Combined Modeling of Eco-Signal Operations Applications

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

Summer Webinar Series

June 25th, 2014

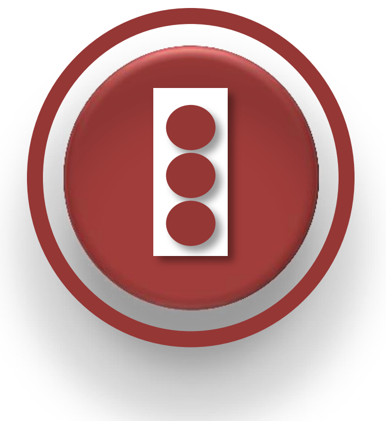
Presentation Overview

- Overview of the Eco-Signal Operations Operational Scenario
- The Modeling Corridor
- Recap of Individual Applications Modeling Results
- Combined Modeling Approach
- Combined Modeling Results
- Potential User Benefits
- Lessons Learned and Opportunities for Future Research

Overview of the Eco-Signal Operations Operational Scenario

- The **Eco-Signal Operations Operational Scenario** uses connected vehicle technologies and applications, as well as signal operational communications technologies, to reduce fuel consumption, greenhouse gas (GHG) and criteria air pollutant emissions on signalized arterial roadways
- The scenario consists of five individual applications, modeled **individually** with modeling results presented in the **AERIS Fall/Winter Webinar Series (November 2013 – March 2014)**
  - *Past webinars can be found at* **http://www.its.dot.gov/aeris/**
- Upon completion of the individual application modeling and analysis, the applications were **modeled together** to investigate the potential benefits of deploying integrated connected vehicle applications along a signalized corridor

Eco-Signal Operations Applications



ECO-SIGNAL OPERATIONS

- Eco-Approach and Departure at Signalized Intersections
- Eco-Traffic Signal Timing
- Eco-Traffic Signal Priority
  - Eco-Transit Signal Priority
  - Eco-Freight Signal Priority
- Connected Eco-Driving
- *Wireless Inductive/Resonance Charging (not modeled)*

Overview of the Eco-Signal Operations Operational Scenario

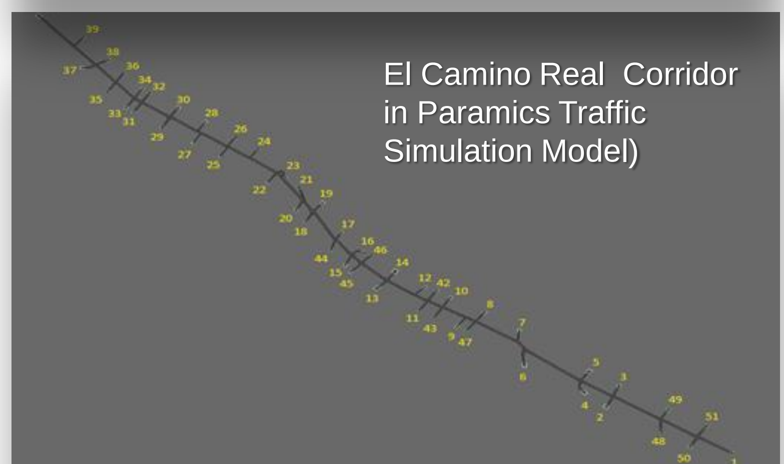
The combined modeling of the Eco-Signal Operations applications sought to answer the following questions:

- *What technical challenges would there be in combining the individual applications?*
- *Would the results of the applications be additive, or would one application nullify or conflict with another?*
- *Do all of the applications affect the same environmental measures, or are they different?*
- *In what conditions do the applications shine, and which do they falter?*

The Modeling Corridor

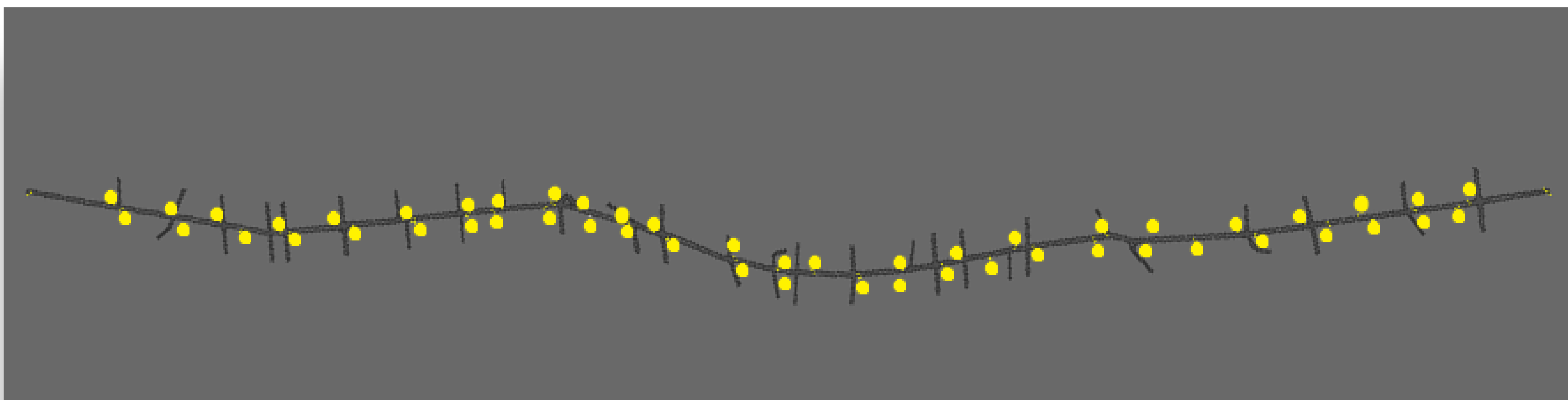
Modeling Corridor: El Camino Real

- A real-world corridor was chosen for analysis and modeling
- El Camino Real is a major north-south arterial connecting San Francisco and San Jose, CA
- The modeling corridor consisted of:
  - A six-mile segment of El Camino Real (using 2005 network and demand conditions)
  - Three lanes in each direction for the majority of the corridor with a 40 mph speed limit
  - 27 signalized intersections that were well coordinated / optimized
  - Intersection spacing that varied from 650 to 1,600 feet



Region of Modeling: El Camino Real in Northern California

- 1.2% freight demand in baseline model
- Mainline transit routes in both directions along the El Camino Real:
  - 10 minute headways between buses (6 per hour)
  - 27 bus stops in each direction, near signalized intersections (includes near-side and far-side stops)



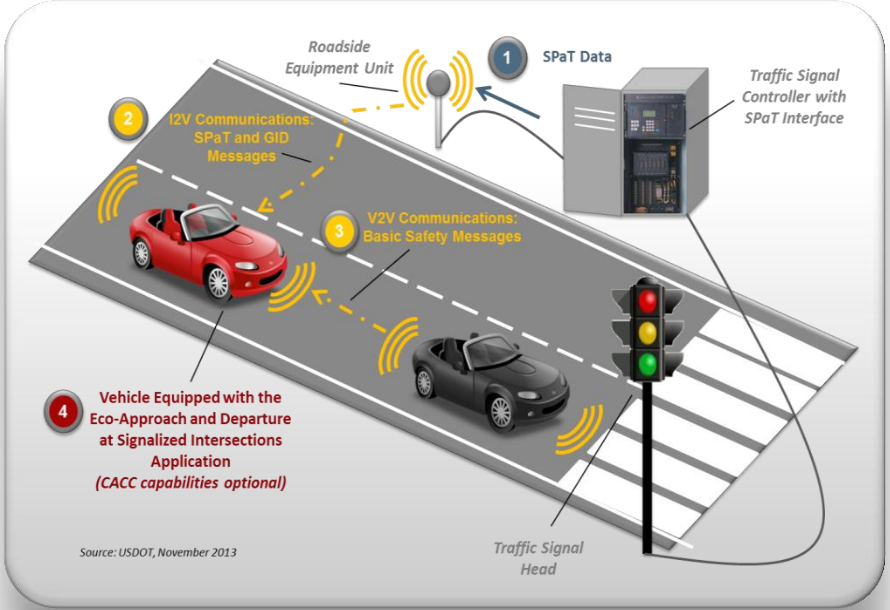
Modeling Corridor: El Camino Real in Northern California

