U.S. DEPARTMENT OF ENERGY SMARTMOBILITY
Systems and Modeling for Accelerated Research in Transportation

NOVEMBER 5, 2020

UNDERSTANDING THE BENEFITS OF CONNECTED & AUTOMATED VEHICLES AND SYSTEM CONTROLS FOR SMART MOBILITY

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U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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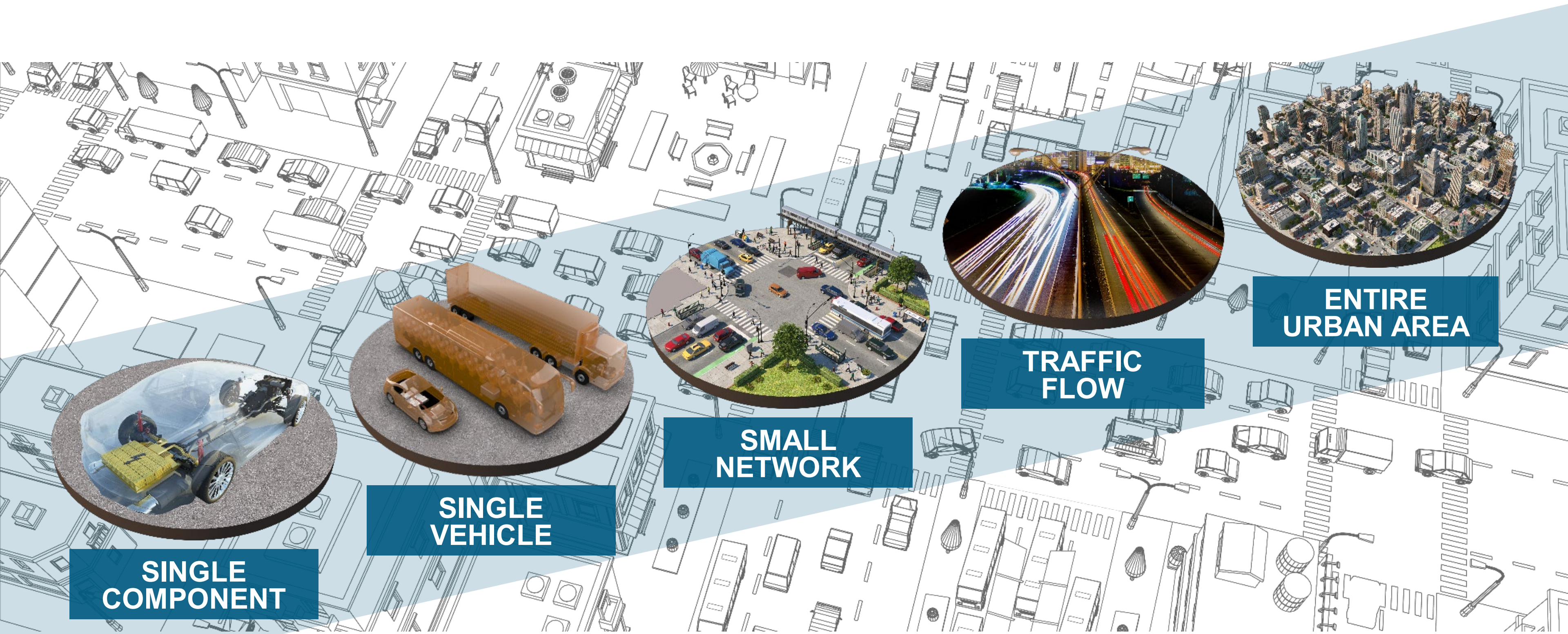
VTO SYSTEMS-LEVEL R&D

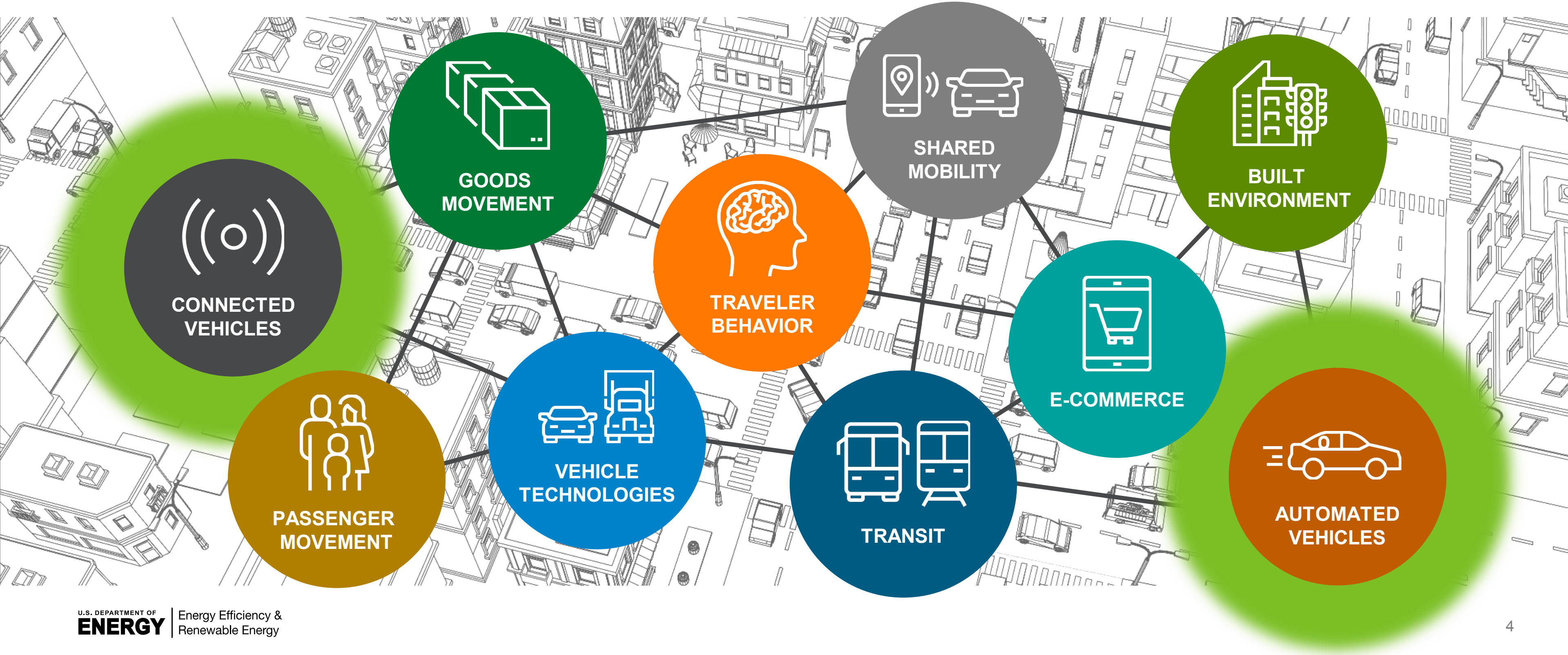


SMART MOBILITY CONSORTIUM

The SMART Mobility Consortium is a multi-year, multi-laboratory collaborative dedicated to further understanding the energy implications and opportunities of advanced mobility solutions.

