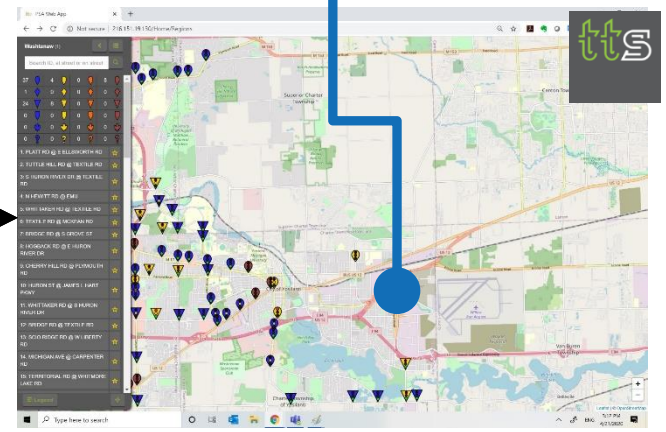
Test Vehicles



- Upwards of 11 test vehicles
- 9 vehicles with CAV capability
- Correlated energy model

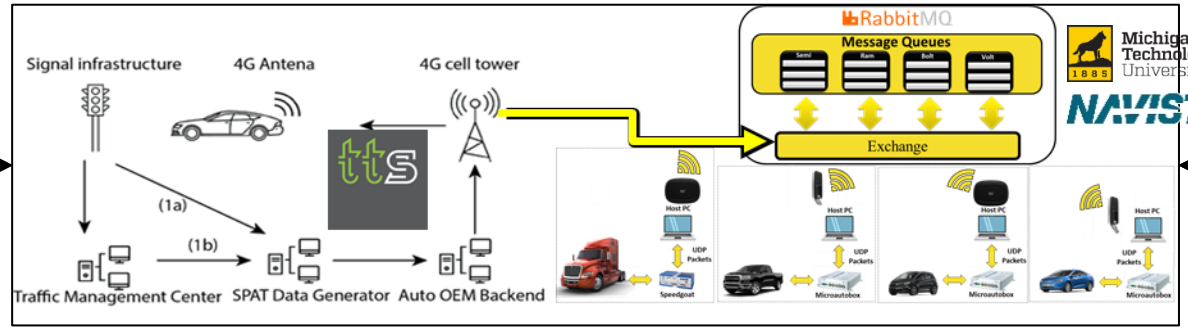
Validation





- ACM Closed Test Track for CAVs
- Real World Road Testing with I2V & V2V

Cellular Connectivity Network (CV2x)



- Cellular connectivity to infrastructure, vehicles, cloud computer and Sim Environment (CAV HiL)

DE-EE0009209
AMR 2021

Approach: Tasks

Plan for FY 2021 – budget period 1, phase 1

- **Development of System of Systems Simulation Environment**
  - Micro traffic simulation with V2x data sharing bus and environment visualization
  - Create and integrate diverse vehicle-powertrain models within environment
  - Integrate and apply previous DOE CAV technologies to vehicle models
- **Expand Connectivity Data Dictionary**
  - SAE J2735 contains minimal to no data relevant to energy and CAV data for cohort coordination
- **Develop Cloud-based Cohort Optimization Algorithm(s)**
  - Engineer infrastructure specific multi-agent optimization algorithm(s) to meet communication latency and performance targets for real time implementation
- **Vehicle Baseline Testing for Energy Consumption & Dynamic Behavior**
  - Perform vehicle testing on road and closed test track on relevant infrastructures to validate simulation environment for energy and driving behavior

Approach: Tasks

Plan for FY 2021 – budget period 1, phase 2

- **Integrate Cohort Optimization Algorithm(s) into Simulation Environment**
- **Integration of Optimization Algorithm(s)**
  - Translate to rack server for vehicle fleet testing & demonstration in budget period 2
  - DOE SuperTruck and ARPA-E NEXTCAR CAV optimization algorithm(s)/method(s) applied to test vehicle fleet
- **Vehicle Dynamics Assessment Tool Setup in Vehicles**
  - Install commercial tools into test vehicles for ADAS drive quality assessment and scoring
- **Vehicle Fleet Connectivity Setup – Cellular**
  - Install hardware, create cellular network for V2V and I2V communication between test vehicles
- **Vehicle Fleet Automated Driving Integration**
  - Demonstrate automated longitudinal control on limited test vehicles and ability to receive speed profile and lane utilization data real time on all connected vehicles