- Detailed simulation modeling was conducted under different **traffic conditions**, **network conditions**, **connected vehicle penetration rates**, and other variables
- Simulation parameters (e.g., car-following logic, lane-change behavior) were **calibrated** using NGSIM data sets
- Many of the applications were initially modeled on a 3-intersection model as a **proof-of-concept** to test the algorithm
- After the initial tests, the application was modeled on the full corridor model of El Camino Real
- Individual modeling was completed first and then individual models were modeled collectively in a single model for **combined** analysis

Recap of Individual Applications Modeling Results

Eco-Approach and Departure at Signalized Intersections Application

Application Overview



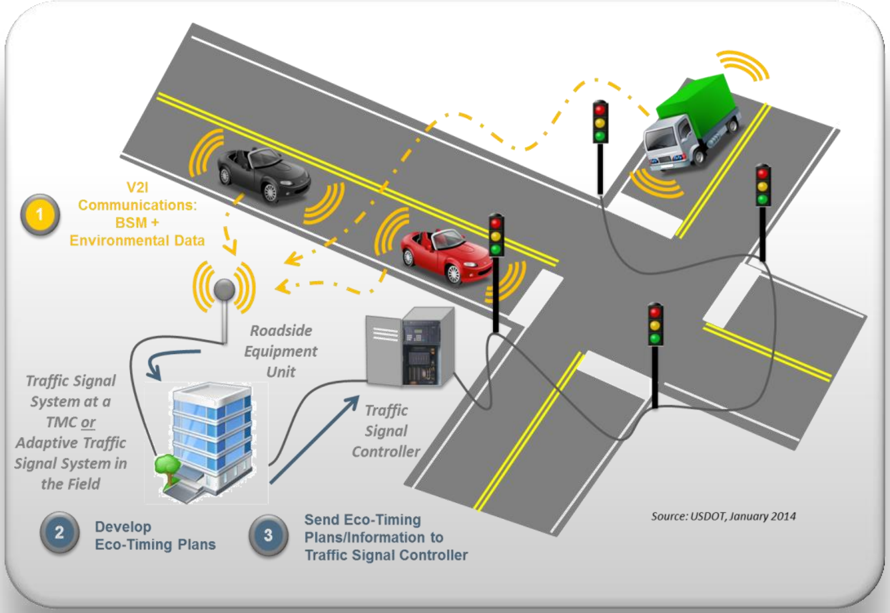
- Collects signal phase and timing (SPaT) and Geographic Information Description (GID) messages using vehicle-to-infrastructure (V2I) communications
- Collects basic safety messages (BSMs) from nearby vehicles using vehicle-to-vehicle (V2V) communications
- Receives V2I and V2V messages, the application performs calculations to determine the vehicle's optimal speed to pass the next traffic signal on a green light or to decelerate to a stop in the most eco-friendly manner
- Provides speed recommendations to the driver using a human-machine interface or sent directly to the vehicle's longitudinal control system to support partial automation

Eco-Approach and Departure at Signalized Intersections Application: Modeling Results

- **Summary of Preliminary Modeling Results**
  - 5-10% fuel reduction benefits for an uncoordinated corridor
  - Up to 13% fuel reduction benefits for a coordinated corridor
    - 8% of the benefit is attributable to signal coordination
    - 5% attributable to the application
- **Key Findings and Takeaways**
  - The application is less effective with increased congestion
  - Close spacing of intersections resulted in spillback at intersections. As a result, fuel reduction benefits were decreased somewhat dramatically.
  - Preliminary analysis indicates significant improvements with partial automation
  - Results showed that non-equipped vehicles also receive a benefit – a vehicle can only travel as fast as the car in front of it
- **Opportunities for Additional Research**
  - Evaluate the benefits of enhancing the application with partial automation

Eco-Traffic Signal Timing Application

Application Overview



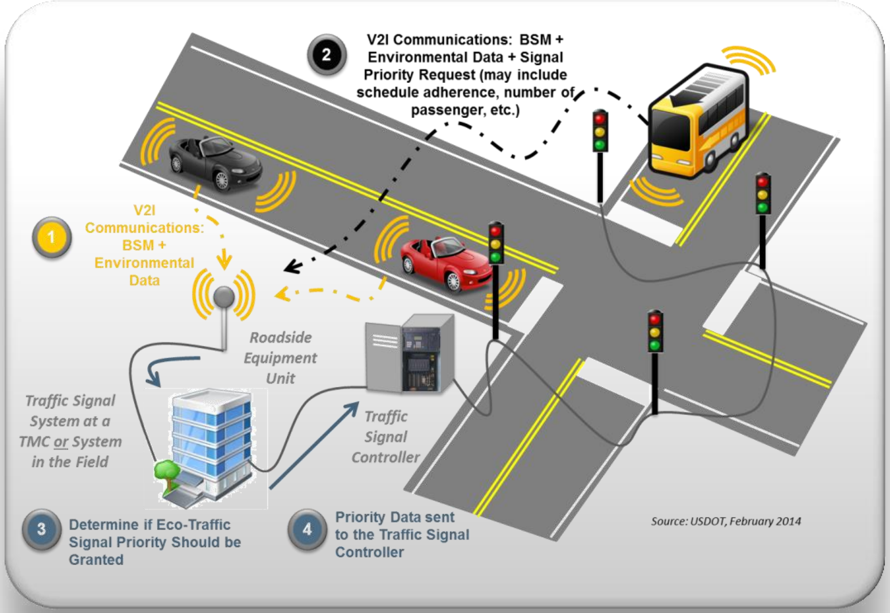
- Similar to current traffic signal systems; however the application's objective is to optimize the performance of traffic signals for the environment
- Collects data from vehicles, such as vehicle location, speed, vehicle type, and emissions data using connected vehicle technologies
- Processes these data to develop signal timing strategies focused on reducing fuel consumption and overall emissions at the intersection, along a corridor, or for a region
- Evaluates traffic and environmental parameters at each intersection in real-time and adapts the timing plans accordingly

Eco-Traffic Signal Timing Application: Modeling Results

- **Summary of Preliminary Modeling Results**
  - Up to 5% fuel reduction benefits at full connected vehicle penetration
    - 5% fuel reduction benefits when optimizing for the environment (e.g., CO_2)
    - 2% fuel reduction benefits when optimizing for mobility (e.g., delay)
- **Key Findings and Takeaways**
  - Optimization of signal timings using environmental measures of effectiveness resulted in mobility benefits in addition to environmental benefits
  - For the El Camino corridor, modeling results indicated that shorter cycle lengths (60 seconds) produce greater benefits than longer cycle lengths (130 seconds)
- **Opportunities for Additional Research**
  - Consider analysis for different geometries (e.g., grid network) and traffic demands (e.g., a corridor with higher volumes on the side streets)
  - Investigate adaptive or real-time traffic signal timing optimization algorithms

