Eco-Lanes: Preliminary Modeling Results

Applications for the Environment: Real-Time Information Synthesis (AERIS) Program

Summer Webinar Series

July 23rd, 2014

Presentation Overview

- Overview of the Eco-Lanes Operational Scenario
- Eco-Lanes Applications
- Simulation Modeling Set-up and Initial Modeling Results
- Conclusions and Lessons Learned

Eco-Lanes Operational Scenario

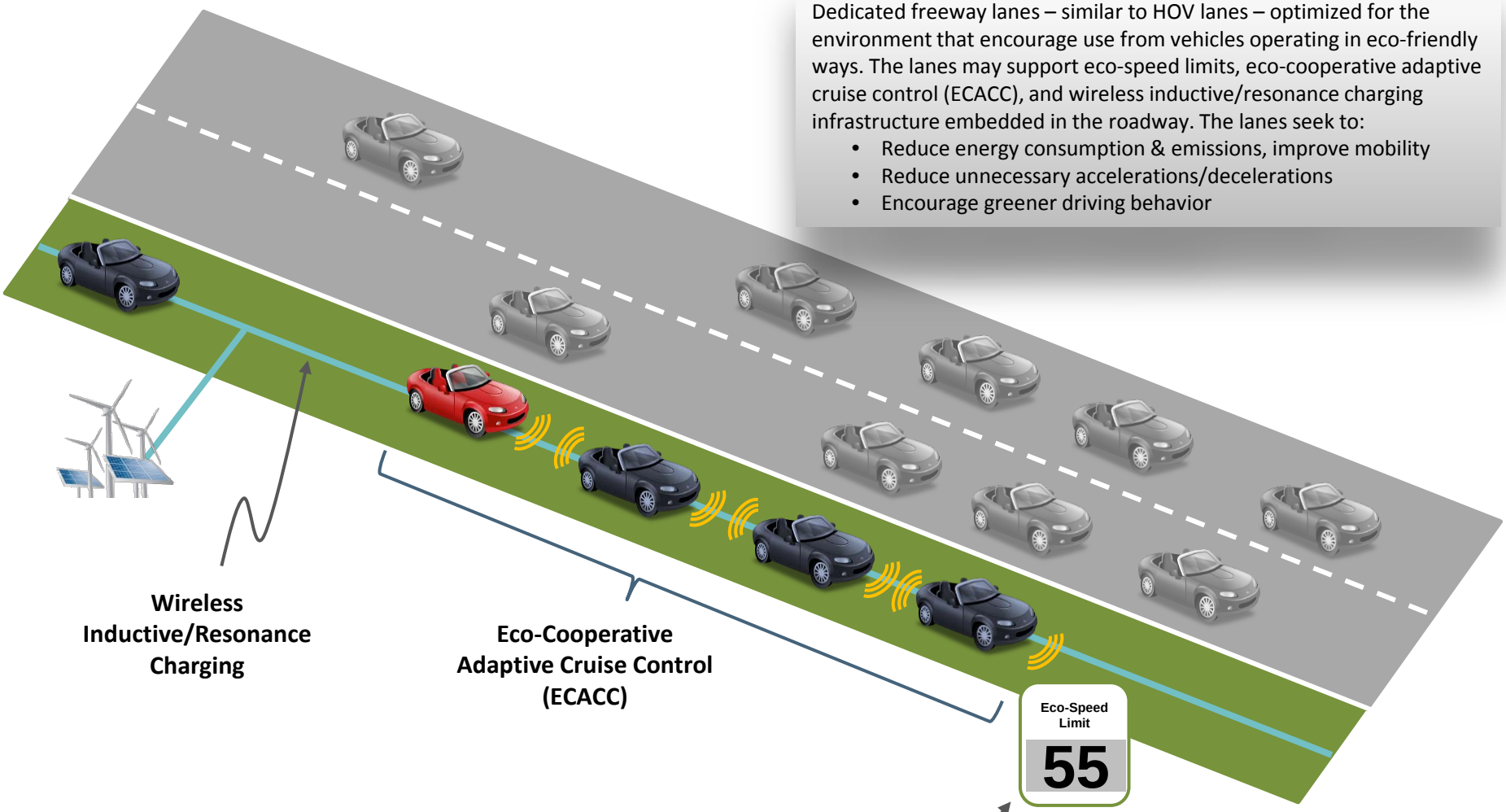
- Dedicated freeway lanes – similar to HOV lanes – optimized for the environment that encourage use from vehicles operating in eco-friendly ways.
- The lanes should:
  - Reduce energy consumption & emissions, improve mobility
  - Reduce unnecessary accelerations/decelerations
  - Encourage greener driving behavior

Eco-Lanes Operational Scenario

Eco-Lanes

Dedicated freeway lanes – similar to HOV lanes – optimized for the environment that encourage use from vehicles operating in eco-friendly ways. The lanes may support eco-speed limits, eco-cooperative adaptive cruise control (ECACC), and wireless inductive/resonance charging infrastructure embedded in the roadway. The lanes seek to:

- Reduce energy consumption & emissions, improve mobility
- Reduce unnecessary accelerations/decelerations
- Encourage greener driving behavior



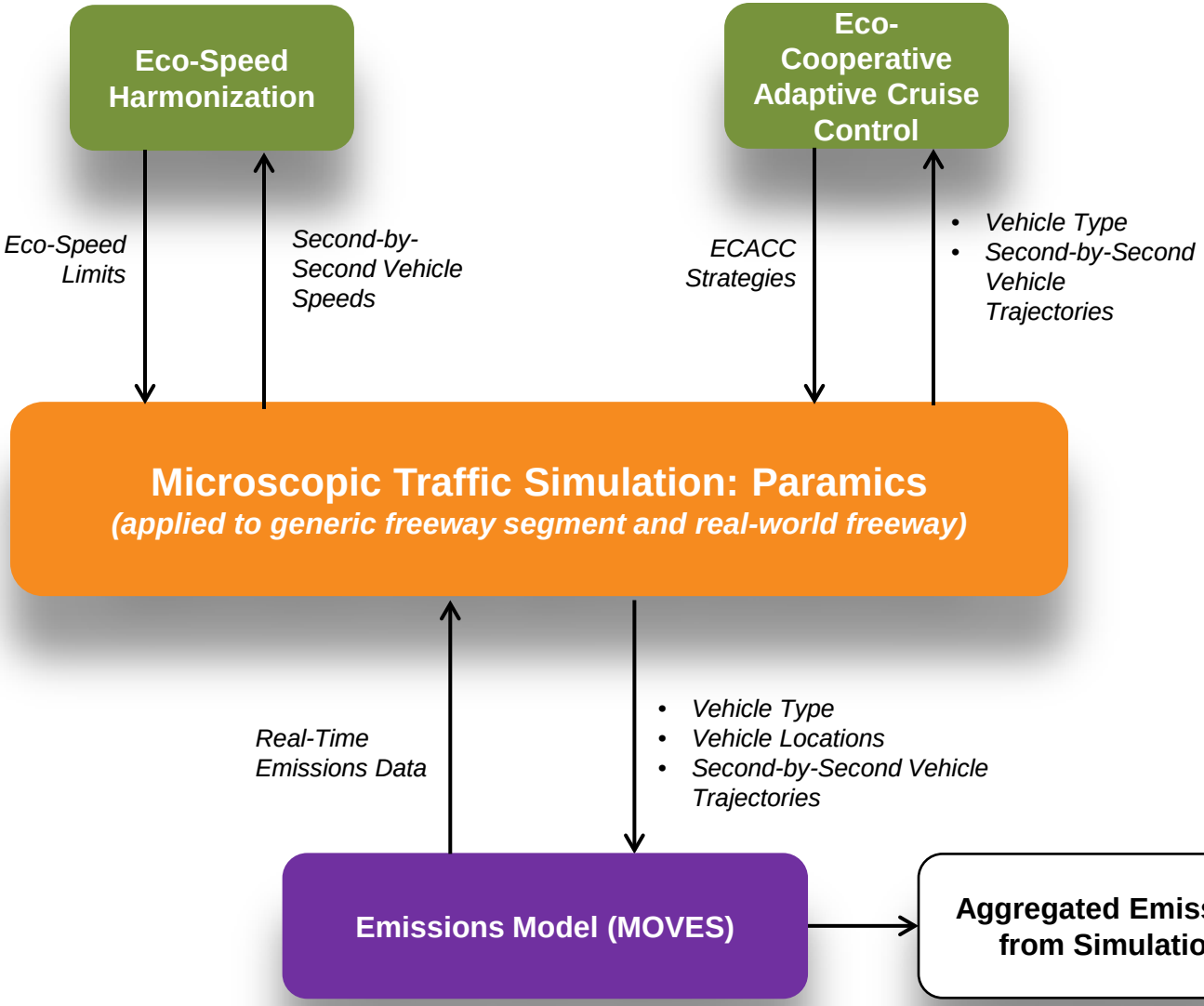
Source: USDOT, July 2014

Eco-Lanes Applications

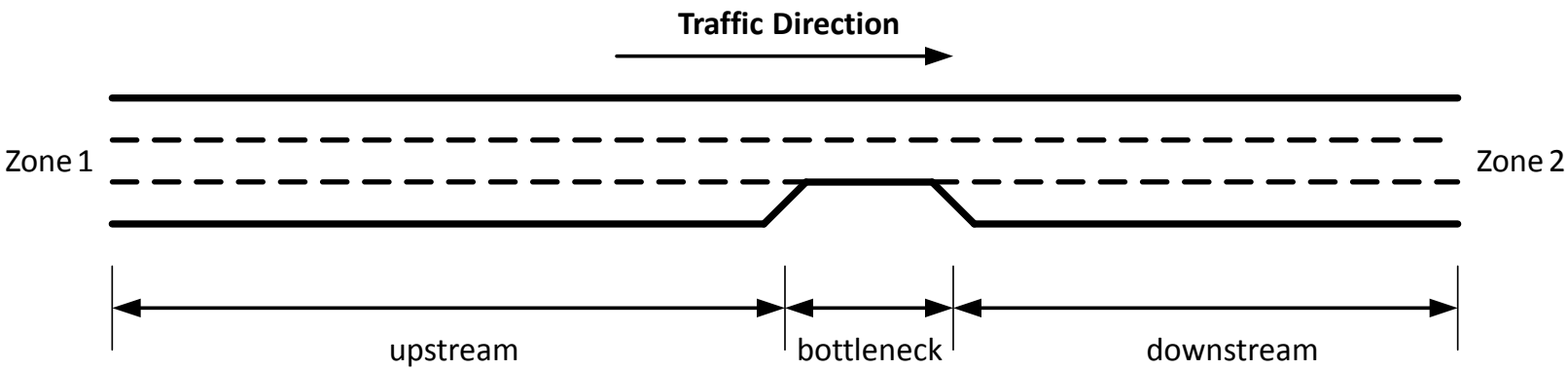
ECO-LANES

- Eco-Lanes Management
- Eco-Speed Harmonization
- Eco-Cooperative Adaptive Cruise Control (ECACC)
- Eco-Ramp Metering *(not modeled)*
- Connected Eco-Driving *(not modeled)*
- Wireless Inductive/Resonance Charging *(not modeled)*
- Eco-Traveler Information Applications *(not modeled)*