Technical Accomplishments and Progress (Overview)

FY2021 Accomplishments (up to AMR)

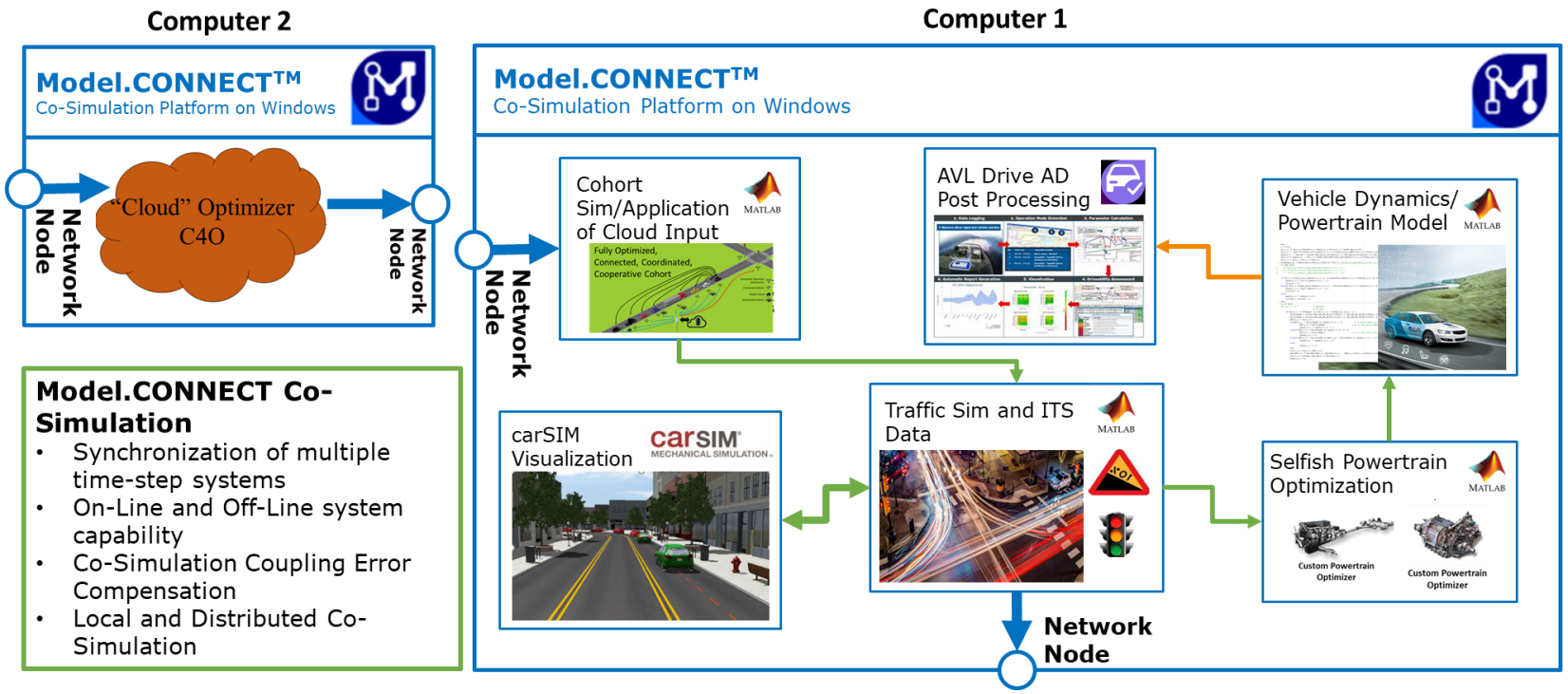
- **Development of System of Systems simulation environment**
  - V2x time synchronized connectivity data sharing bus
  - Incorporation environment and maneuver visualization via CARSim
- **Generated matrix of vehicle-powertrain variants of LD and HD classification**
  - Model order reduction for matrix of combinations underway
- **Expansion of SAE J2735 V2x data dictionary**
- **Initial engineering of cohort optimization technique(s) underway**
  - Literature review of infrastructures, methods and algorithm development
- **Established cellular based V2x vehicle-infrastructure communication network for vehicle test fleet**
  - V2V communication and data sharing verified and functional
  - I2V signalized intersection SPaT via cellular to vehicles

Technical Accomplishments and Progress: System of Systems Environment

Environment Description:

- Micro traffic
- Configurable infrastructure(s) and traffic scenarios
- Diverse vehicle-propulsion models
- CAV and nonCAV agents
- Time synchronizing V2x connectivity bus
- Modular integration for cohort optimization algorithms
- Visualization of cohort maneuvers in environment

Co-Simulation Environment



Takeaway: Comprehensive simulation environment for development and evaluation of multi-agent CAV's for mobility and energy performance.

