EEMS016
Pillar: CAV

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

Energy Efficient Connected and Automated Vehicles

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ARGONNE NATIONAL LABORATORY

2019 DOE Vehicle Technologies Annual Merit Review - June 2019

Argonne NATIONAL LABORATORY
INL Idaho National Laboratory
BERKELEY LAB
OAK RIDGE National Laboratory
NREL NATIONAL RENEWABLE ENERGY LABORATORY

Project Overview

Timeline

- Project start: Oct. 2016
- Project end: Sep. 2019
- Percent complete: 75%

Budget

- Total Funding (3 years): $2.3M
- FY18 Funding: $660,000
- FY19 Funding: $850,000

Partners

- Argonne: lead
- LLNL, LBNL: test data

Barriers

- Eco-driving research rarely integrates **advanced powertrain technologies**
- Combining dynamics and powertrain control results in **complex control problems**
- **Real-world implementation** often challenging
- Many **exogenous factors** (e.g. traffic), affect energy saving potential of eco-driving
- **Lack of practical tools** for "powertrain-aware" eco-driving algorithm development

Project Objectives and Relevance

CAV Eco-Driving Control: can we save energy through control of speed *and* powertrain? How much?

- For multiple powertrains: Conv., HEV, EV
- Automation levels 2 to 5
- For entire missions: real-world routes with mix of cruise-control, car-following, intersection approach and departure
- "Real-world implementable:" realistic I/Os, high-frequency feedback loop, adapted to powertrain response time

Enable energy efficient future mobility systems

CAV Simulation (RoadRunner): how to simulate CAVs, baseline, current and future technologies?

- Advanced powertrain technologies
- Multiple vehicles
- Road (speed limits, traffic lights, etc.)
- Driver (human or automated) reacting to environment
- Communication (V2X) & sensors

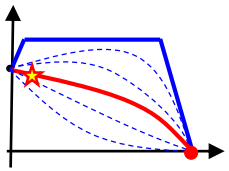
Tool for eco-driving research

Approach

CAV Eco-Driving: Control of Powertrain AND Longitudinal Speed

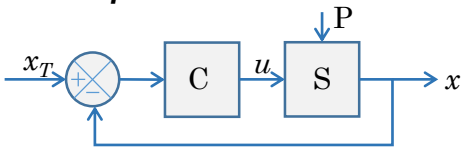
A. Optimization & Trajectory planning

- *Future horizon >> most energy-efficient state & control trajectory (speed, torque, SOC, etc.)*
- *Optimal control, Quadratic programming, etc.*



B. Real-Time Control

- *Current state >> what command to follow optimal state & ctrl. trajectory?*
- *MPC, Feedback loops, transients, dynamics*



Driving Scenarios

Powertrains

ROAD RUNNER

Energy Impacts

Real-World Data

Chassis Dyno
Track
On-road

CAV Modeling and Validation

Platooning, ACC, Human Driving

Milestones

Energy impact of eco-driving strategies under different scenarios
✓*Complete*

Eco-driving: Demonstrate a "real-world implementable" controller working online in RoadRunner environment
✓*On track*

Quantify energy impact of advanced optimal eco-driving over a range of representative scenarios
✓*On track*

Validate model of a CAV
✓*Complete*

RoadRunner: Complete the development and validation of human and automated driver models.
✓*On track*

Accomplishments:
Model Validation in RoadRunner

Validated Model of a 3-Truck Platoon

With EEMS033

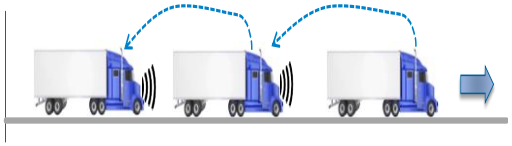
Field test of CACC trucks

Test data of 3-truck CACC operation at freeway speed for modeling & validation. (**EEMS033**)

Data analysis

Importing test data into Autonomie, Analysis on shifting pattern, initial position,..

IDM/ACC/CACC development



Vehicle model /controller calibration

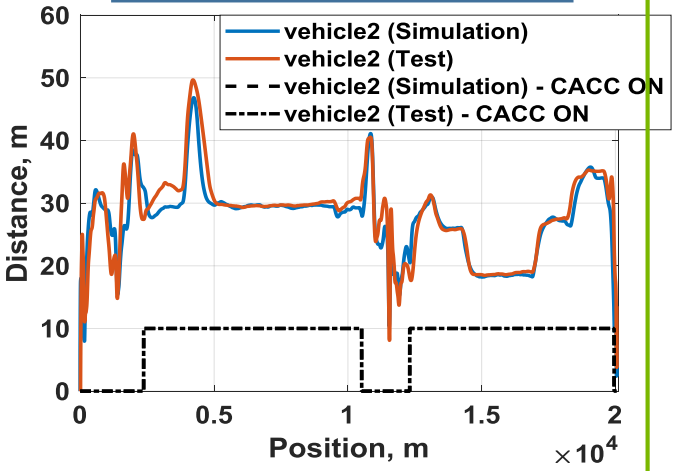
Conv. Class8 Linehaul with 12 speed transmission in Autonomie

Model validation

ROAD RUNNER

Compare test data with simulation results

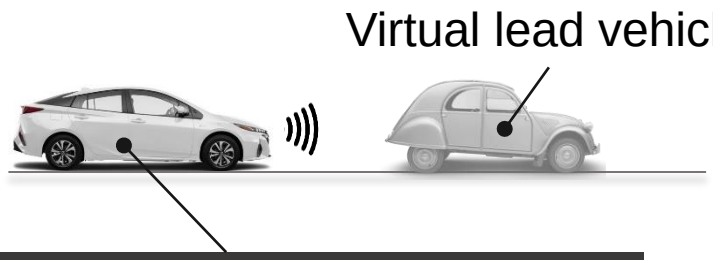
Inter-vehicle gap



Fuel Consumption : (Δ< .5%)

Validating Prius Prime PHEV ACC Model

With EEMS041

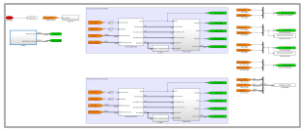


Ego vehicle

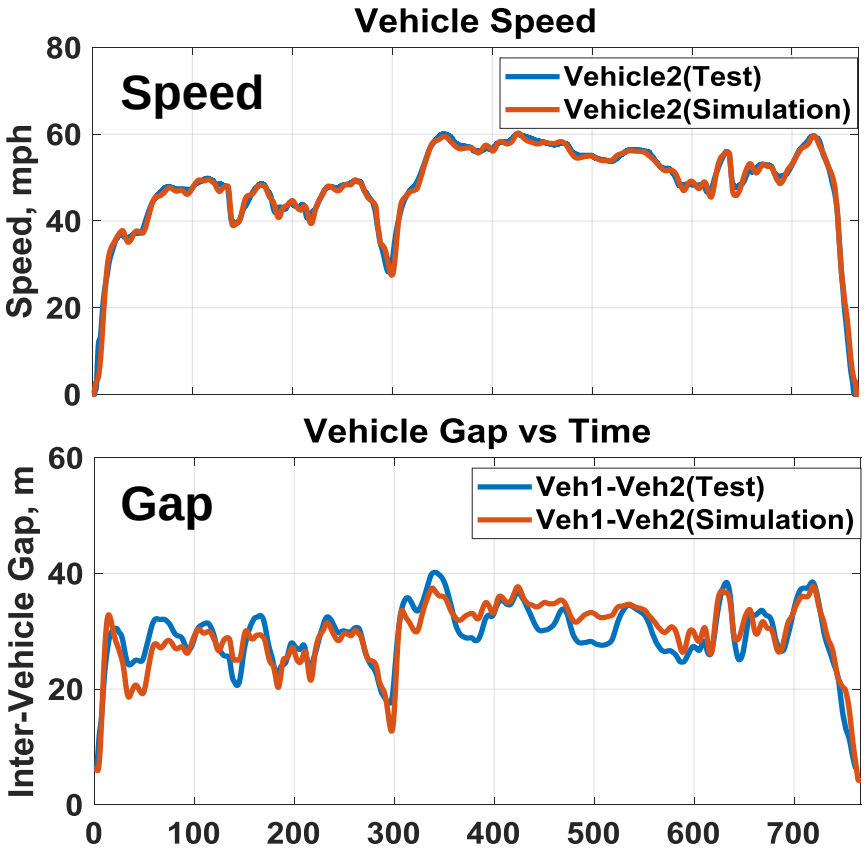
Chassis Dynamometer

*Toyota Prius Prime PHEV w/ sensor override to emulate distance to preceding vehicle, stock Adaptive Cruise Control (ACC) – **EEMS041***