Eco-Traffic Signal Priority Application

Application Overview



- Allows either transit or freight vehicles approaching a signalized intersection to request signal priority
- Considers the vehicle's location, speed, vehicle type (e.g., alternative fuel vehicles), and associated emissions to determine whether priority should be granted
- Information collected from vehicles approaching the intersection, such as a transit vehicle's adherence to its schedule, the number of passengers on the transit vehicle, or weight of a truck may also be considered in granting priority
- If priority is granted, the traffic signal would hold the green on the approach until the transit or freight vehicle clears the intersection

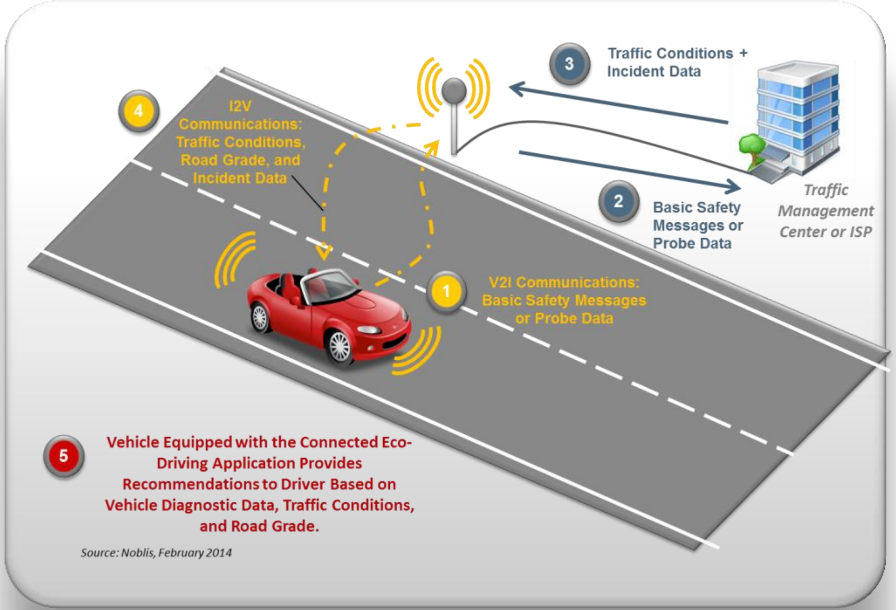
Eco-Traffic Signal Priority Application: Modeling Results

- **Summary of Preliminary Modeling Results**
  - Eco-Transit Signal Priority provides up to 2% fuel reduction benefits for transit vehicles → Up to $669,000 annual savings for fleet of 1,000 transit vehicles driving 44,600 miles each on arterials a year; larger fleet of 3,000 vehicles →$2M
  - Eco-Freight Signal Priority provides up to 4% fuel reduction benefits for freight vehicles → Up to $649,000 annual savings for fleet of 1,000 city delivery vehicles driving 30,000 miles on arterials each year; large fleet of 80,000 vehicles → $51M
- **Key Findings and Takeaways**
  - Eco-Transit Signal Priority
    - Reduced emissions for buses; however in some cases, signal priority was detrimental to the overall network
    - Provided greater overall environmental benefits when the bus' adherence to its schedule was considered by the algorithm
  - Eco-Freight Signal Priority
    - Passenger vehicles and unequipped freight vehicles also saw reductions in emissions and fuel consumption, benefiting from the additional green time
- **Opportunities for Additional Research**
  - Investigate advanced algorithms that collect data from all vehicles and evaluate impacts of granting priority in real-time

Connected Eco-Driving Application

Application Overview

- Connected Eco-Driving provides customized real-time driving advice so drivers can adjust their driving behavior to save fuel and reduce emissions.
- Driving advice includes recommended driving speeds, optimal acceleration, and optimal deceleration profiles



- Receives V2I and V2V messages, the application determines the vehicle's optimal acceleration and deceleration profiles to navigate the corridor in the most eco-friendly manner
- Provides these recommendations to the driver using a human-machine interface or sent directly to the vehicle's longitudinal control system to support partial automation

Connected Eco-Driving Application: Modeling Results

- **Summary of Preliminary Modeling Results**
  - Up to 2% fuel reduction benefits at full connected vehicle penetration
  - Up to 2% dis-benefit in mobility due to smoother and slower accelerations to meet environmental optimums
- **Key Findings and Takeaways**
  - The application is much more amenable to different levels of congestion than the other Eco-Signal Operations applications
  - Results showed that non-equipped vehicles also receive a benefit – a vehicle can only travel as fast as the car in front of it
- **Opportunities for Additional Research**
  - The decision module could be further improved, taking into account the real-time information of the preceding vehicle
  - Automated longitudinal control could be integrated to further improve compliance with the speed, acceleration, and decelerations
  - Future research could consider could consider roadway grade and downstream traffic conditions, which were not modeled

Combined Modeling Approach

Modifications to Support Combined Modeling

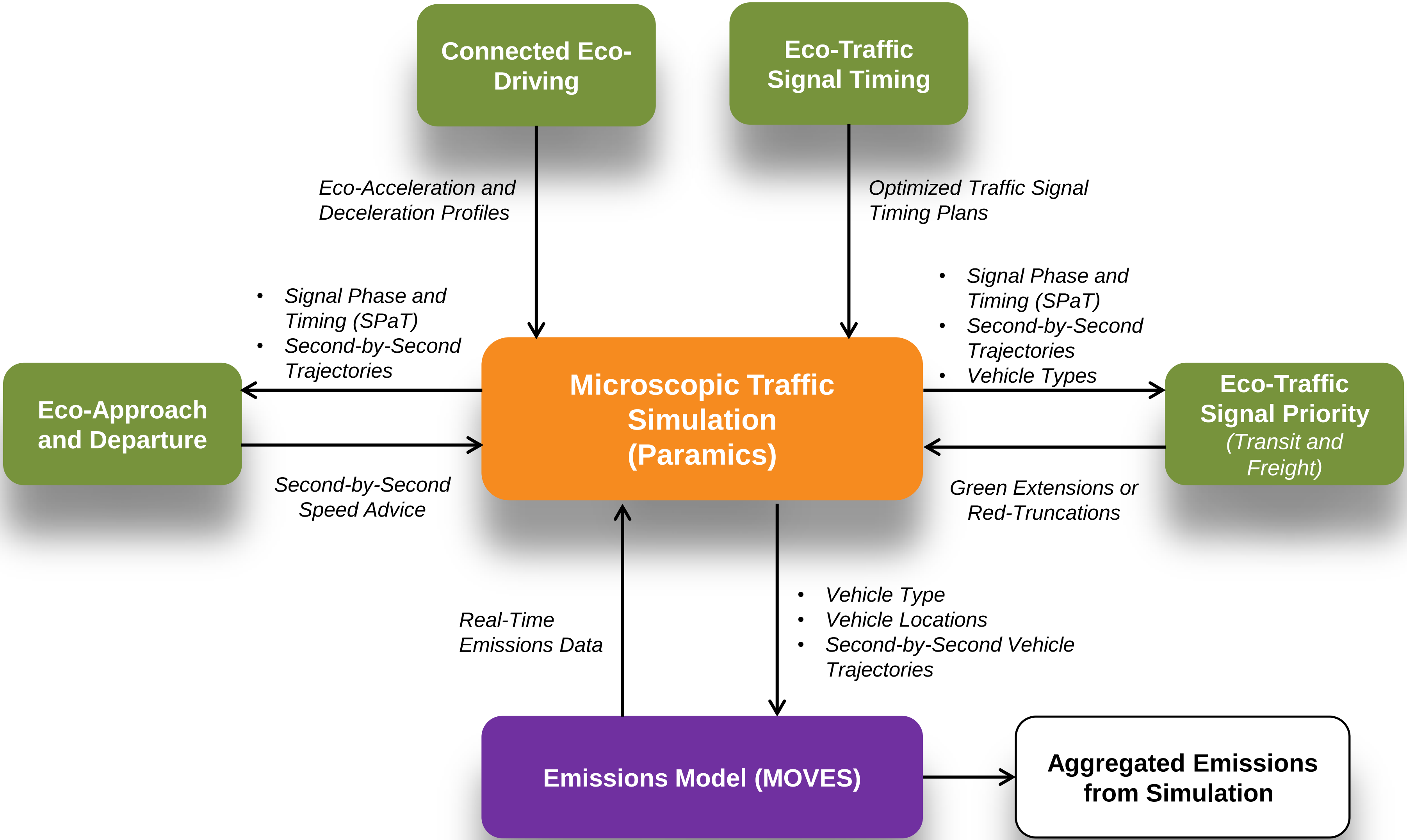
- To successfully integrate the modules for combined modeling, the following actions were implemented:
  - The Eco-Traffic Signal Timing genetic algorithm (GA) was run before the modeling as the new signal timing plan for which the other four applications run in combination
  - The Eco-Transit Signal Priority and the Eco-Freight Signal Priority application APIs were combined to form a “combined” priority application
  - A new API was developed to track priority requests from both freight and transit vehicles
  - An additional module developed to handle “conflicting” priority requests