Simulation Tools

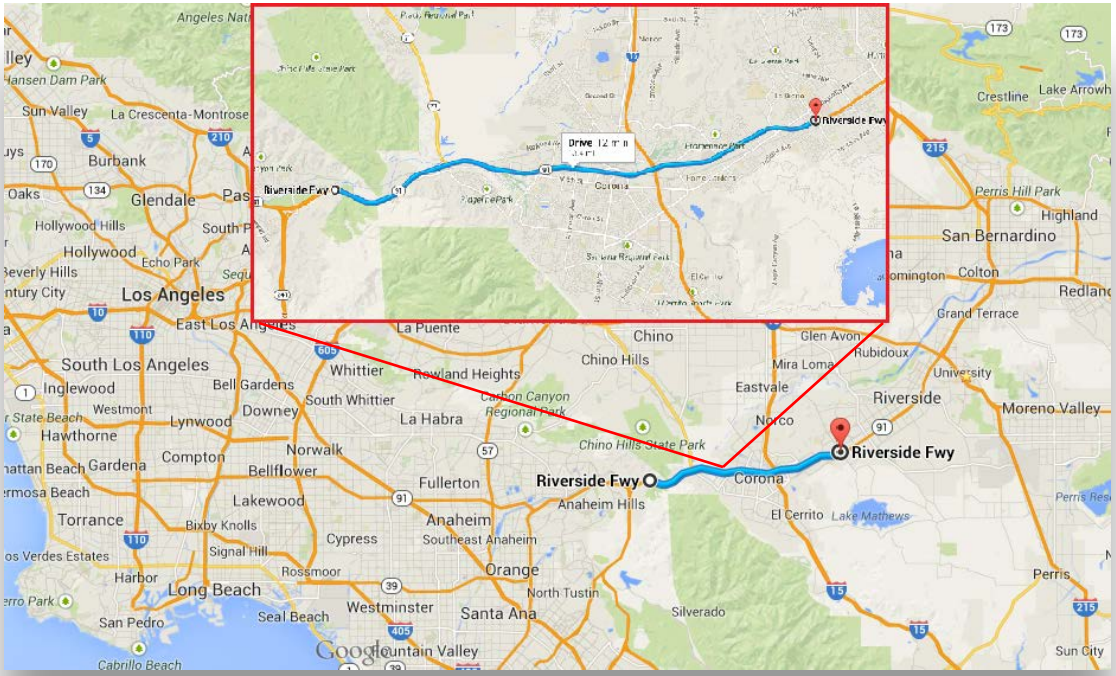


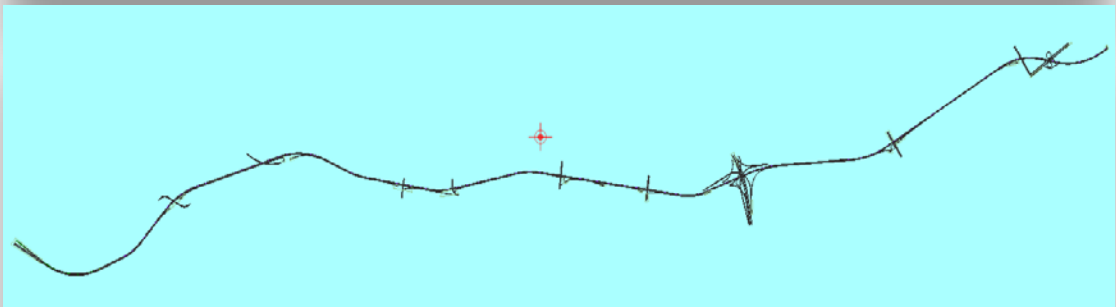
Generic Freeway Segment



California SR-91 E

- Busy freeway corridor in Southern California
  - 3 or 4 general purpose lanes each in direction
  - 1 high occupancy vehicle (HOV) lane each in each direction
  - 60 mph speed limit
  - Often suffers from level-of-service (LOS) C - F conditions





Eco-Lanes Modeling Matrix

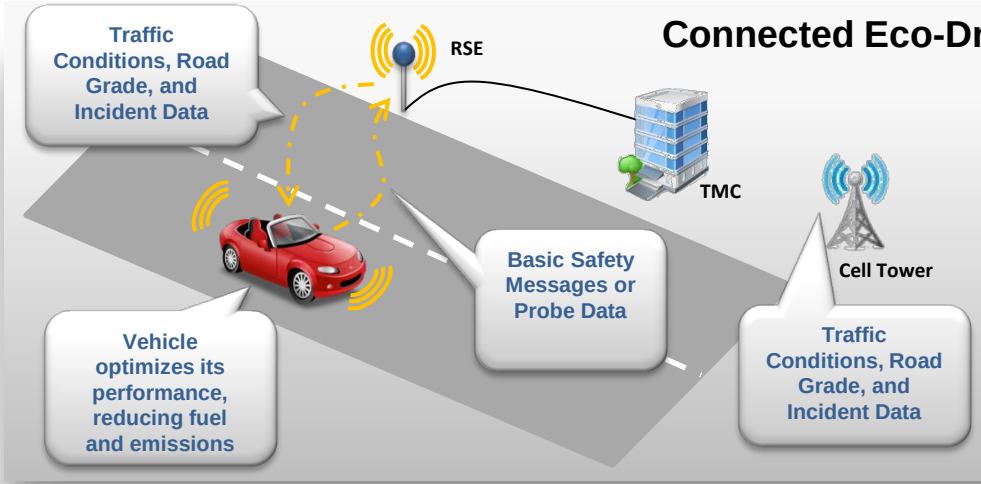
Eco Lanes Modeling	Generic Freeway	Real-world (California SR-91)
Eco-Speed Harmonization	• Algorithm complete* • Sensitivity analysis on V/C and penetration rate	• Network coded/calibrated • Algorithm specifically tuned • Final simulation tests underway
Eco-Cooperative Adaptive Cruise Control (ECACC)	• Algorithm complete** • Volume analysis, triggering distance sensitivity analysis	• Network coded/calibrated • Algorithm specifically tuned • Final simulation tests underway
Eco-Speed Harmonization + ECACC	• Combined algorithm complete • Simulation tests underway	• Network coded/calibrated • Algorithm specifically tuned • Simulation tests underway

* Modification of: M. Barth and K. Boriboonsomsin, "Energy and Emissions Impacts of a Freeway-Based Dynamic Eco-Driving System," *Transportation Research Part D: Environment*, Vol. 14, Elsevier Press, pp. 400-410, 2009.

** Variation of: V. Milanes, S. Shladover, J. Spring, C. Nowakowski, H. Kawazoe, and M. Nakamura, "Cooperative Adaptive Cruise Control in Real Traffic Situations, "*IEEE Transactions on ITS*, Vol. 15, No 1, pp. 296 - 305, 2014.

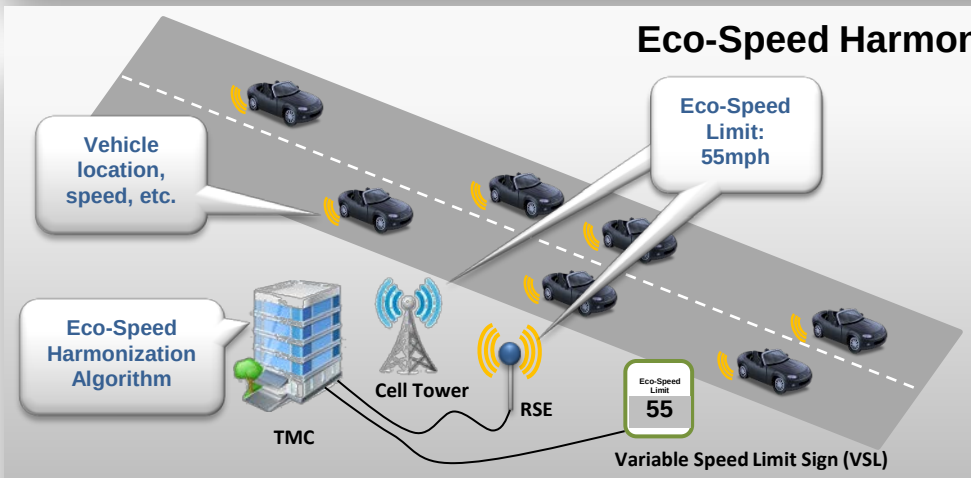
Connected Eco-Driving and Eco-Speed Harmonization

Connected Eco-Driving



- Connected Eco-Driving provides customized real-time driving advice to drivers, allowing them to adjust behaviors to save fuel and reduce emissions.
- This advice includes recommended driving speeds, optimal acceleration and deceleration profiles based on prevailing traffic conditions, road grade, etc.
- The application may also consider vehicle-assisted strategies, where the vehicle automatically implements the eco-driving strategy (i.e., change gears, switch power sources, or use start-stop capabilities to turn off the vehicle's engine while it is sitting in congestion).