RoadRunner



Previously validated Prius Prime PHEV Autonomie model + new ACC model

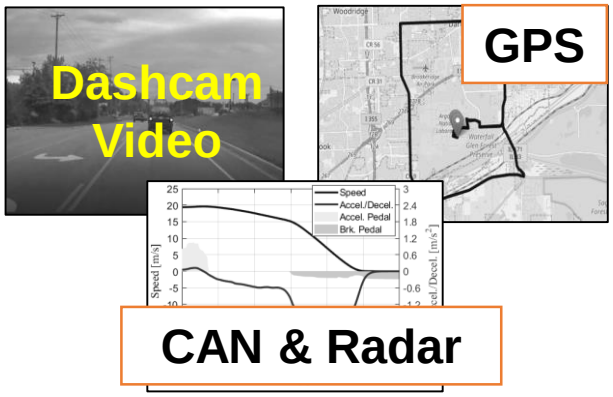


Developed Human Driver Model

With EEMS045

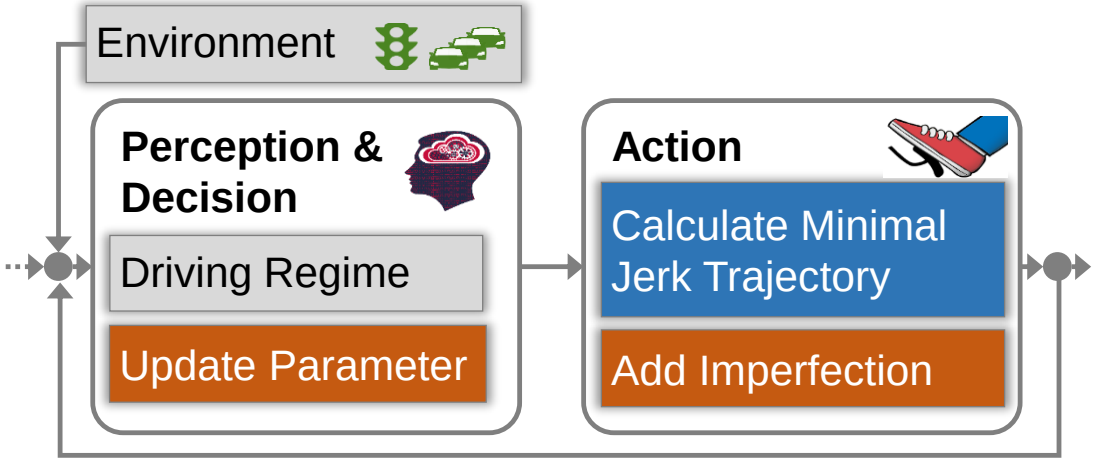
"Feature-Rich" On-Road Data Collection

Instrumented vehicles

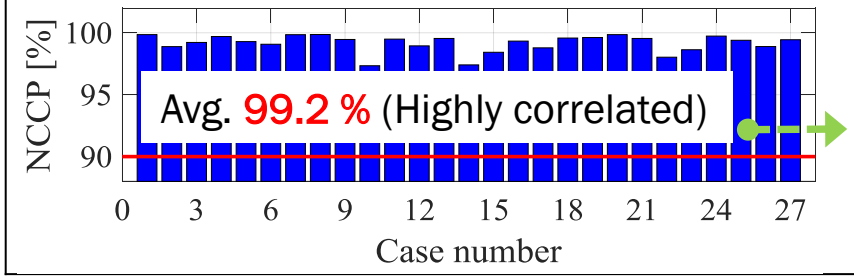


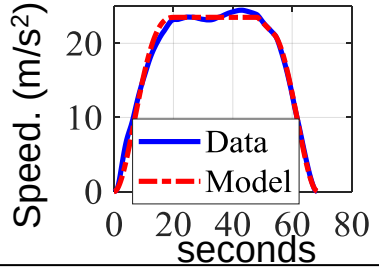
Human Driver Model Development

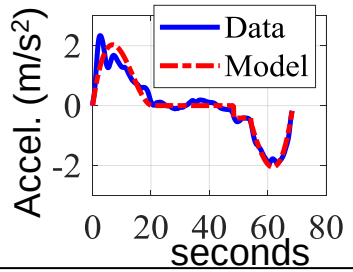
- Data-driven ( ) and Analytical Approach ( )



Model Validation (Compare experimental data with model)

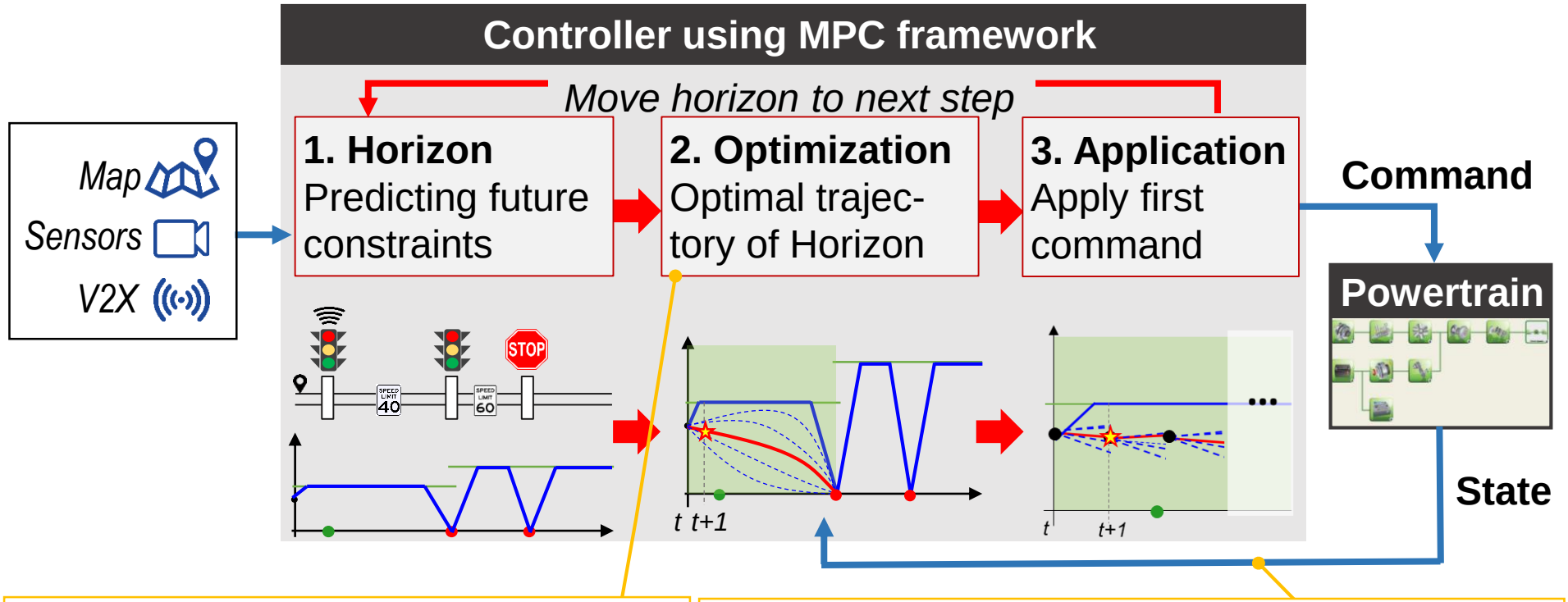






Accomplishments: Real-World Implementable Eco-Driving Control for CAVs

Model-Predictive Control (MPC) Framework for Real-Time Implementation of Optimization Algorithms



Optimization algorithms (solvers)

- Quadratic Programming (QP)
- PMP for dynamics only
- PMP for dyn. + powertrain

Feedback loop allows real-time implementation:

- Optimization model is simplified
- Knowledge of environment is imperfect
- Future speed of preceding vehicle unknown