Technical Accomplishments and Progress: Vehicle-Propulsion System Models

Vehicle Model Details:

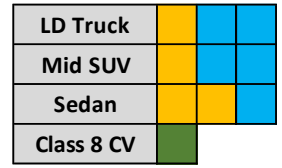
- Matrix of LD and HD vehicles
  - C-sedan to Class 8
  - Test vehicles available for validation
  - Certain models developed from previous/current DOE & ARPA-E projects
- Propulsion includes EV, HEV, PHEV and ICE – gas & diesel
- Full order models derived from test data and
- Model order reduction necessary for layered optimization → computation time
  - Models reduced in order & complexity to significantly reduce run time but retain physics and fidelity → +/- 2% of actual energy

Model Matrix

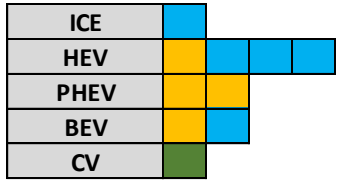
ICE	HEV		PHEV	BEV	CV HD
	P0 48V HEV	P2 HV HEV			
LD Truck	Ram eTorque	Mid SUV	Volt II	Bolt	Prostar MF13
	F150		Pacifica	Mid SUV	
	C Sedan				

Key: MTU; BorgWarner; Navistar

Mix by Platform Type



Mix by Propulsion System Type



Vehicle – Propulsion Models Currently Developed and Incorporated into Simulation Environment

Michigan Technological University

BEV

PHEV

ICE

BorgWarner

BEV

ICE

NAVISTAR

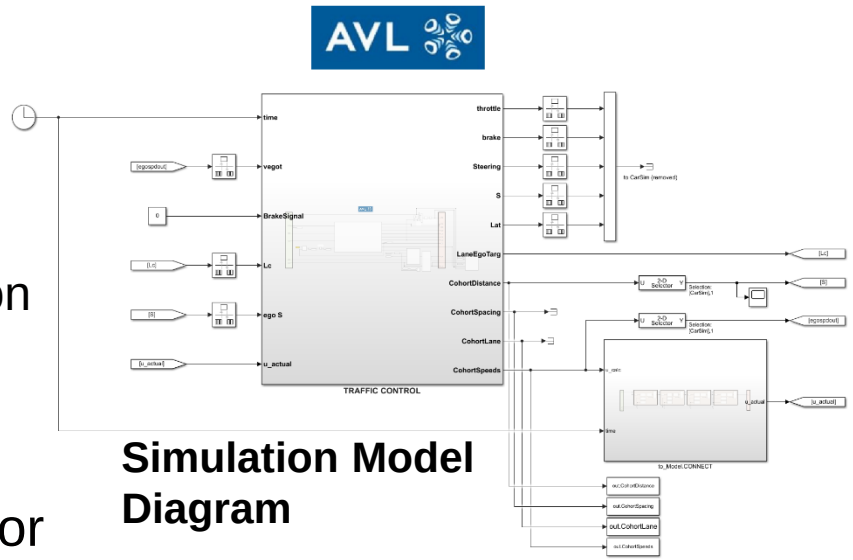
ICE

Takeaways: Diverse mix of vehicle-propulsion systems to assess CAV cohort energy impact. Energy prediction accuracy +/-2% of vehicle data and/or full order models. Real time optimization compatible.