Combined Modeling of Applications as Implemented in Simulation

To model the Eco-Signal Operations applications, there were three vital components:

- **Microscopic Traffic Simulation:** in order to test the priority algorithm in simulated conditions in real-time, **Paramics** micro simulation program was used
- **Eco-Signal Operations Application APIs:** the individual original and modified **Paramics APIs** for the 5 applications were implemented, which simulated connected vehicle technology
- **Emissions Model:** the environmental modeling program **MOVES** was coded as an API to use with Paramics that provided real-time emissions from the simulation

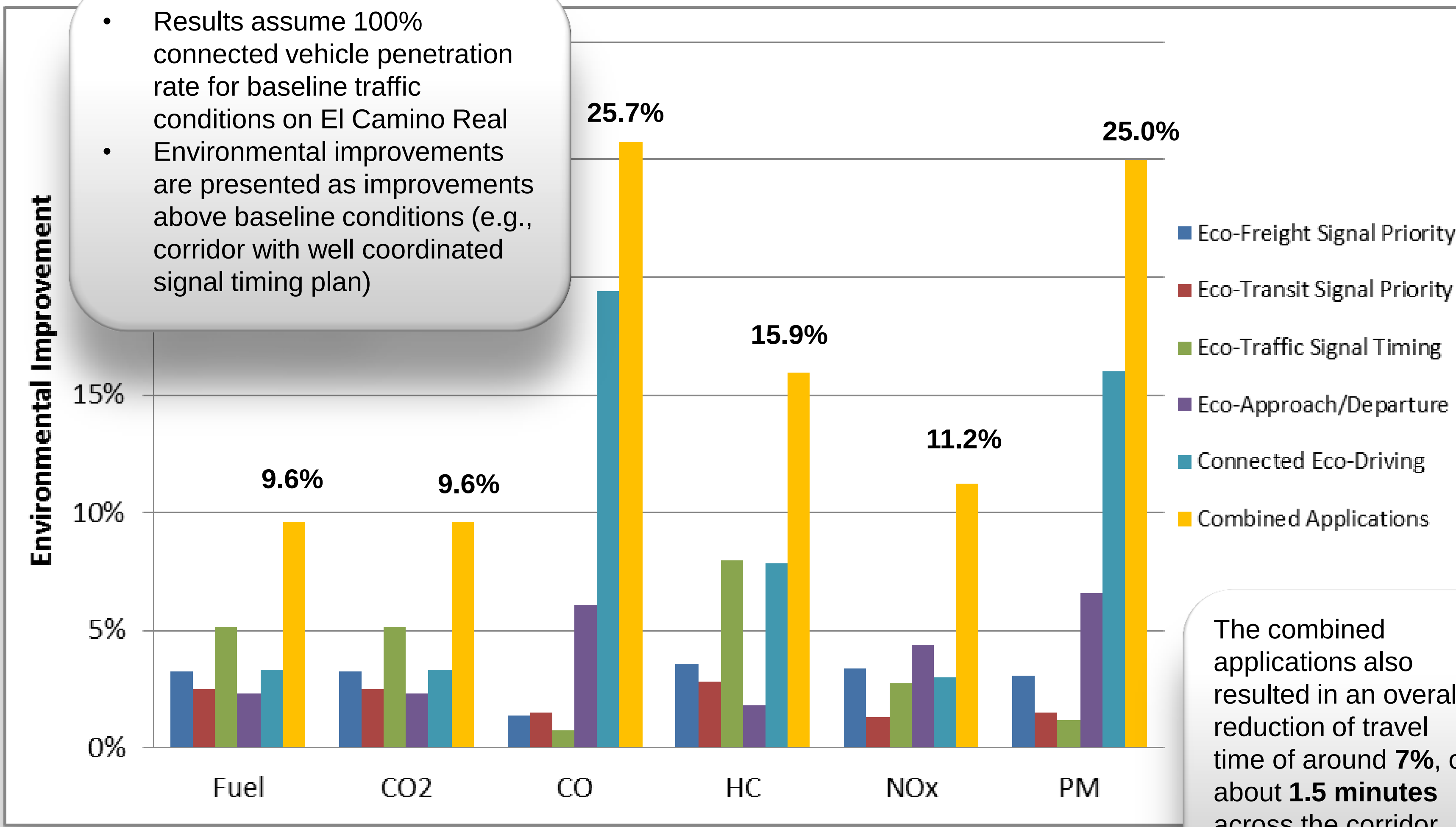