Argonne National Laboratory | Berkeley Lab | Idaho National Laboratory | NREL National Renewable Energy Laboratory | Oak Ridge National Laboratory

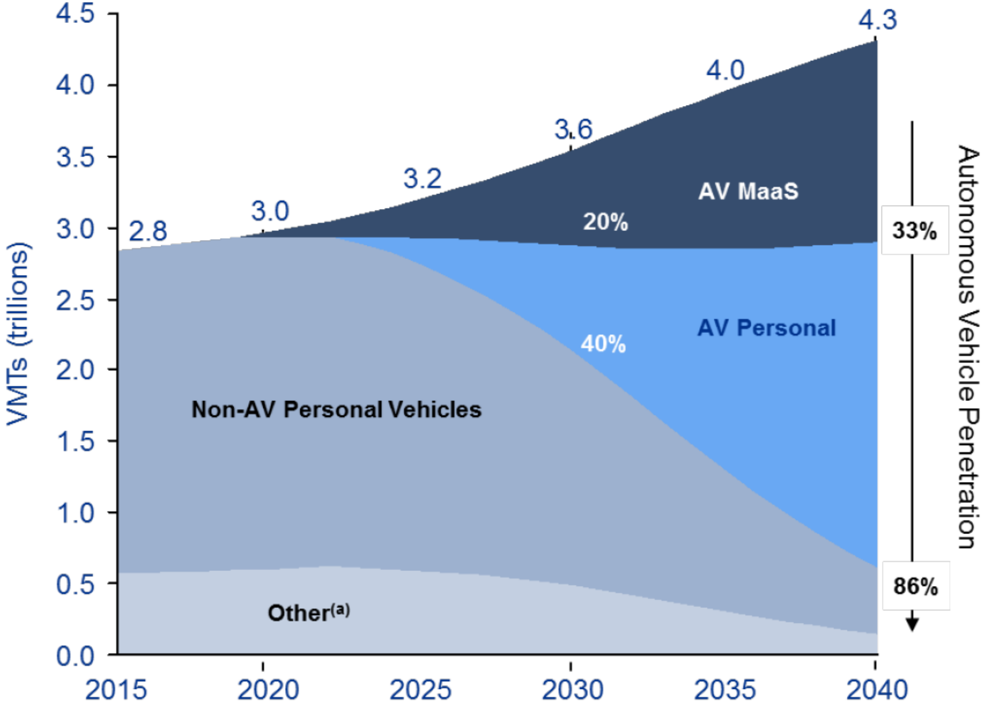
TRANSPORTATION IS A SYSTEM OF SYSTEMS



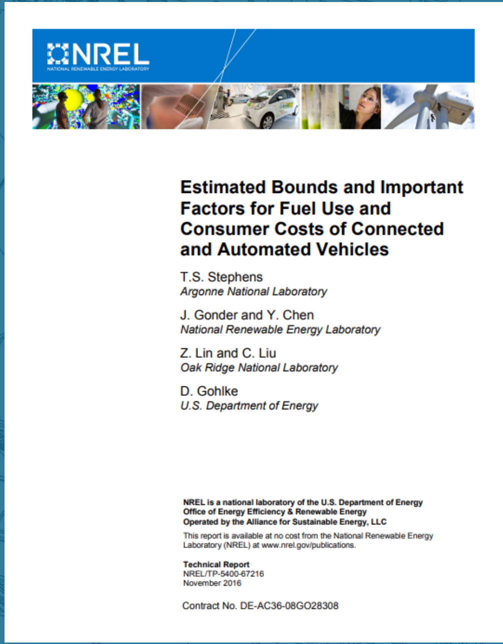
Source: Ford Motor Company

Vehicle Miles Traveled by Ownership Type & Mode

Source: J. Anderson, KPMG



CAVS BOUNDING STUDY (2016)


NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Estimated Bounds and Important Factors for Fuel Use and Consumer Costs of Connected and Automated Vehicles

T.S. Stephens
Argonne National Laboratory

J. Gonder and Y. Chen
National Renewable Energy Laboratory

Z. Lin and C. Liu
Oak Ridge National Laboratory

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U.S. Department of Energy

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Office of Energy Efficiency & Renewable Energy
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This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Technical Report
NREL/TP-5400-67216
November 2016

Contract No. DE-AC36-08GO28308

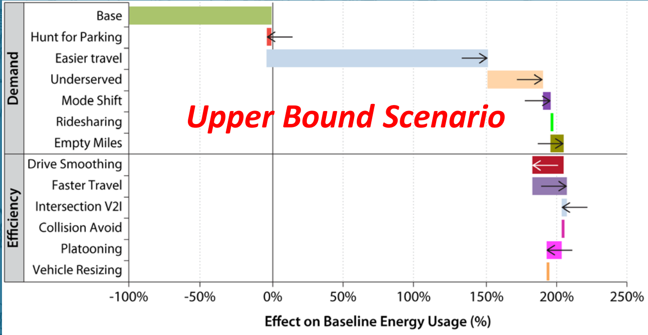
+200%

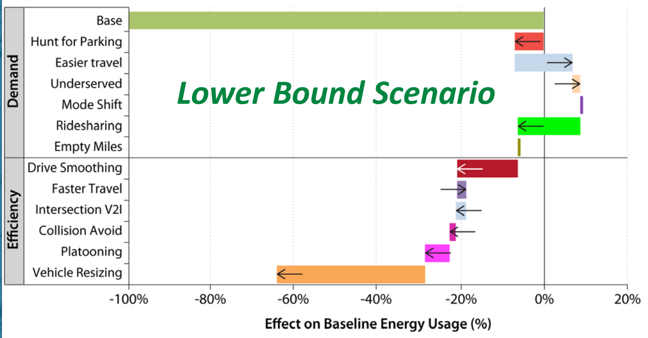
Potential Increase in Energy Consumption

2050 Baseline Energy Consumption

Potential Decrease in Energy Consumption

-60%





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CONNECTED AND AUTOMATED VEHICLES

- LEVELS OF AUTOMATION
- TYPES OF CONNECTIVITY
- CLASSES OF VEHICLES
- POWERTRAIN TYPES
- CONTROLS OBJECTIVE
- TECHNOLOGY ADOPTION
- OPERATING ENVIRONMENT
- TEST PROCEDURES

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MOBILITY FOR OPPORTUNITY

FOR MORE INFORMATION

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RESEARCH QUESTIONS

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CONNECTED AND AUTOMATED VEHICLES

Identifying the energy, technology, and usage implications of connectivity and automation and identifying efficient CAV solutions

1. How will connected and automated vehicles and systems behave in the real world?
2. What are the GHG, energy, technology and usage implications of connectivity, automation, and the combination of both technologies?
3. What is the best way to harness CAVs for reduced energy use and improved mobility in transportation?

RESEARCH FOCUS AREAS

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1) Prototype Development, Experimentation, and Large-Scale Data Analysis