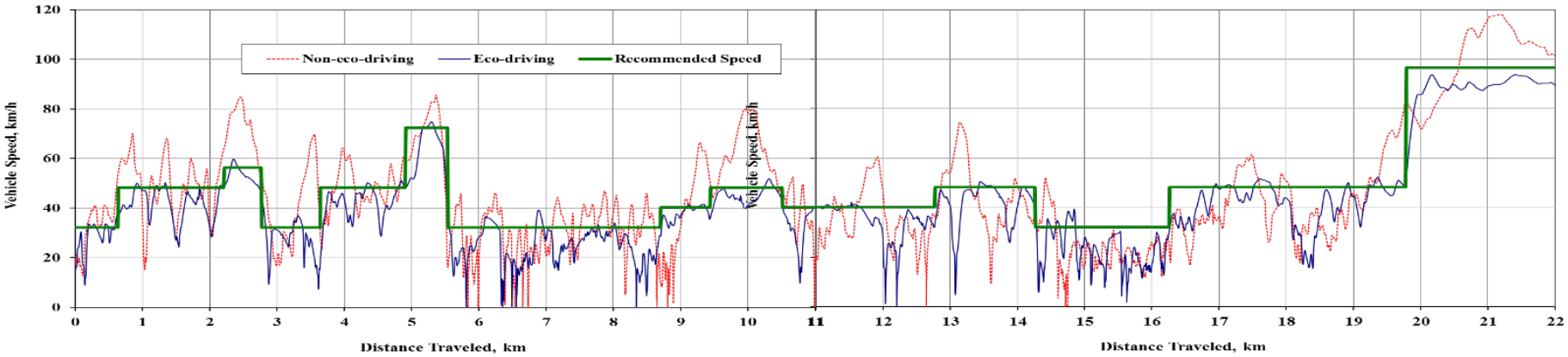
Eco-Speed Harmonization



- Eco-Speed Harmonization is similar to current VSL applications, although the speed recommendations seek to minimize emissions and fuel consumption along the roadway.
- Speed harmonization assists in maintaining flow, reducing unnecessary stops and starts, and maintaining consistent speeds, thus reducing fuel consumption, GHG emissions, and other emissions on the roadway.
- Eco-speed limits can be broadcast by roadside equipment (RSE) units (or cellular) and received by on-board equipment (OBE) units or displayed on VSL signs located along the roadway.

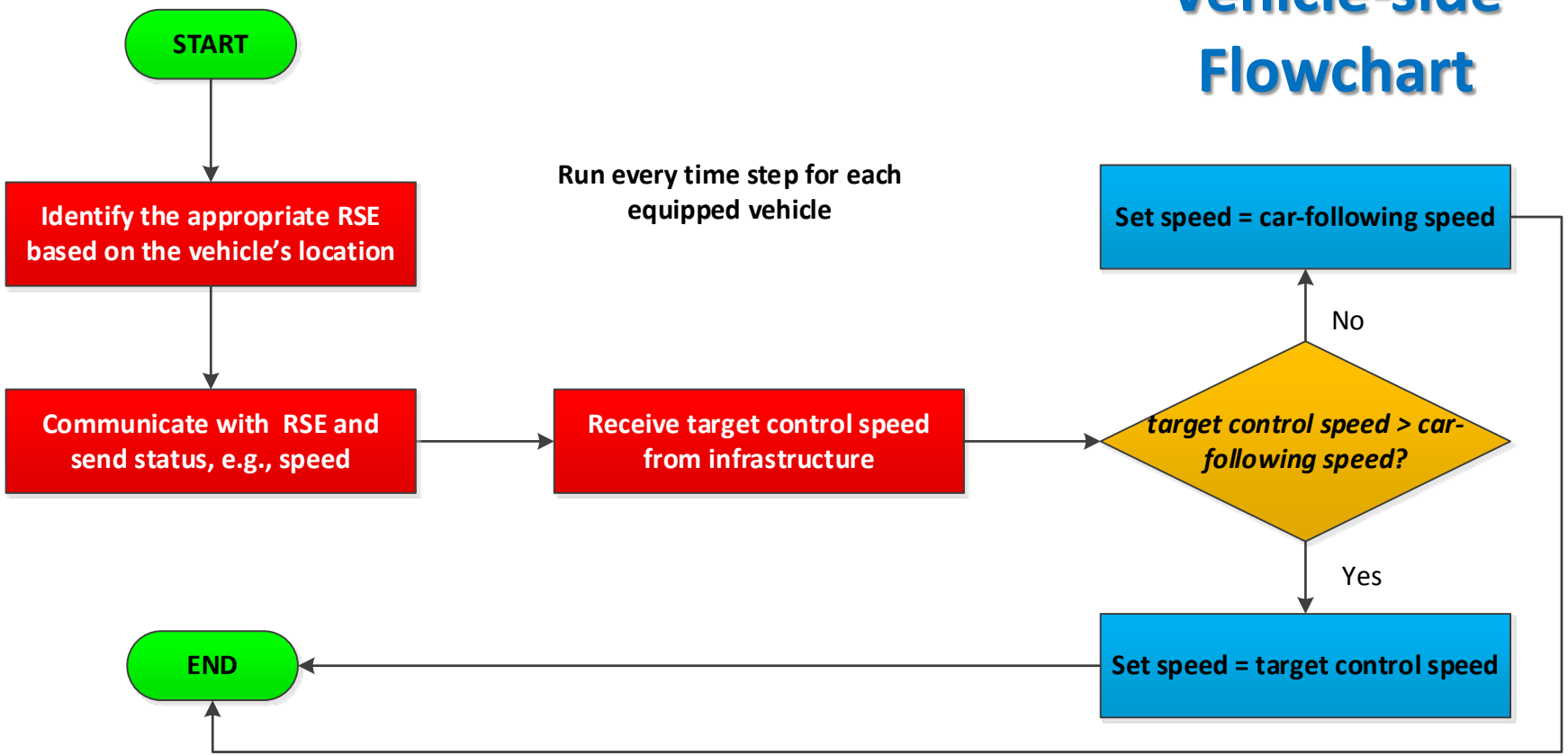
Eco-Speed Harmonization

- Leverage connected vehicle technologies to determine eco-speed limits to mitigate the impacts from traffic congestion (resulting from either recurrent bottlenecks or incidents), based on the following information:
  - **Downstream traffic conditions (current focus)**
  - Roadway geometry (e.g., roadway grade)
  - Weather information, and
  - Greenhouse gas (GHG) and criteria pollutant emissions



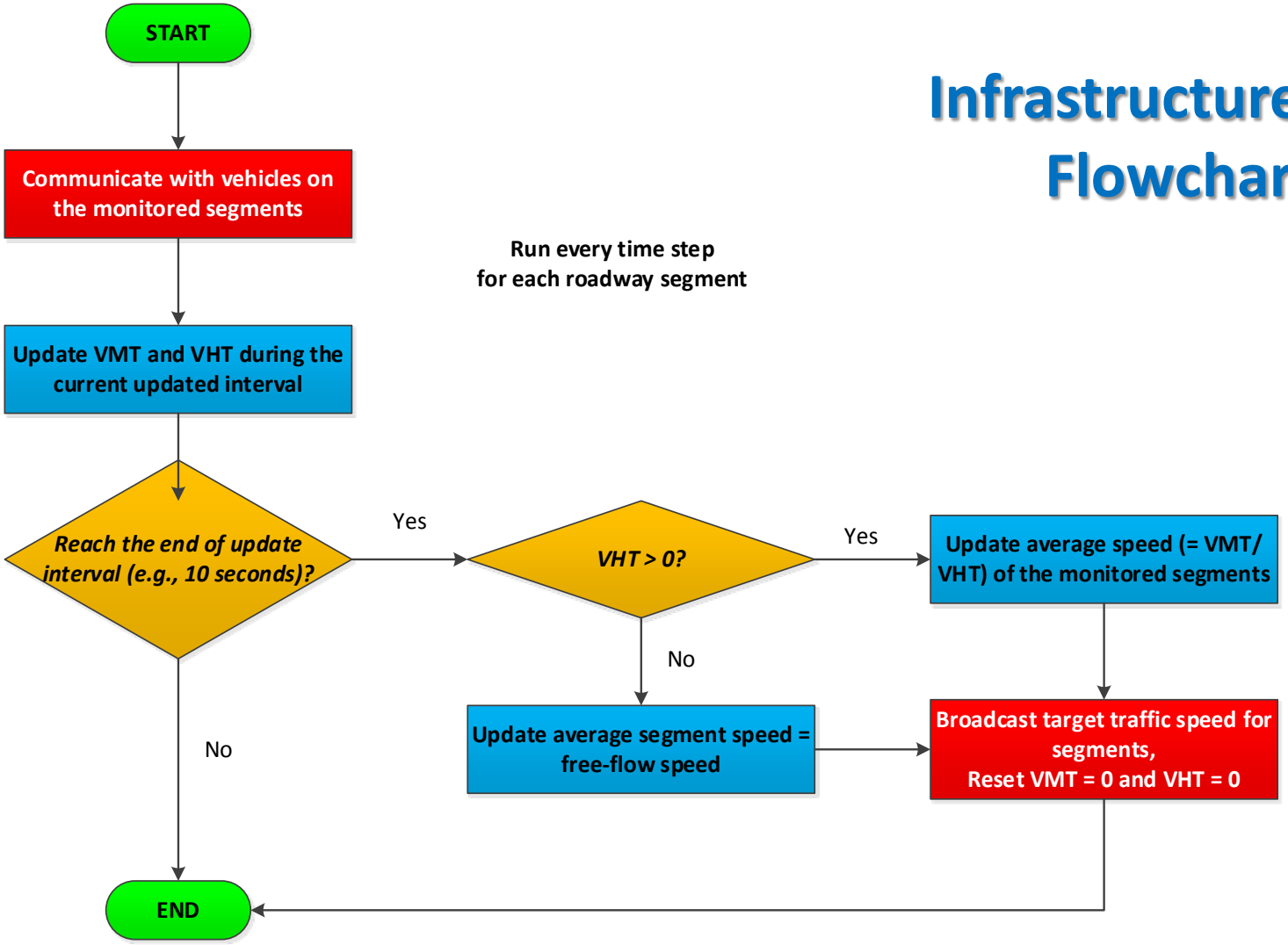
Eco-Speed Harmonization Algorithm (1)

