UNITED STATES
DEPARTMENT OF TRANSPORTATION

Preliminary Eco-Traffic Signal Priority (for Transit and Freight) and Connected Eco-Driving Modeling Results

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

Fall/Winter Webinar Series

February 12th, 2014

Presentation Overview

Eco-Traffic Signal Priority Application

- Modeling Approach of Eco-Traffic Signal Priority
- Eco-Freight Signal Priority Application
  - Eco-Freight Signal Priority Algorithm
  - Preliminary Simulation Results
  - Conclusions and Potential Future Research
- Eco-Transit Signal Priority Application
  - Eco-Freight Signal Priority Algorithm
  - Preliminary Simulation Results
  - Conclusions and Potential Future Research

Connected Eco-Driving Application

- Connected Eco-Driving Algorithm
- Preliminary Simulation Results
- Conclusions and Potential Future Research

ECO-TRAFFIC SIGNAL PRIORITY

Eco-Traffic Signal Priority

The Eco-Traffic Signal Priority application seeks to use connected vehicle technologies and data to provide signal priority to either freight or transit vehicles with an environmental focus:

- The application monitors the vehicle's location, speed, vehicle type, adherence to schedule, weight, and associated emissions to determine whether priority should be granted
- If priority is granted, the green phase on the approach is held or a green phase of an adjacent approach is terminated early until the transit or freight vehicle clears the intersection

Eco-Traffic Signal Priority

- The Eco-Traffic Signal Priority Application is made up of two separate, but similar applications which were implemented and modeled separately:
    - Eco-**Freight** Signal Priority
    - Eco-**Transit** Signal Priority
- The applications are separately tailored to fit the unique aspects of freight vs. transit vehicles and the data that can be obtained from these vehicles using connected vehicle technologies
- A future implementation of the Eco-Traffic Signal Priority application **in practice** would require a combination of the two, which examines different vehicle types for **competing requests**

Eco-Traffic Signal Priority Hypothesis

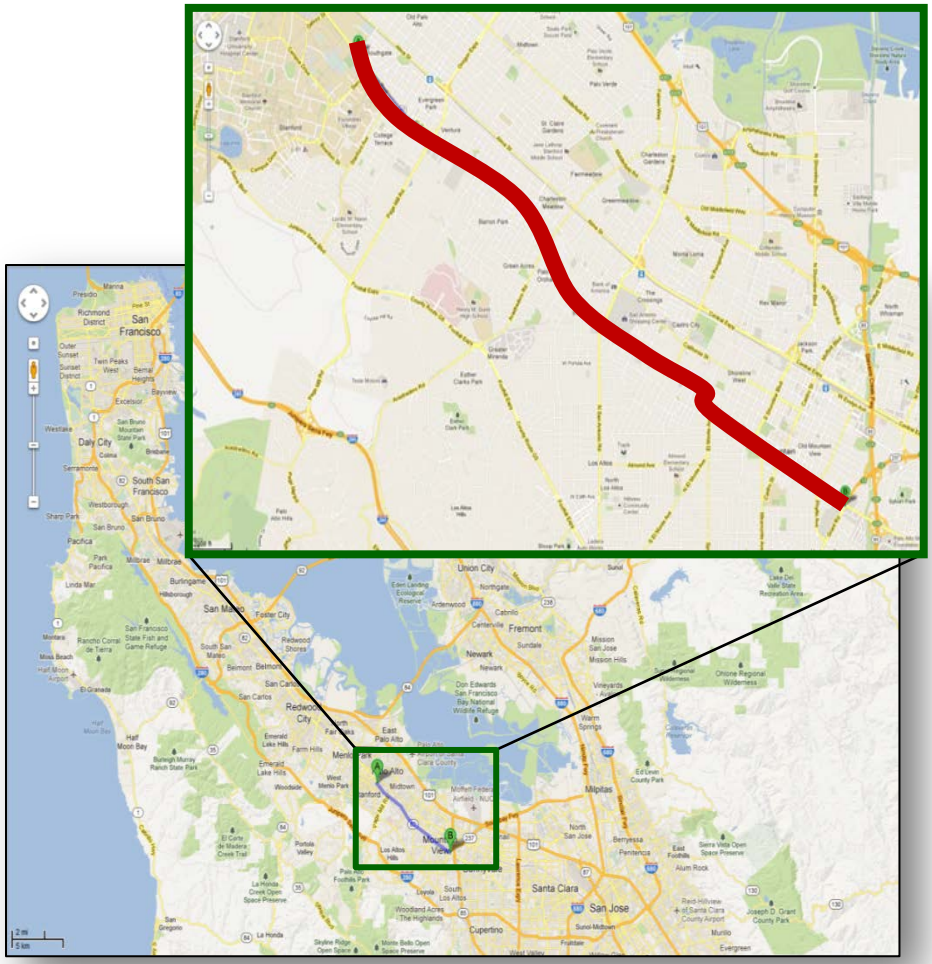
If the Eco-Traffic Signal Priority application is used to grant signal priority to selected transit and freight vehicles based on the transit vehicles' adherence to schedule, location, speed, size, vehicle class and traffic and environmental characteristics of all vehicles at the signalized intersection, ***then*** there will be emissions reductions and lowered fuel consumption during congested traffic conditions in the range of:

- **1%–2%** under partial connected vehicle penetration and
- **2%–4%** under full connected vehicle penetration

MODELING APPROACH

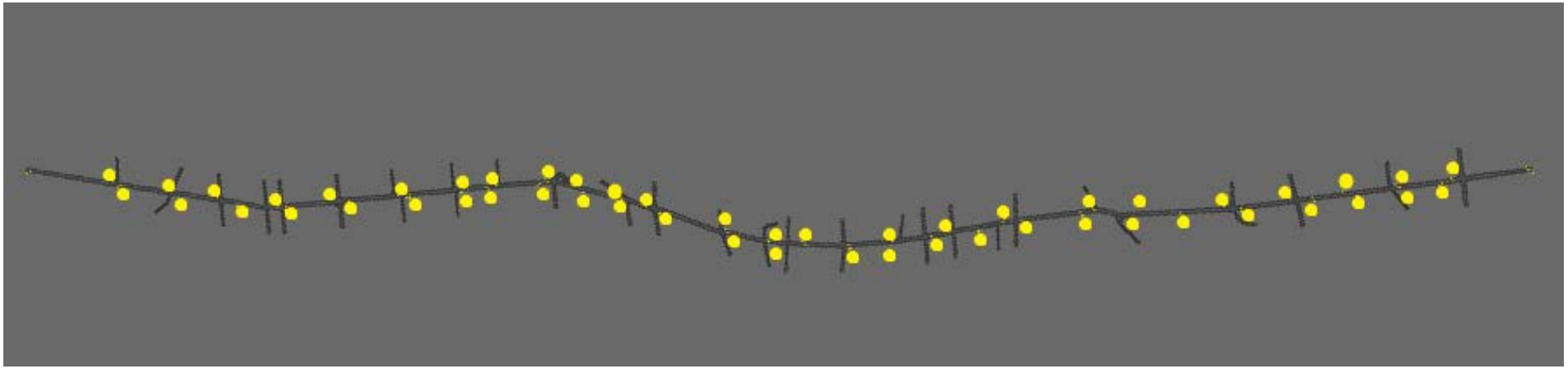
Region of Modeling: El Camino Real in Northern California

- 6-mile segment between
  - Churchill Ave in Palo Alto and Grant Rd in Mountain View
- 2005 Network and Demand conditions
- 27 signalized intersections
- Fixed timing plans and well coordinated signals
- Mostly three lanes in each direction
- Parallel to the US-101 freeway



Region of Modeling: El Camino Real in Northern California

- Low freight demand in baseline model of 1.2%
- 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 to signalized intersections