2) Evolving and Validating CAV Modeling Portfolio

Integrated in SMART Mobility Modeling Workflow

3) Impacts of CAVs within Near-Term Transportation Systems

4) CAV-enabled Opportunities for Reduced Consumption and Congestion

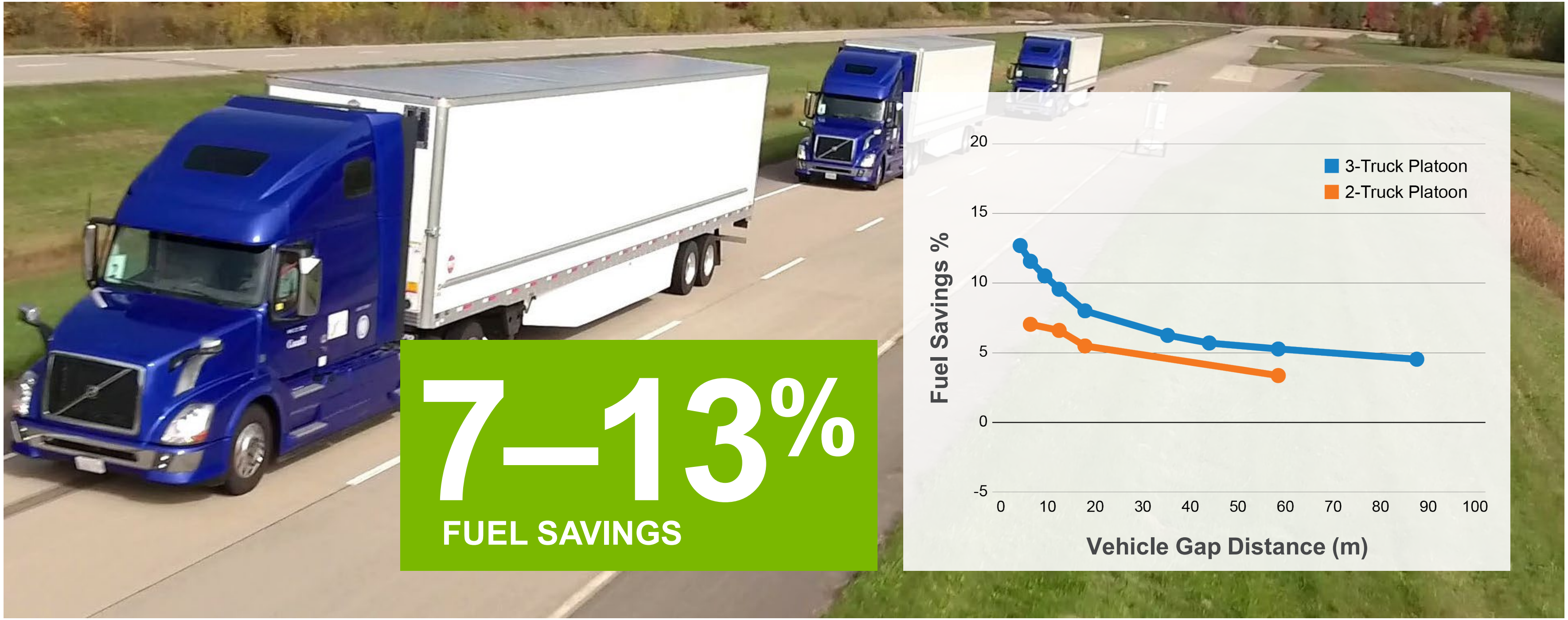
CONNECTED AND AUTOMATED VEHICLES RESEARCH HIGHLIGHTS

CLASS 7/8 TRUCK CAV-ENABLED EFFICIENCY OPPORTUNITIES

Platooning could cut diesel use over 1 billion gallons

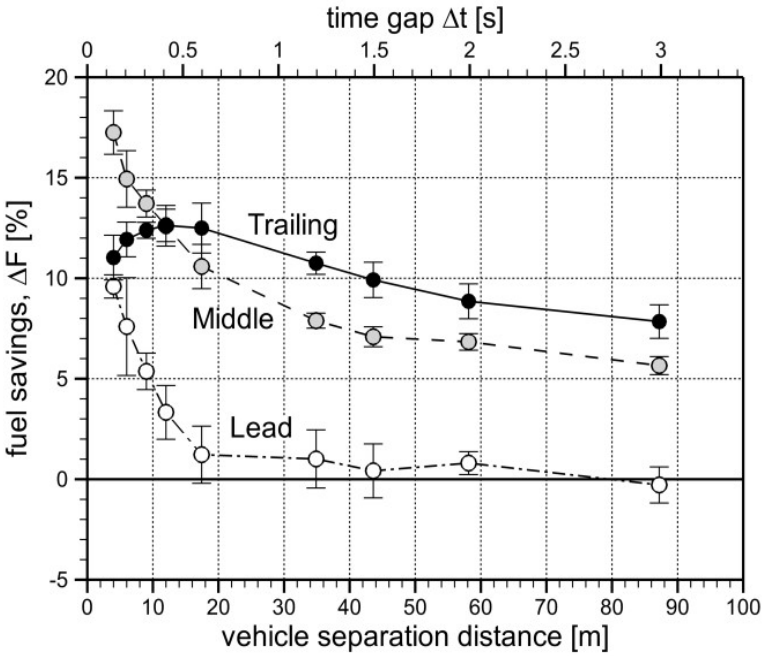
PLATOONING REDUCES TRUCK FUEL USE

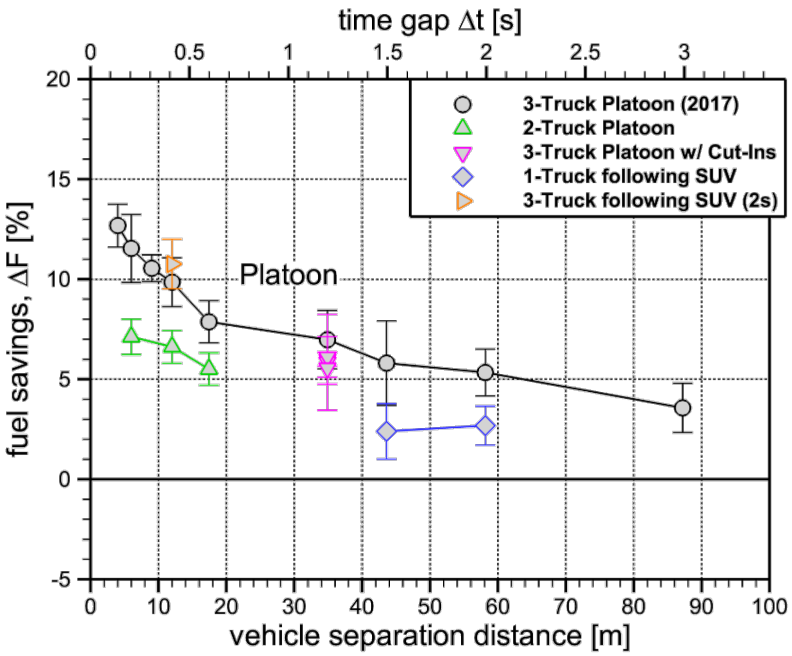
Overall savings depends on platoon configuration and speed



EXPLORING REAL-WORLD PLATOONING VEHICLE SENSITIVITIES

Individual vehicle savings depend on truck spacing and position

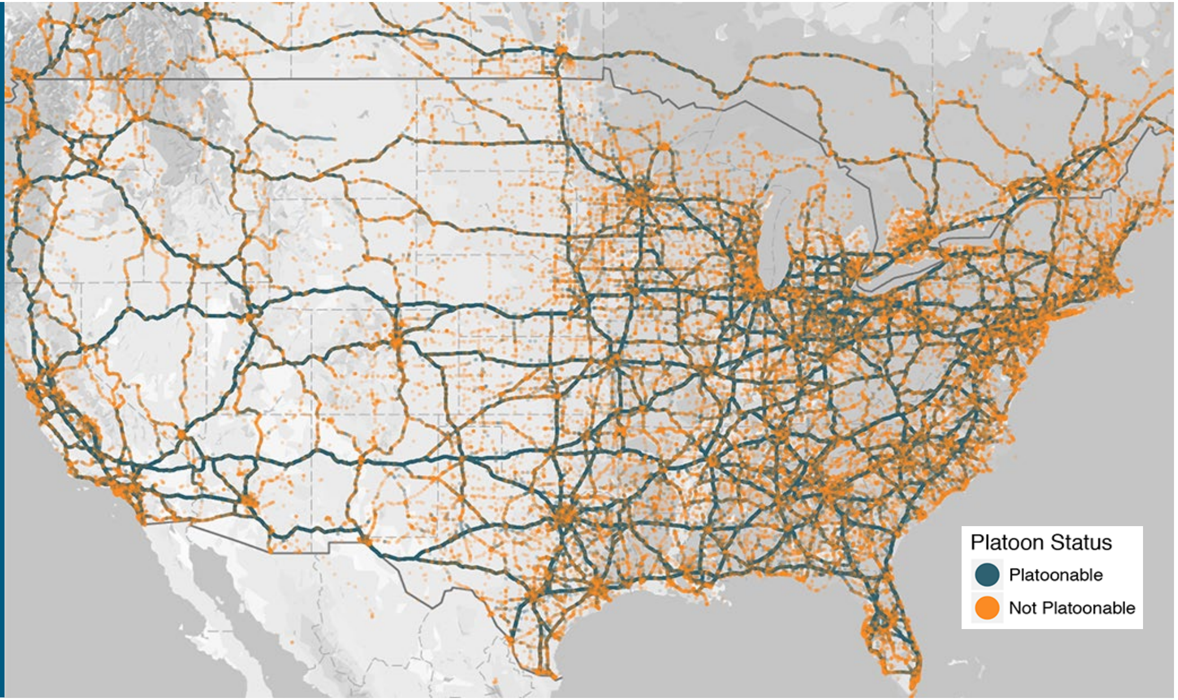




CLASS-8 TRUCK ON-ROAD PLATOON OPPORTUNITIES

60% of interstate and highway miles may be platoonable

- **Travel speed at least 50 mph for aerodynamic benefit**
- **Truck locations and schedules considered in platoon formation:**
  - within a **15 mile** radius
  - within a **15 minute** travel time window