Vehicle-side Flowchart



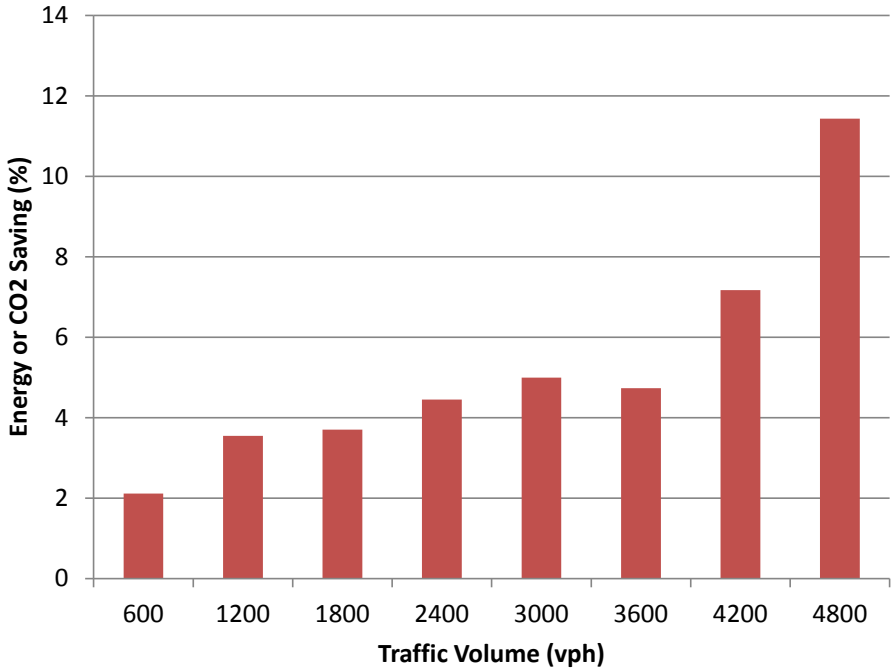
Eco-Speed Harmonization Algorithm (2)

Infrastructure-side Flowchart



Eco-Speed Harmonization Results (1 of 2)

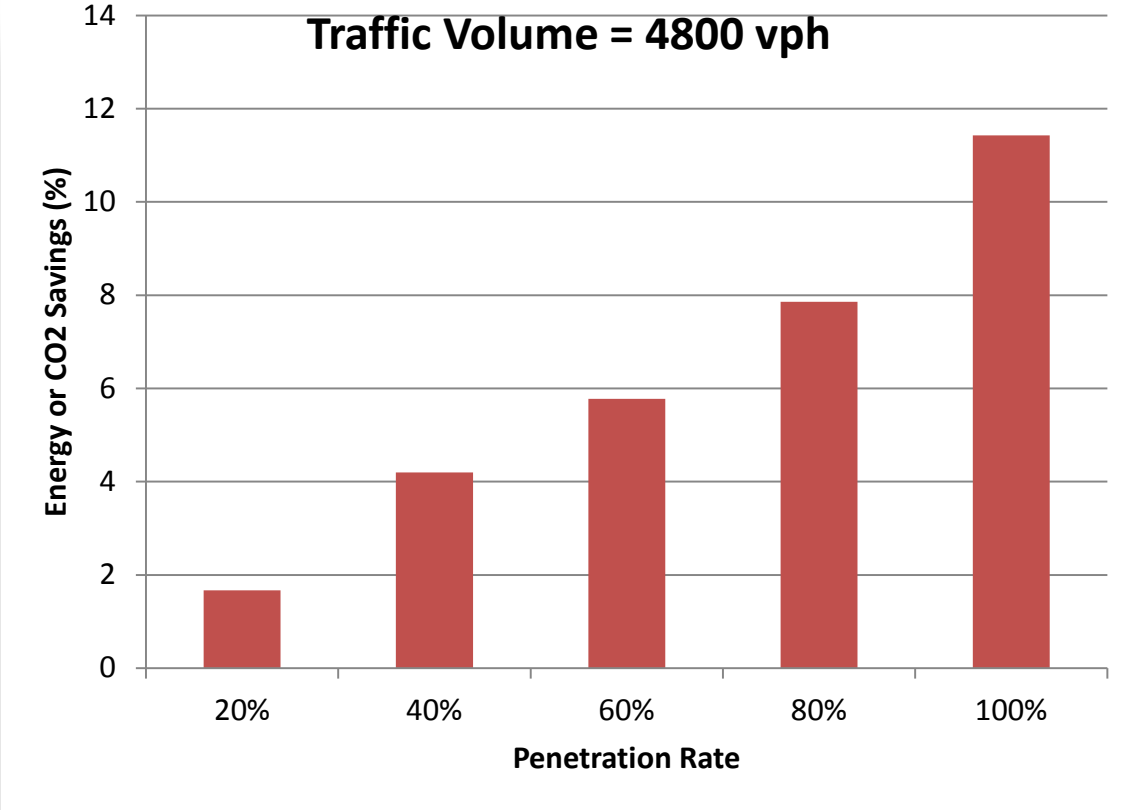
- Example maximum energy savings as a function of traffic volume, with 100% connected vehicle penetration rate (comparing baseline at 60 mph speed limit vs. Eco-Speed Harmonization free flow speed = 50 mph)



- Maximum energy savings result in an approximate 8% to 10% reduction in mobility
- Typical energy savings in the range of 4% to 8% if mobility is kept the same (i.e., Eco-Speed Harmonization free flow speed = baseline 60 mph speed limit)

Eco-Speed Harmonization Results (2 of 2)

- Example energy savings as a function of connected vehicle penetration rate, at high traffic volume of 4800 vph
- Tuned for maximum energy savings with a baseline at 60 mph speed limit vs. Eco-Speed Harmonization free flow speed = 50 mph



Eco-Speed Harmonization Initial Observations

- Maximum energy and CO_2 savings tend to occur at higher traffic volumes (near full capacity) in the range of 5% to 12% with a mobility reduction of ~8%; with no mobility change, energy savings is in the 4% to 8% range
- Energy and CO_2 savings increase with increased penetration rate, maximizing at 100% penetration
- A combination of connected vehicle technology and variable speed limit signs can be used to maximize savings in early deployment
- It is expected that the energy and CO_2 benefits will be slightly reduced with a real-world highway (with varying traffic volume, on-ramps, off-ramps, etc.

Eco-Cooperative Adaptive Cruise Control (ECACC)

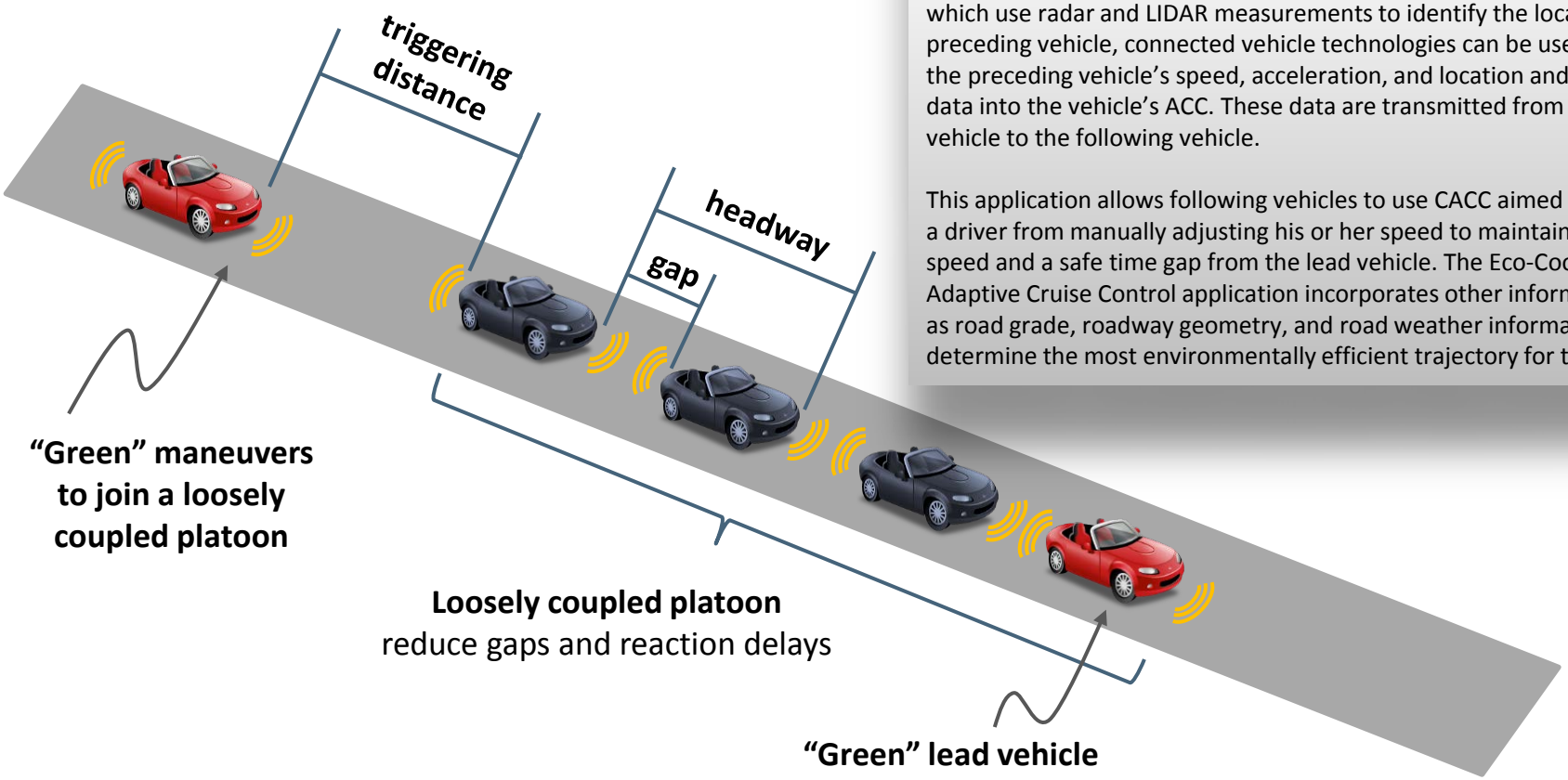
- Coordinate the maneuvers of neighboring vehicles via vehicle-to-vehicle (V2V) communication to encourage eco-friendly operation
- Similar to conventional cooperative adaptive cruise control (CACC): reducing gaps and reaction delays within loosely coupled platoon
- Unlike conventional CACC: “greener” vehicle maneuvers, smoother platoon leader operation

Eco-Cooperative Adaptive Cruise Control (ECACC)

Eco-Cooperative Adaptive Cruise Control

The Eco-Cooperative Adaptive Cruise Control application is an extension to the adaptive cruise control (ACC) concept. Eco-Cooperative Adaptive Cruise Control includes longitudinal automated vehicle control while considering eco-driving strategies. Expanding on existing ACC systems, which use radar and LIDAR measurements to identify the location of the preceding vehicle, connected vehicle technologies can be used to collect the preceding vehicle's speed, acceleration, and location and feed these data into the vehicle's ACC. These data are transmitted from the lead vehicle to the following vehicle.