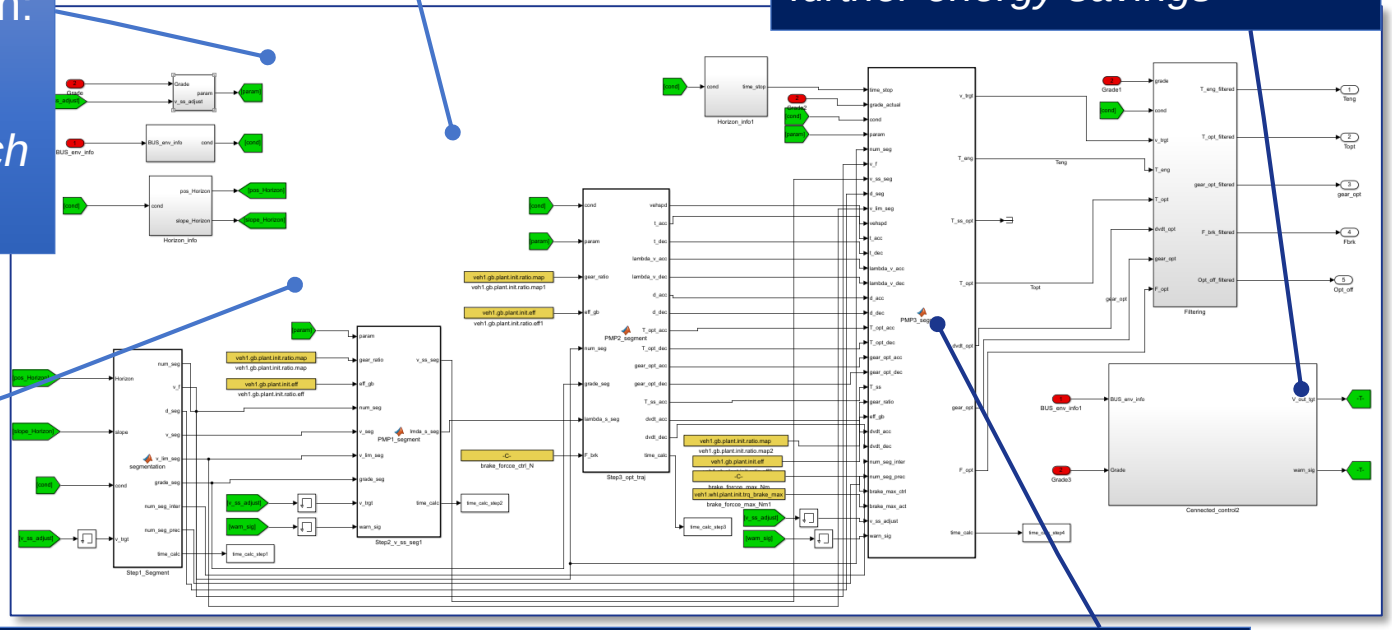
MPC Controller Implemented in RoadRunner with Various Optimization Options

Interfaces with complex dynamic systems; deals with **transients**, **constraints**, **delays**, etc.

Eco-approach with V2I: *Can use traffic signal phase and timing if available for further energy savings*

Works for entire mission:
- *cruising*
- *car-following*
- *intersection approach and departure*

Real- world Implementable



Two **optimization** options:
- 1. **Speed/Acceleration optimization** only (EcoDrv Spd/Accel)
- 2. **Powertrain and speed co-optimization** (EcoDrv PT+Spd)

1. Speed Optimization with Analytical Solution (No Powertrain)

EcoDrv Spd/Accel

Eco-Driving Optimal Control Problem

$$J = \int_{t_0}^{t_f} a^2 \, d\tau \quad + \quad \begin{aligned} \dot{s} &= v \\ \dot{v} &= u \end{aligned}$$

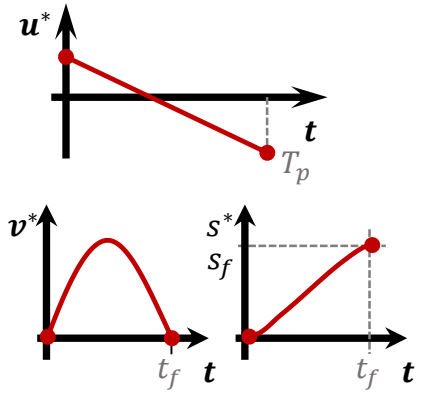
Minimize Acceleration — ***Vehicle Dynamics***

Command $u = a$ (acceleration)
States s : distance, v : speed

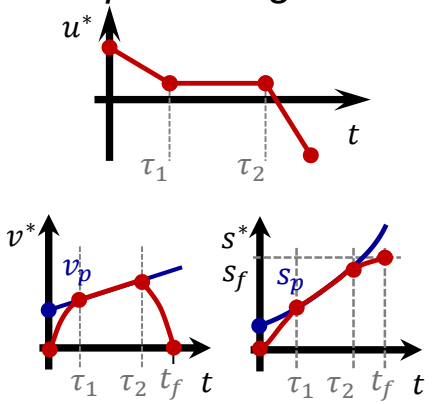
Simple analytical solution

Pontryagin Minimum Principle (PMP)

Without preceding vehicle



With preceding vehicle

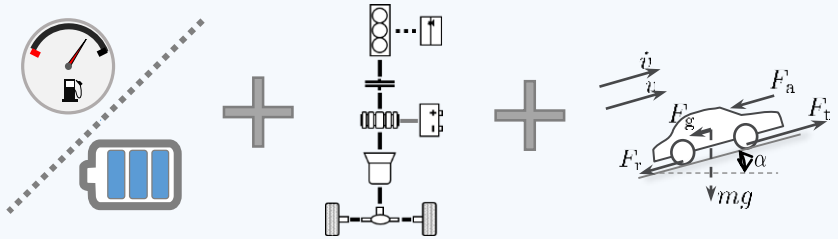


- Simple model allows analytical solution
- Powertrain not taken into account, so it can be applied to any vehicle
- Not sensitive to grade

2. Optimization for Combined Powertrain and Speed Control

EcoDrv PT+Spd

Eco-Driving Optimal Control Problem



Minimize Fuel/Energy + ***Powertrain Dynamics*** + ***Vehicle Dynamics***

Command = torques, gear, clutch

- Powertrain-specific to achieve maximum energy savings
- Takes into account grade
- Requires some numerical solvers

Pontryagin Minimum Principle (PMP)

Minimize Hamiltonian

$$H = P + \lambda_v \dot{v} + \lambda_s \dot{s}$$

Power

P_f Fuel power (Conv)

P_b Electric power (EV)

$P_f + \lambda_E P_b$ Equivalent power (HEV)

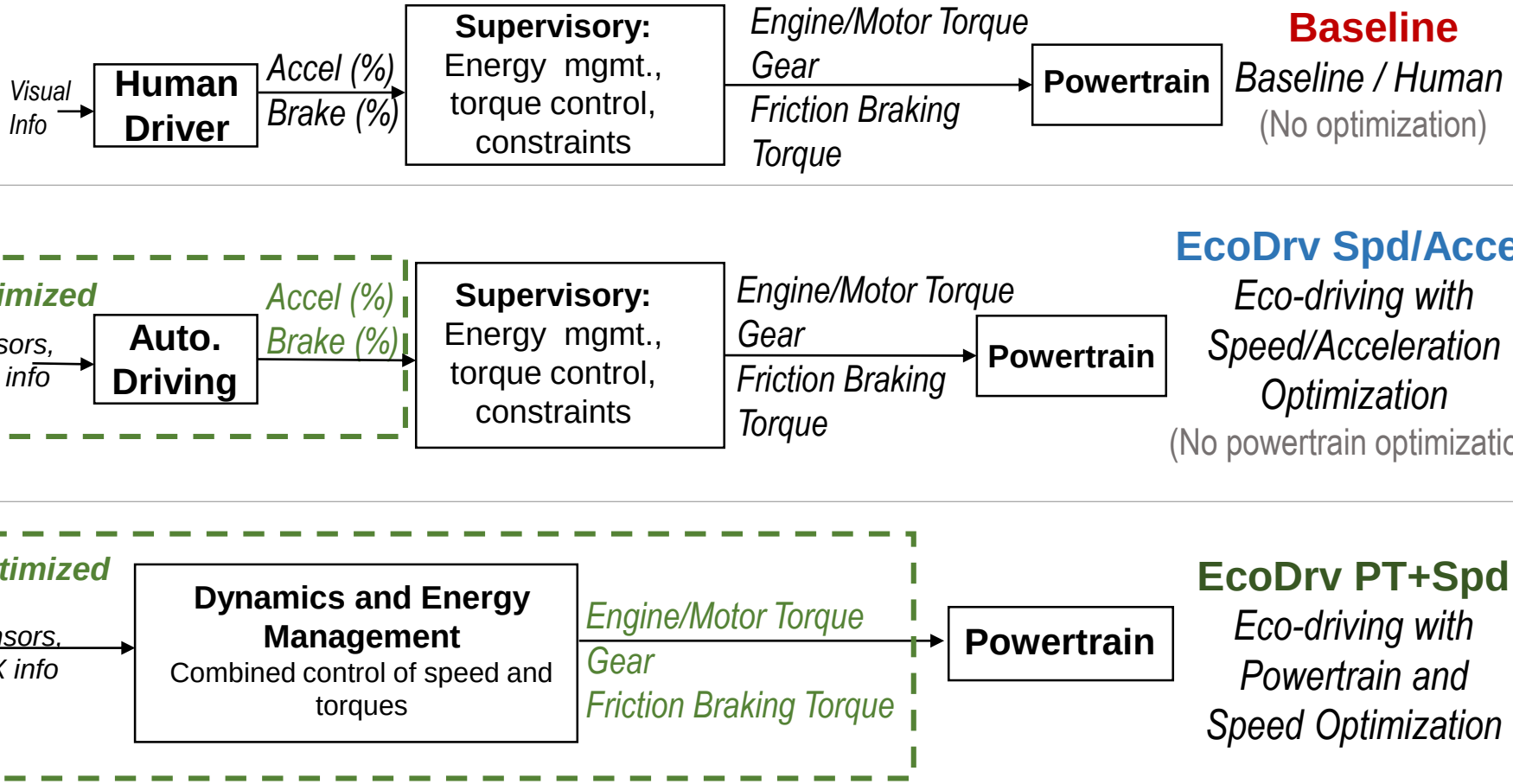
veh. dynamics

Completed optimization algorithm for:

- 3 powertrains (Conv., EV, HEV)
- Periodic control (“Pulse and Glide”)
- Stop approach and departure
- Car-following

Milestone 2018Q4 | ✓*Complete*

Summary of Control Strategies Used in Case Study

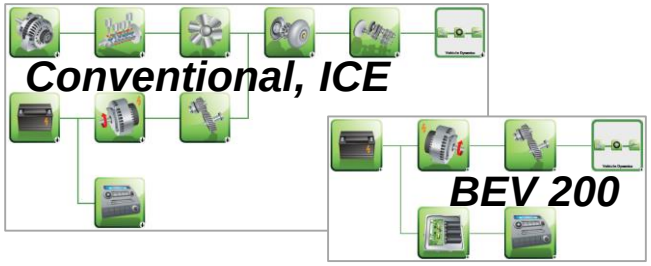


Accomplishments:
Energy Impact of CAV Eco-Driving Control
(Preliminary Results)

Simulation Setup: A Large Number of Scenarios for a Representative Energy Impact Evaluation

Vehicles

Midsize, Current Tech.



Routes

Real-world routes
Data from HERE maps
14 Mixed
6 Suburban
8 Urban
16 Highway

Scenario

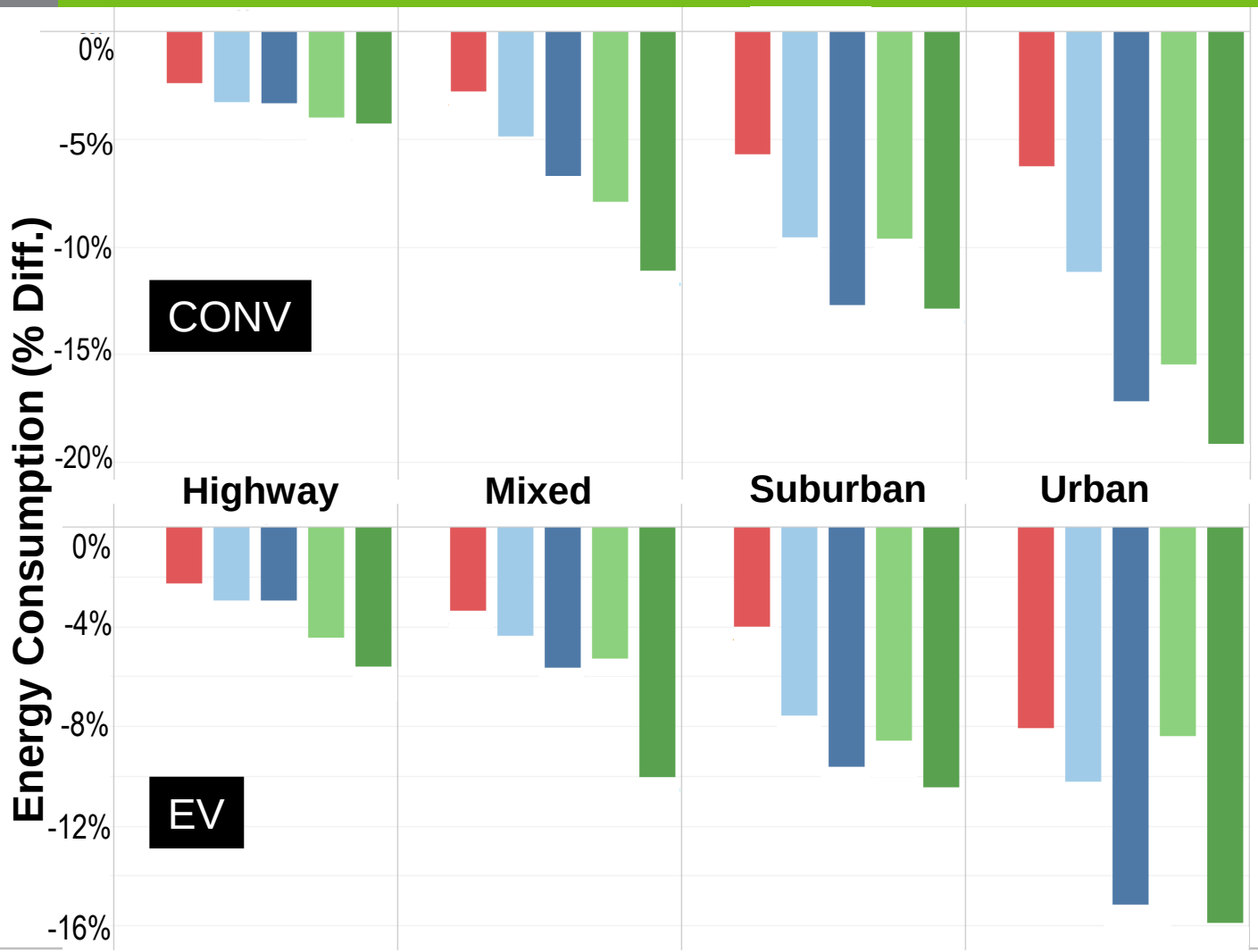
2 vehicles

Traffic signal phase and timing info (V2I): 0% or 100%

Control

Control	Description
Baseline	Baseline, no optimization
EcoDrv Spd/Accel	Eco-driving with Speed/Acceleration Optimization
EcoDrv PT+Spd	Eco-driving with Powertrain and Speed Optimization

Lead Vehicle: Eco-Driving Saves Energy; Greater Savings with Powertrain Awareness and V2I