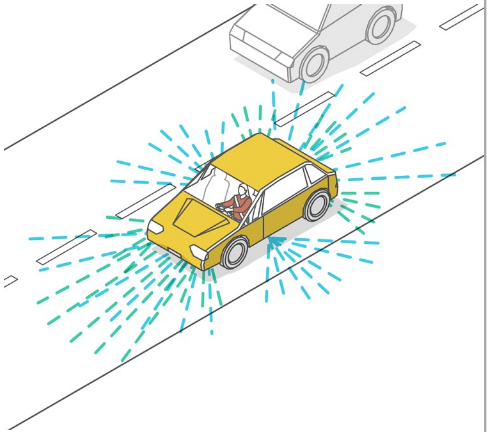


MANY ECO-FUNCTIONALITIES ENABLED AT LOWER ELECTRICAL LOADS

Significant benefits with loads much lower than driverless

400 W AUTOMATED ECO-DRIVING

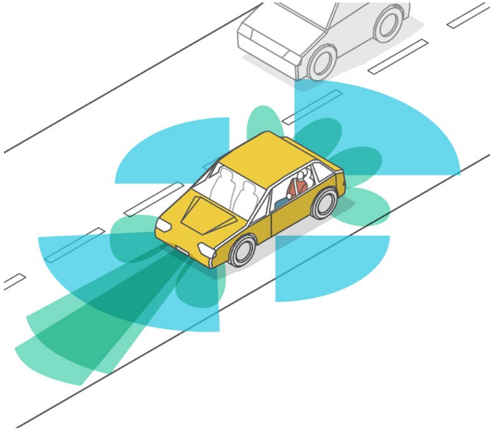
- Highway cruising and coordination
- Eco-approach
- Eco-signal
- Highway lane changes
- Vehicle repositioning and low speed operation



2,000 W DRIVERLESS

In addition:

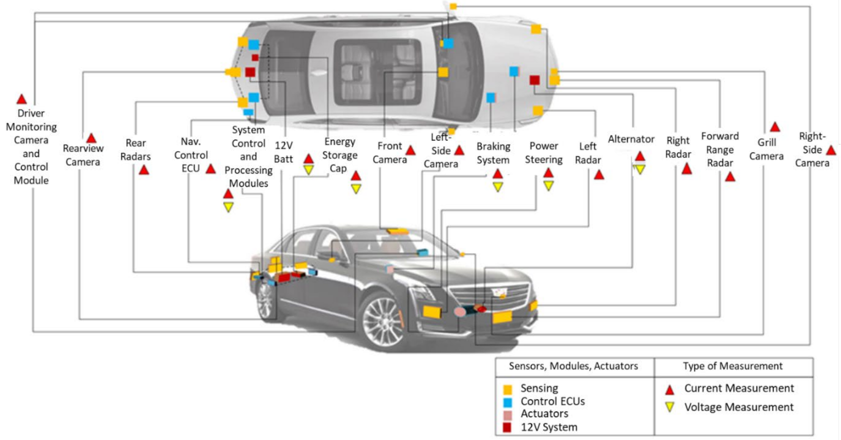
- Driverless operation including in dense urban environment



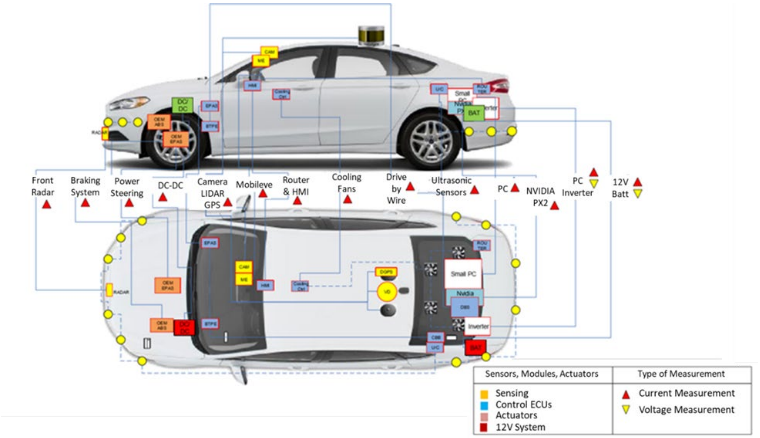
FUNCTIONALITIES ENABLED ACROSS A SPECTRUM OF ACCESSORY LOADS

Real-world vehicles testing highlights sensitivities and insights

Cadillac Super Cruise (~100W)

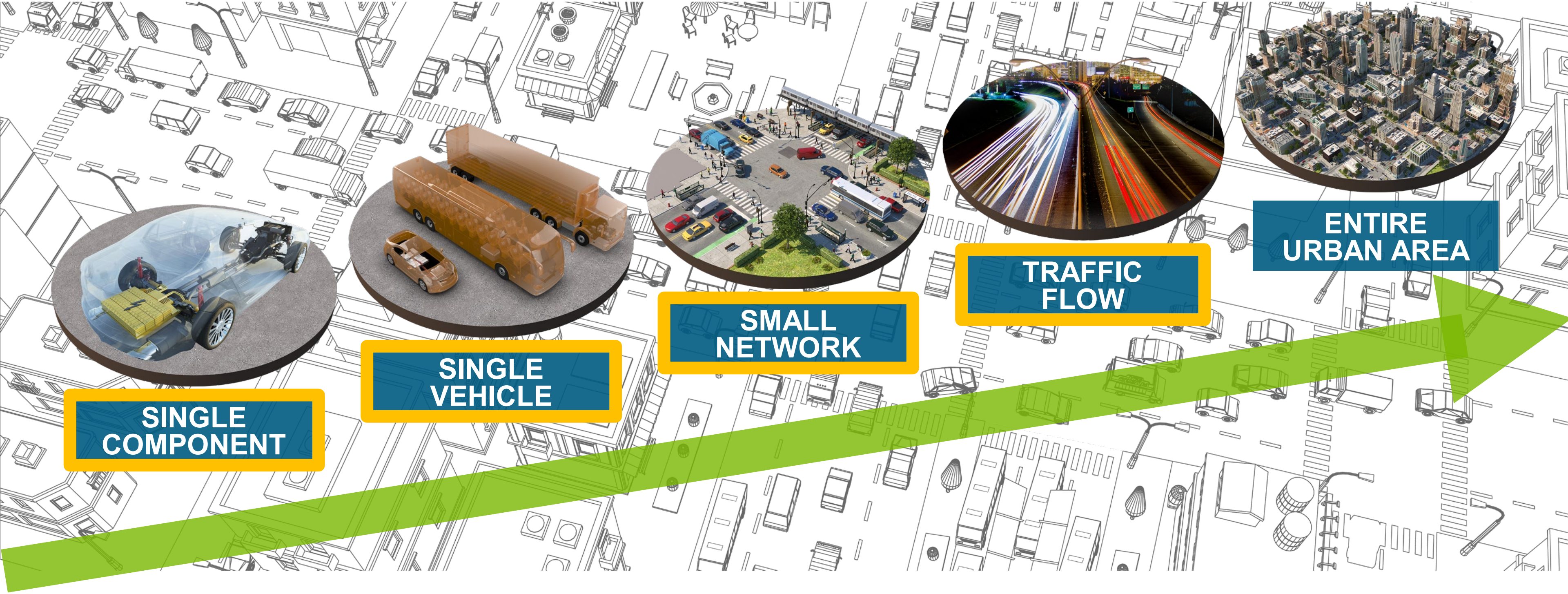


FEV Smart Demonstrator (~380W)



Automation loads are rapidly evolving –
balancing safety, additional functionality, processing improvements!