This application allows following vehicles to use CACC aimed at relieving a driver from manually adjusting his or her speed to maintain a constant speed and a safe time gap from the lead vehicle. The Eco-Cooperative Adaptive Cruise Control application incorporates other information, such as road grade, roadway geometry, and road weather information, to determine the most environmentally efficient trajectory for the vehicle.



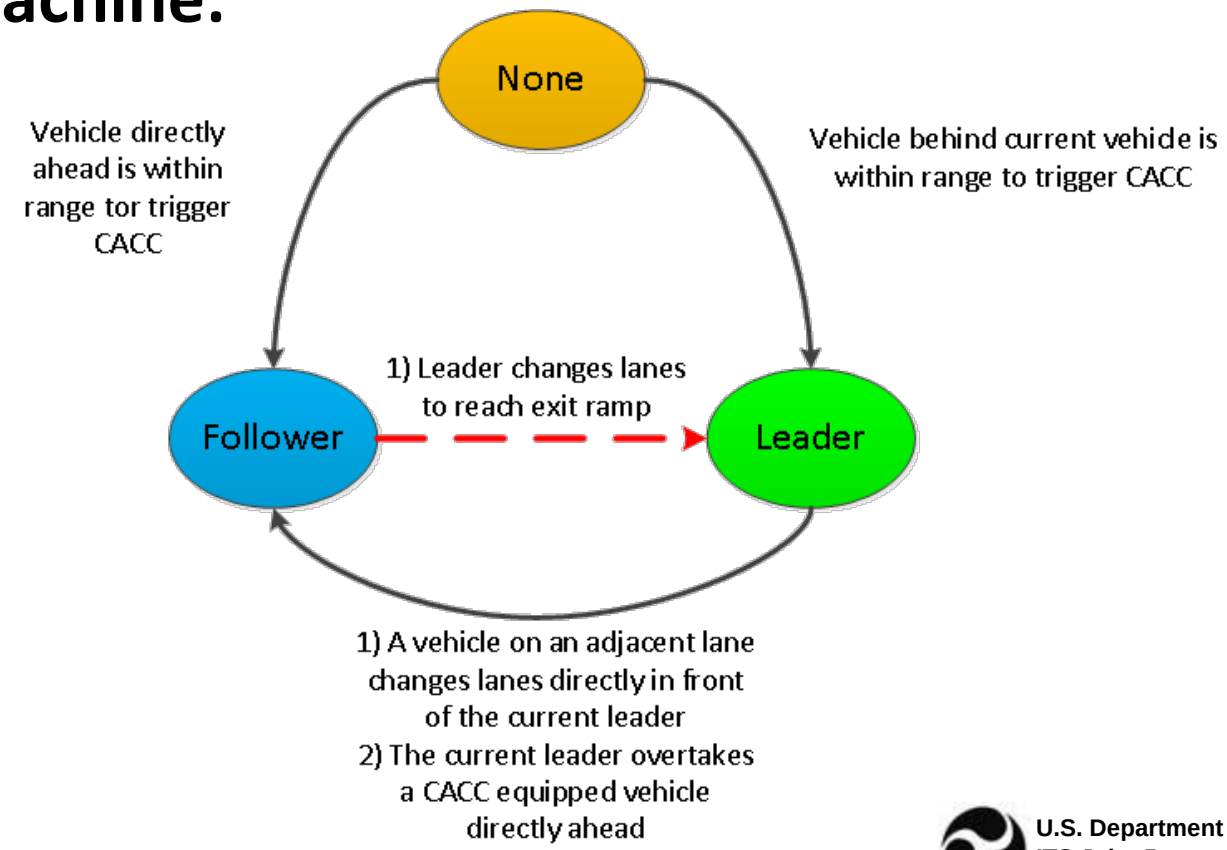
Source: USDOT, July 2014

ECACC Definitions

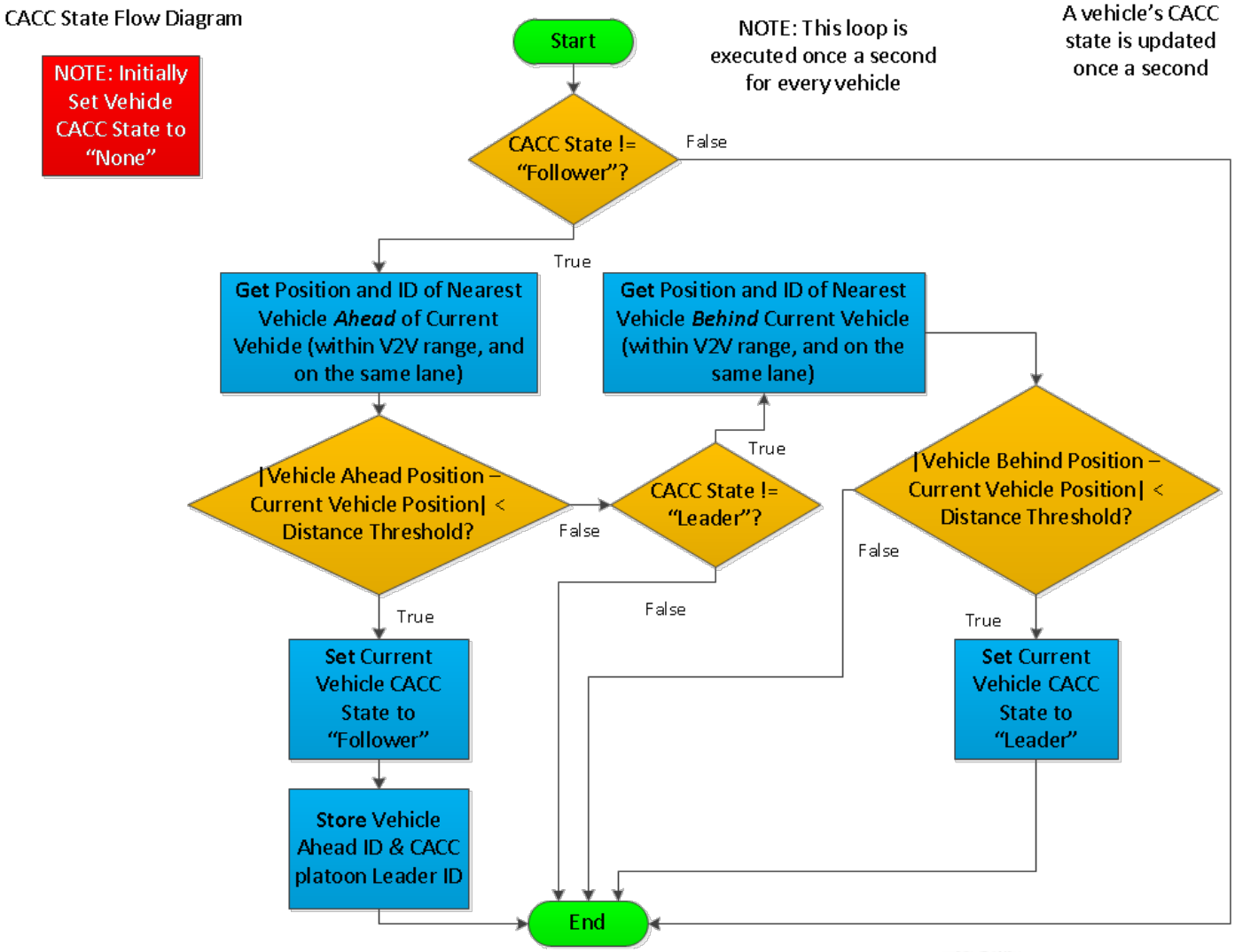
Definitions:

	Front Bumper – Front Bumper	Back Bumper – Front Bumper
Time	*Headway*	*Gap*
Distance	*Clearance*	*Spacing*

State Machine:



ECACC Algorithm (1)