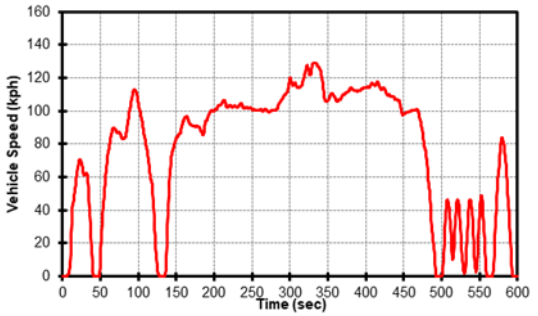
Technical Accomplishments and Progress: Initial Simulation Environment Results – nonCAV Cohort in Traffic

Simulation Description:

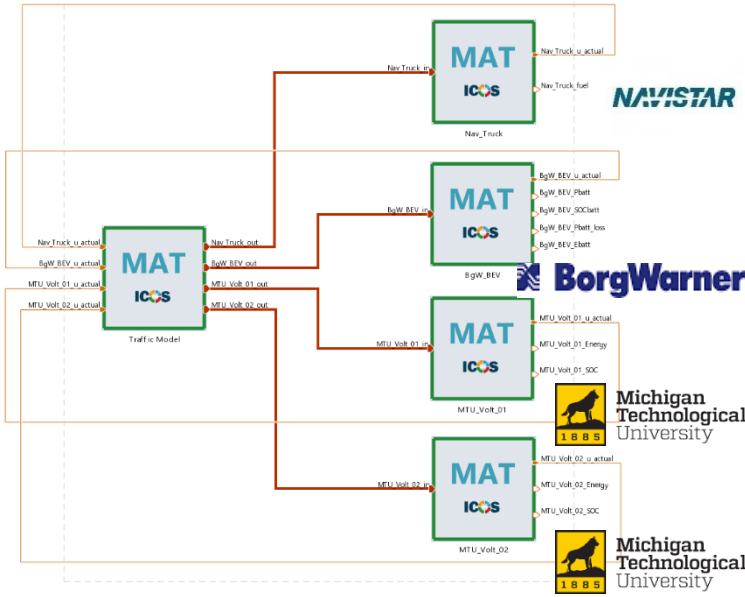
- US06 speed profile as example trajectory only
- 13 total vehicles
  - 4 vehicles with energy models –non CAV cohort
  - 9 vehicles as actors with driver models only
- Typical aggressive highway behavior
  - LD pass HD, HD can't keep pace
- Connectivity bus also configuration of V2x data sharing and will synchronize time steps of CAV's participating in the cohort