REFINING THE DOE VTO R&D PORTFOLIO



More details in SMART Mobility Modeling Workflow presentation

EVOLVING SIMULATION PORTFOLIO

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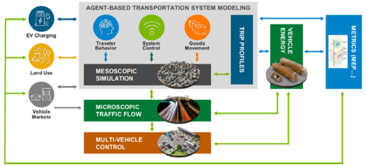
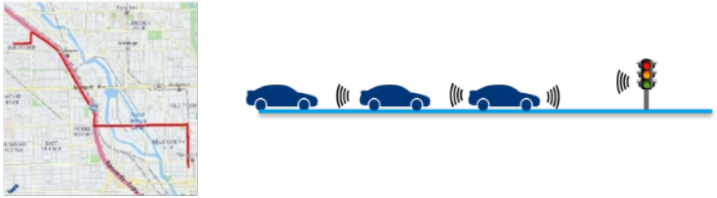
RoadRunner: Trip-Level simulation of powertrain and driving dynamics for energy-focused CAV controls development and evaluation

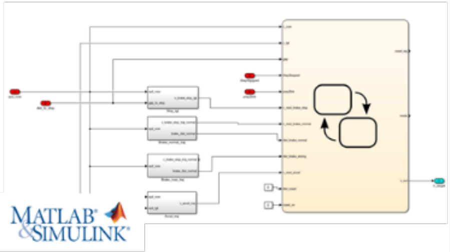


1. User Defines Scenario and Selects Powertrain

- Route (from HERE maps or synthetic)
- Connectivity level of traffic signals
- Number of vehicles
- Vehicle class and powertrain (Autonomie)
- Connectivity level of vehicles
- Driving control (human, automated, eco-driving, etc.)



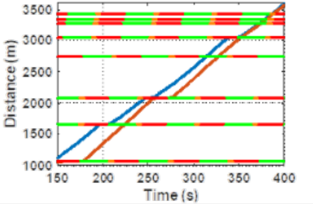
2. Simulink Model Building (Automated) and Simulation



3. Post-Processing & Quality Check (Automated)

4. User Analyzes Simulation Results

- Energy consumption
- Powertrain operating conditions
- Space/time trajectories
- Intersection crossings
- Inter-vehicle gap