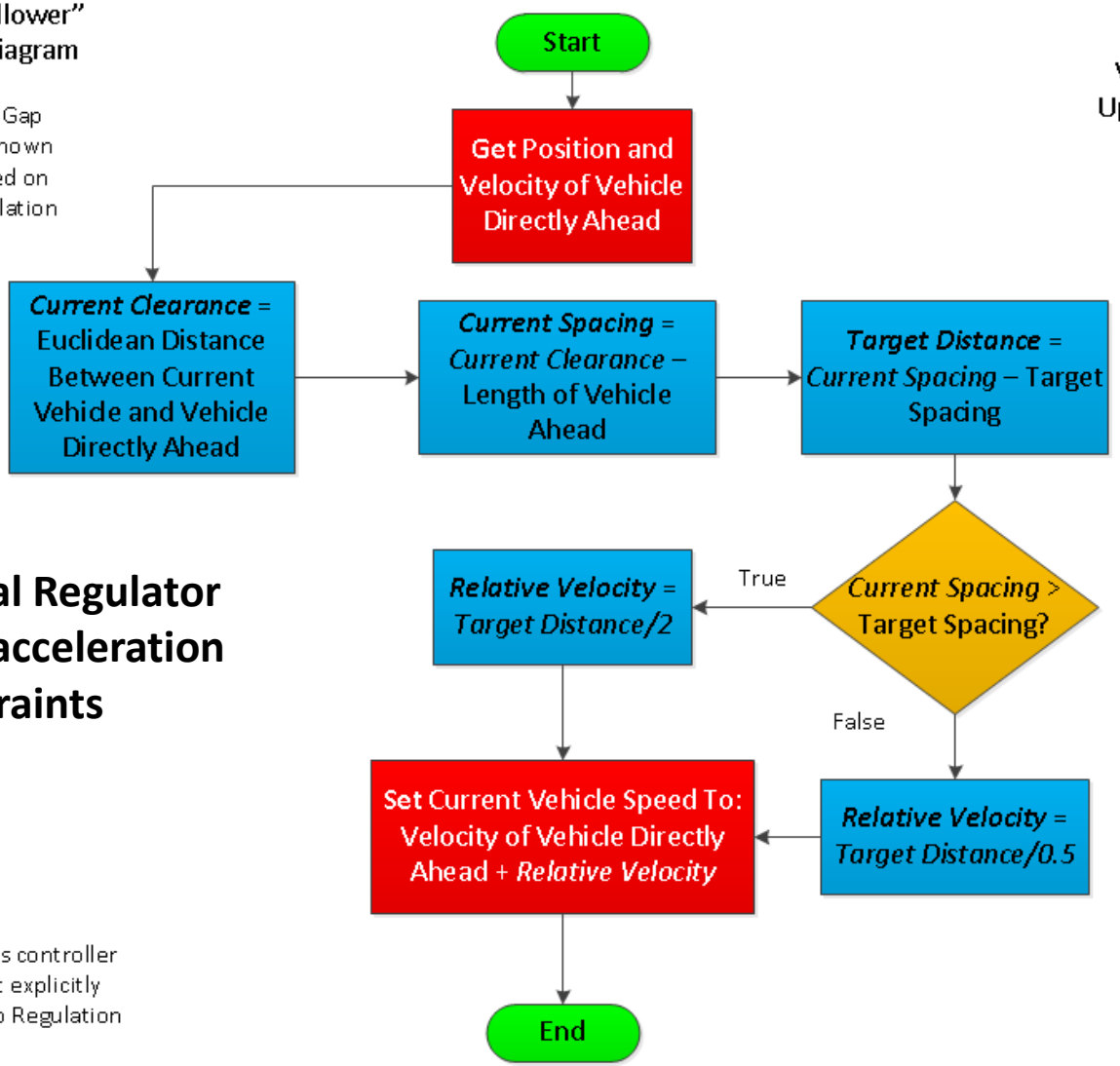


ECACC Algorithm (2)

CACC "Follower" Level 2 Diagram

NOTE: The Gap Controller shown here is based on Spatial Regulation

A "Follower" Vehicle's Speed is Updated Once Every Time Step



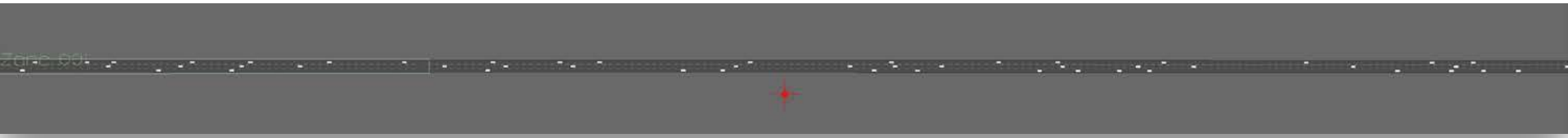
NOTE: Target Spacing is the sole parameter for Spatial Regulation

Spatial Regulator with acceleration constraints

NOTE: This controller does not explicitly model Gap Regulation

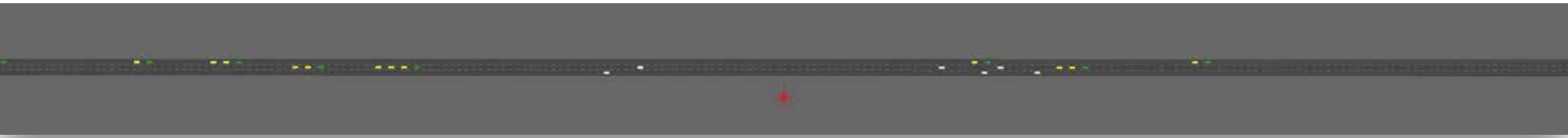
ECACC Video – Low Volume (4,000 vph)

Baseline



Upstream Segment with CACC Platoon Formation

Downstream Segment with CACC Platoons



ECACC Video – High Volume (6,000 vph)

Baseline

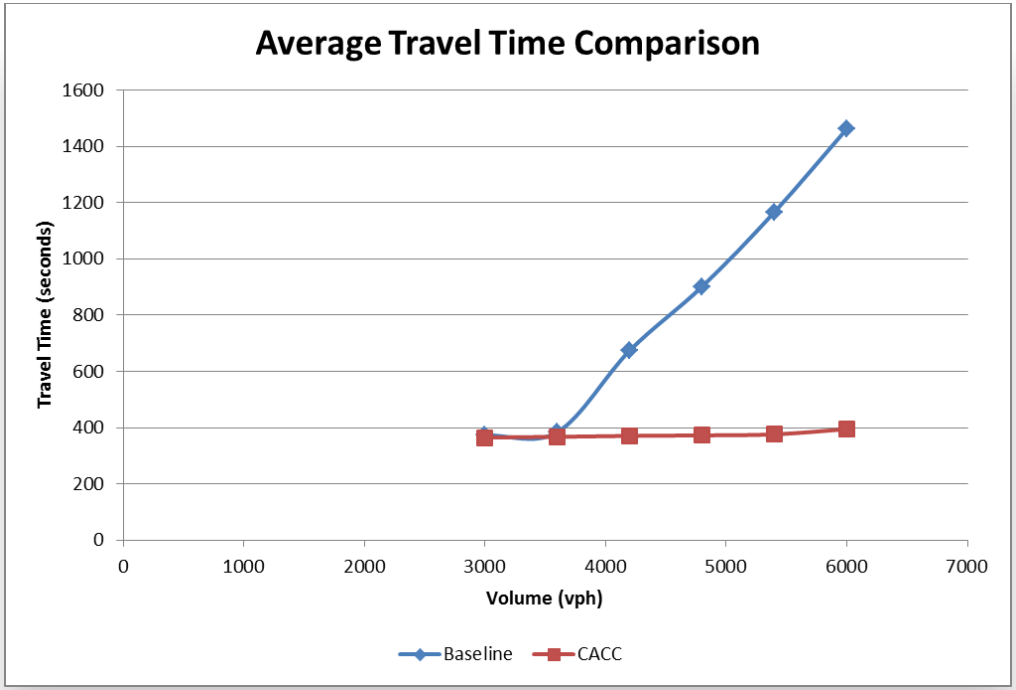
Upstream Segment with CACC Platoon Formation

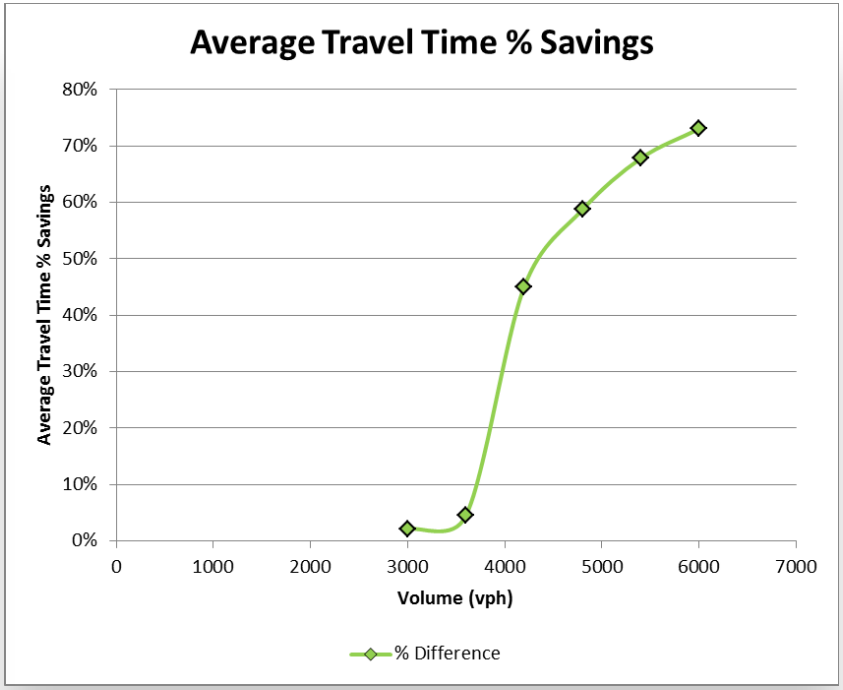
Downstream Segment with CACC Platoons

ECACC on Generic Freeway

Average Travel Time and Savings over Traffic Volume

- 100% penetration rate/compliance rate
- Triggering distance = 40 meters, vehicle spacing = 5 meters
- Constant demand profile
- Homogeneous vehicle type