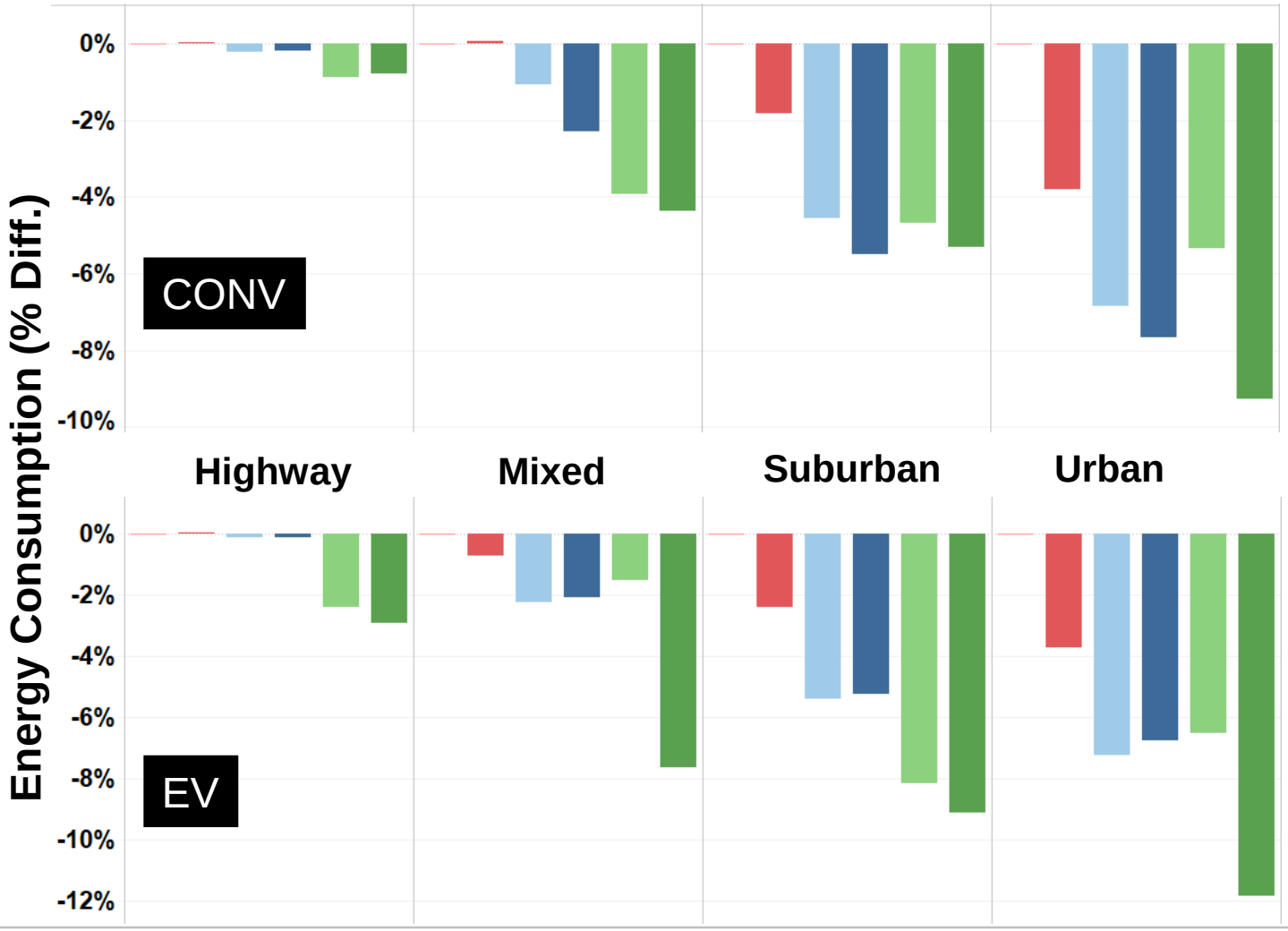
Control

- **Baseline**
- **Baseline + V2I**
- **EcoDrv Spd/Accel**
- **EcoDrv Spd/Accel, V2I**
- **EcoDrv PT+Spd**
- **EcoDrv PT+Spd,V2I**

Scenario

Lead vehicle, control vs baseline

Non-Equipped Vehicles also Save Energy Thanks to Optimized Lead Vehicle



Control

- Baseline
- Baseline + V2I
- EcoDrv Spd/Accel
- EcoDrv Spd/Accel,V2I
- EcoDrv PT+Spd
- EcoDrv PT+Spd,V2I

Scenario

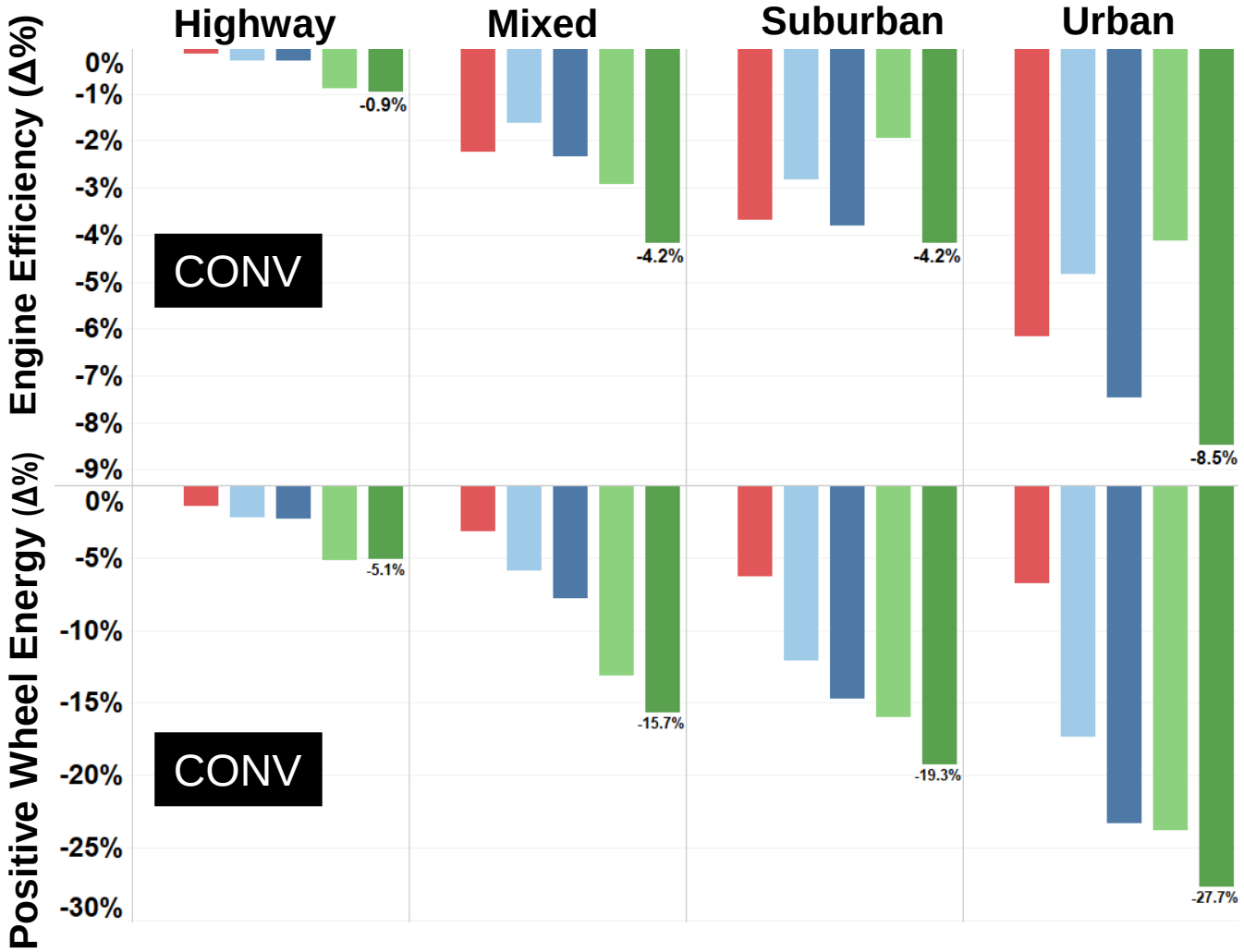
Baseline Optimized

Vs.

Baseline Baseline

We are looking at the consumption of the following vehicle

Eco-Driving Reduces Engine Efficiency and Positive Tractive Energy



Control

- Baseline
- Baseline + V2I
- EcoDrv Spd/Accel
- EcoDrv Spd/Accel, V2I
- EcoDrv PT+Spd
- EcoDrv PT+Spd,V2I

Scenario
Lead vehicle, control vs baseline

Closing Remarks

Response to Previous Year Reviewers' Comments

Reviewer Comments	Response
Reviewer prefers this approach *over stating large fuel economy improvements for very specific situations*	We significantly expanded the number of scenarios to make our results even more representative
Why both an offline (optimization) and online *(model predictive control [MPC]) framework had been used [?]*	Optimization finds optimal trajectories over a horizon. MPC provides a framework to use these optimization algorithms in real-time with a feedback loop.
Increased collaboration with OEMs is needed *to ensure optimal control assumptions are possible in a production setting, and to correlate results with currently developed CAV systems.*	• Models of existing CAV validated when data becomes available. • Team had positive feedback from OEM R&D. • We are building partnerships to demonstrate our control algorithms in actual vehicles (FY20 and beyond, provided funding)

Partnerships and Collaborations

BERKELEY LAB	Truck platooning data [**EEMS033**] CACC testing data (future work) [**EEMS059**] Mortar task (RoadRunner + micro-simulation) [**EEMS076**]
Lawrence Livermore National Laboratory	Aerodynamic drag reduction coefficients from 3D modeling and wind tunnel
TARDEC	Demonstrating RoadRunner for TARDEC use cases
Argonne NATIONAL LABORATORY Advanced Mobility Research	“Feature-rich” on-road test data from [**EEMS045**] “Math-to-lab-to-road” initiative [**EEMS041**]
Other SMART	RoadRunner Core development [**EEMS058**] Autonomie vehicles for SMART studies [**EEMS058**]
OEMs	Presentations, discussions, sharing of prototypes

Remaining Challenges and Barriers

- *Human and CAV model development in RoadRunner:*
  - **Quality data is in short supply**, limiting how representative models are
  - Human driver model improvements so far focused on **stop approach**
- *Eco-driving controller with optimization of speed and powertrain:*
  - **Conventional** and **EV** powertrain for now
  - Some **manual tuning** required (e.g. setting target speed)
  - **Powertrain dynamics** & Drivability/NVH need to be improved (shifting events, accelerations)
- *CAV energy impact case study:*
  - **2 Autonomie** vehicles for now (Conv., EV with current technology)
  - **Traffic** situations not modeled at this point
  - **Travel time** not exactly the same

Proposed Future Research*

- *Continue human and CAV model development in RoadRunner*:
  - Improve acceleration and cruising modes for the **human driver model**
  - Complete CAV validation work (**Prius ACC**, **CACC**)
- *Finalize eco-driving controller with optimization of speed and powertrain:*
  - Complete controller for **HEV**
  - Improve handling of **transients**
- *Rerun larger and more representative CAV energy impact case study:*
  - Add vehicles with **future technologies** (e.g. better efficiency and higher accessory load for future vehicles) developed for SMART
  - Add scenarios with **traffic [EEMS076]**
  - Analyze **energy savings/travel time trade off** for each controller

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

Summary: On-Track to Complete Original Year 3 Goals

Developed models and algorithms

- ✓ **Validated RoadRunner models** of human driving, truck platooning, ACC
- ✓ **Developed real-world implementable CAV eco-driving controllers:**
  - *Optimization of powertrain AND speed*
  - *Multiple powertrains: conventional, EV, HEV (in progress)*

Evaluated energy impact

- **5% to 17%** energy savings for CAV in lead position w/ V2I
- Optimizing powertrain AND speed saves extra **1-5%**
- V2I brings **3% to 8%** (pts) extra savings
- Non-CAVs also benefit (**~10%** savings) [following a CAV]

Future research

FY20 & Beyond
(Provided funding)

- Expanded impact case study
- Collaborative eco-driving
- In-vehicle/on-road testing and demo
- Powertrain design optimization for CAVs

EEMS016
Energy Efficient Connected and Automated Vehicles

Thank you!