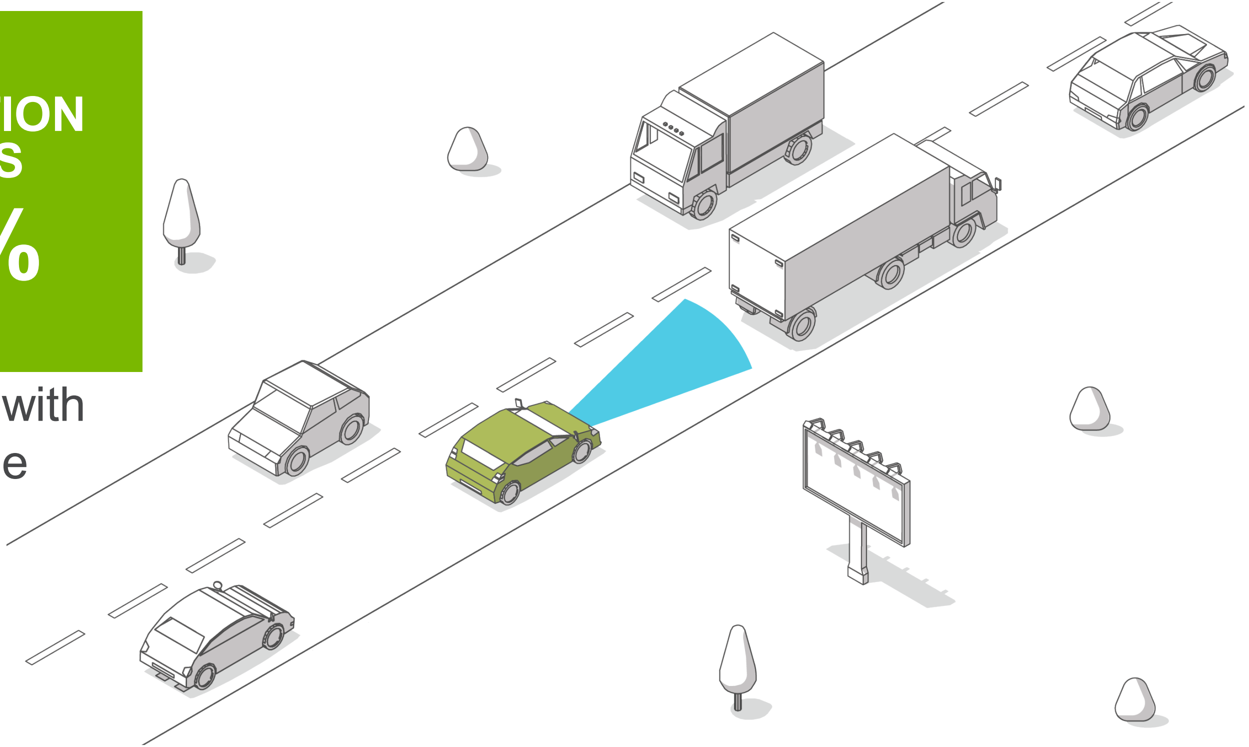
INDIVIDUAL ACC VEHICLE IMPROVES ENERGY CONSUMPTION

Impact of surrounding vehicles not included

FUEL CONSUMPTION DECREASES

5-7%

Collaboration with Volvo Drive Me Field Trials



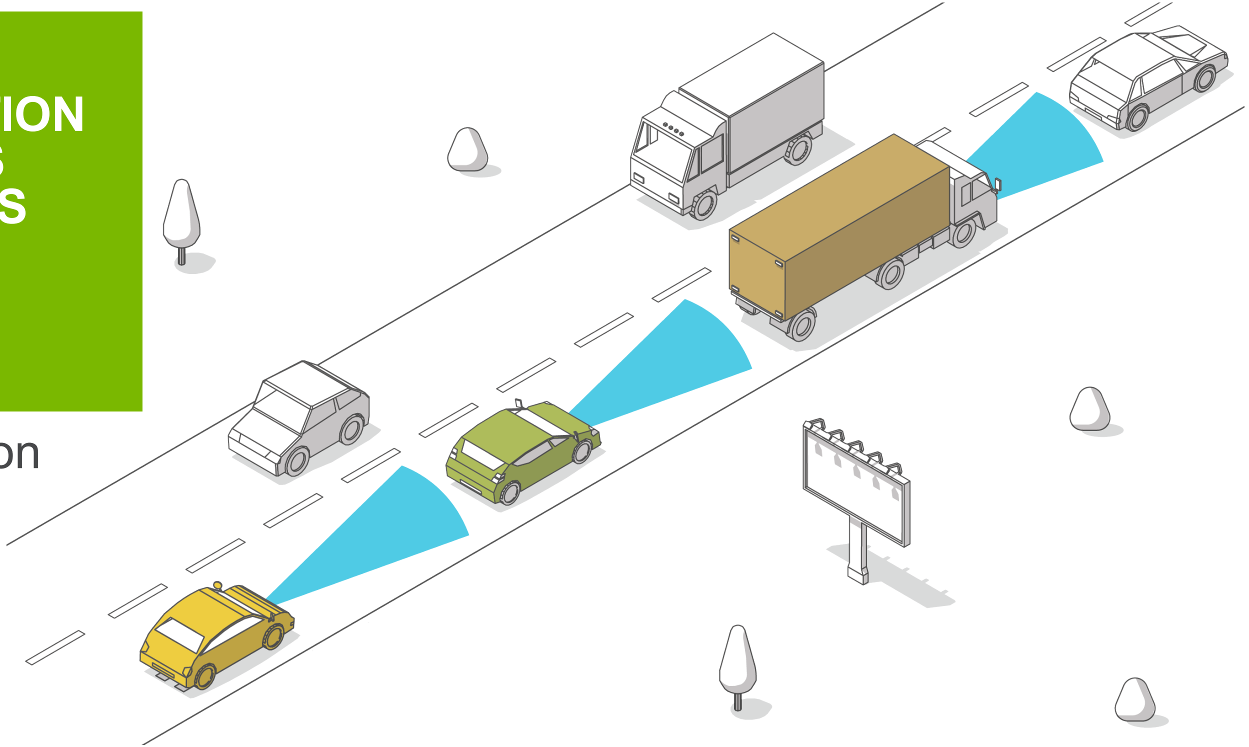
HIGH ACC PENETRATION MAY NEGATIVELY IMPACT TRAFFIC

Lack of communication leads to traffic instabilities, congestion

FUEL CONSUMPTION INCREASES AS MUCH AS

60%

Microsimulation

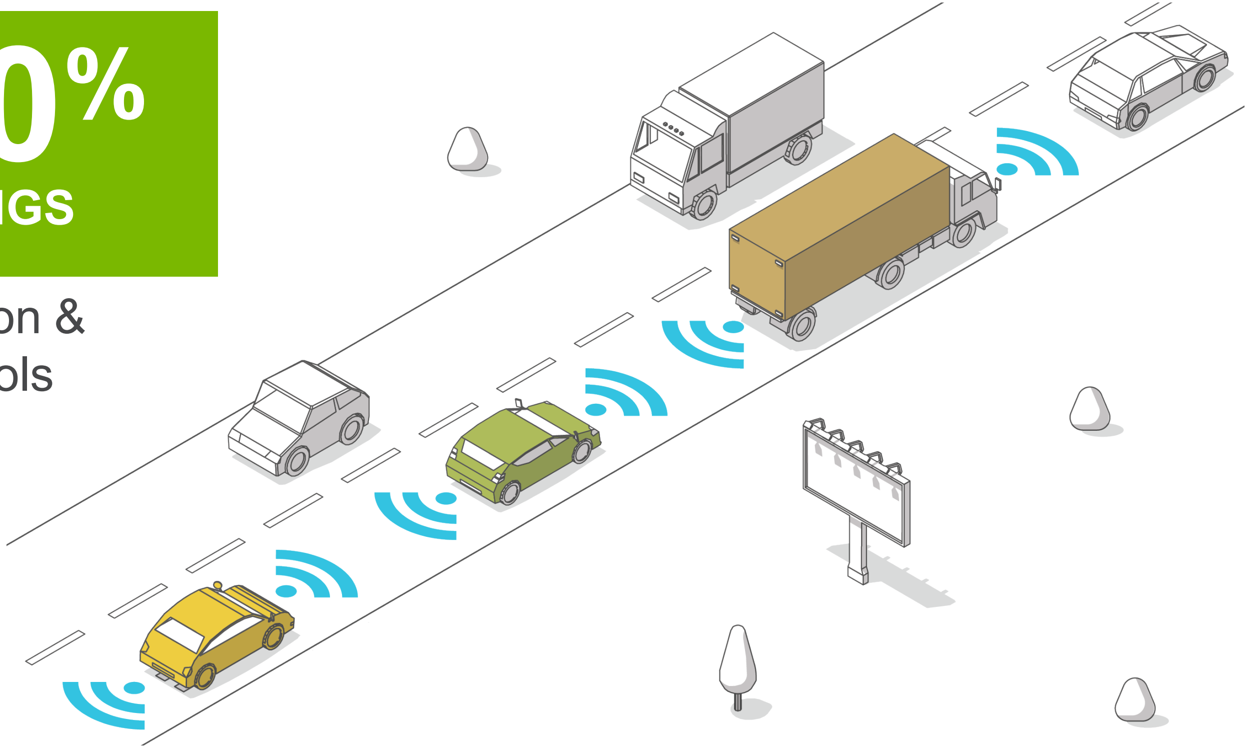


CACC HELPS TRAFFIC FLOW, LOWERS ENERGY USE

Vehicle communication + automation improves traffic flow

UP TO 20% FUEL SAVINGS

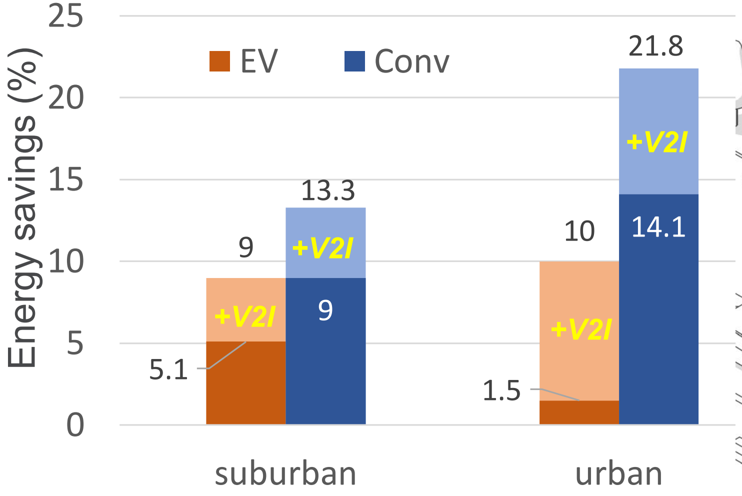
Communication &
Refined controls