Simulation Model Diagram



Connectivity Data Bus with 4 vehicle-propulsion system models

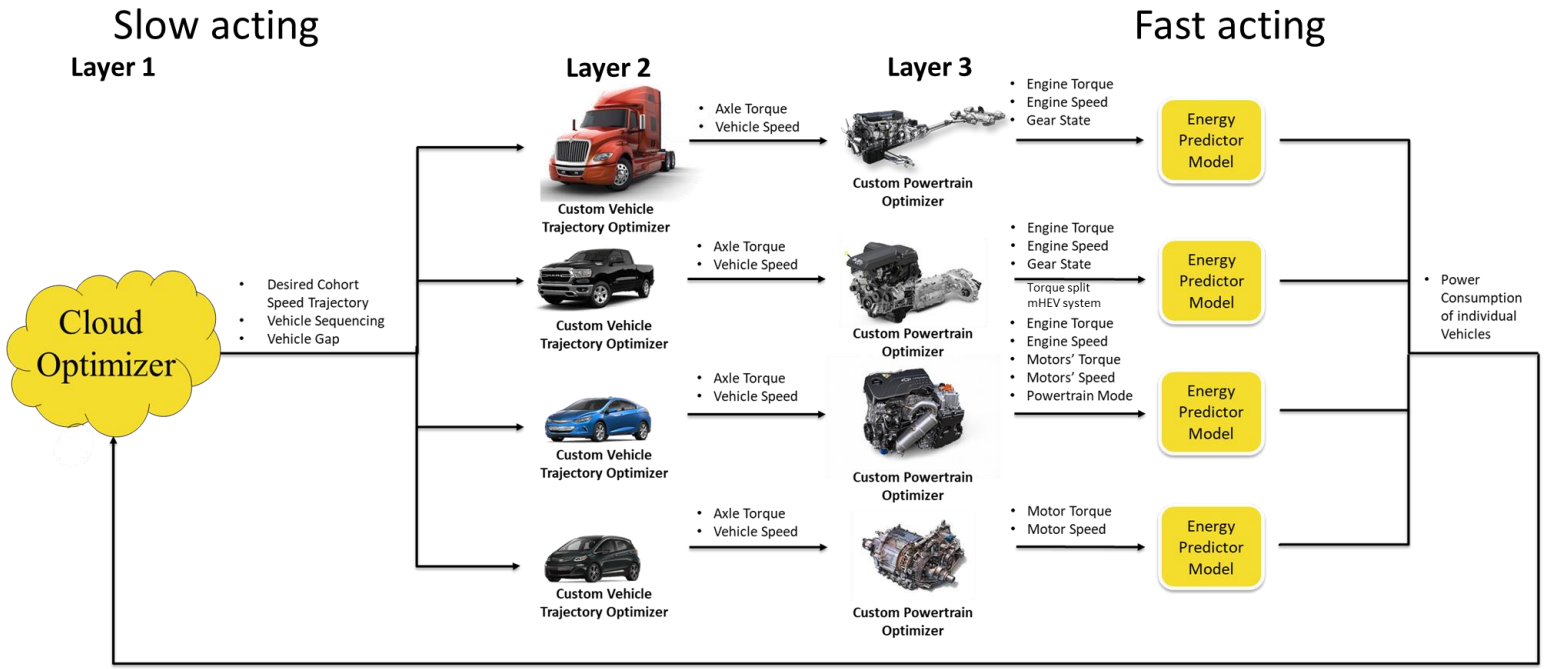


Takeaway: Team has developed and will continue to modify and add capability to transform the environment into a CAV cohort optimization tool and explore various scenarios and edge cases

Technical Accomplishments and Progress: Initial Cohort Optimization Methods Engineering

Cohort Optimizer Description:

- Layered optimization approach on varying horizon and response times
- Each traffic infrastructure cohort optimization is a conglomerate of individual CAV techniques and brokered for least energy consumption constrained to safety and infrastructure limits
- Investigating potential methods for constrained, multi-agent optimal control and path planning



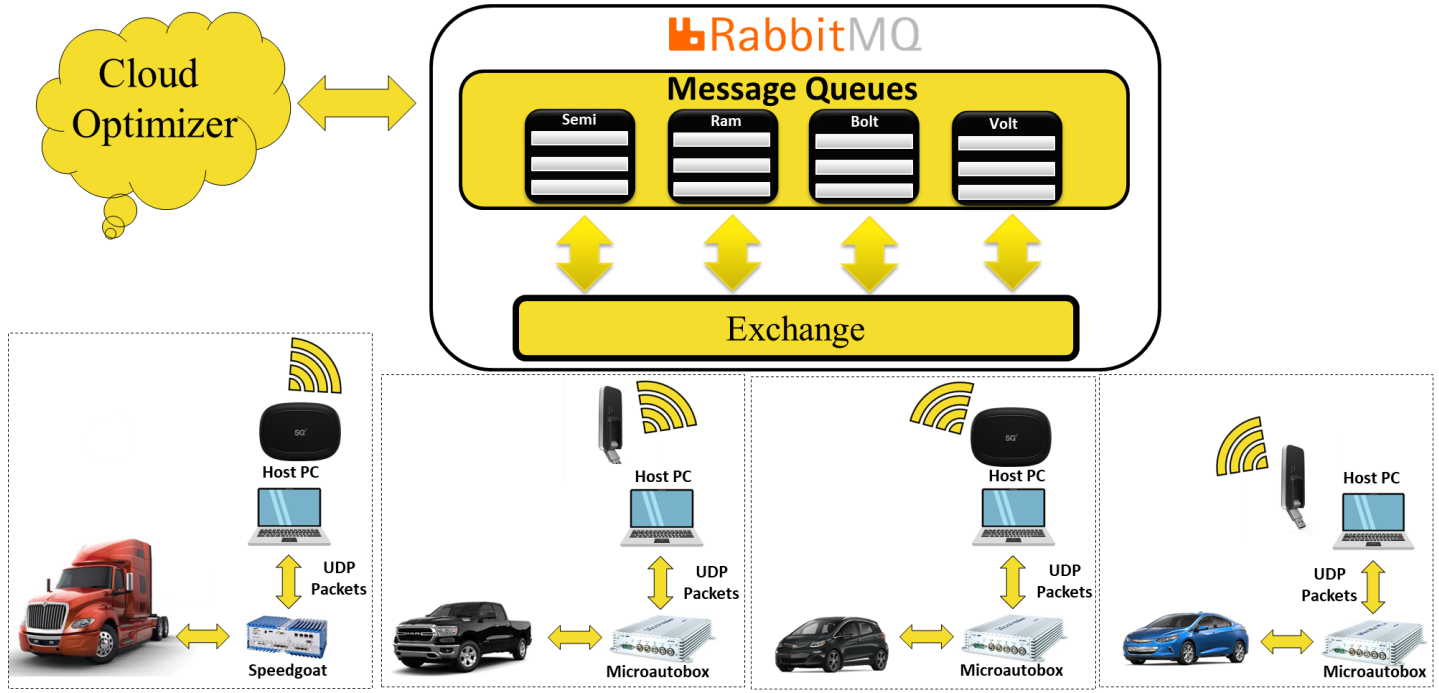
Maneuvers to be Optimized	Infrastructure		
	Signalized Intersection	Arterial Corridor	Highway Section
Platoon Formation	◆	◆	◆
Platoon Trajectory Optimization	◆		◆
CACC	◆	◆	◆
Eco AnD	◆	◆	
Vehicle Entering/Leaving		◆	◆
Trajectory Optimization b/w intersections		◆	
Lane Utilization		◆	◆