Dominik Karbowski

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Daliang Shen

Jihun Han

Technical Back-up Slides

RoadRunner: a Framework to Simulate Powertrain and Driving Dynamics for CAVs

ROAD RUNNER

- ☑ Eco-driving control for CAVs
- ☑ CAV energy impacts
- ☑ Powertrain Component operating conditions
- ☑ Predictive Powertrain Control

MATLAB & SIMULINK — Matlab/Simulink, 10ms sample time, dynamic models

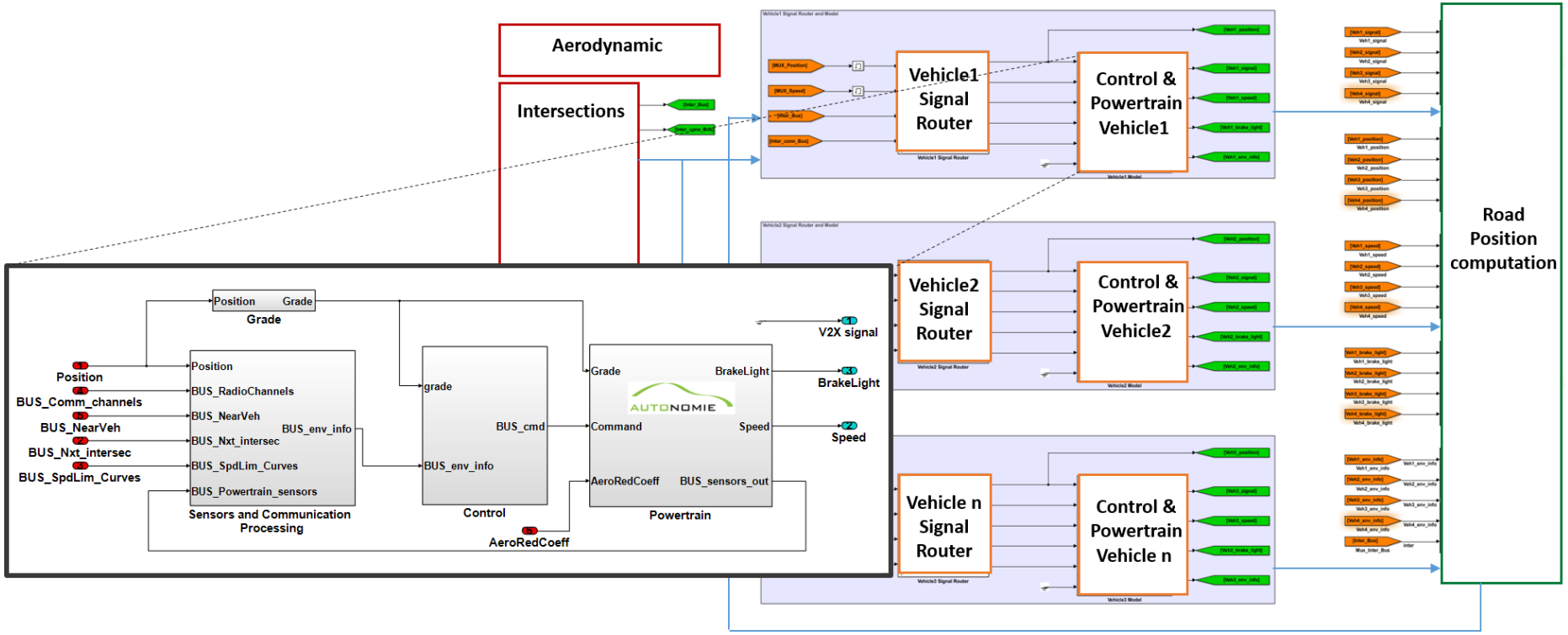
AUTONOMIE — Full powertrains models for from Autonomie

here — Road attributes from HERE maps

CARLA — Links with CARLA

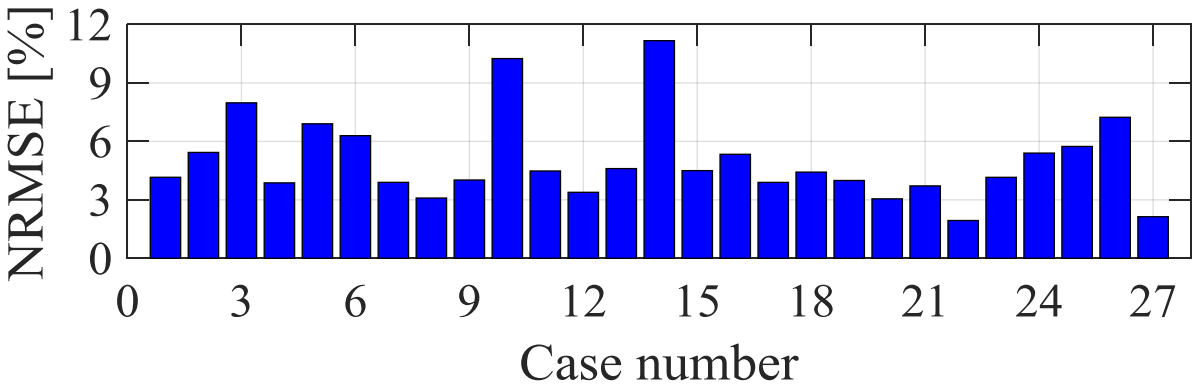
3D environment for autonomous driving

RoadRunner Model Architecture



Validated Human Driver Model

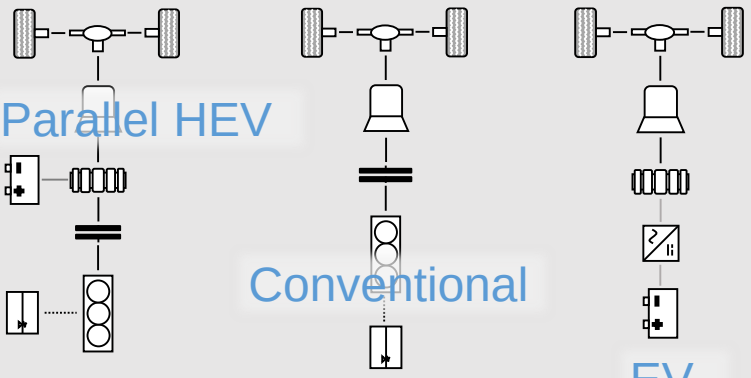
- Two Measures
  - Normalized Cross Correlation Power (NCCP)
    - $\text{NCCP} = \frac{\max[R_{xy}(\tau)]}{\max[R_{xx}(\tau), R_{yy}(\tau)]}$, where $R_{xy} = \lim_{T\to\infty} x(t) \circ y(t-\tau)dt$
  - Normalized Root-Mean-Squared-Error (NRMSE)
    - $\text{NRMSE} = \frac{\sqrt{\sum_{i=0}^{T}(x_i - y_i)^2/T}}{(y_{\max} - y_{\min})}$
- Validation Results for 27 cases



Avg. 5.02 % (small error)

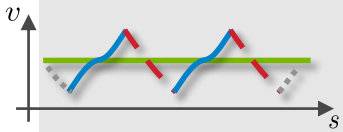
Optimization for Combined Powertrain and Speed Control in Various CAV Scenarios