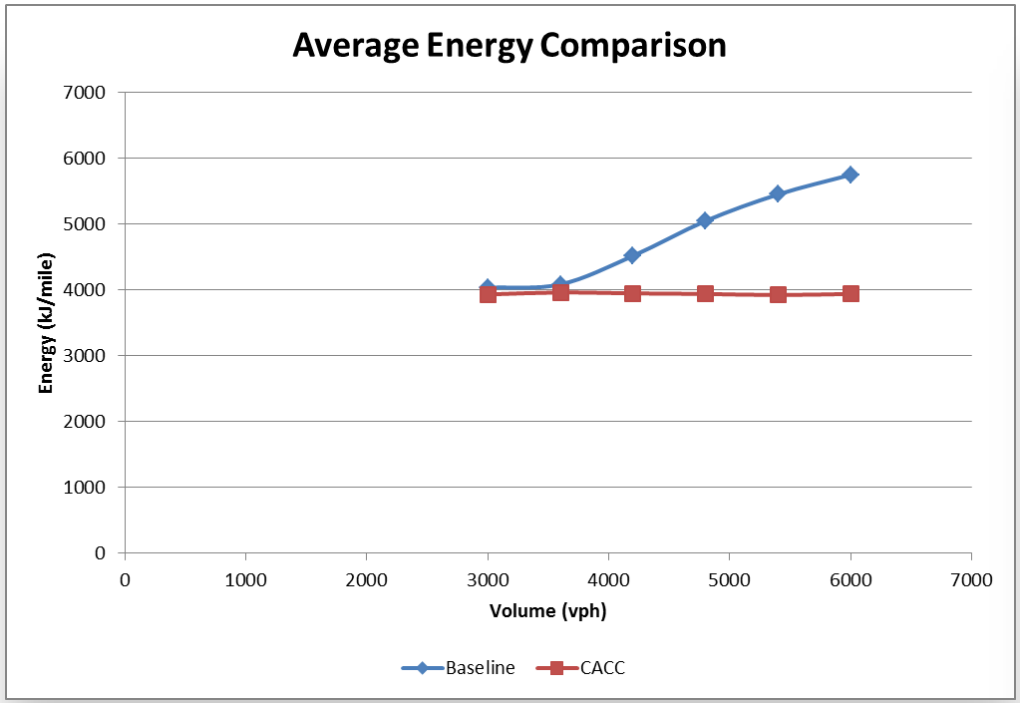


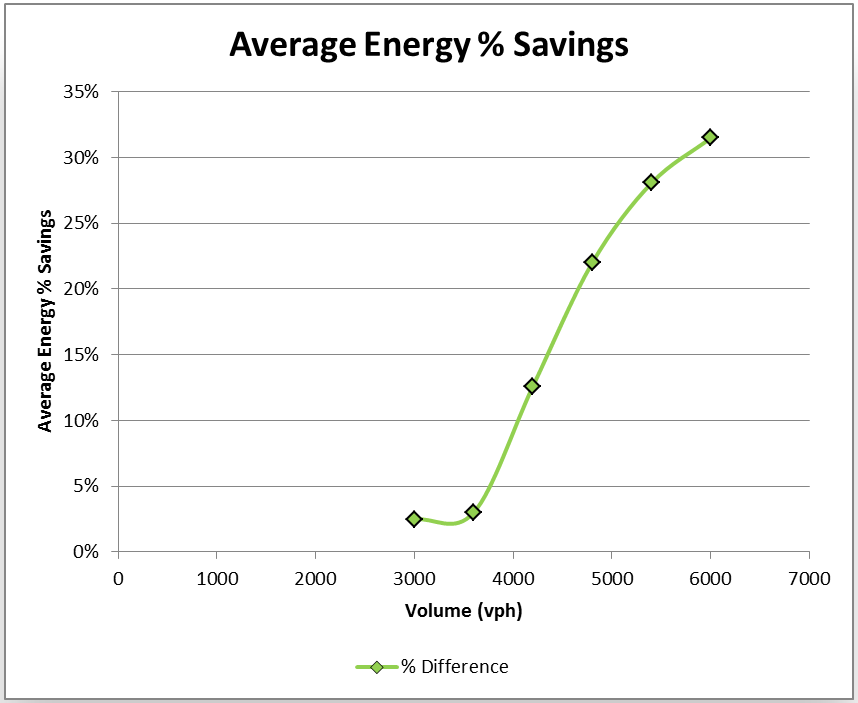


ECACC on Generic Freeway

Average Energy Consumption over Traffic Volume

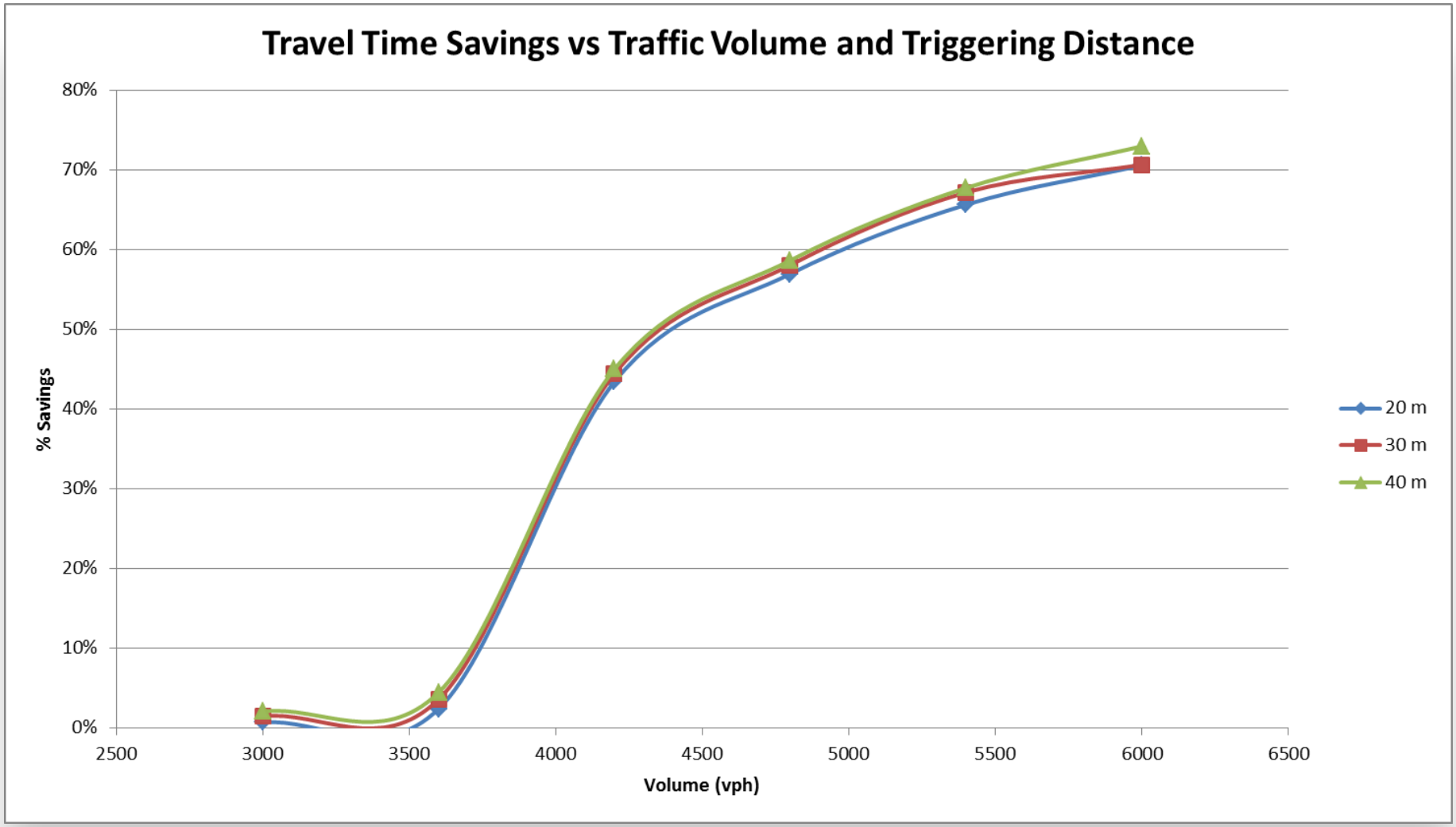
- 100% penetration rate/compliance rate
- Triggering distance = 40 meters
- Constant demand profile
- Homogeneous vehicle type