Modeling Approach

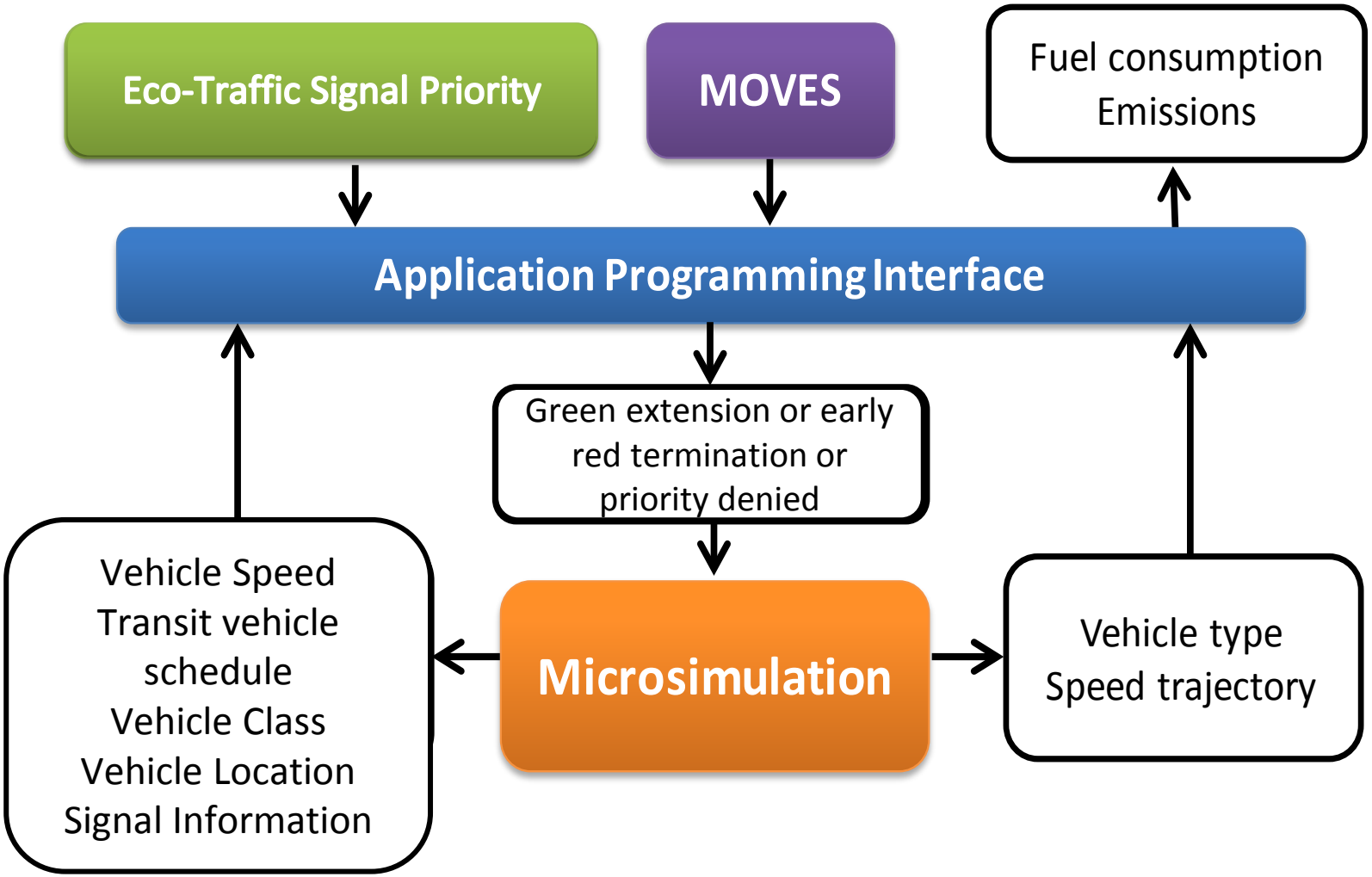
- Conduct detailed simulation modeling and test benefits under different **traffic conditions**, **network conditions**, **technology penetration rates**, and other variables
- Simulation parameters (car-following logic, lane-change behavior) calibrated using NGSIM data sets
- The algorithms and logic for both applications were initially tested on a small, 3-intersection model as a proof-of-concept to test the algorithm
- After the initial tests, the application was tested on a full corridor model of the El Camino Real, near Palo Alto, CA
- Later tie-in with other AERIS applications for a combined analysis

Eco-Traffic Signal Priority Application Implemented in Simulation

To test the Eco-Traffic Signal Priority Application, there were three vital components:

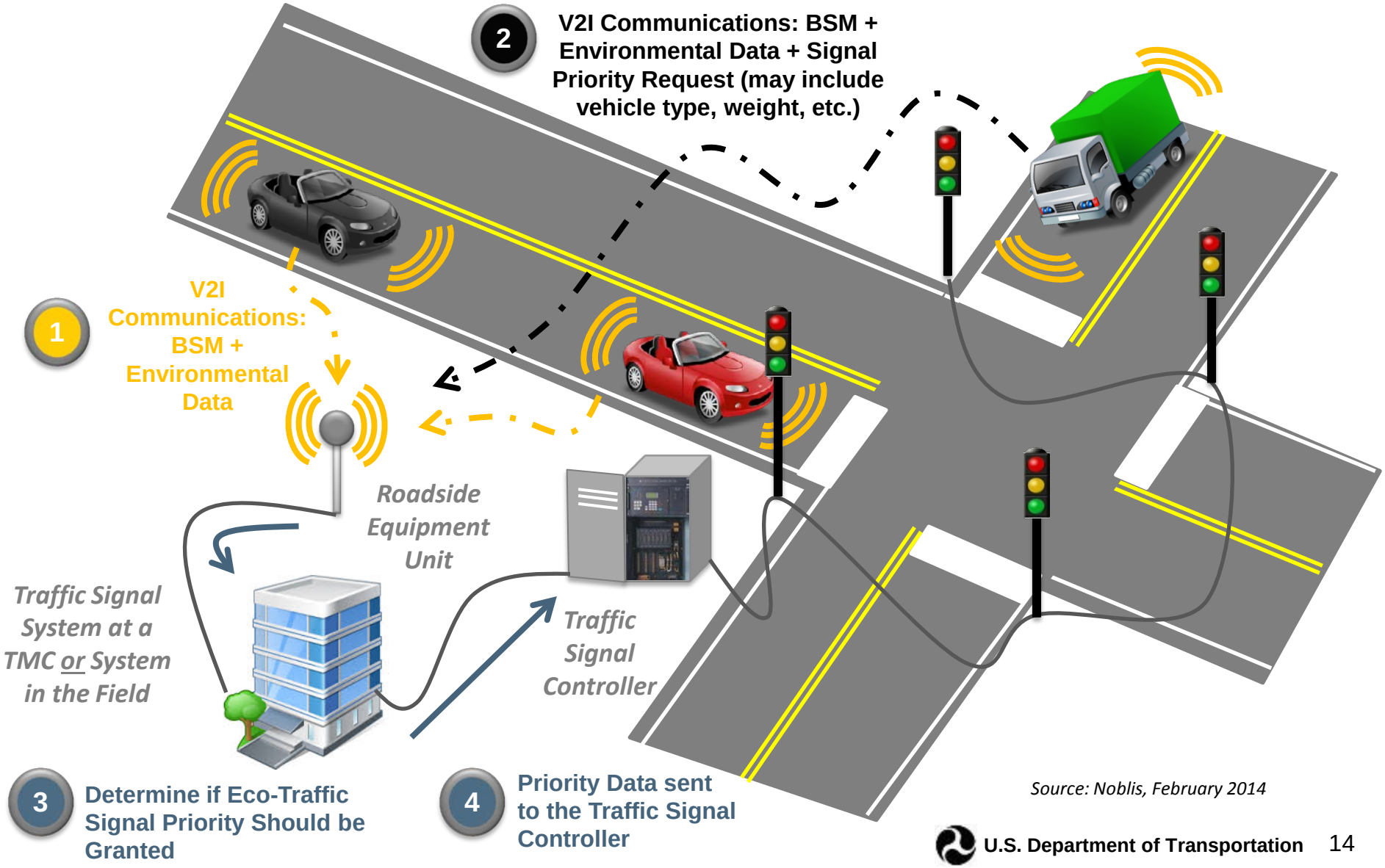
- Microsimulation Component: in order to test the priority algorithm in simulated conditions in real-time, **Paramics** microsimulation program was used
- Traffic Signal Priority Component: algorithms were developed for both the **Eco-Freight Signal Priority** and **Eco-Transit Signal Priority** applications as APIs with Paramics, which simulated connected vehicle technology
- Environmental Monitoring Component: the environmental modeling program **MOVES** was coded as an API to use with Paramics that provided real-time emissions from the simulation

Eco-Traffic Signal Priority Application Implemented in Simulation



ECO-FREIGHT SIGNAL PRIORITY

Eco-Freight Signal Priority



Source: Noblis, February 2014

Eco-Freight Signal Priority Algorithm

- When determining priority for freight vehicles in this application, **we ask ourselves:**

  "Not only can we give priority, but should we…?"