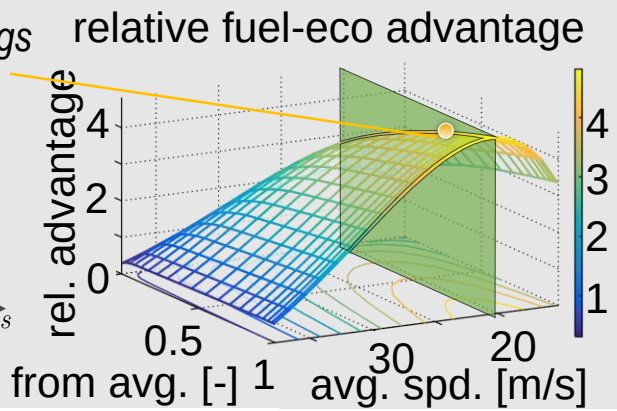
3 Powertrain Options



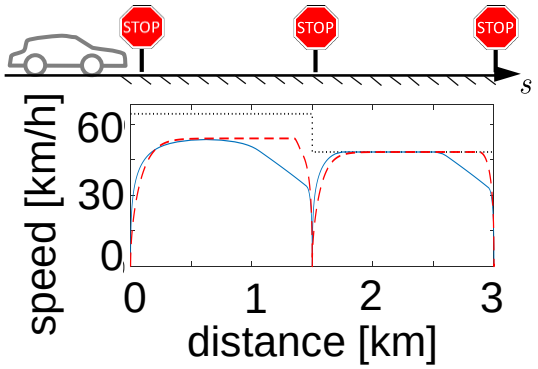
Periodic Cruise-Control

Up to 4.8% savings on highway

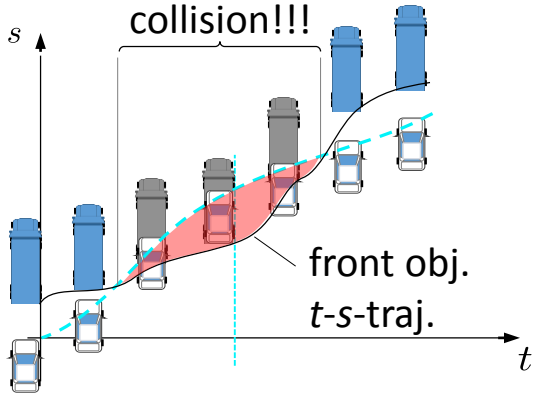




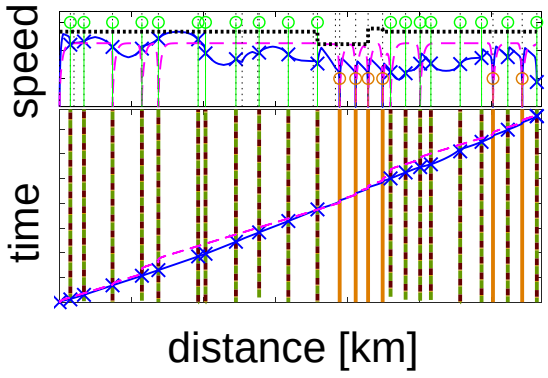
Stop Approach & Departure



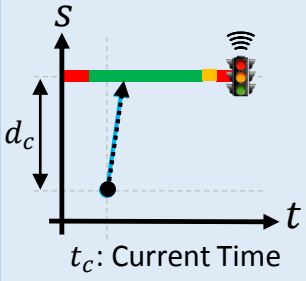
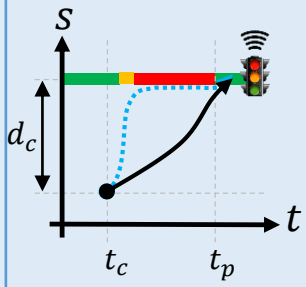
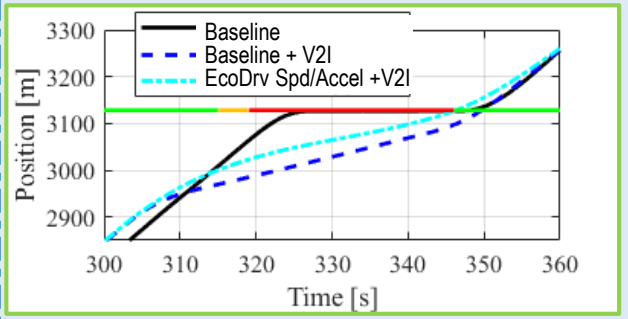
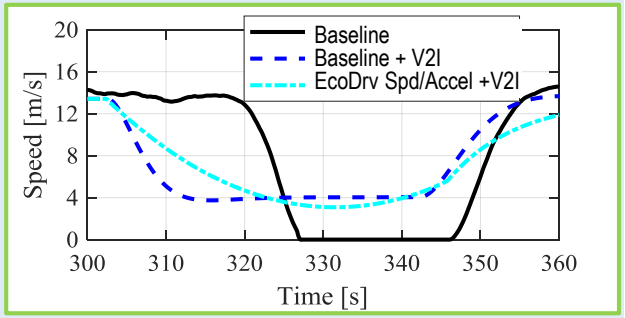
Car-Following



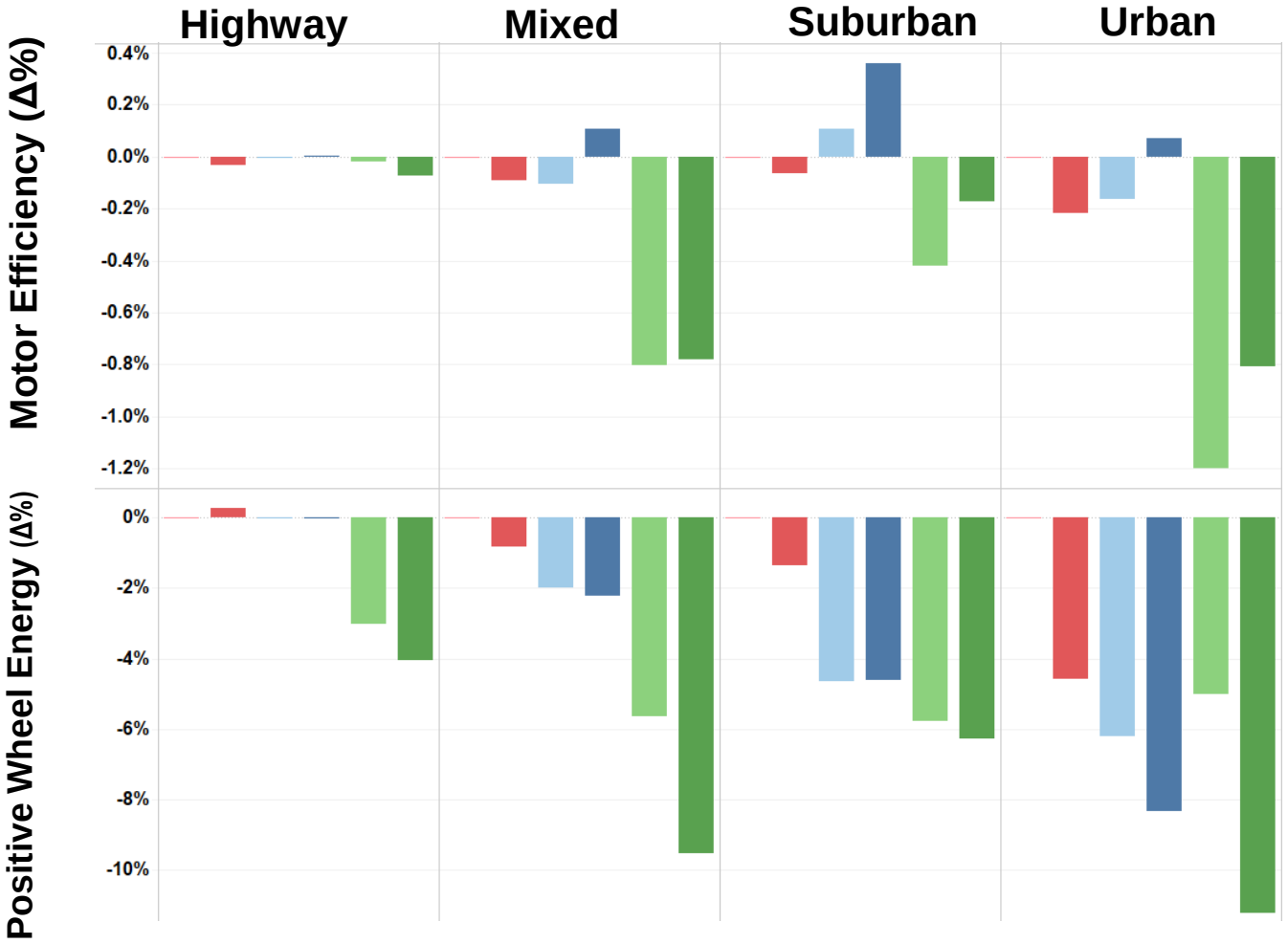
Signal Phase & Time



Traffic Signal Eco-Approach with V2I Approach

		Pass situation	Stop situation	Results
			 Vehicle cannot pass within current green light phase	
Baseline		Pass	Stop and go	
Eco-approach	Baseline + V2I	Pass	Decelerate first and then cruise	
	EcoDrv Spd/Accel +V2I	Pass	Decelerate optimally	