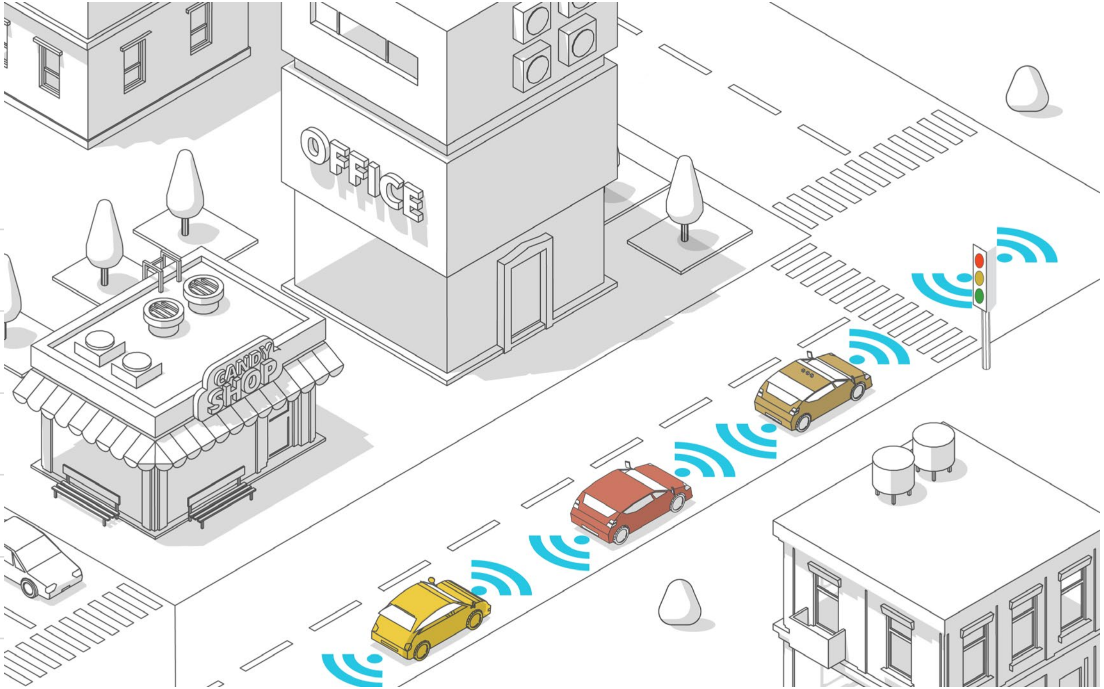


VEHICLE AND POWERTRAIN CONTROL OFFERS SIZABLE BENEFITS

Adaptation to conditions, other vehicles, traffic lights

UP TO 20% INDIVIDUAL VEHICLE FUEL CONSUMPTION REDUCTION





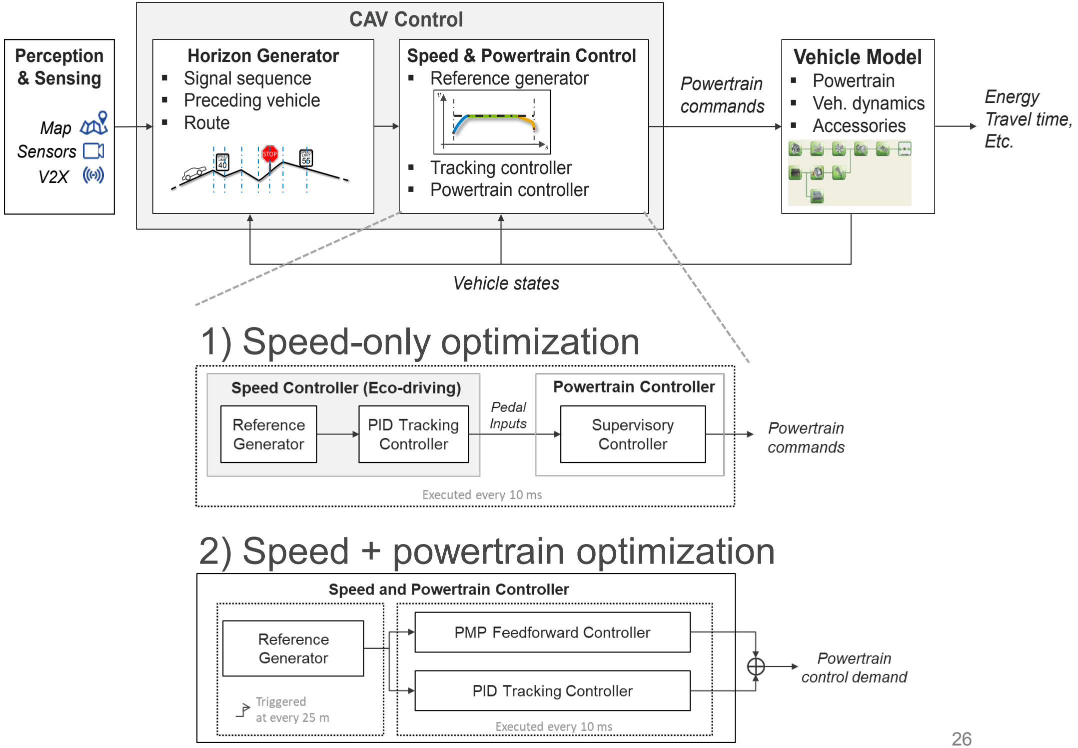
CAV-ENABLED VEHICLE AND POWERTRAIN CONTROL

Large-scale study of real-world implementable controls

Large-scale Simulation Study

4000+ simulations including…

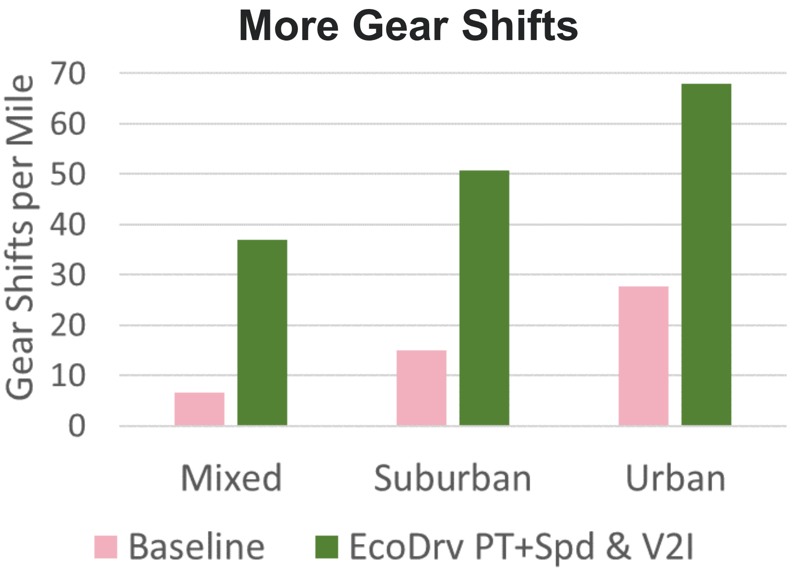
- Powertrain type + tech. scenario (Conv, HEV, BEV & current/future)
- Control type
- I2V connectivity
- Different lead/follow scenarios
- Real-world routes extracted from HERE maps (highway, suburban, urban, mixed)