Takeaway: Team is at initial stages of researching options for multi-agent optimization with each CAV agent providing detailed selfish optimal control to the cloud computation

Technical Accomplishments and Progress: Cellular Vehicle Connectivity Network (CV2x)

CV2x Features:

- Cellular based SPaT data
  - Wide availability of connected intersections real world and at ACM
- Debug work with partners can be done without close proximity
- Through message que broker, can customize data dictionary
- Secure VPN connection
- With cellular connectivity team can connect test vehicles to simulation environment for CAV HiL computations
  - Test and model vehicles exist for project



Takeaway:
1.) Team has established connectivity between test vehicles and infrastructure
2.) Virtual environment tools enabler for direct utilization on the vehicle test fleet as centralized or decentralized computations for cohort coordination CAV HiL

Responses to Previous Year Reviewers' Comments

No prior review(s)

This is the first year of review for this project and no reviewer comments are available

Collaboration and Coordination with Other Institutions

Outside VTO

Collaborators	Type	Role	Extent
Michigan Technological University	University	Prime	Program management LD vehicle-powertrain models and optimization methods LD test vehicles
American Center for Mobility	Nonprofit	Sub	Closed test track facility LD test vehicles
AVL Powertrain	Business – Mobility Consultant	Sub	System of system simulation environment, simulation, optimization, CAV drive quality evaluation
BorgWarner	Business – Tier 1	Sub	LD vehicle-powertrain models and optimization methods
Navistar	Business - OEM	Sub	HD vehicle-powertrain models and optimization methods, HD test vehicle
Traffic Technology Services	Business – Mobility/Connectivity	Sub	Cellular connectivity to signalized intersections and virtual intersection placement for SPaT

Remaining Challenges and Barriers

Barriers

V2V data exchange containing energy consumption characteristics and forward prediction horizon for sufficiency of optimization problem for CAV cohort and move away from leader-follower paradigm

Technical Challenges

- Development of multi-agent optimization techniques that can run near real time to produce vehicle trajectory profiles
- Layering ego connected vehicle energy optimization and automated vehicle path planning with cohort planning in time for actual vehicle maneuvering
- Implementation and integration of cellular network, optimization methods and automated driving capabilities within vehicle test fleet followed by infrastructure specific testing and maneuvers

Proposed Future Research

FY 2021

- Completion of simulation environment and analysis
  - Develop and validate matrix of reduced order vehicle-propulsion models
  - Finish cohort optimization algorithms and incorporate in simulation environment
  - ***Conduct initial vehicle testing of nonCAV for baseline energy consumption and correlation***
  - Perform matrix of simulations varying infrastructure, vehicle, propulsion, connectivity & automation
- Continue vehicle fleet development for connectivity and energy optimization control and coordination
  - ***Link simulation environment connectivity bus to test vehicles for CAV HiL for computations***
- Activities setup budget period 2 vehicle testing, validation and demonstration of potential energy reductions for three infrastructures

FY 2022

- **Go/No Go** – simulation readiness of mixed CAV cohort optimization and successfully generate energy savings ≥10% for infrastructure scenarios *
- Completion of test vehicle fleet setup for cohort connectivity and automation and testing of matrix of maneuvers on varied infrastructures as determined from simulation environment for performance gains in energy consumption and mobility