Eco-Driving Reduces Motor Efficiency and Positive Tractive Energy



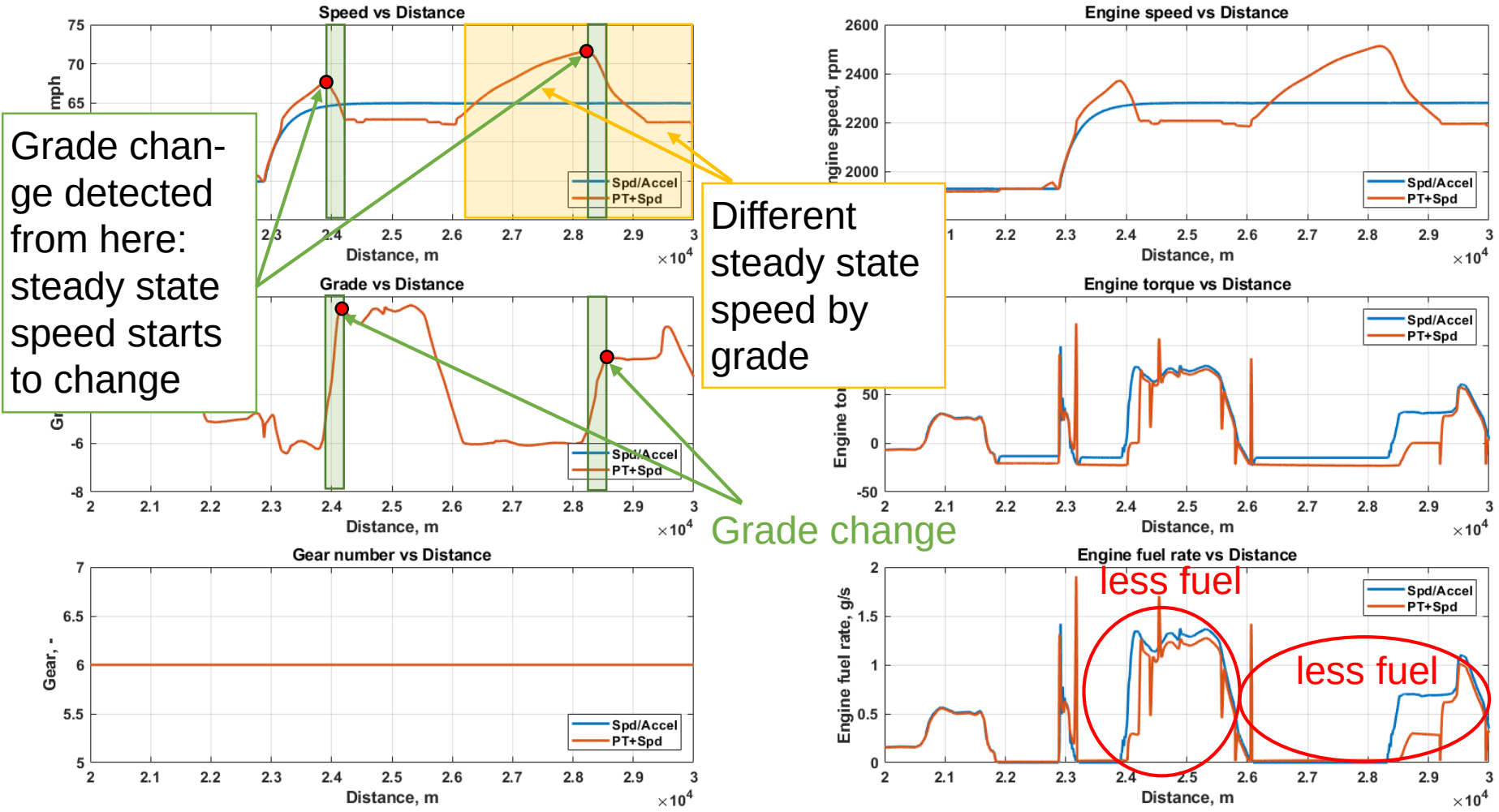
Control

- Baseline
- Baseline + V2I
- EcoDrv Spd/Accel
- EcoDrv Spd/Accel, V2I
- EcoDrv PT+Spd
- EcoDrv PT+Spd,V2I

Scenario

Lead vehicle, control vs baseline EV

How Does Eco-Driving (PT+Spd) Save Fuel?
Case of cruising with grade information



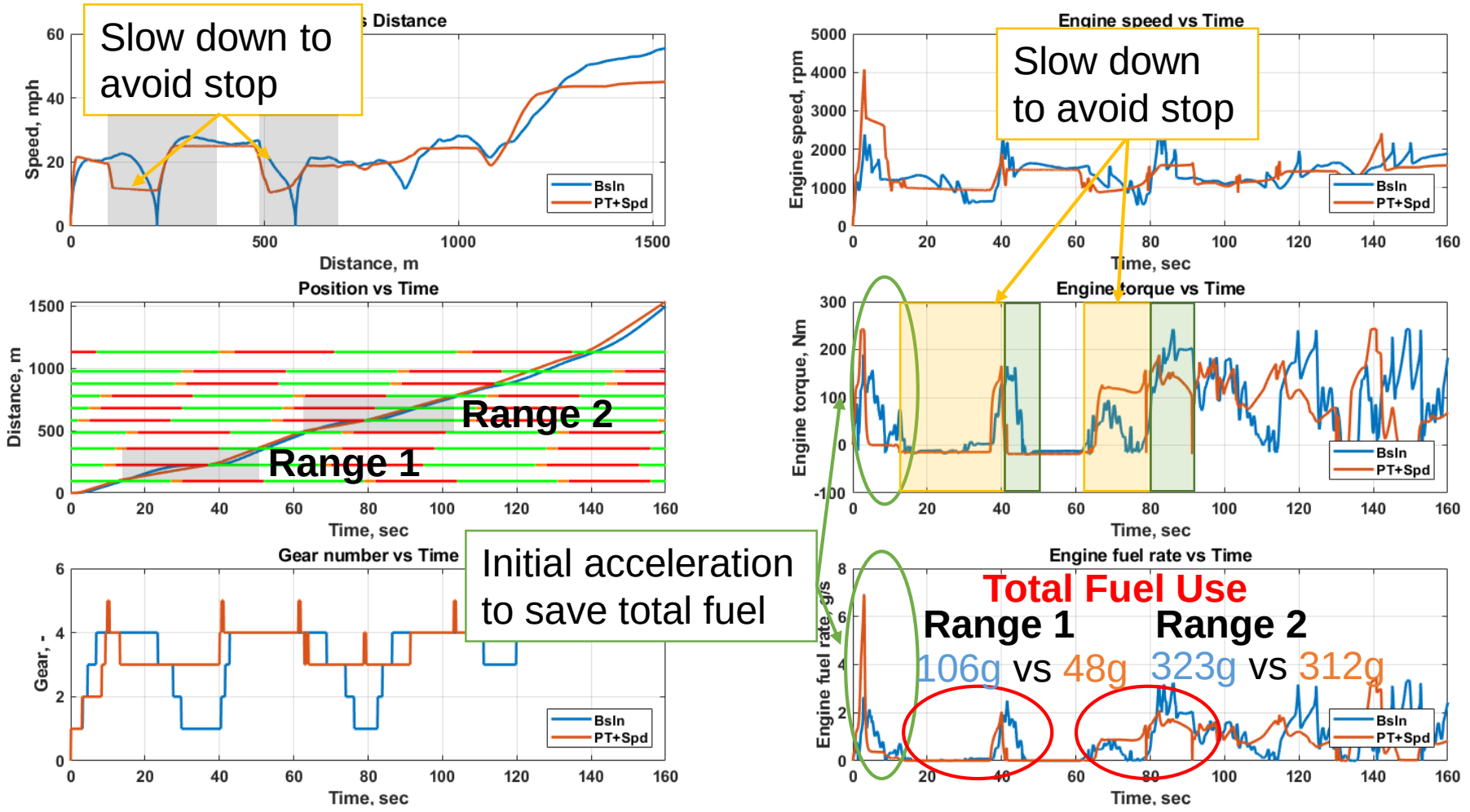
Grade change-ge detected from here: steady state speed starts to change

Different steady state speed by grade

Grade change

I-5 Highway trip between Oregon and California

How Does Eco-Driving (PT+Spd) Save Fuel?
Urban Driving with V2I



Urban trip in Seattle