Combined Modeling Approach



Combined Modeling Results

Environmental Impacts of Combined Applications

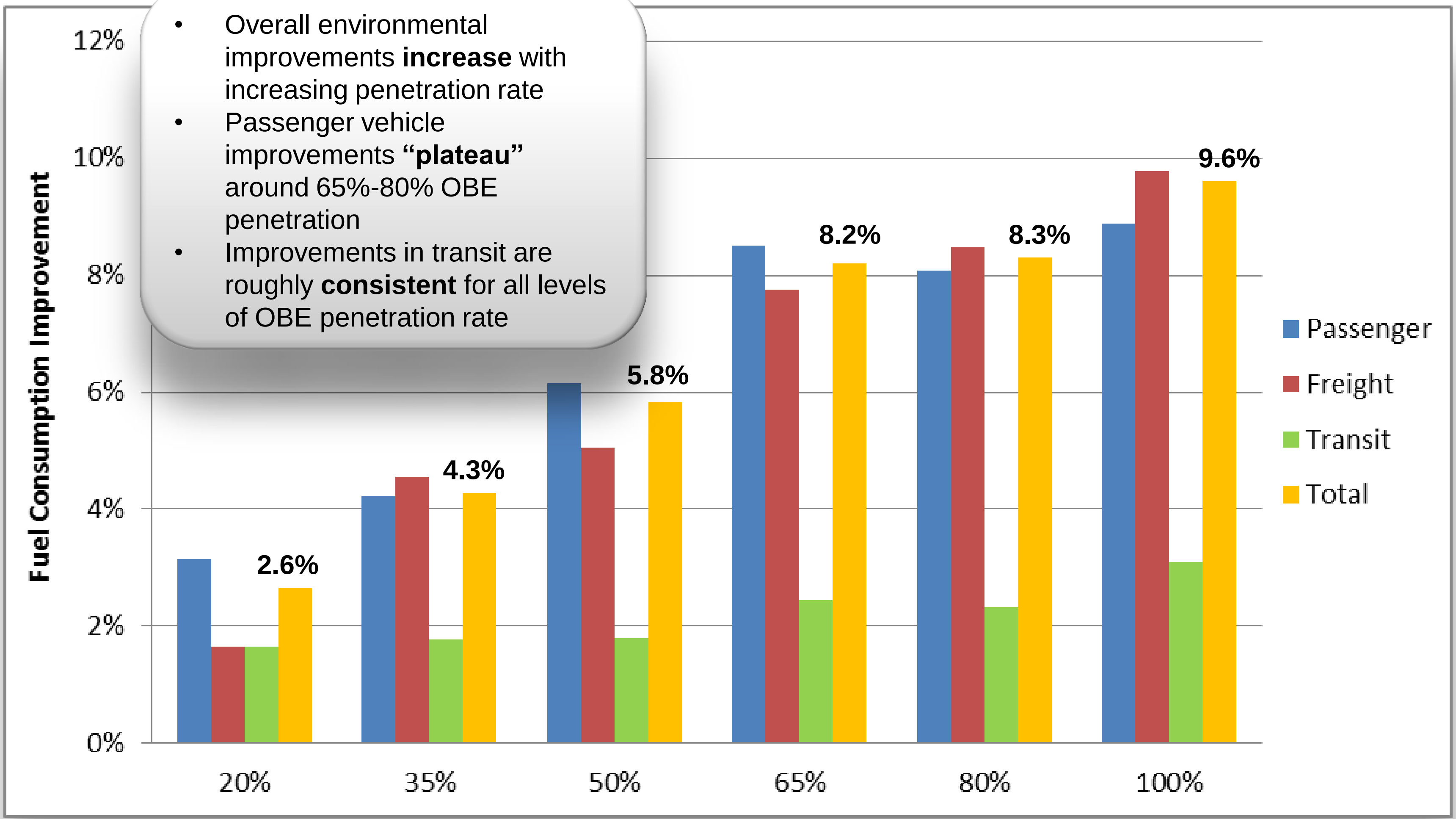
- Results assume 100% connected vehicle penetration rate for baseline traffic conditions on El Camino Real
- Environmental improvements are presented as improvements above baseline conditions (e.g., corridor with well coordinated signal timing plan)



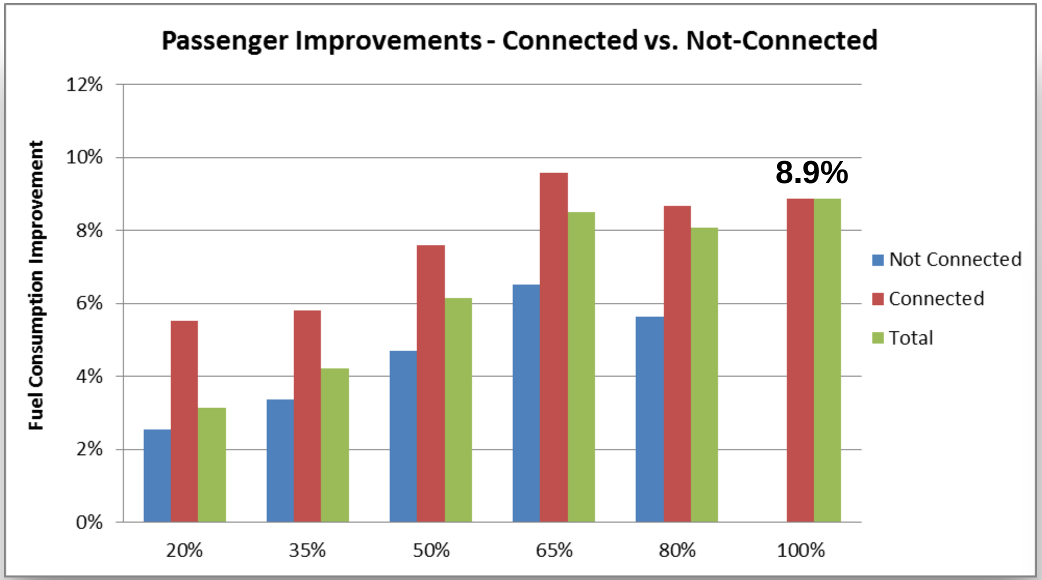
The combined applications also resulted in an overall reduction of travel time of around **7%**, or about **1.5 minutes** across the corridor

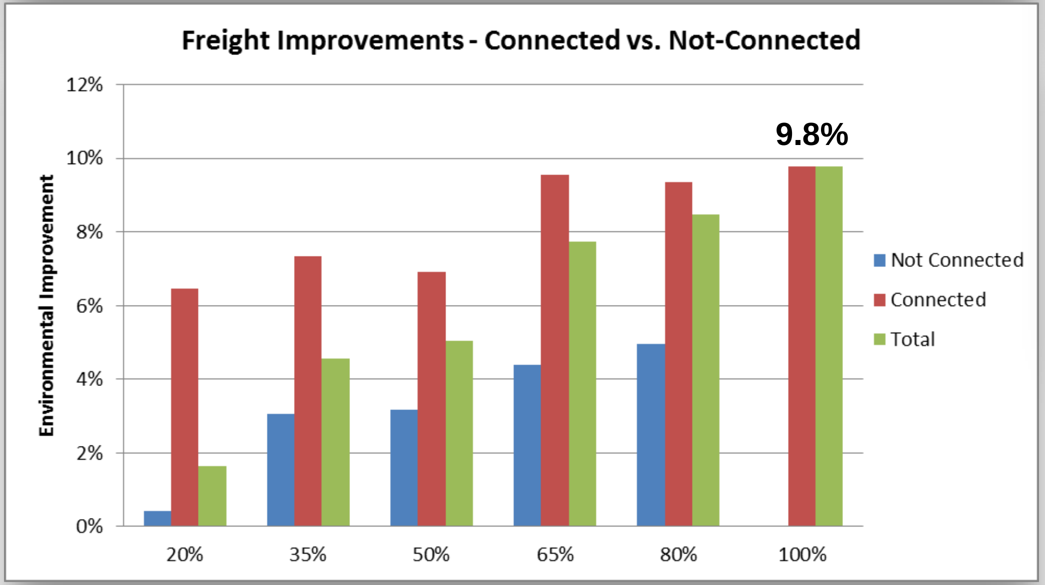
Impact on the Environment due to Increasing OBE Penetration Rates