* See technical backup slides for details

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

Summary Slide

Objective: Energy reductions of 10-50% for mixed vehicle cohorts on various infrastructures through cloud based optimization and coordination via connectivity and drive automation

FY2021 Efforts and Accomplishments (at time of 2021 AMR):

- Creation of System of Systems simulation environment targeted towards CAV optimization on various time horizon and traffic infrastructure scales
- Initial setup of test vehicle fleet cellular connectivity network, implementation of infrastructure communication and integration of CAV & cohort optimization methods

Future FY2021 and FY2022 Efforts:

- Complete matrix of vehicle-propulsion models, simulation environment for cohort optimal control and analyze matrix of infrastructure, vehicle and CAV technology factors to develop vehicle fleet test scenarios
- ***Team will work to link simulation environment computation capability with test vehicles for CAV HiL cohort coordination → links simulation with test to demonstration***
- Complete test vehicle CAV setups for coordinated cohort energy reductions and execution field demonstrations

Impact to VTO Objectives: This project leverages commercial traffic, vehicle and energy simulation tools, validated vehicle-propulsion system models and CAV hardware and energy optimal control techniques previously funded by DOE & ARPA-E to bring collaborate energy based control to vehicle cohorts

Technical Back-Up Divider Slide

Technical Back-Up Slides: Infrastructure Energy Reductions and planned Test Factors

The project goals are to demonstrate energy consumption reductions at the cohort and individual vehicle level for three traffic infrastructure scales that range from 10 to 50%. The range of energy reduction realized will be highly dependent on the infrastructure being assessed along with the composition of the cohort of vehicles and the vehicle based test factors contained in the table below.

Infrastructure Approach	Manevuer(s)	Distance	** Energy Savings	Results Method	Number of Vehicles in Test
1.) Signalized Intersection	Approach	~ 0.4 km	20 to 50 %	Simulation, Closed Test Track, Public Roads	2 to 6
	Departure	~ 0.3 km	10 to 40 %	Simulation, Closed Test Track, Public Roads	2 to 6
2.) Arterial Corridor	Multi-lane, intersection coridor	up to 8 km	10 to 25 %	Simulation, Closed Test Track	4 to 8
	Speed changes & merging	up to 8 km	15 to 25 %	Simulation, Closed Test Track	2 to 4
3.) Highway Driving	Limited access highway driving	up to 16 km	10 to 15 %	Simulation, Closed Test Track	4 to 8
4.) Integrated Drive Cycle	Includes infrastructures 1 thru 3 in an amalagated closed test track configuration	20 km	10 to 25 %	Simulation, Closed Test Track	4 to 8