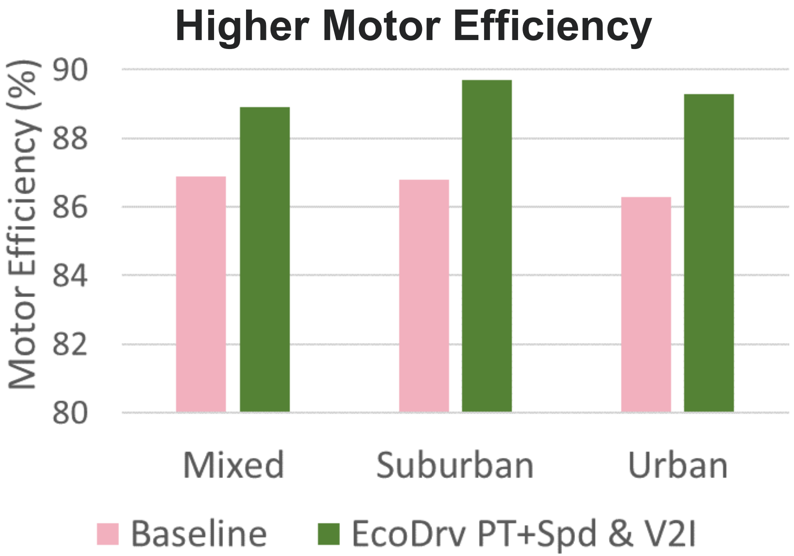


CAV-ENABLED VEHICLE AND POWERTRAIN CONTROL IMPACTS

Optimal CAV control also impacts component usage and efficiency

Large-scale Case Study Results - *HEV Component Sensitivities*



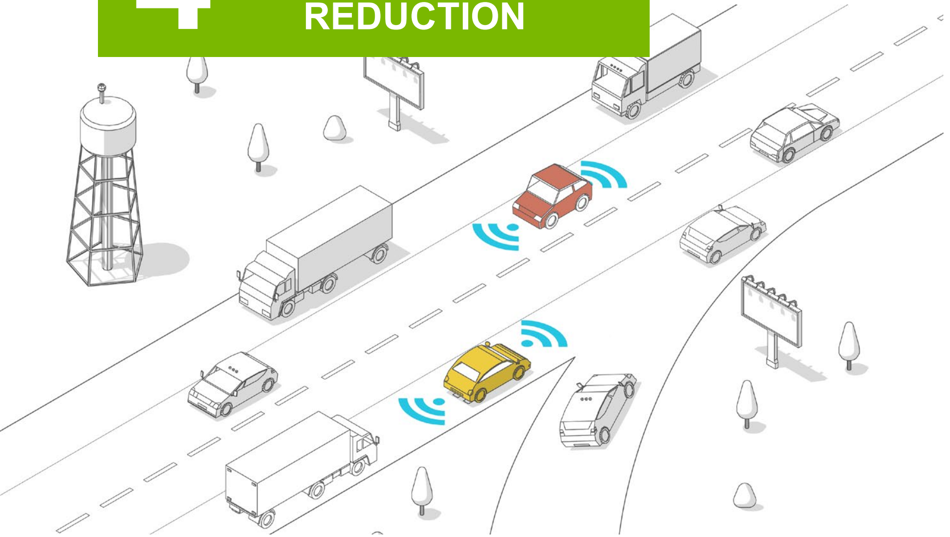


MODEST MARKET SHARE OF CAVS PROVIDES MERGING BENEFITS

Improvements estimated on 7 miles of I-75 Corridor

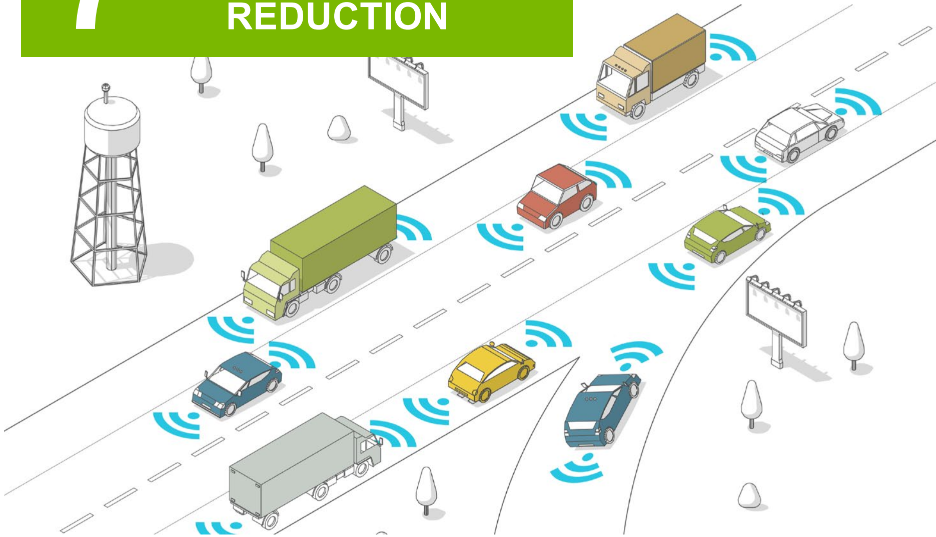
20% CAV PENETRATION

4% FUEL CONSUMPTION REDUCTION



100% CAV PENETRATION

7% FUEL CONSUMPTION REDUCTION



CAVS OPTIMAL COORDINATION FRAMEWORK

$$\min_{u_i} J = \min_{u_i} \frac{1}{2} \sum_{i=1}^{n} \int_{t_i^0}^{t_i^f} u_i^2 \, dt$$

Subject to:

Vehicle dynamics

$$\dot{p}_i(t) = v_i(t)$$
$$\dot{v}_i(t) = u_i(t),$$

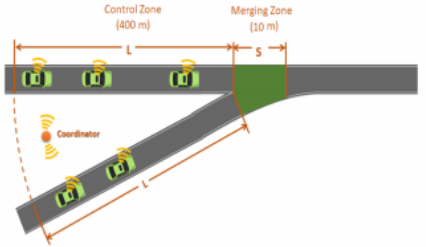
Boundary conditions

$$\dot{p}_i(t_i^0) = 0, \quad \dot{p}_i(t_i^f) \text{ given}$$
$$\dot{v}_i(t_i^0) \text{ given}, \quad \dot{v}_i(t_i^f) \text{ given}$$

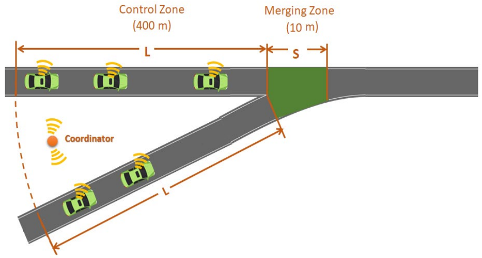
Safety Constraint

$$u_i \in R_i, \qquad R_i \triangleq \{u_i(t) \in [u_{\min}, u_{\max}] \,|\, p_i(t) \le p_k(t) - \delta,$$
$$v_i(t) \in [v_{\min}, v_{\max}], \forall i \in \mathcal{N}(t), |\mathcal{N}(t)| > 1, \forall t \in [t_i^0, t_i^f]\},$$

*Where R_i is the control interval, δ a safe headway distance and **k** the leader of vehicle **i**.*

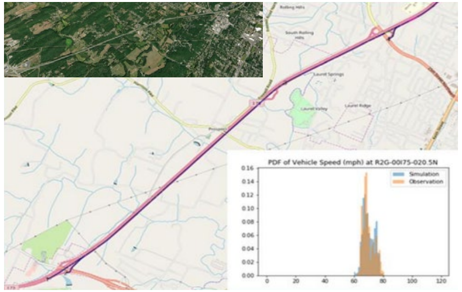


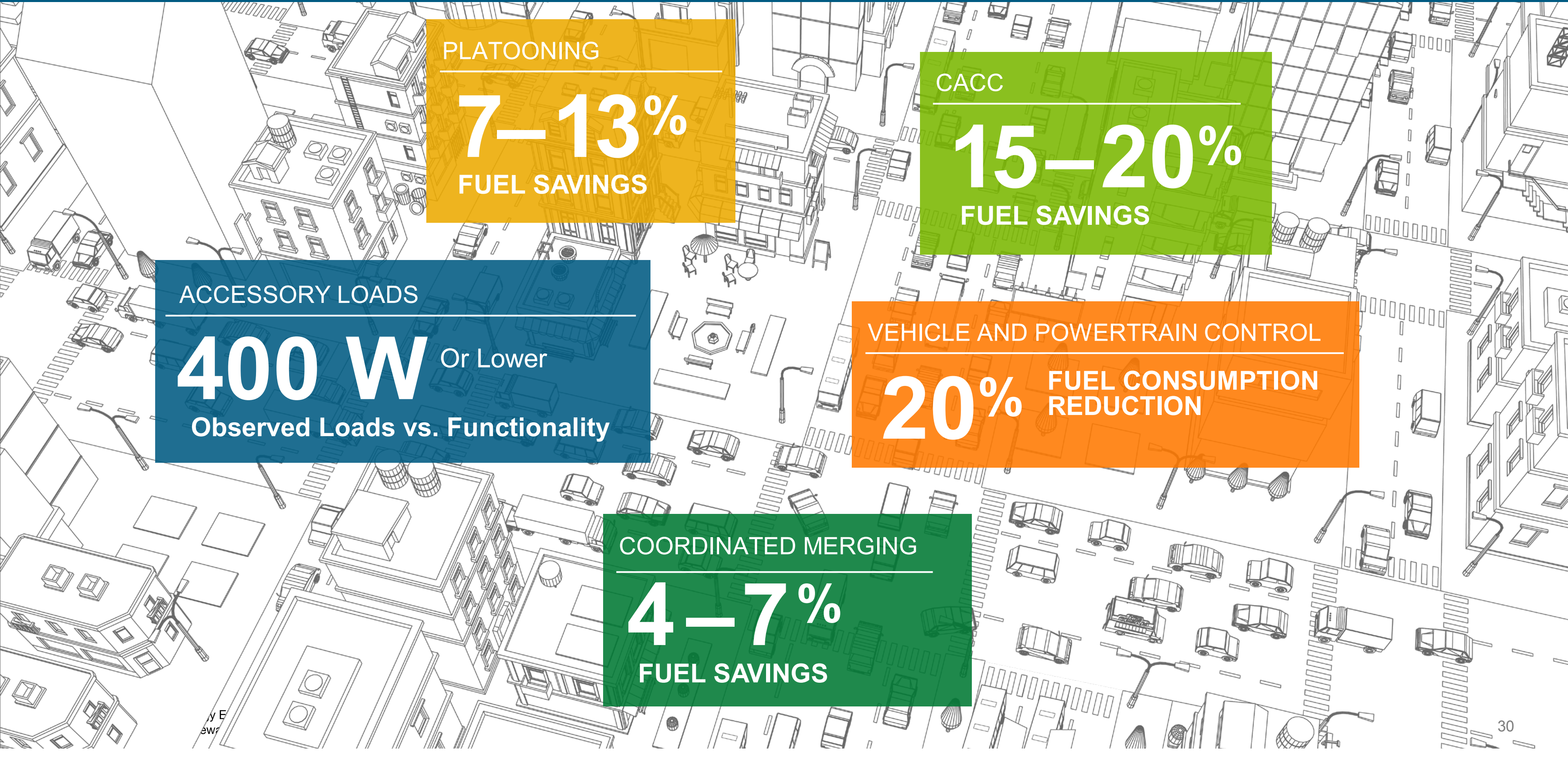
Simplified On-ramp Merge



Realistic On-ramp Merge

I-75 Real-world Corridor





PLATOONING

7–13%

FUEL SAVINGS

CACC

15–20%

FUEL SAVINGS

ACCESSORY LOADS

400 W Or Lower

Observed Loads vs. Functionality

VEHICLE AND POWERTRAIN CONTROL

20% **FUEL CONSUMPTION REDUCTION**

COORDINATED MERGING

4–7%

FUEL SAVINGS

Thanks to the CAV Focus Area Principal Investigators and Contributors:

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- **Many other researchers and collaborators!**

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