- Overall environmental improvements **increase** with increasing penetration rate
- Passenger vehicle improvements **"plateau"** around 65%-80% OBE penetration
- Improvements in transit are roughly **consistent** for all levels of OBE penetration rate



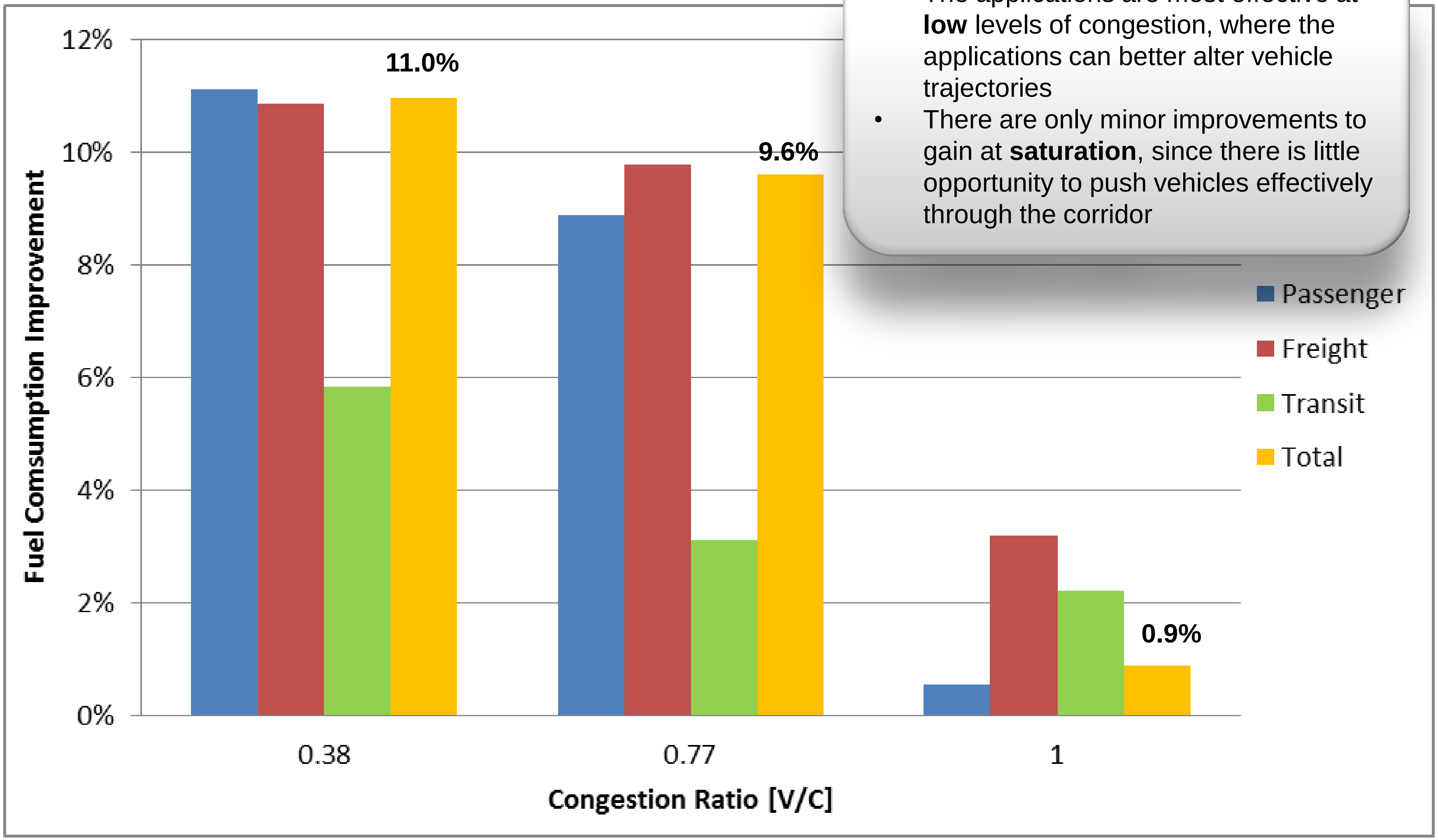
Secondary Impacts for Non-Connected Vehicles





- Non-connected vehicles receive incidental improvements from the applications benefitting from additional green time and improved speed profiles on the mainline
- This occurs at both low and high connected vehicle penetration rates

Impact of Demand/Congestion

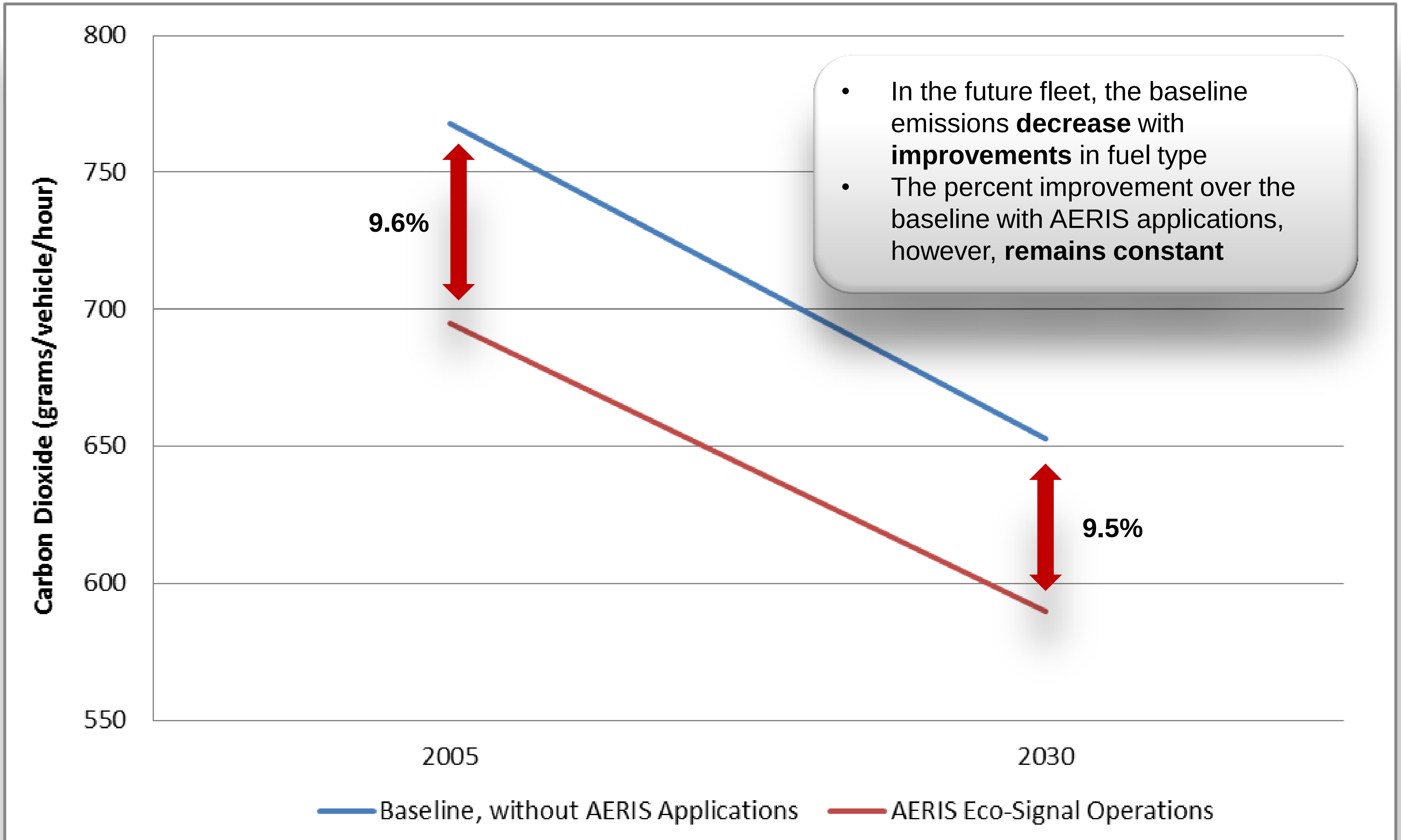


- The applications are most effective at **low** levels of congestion, where the applications can better alter vehicle trajectories
- There are only minor improvements to gain at **saturation**, since there is little opportunity to push vehicles effectively through the corridor