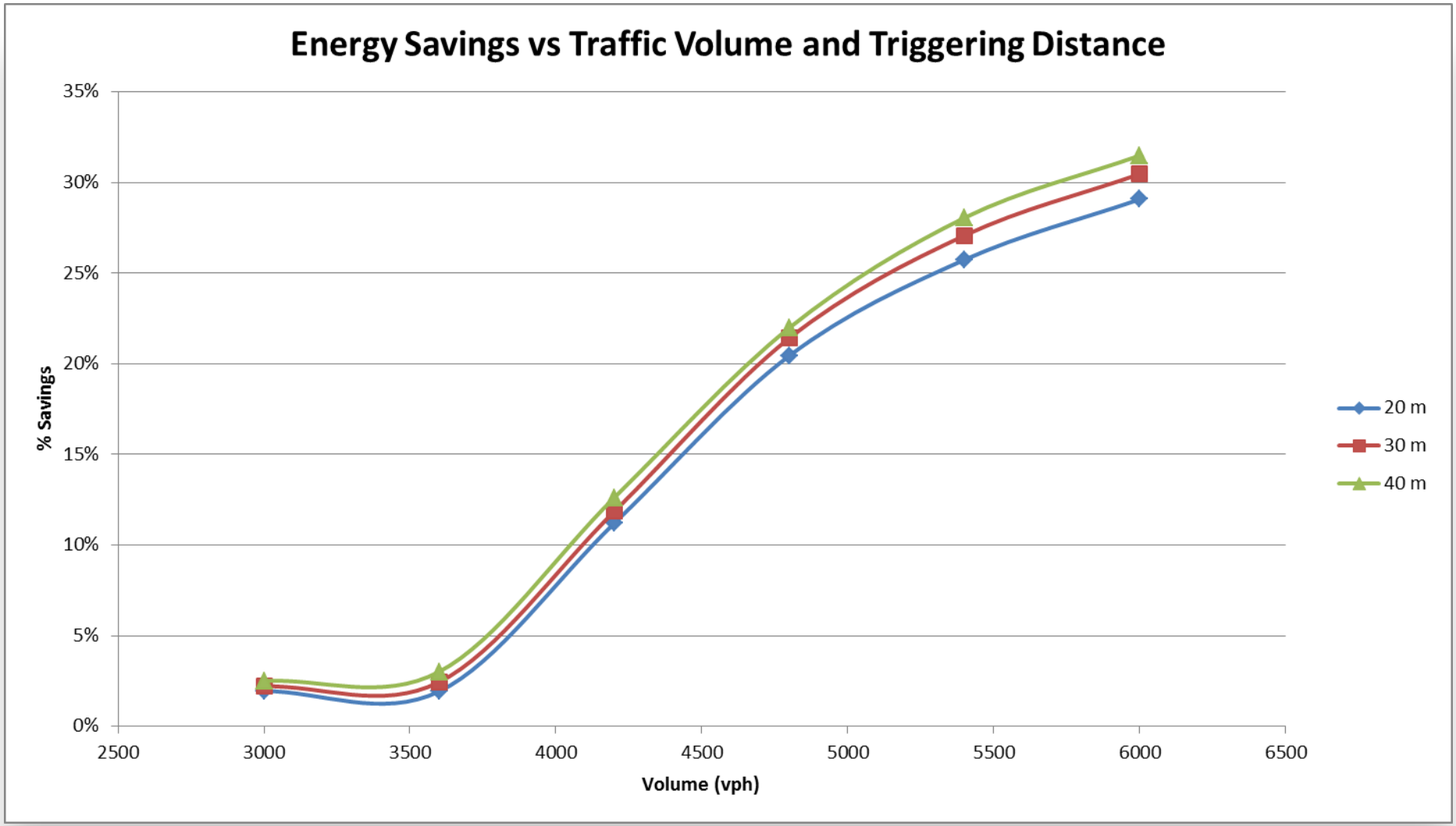
ECACC on Generic Freeway

Sensitivity Analysis of Triggering Distance (Travel Time Savings)



CACC on Generic Freeway

Sensitivity Analysis of Triggering Distance (Energy Savings)



ECACC General Observations

- Note that the aforementioned results are based on:
  - 100% penetration rate and compliance rate, no on-ramp(s)/off ramp(s)
  - No lateral maneuvers (merging, splitting, etc.)
- As expected, increased traffic throughput due to ECACC introduction provides benefits in both mobility and environmental factors
- **Key parameters:** triggering distance of when a vehicle joins a platoon; intra-platoon spacings
- **Best Case:** selection of a long triggering distance encourages platoon formation and improves merging behavior

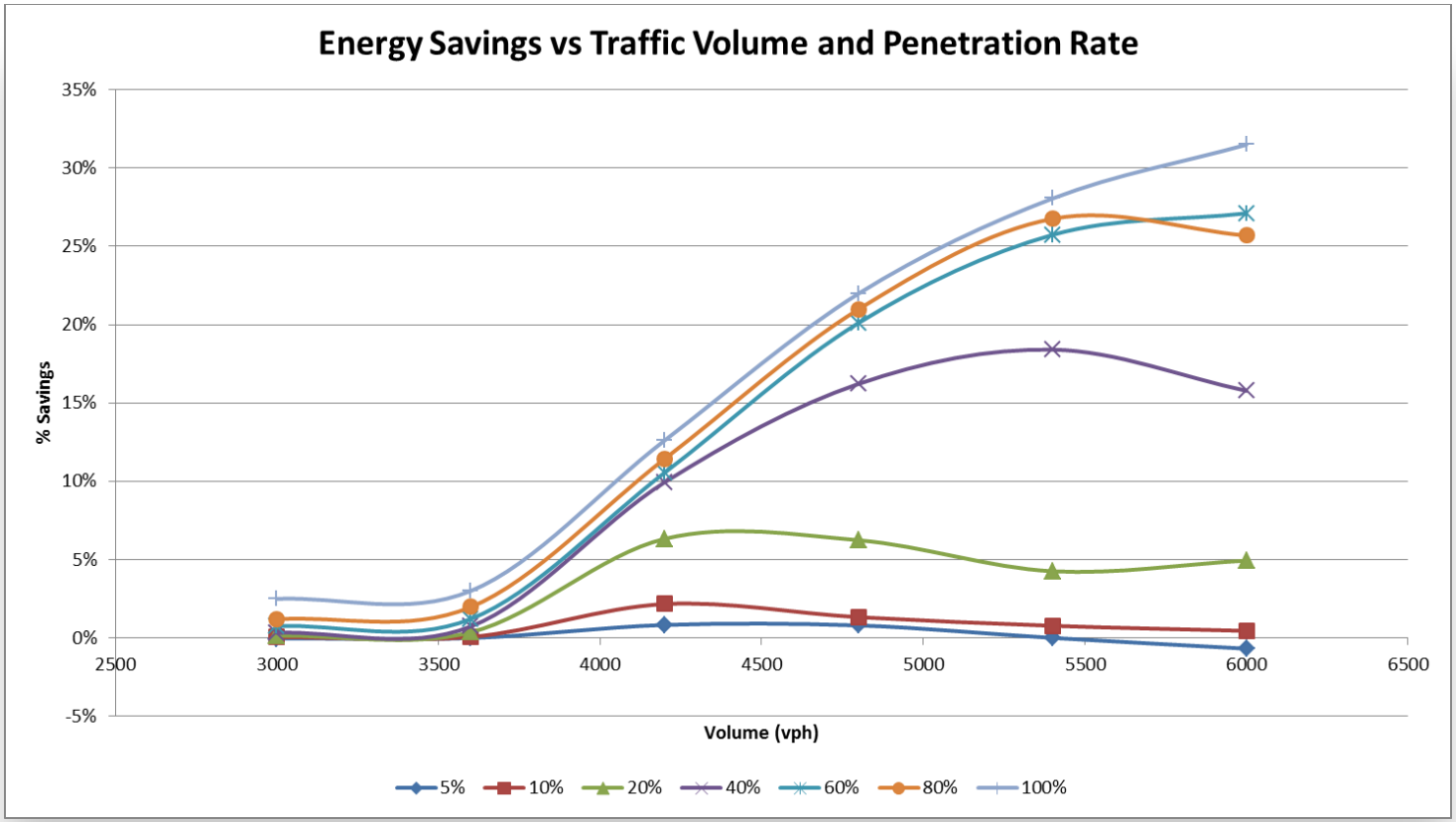
ECACC – Lateral maneuvers are important

- With on-ramps, off-ramps, multiple lanes with lane drops, lateral maneuvers become necessary
- Lateral maneuvers: merging into a lane with platoons, splitting from a platoon, etc.
- Lateral maneuvers cause additional accelerations and decelerations and therefore slightly reduce the maximum energy savings benefits of ECACC

Example platoon split and merge maneuvers

Penetration Rate Analysis for ECACC

- Energy and CO_2 savings are less than the maximum if the penetration rate of the technology is reduced
- With fewer equipped vehicles, the number of loosely coupled platoons are reduced



ECACC General Summary

- Energy and CO_2 savings depend on a number of factors, peaking around 30% for 100% penetration rate on a generic freeway segment without variable traffic demand and on-ramps/off-ramps
- Energy and CO_2 savings maximum at 100% penetration rate, somewhat less with lower penetration rate (e.g., 15% savings at 40% penetration rate)
- Lateral maneuvers: energy and CO_2 benefits are reduced with a real-world highway scenario due to varying traffic volume, on-ramps, off-ramps, and increased lateral maneuvers
- Combining Eco-Speed Harmonization (for leader vehicles) and ECACC should provide additive benefits

Eco-Lanes Modeling Summary Results

Eco Lanes Modeling	Generic Freeway	Real-world (California SR-91)
Eco-Speed Harmonization	• up to 12% max energy savings with ~8% reduction in mobility • 4% to 8% energy savings with no mobility impact	• Expected 3% to 10% energy savings;
Eco-Cooperative Adaptive Cruise Control (ECACC)	• Up to 30% energy savings • Increased capacity (2x)	• Expected 10% to 15% energy savings; improved mobility
Eco-Speed Harmonization + ECACC	• Expected 15%+ energy savings	• Expected 10%+ energy savings

Future Research

- Continue to examine a variety of real-world roadway scenarios to determine overall effectiveness
- Further develop the sophistication of the algorithms to account for all traffic scenarios
- Further develop lateral maneuvers for ECACC
- Apply and adapt the algorithms for arterial roadways:
  - initial eco-speed harmonization for arterials has shown great promise
  - ECACC should provide great energy savings for queues at traffic lights

Lessons Learned

- Eco-Speed Harmonization (ECH) and Eco-Cooperative Cruise Control (ECACC) offer greater opportunities for energy savings, particularly as congestion increases
- ECACC offers a dual mobility – energy benefit

Free Flow Traffic Conditions → **Congested Traffic Conditions**

ECO-LANES

Connected Eco-Driving

Eco-Speed Harmonization

Eco-Cooperative Adaptive Cruise Control

When traffic conditions are severely congested, there are limited opportunities for Connected Vehicle Applications of all types to provide mobility or environmental benefits

Research Team

- **University of California-Riverside:**
  - Matthew Barth (principal investigator)
  - Guoyuan Wu, Kanok Boriboonsomsin (research faculty)
  - David Kari, Qiu Jin (graduate students)
- **Booz Allen Hamilton:**
  - Sean Fitzgerel
  - Balaji Yelchuru
  - Sudeeksha Murari
- **Many others have contributed:**
  - AERIS research team partners

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Upcoming AERIS Webinars

- 2014 AERIS Summer Webinar Series
  - *Webinar #1: Combined Modeling of Eco-Signal Operations Applications*

    Wednesday, June 25th, 2014 at 1:00 pm EST
  - *Webinar #2: Preliminary Eco-Lanes Modeling Results*

    Wednesday, July 23rd, 2014 at 1:00 pm EST
  - Webinar #3: Preliminary Low Emissions Zones Modeling Results

    Wednesday, August 20th, 2014 at 1:00pm EST

  Registration: www.itsa.org/aerissummer2014

- For more information on the AERIS Program and access to past webinars, visit: http://www.its.dot.gov/aeris/