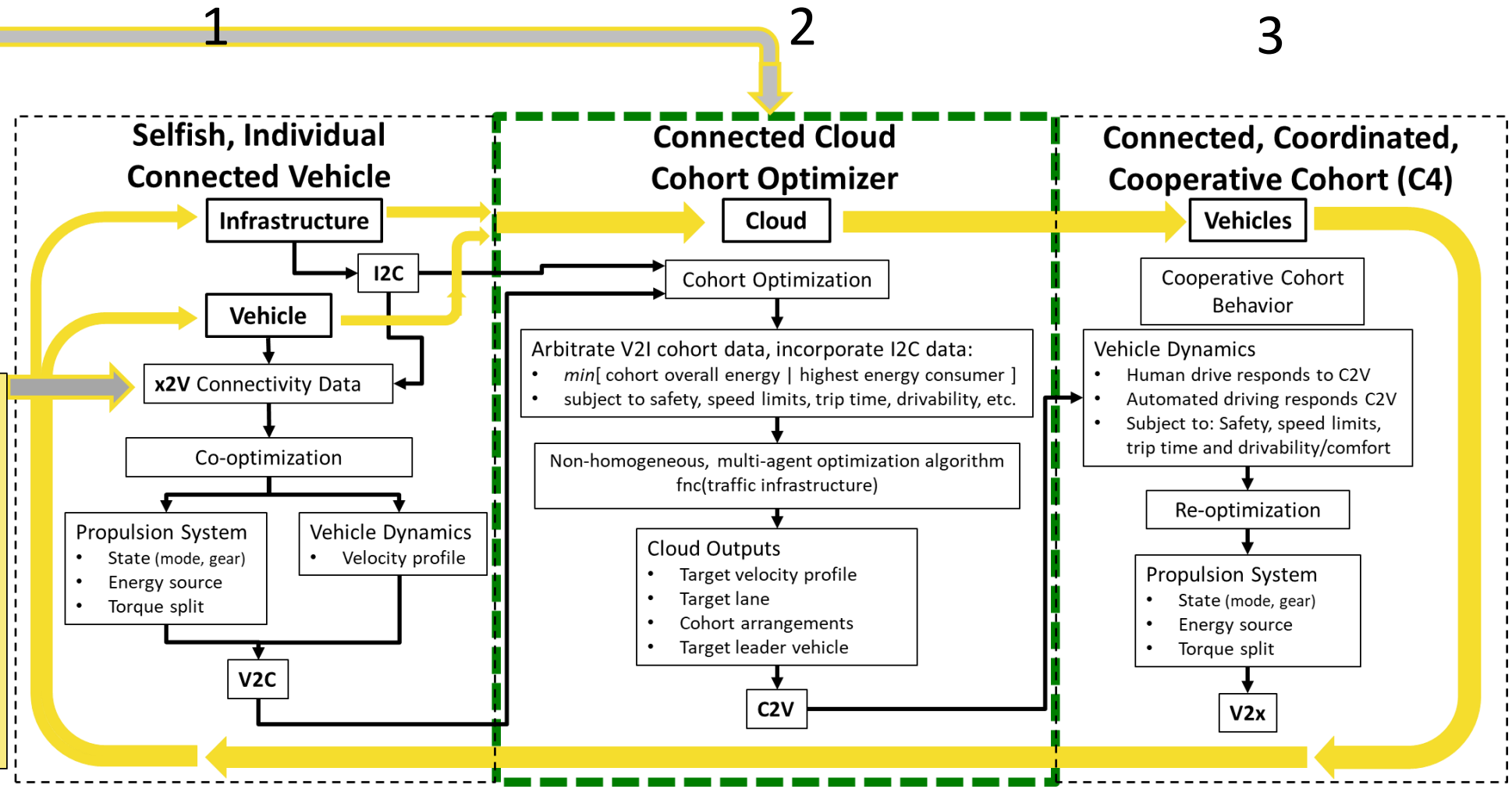
** Anticipated range of energy savings, but highly dependent on infrastructure, maneuver, cohort composition and simulation or test factors

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

Technical Back-Up Slides:
High Level Graphic – Technology Development

V2V – *current state SAE J2735*
- Velocity
- Vehicle spacing
- Vehicle position
- Lane utilization
- Road conditions
- Travel direction
- Turn indication
- Vehicle dimensions
- …

V2V – *project proposed expanded*
- V2V current state
- Vehicle class
- Automation level
- Automated driving system status
- Vehicle mass (learned)
- Vehicle Road load coefficients (learned)
- Propulsion system configuration
- Propulsion system state (EV, HEV, ICE, etc.)
- CAV projection horizon (time, distance)
- Projected velocity profile
- Desired path trajectory (route)
- Projected energy consumption



Technical Back-Up Slides:
Expanded V2V Signal List for Cohort Optimization

S.No.	Signals from J2735
1.	Vehicle ID
2.	Transmitting Time
3.	Current Location
4.	Heading
5.	Current Lane
6.	Current Speed
7.	Current Acceleration
8.	Steering Wheel Angle
9.	Steering Wheel Angle Rate of Change
10.	Propulsion System/Gear State
11.	Vehicle Mass (Nominal)
12.	……
…	……

S.No.	Additional Signals
…	…..
13.	Vehicle/Powertrain Type
14.	Gap to Vehicle in Front
15.	Vehicle Mass
16.	Vehicle Mass (Learned)
17.	Road Load Coefficients (Nominal)
18.	Road Load Coefficients (Learned)
19.	Trailer Information (dimensions)
20.	Level of Automation
21.	Automation Status
22.	Connectivity Capacity
23.	Connectivity Status
24.	Battery state of charge
25.	Projected velocity for ‘x’ sec
26.	Projected energy consumption for ‘x’ sec

ICE
EV
HEV
PHEV

OEM Curb vs. learned during driving

OEM published to EPA

F0,learned
F1, learned
F2, learned
F2p, estimated/learned

Ego vehicle VD&PT co-optimization for energy independent of cohort