Future Fleet Impact Estimation

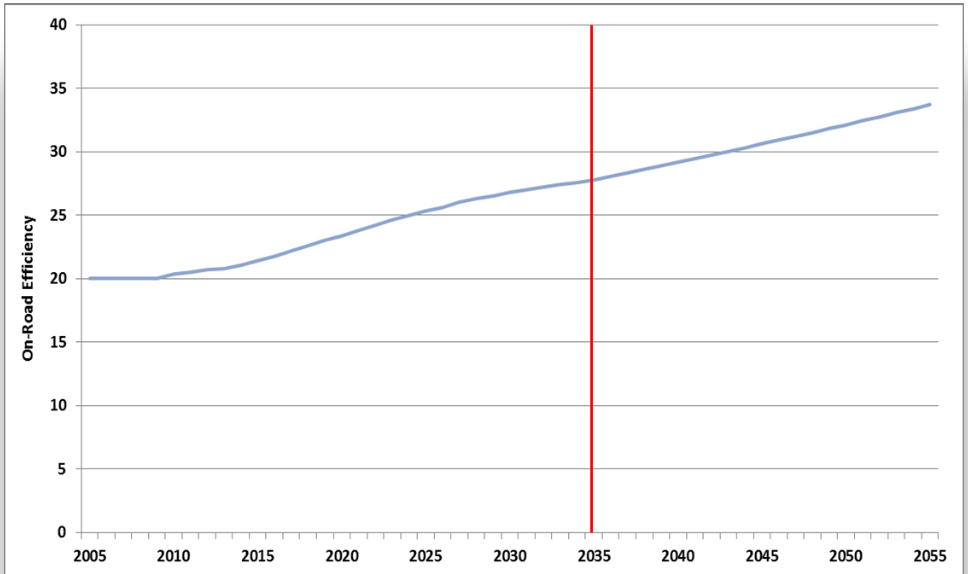
- With estimated improvements in fuel efficiency and increased penetration of hybrid/electric vehicles, it was important to see if similar results could be obtained in future fleets:
  - The 2011 California Emissions Factor (EMFAC2011) model was used to estimate the composition of the **2030 fleet mix** for age and fuel type distribution
  - The baseline model was run for the 2030 fleet mix to determine the **baseline changes** in emissions in the future
  - Then the future 2030 fleet mix was used with the **combined Eco-Signal Operations applications** to determine the impact

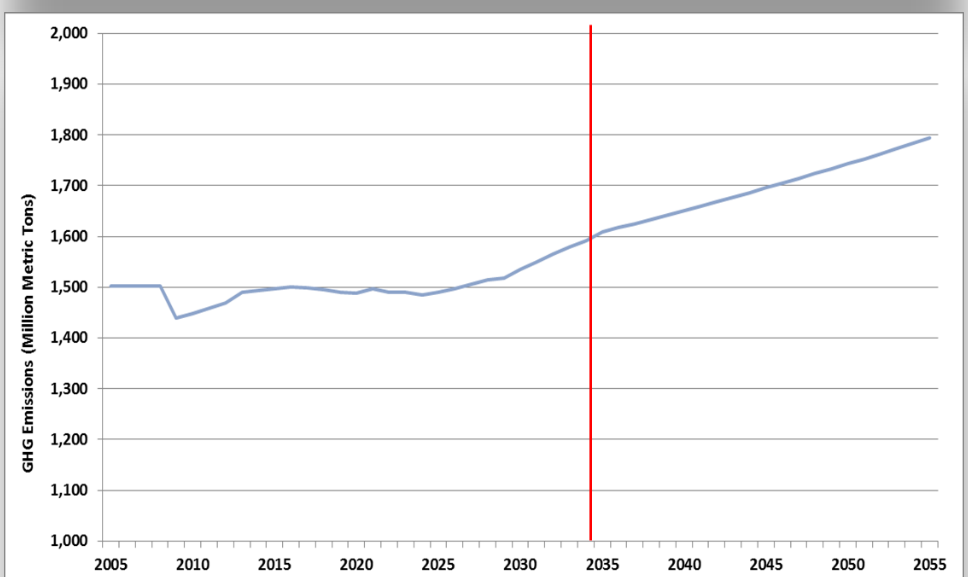
Difference in Impact between 2005 and 2030 Fleet Mixes



- In the future fleet, the baseline emissions **decrease** with **improvements** in fuel type
- The percent improvement over the baseline with AERIS applications, however, **remains constant**

Why Care about Future Impacts?





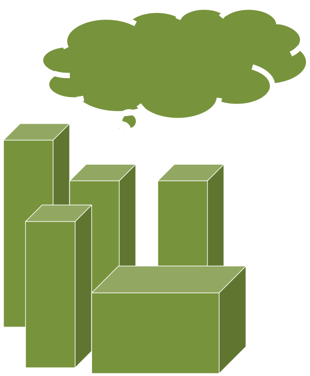
- While fuel efficiency is predicted to improve in future years, predicted future VMT **will actually increase** overall emission volumes
- Modeling of the Eco-Signal Operations applications show that future percentage improvements are **similar**
- The applications will help **mitigate** future predicted increases in GHG emissions

Potential User Benefits

Estimating Potential Benefits to Users

AERIS applications help drivers reduce their carbon footprint and reduce their fuel consumption. **Drivers help the environment and save money at the pump.**

Fleet operators also benefit from AERIS applications. **Fuel savings help fleet operators save fuel costs resulting in lower operating costs.**



AERIS applications benefit cities, helping reduce emissions and improving the city's air quality. AERIS applications also help reduce congestion and support sustainable transportation solutions.

- Assuming a corridor with average traffic congestion
  - Modeling results indicate the following benefits:
    - **Light vehicles: 9.6% reductions in fuel consumption**
    - **Freight: 9.8% reductions in fuel consumption**
    - **Transit: 3.1% reductions in fuel consumption**
  - Gasoline costs:
    - $3.67/gallon (light vehicle and SUV)
    - $3.95/gallon for diesel (trucks)
    - $3.00/gallon estimated for mix of CNG and diesel fleets (transit)
  - Average miles traveled on arterials:
    - Light duty vehicle and SUVs: 8,250 miles
    - City delivery truck: 30,000 miles
    - Transit: 44,600 miles
  - Estimated Benefits
    - Light Vehicle, 23 MPG **~ $126 per year**
    - Sport Utility Vehicle (SUV), 17 MPG **~ $170 per year**
    - City Delivery Fleet (1,000 vehicles), 7.3 MPG ~ **$1.6M per year**
    - Transit Fleet (1,000 vehicles), 4 MPG ~ **$918,000 per year**

Lessons Learned and Opportunities for Future Research

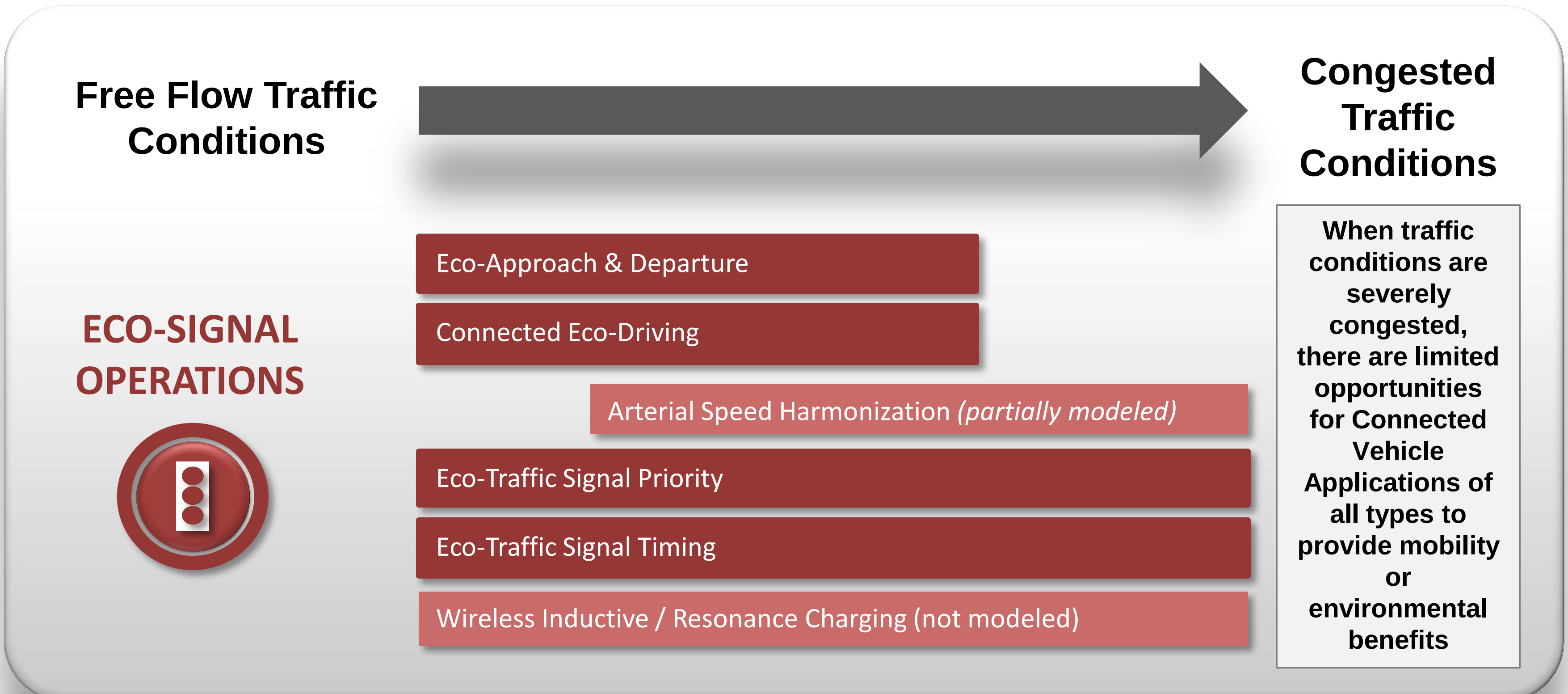
Lessons Learned

With the results of the combined modeling, we can answer some of the questions we hypothesized before the analyses:

- The combined applications may not be additive of the results of the individual modeling results, but modeling showed that **none of the applications conflicted with each other**
- Individual application gains of 2% to 5% are good, but when combined, the **total impact** is quite significant in terms of fuel savings and emission reductions (9.6% benefits at full connected vehicle penetration)
- Noticeable benefits can be gained **even at low** connected vehicle OBE penetration rates, which is promising for early adopters of connected vehicle technologies and AERIS applications
- Environmental benefits **increase with increasing levels** of OBE penetration rate for all individual applications, as well as when combined

Lessons Learned

- Applications work better in **lower congestion**, since there is more opportunity for vehicles to modify their trajectory and to improve signal timings



Lessons Learned

- Non-connected vehicles receive **incidental benefits** from improved signal timings, granted signal priorities, and speed advice meant for the connected vehicles
- Most of the applications have corresponding improvements in **mobility** measures, such as delay and travel time
- Communication delay did not have a noticeable impact on the results, indicating the opportunity for **great flexibility** in wireless communication technology
- Varying the multiple sensitivity parameters during the analyses, such as decision distance and extension maximums, was shown to increase potential benefits, proving the **customizability** of applications to suit location-specific needs

One Final Thought…

- Since the El Camino Real corridor was a well-timed corridor, the environmental results gained from the applications are **conservative**
- Many municipalities and regions around the country have sub-optimal optimizations and traffic conditions
- Research has shown that **better benefits** can be obtained in uncoordinated traffic signal systems
- Therefore, there is **potential** to gain greater environmental benefits from the Eco-Signal Operations applications in real-world situations

Opportunities for Future Research

- **Compliance rate** could be further investigated to better models the drivers' willingness and ability to follow the speed advice recommendations
- Additional modeling could be considered on different corridor demand configurations (e.g., a corridor with higher demands on the side streets, an urban grid, etc.)
- The resultant signal timings from running the Eco-Approach and Departure and the Eco-Traffic Signal Timing applications **in combination** could be greatly improved if the optimization process included the eco-friendly speed advice to vehicles during the runs
- More **aggressive assumptions** of electric and hybrid fuel vehicles (more aggressive than EMFAC2011) could be considered in future modeling efforts

Opportunities for Future Research

- While commercial products do not exist for the Eco-Signal Operations applications (or other connected vehicle applications), the AERIS Program sees opportunities to work with the adopter community to move these concepts toward deployment.
- Future research opportunities include:
  - Continuing to **enhance the underlying algorithms;**
  - Developing **prototypes of the applications** to test their efficacy and usefulness;
  - Working with the adopter community (e.g., state and local DOTs, vehicle OEMS, traffic control industry, etc.) to **pilot AERIS applications in a real-world environment including the USDOT's CV Pilots initiative**; and
  - Transferring benefits and lessons learned to entities likely to deploy the applications.

Eco-Signal Operations Modeling Team

- **Booz Allen Hamilton**
  - Balaji Yelchuru (Principal Investigator)
  - Sean Fitzgerel
  - Sudeeksha Murari
- **University of California, Riverside**
  - Matt Barth (Principal Investigator)
  - Guoyuan Wu (Postdoctoral Fellow)
  - Haitao Xia (Graduate Student)
- **University of New South Wales**
  - Travis Waller (Principal Investigator)
  - Vinayak Dixit
  - Kasun Wijayaratna (Graduate Student)
  - Tuo Mao (Graduate Student)
- **AERIS Research Team Partners**

Upcoming AERIS Webinars

- 2014 AERIS Summer Webinar Series
  - 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: http://www.its.dot.gov/aeris/