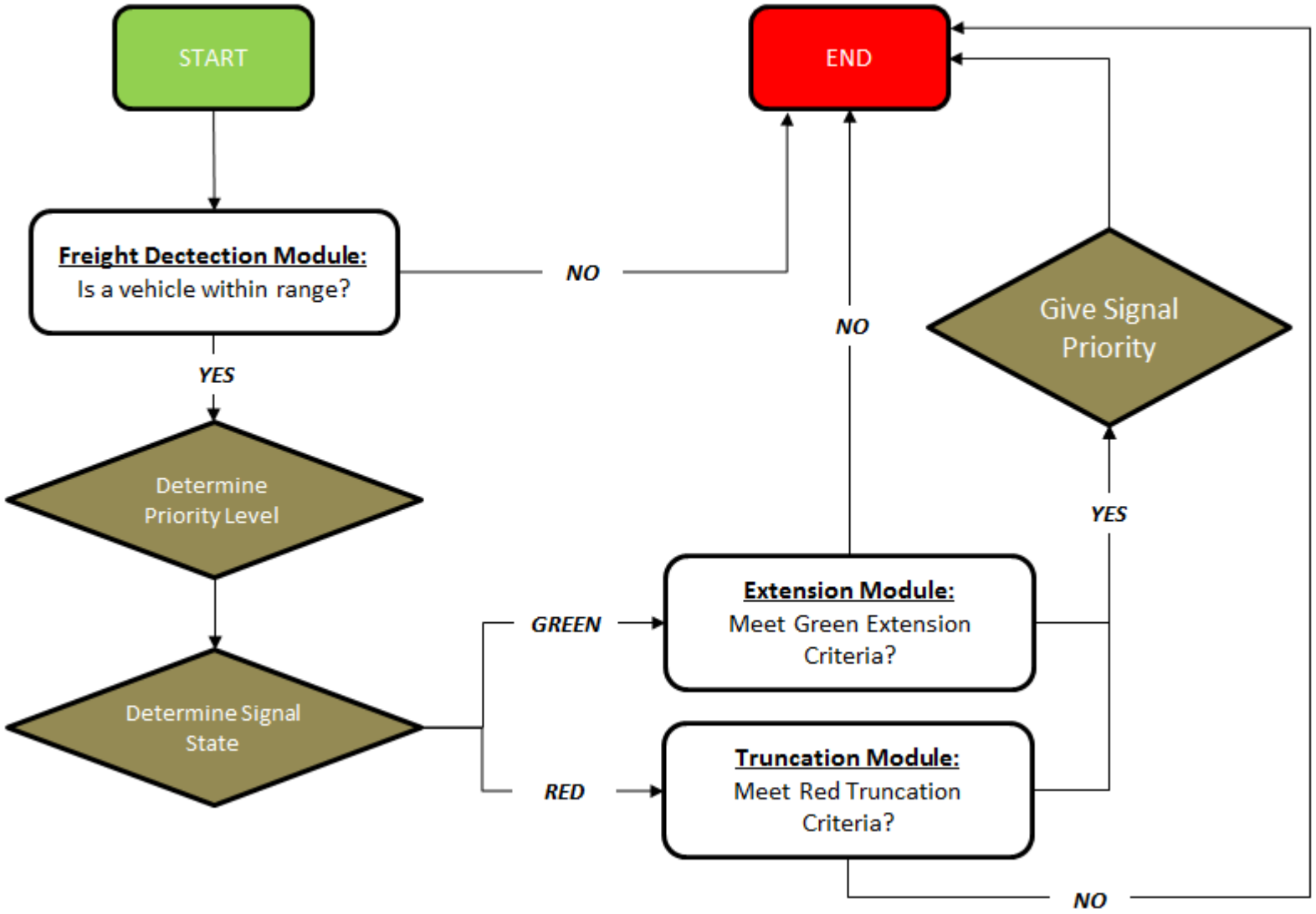
- Freight vehicles have a large impact on the overall emissions of the system, but sometimes granting a priority could be an **overall detriment**
- Freight vehicles approaching the intersection are assigned a **"priority level" which is based on:**
  - **Freight class** – *What type of freight vehicle?*
  - **Platooning status** – *Are the vehicles naturally grouped?*
  - **Emission Rate** – *What is the average rate/hr for the given Freight class?*

Eco-Traffic Signal Priority Application Implemented in Simulation

The three priority levels are used by the algorithm to determine the urgency and importance of the request:

- Priority Level 1: A **platoon** of freight vehicles containing at least **one or more of high polluting vehicles** (by emission rate)
  - *May request green extension or max red truncation*
- Priority Level 2: A **platoon** of lighter freight class vehicles, or a single **high polluting vehicle**
  - *May request green extension or half of max red truncation*
- Priority Level 3: A **single freight vehicle**, of a lighter pollutant class
  - *May only request green extension*

Eco-Freight Signal Priority Algorithm

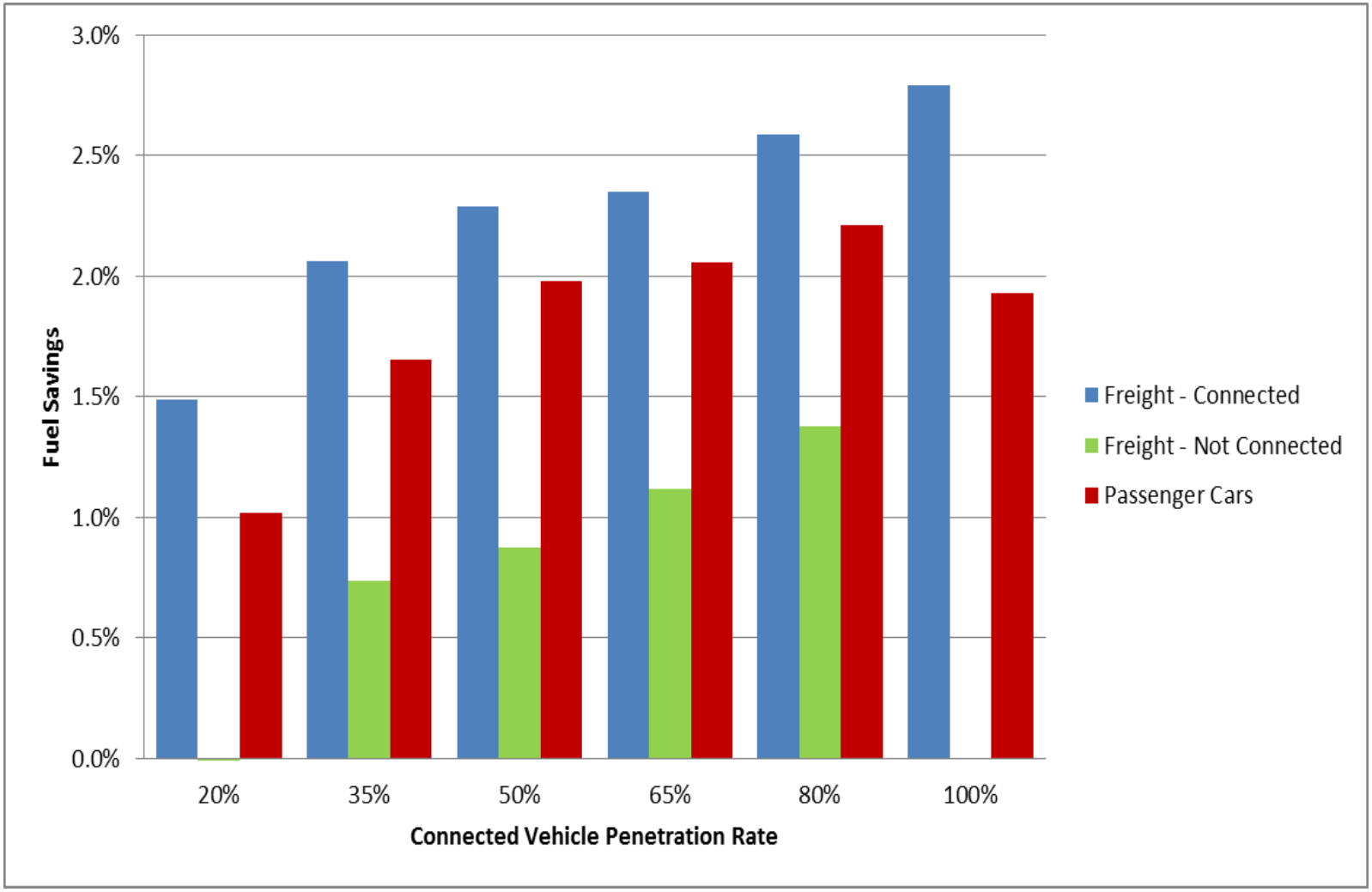


Modeling Results and Analyses

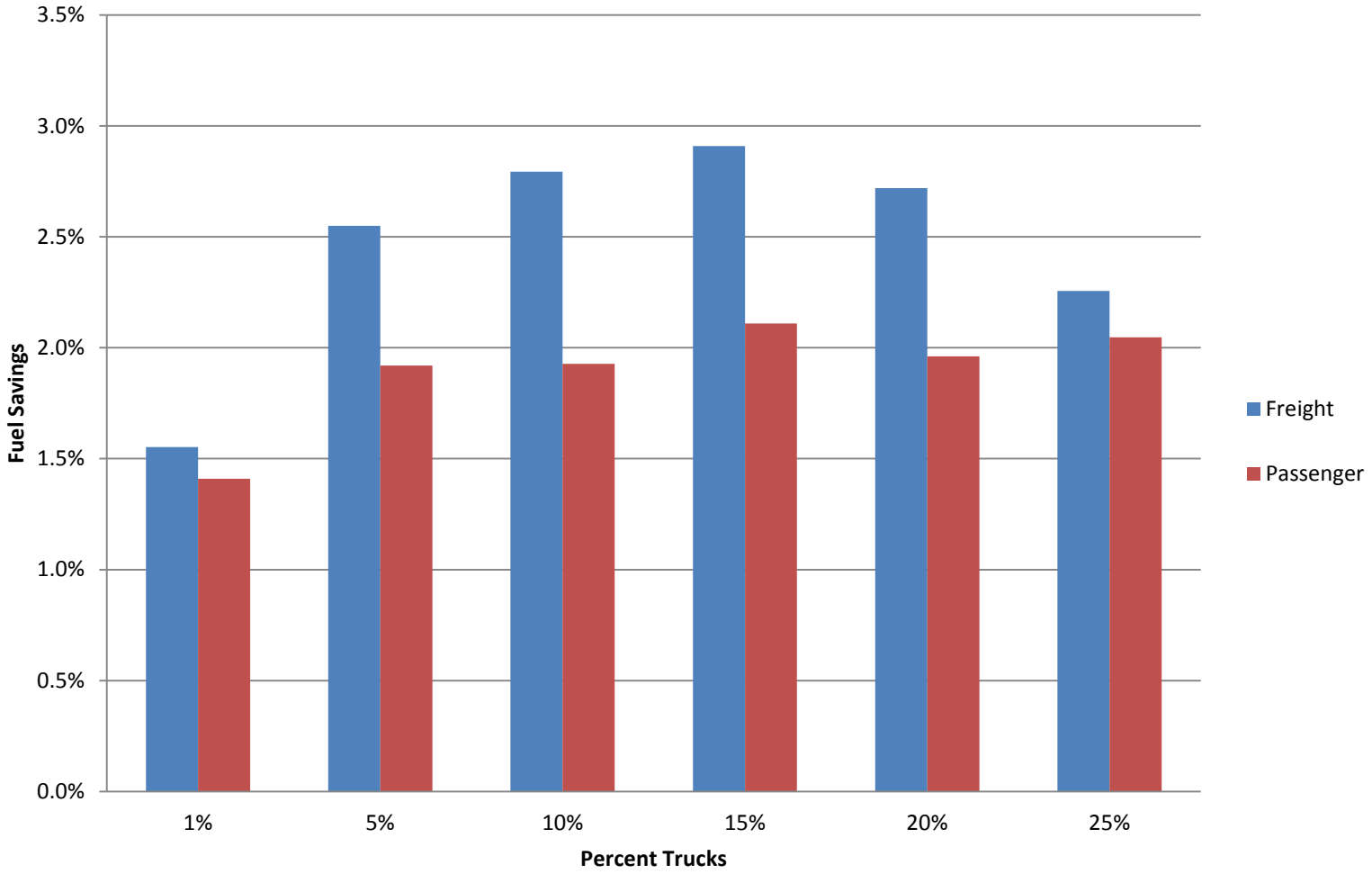
It was important to test different parameters, to understand the impact of the application in different situations, such as:

- **Penetration rate** of the connected vehicle technology, specifically the penetration of the on-board equipment
- Different **percentage of trucks** in traffic along the corridor
- Effects of equipment **communication distance**
- Effects of **maximum extension threshold** on granting priority

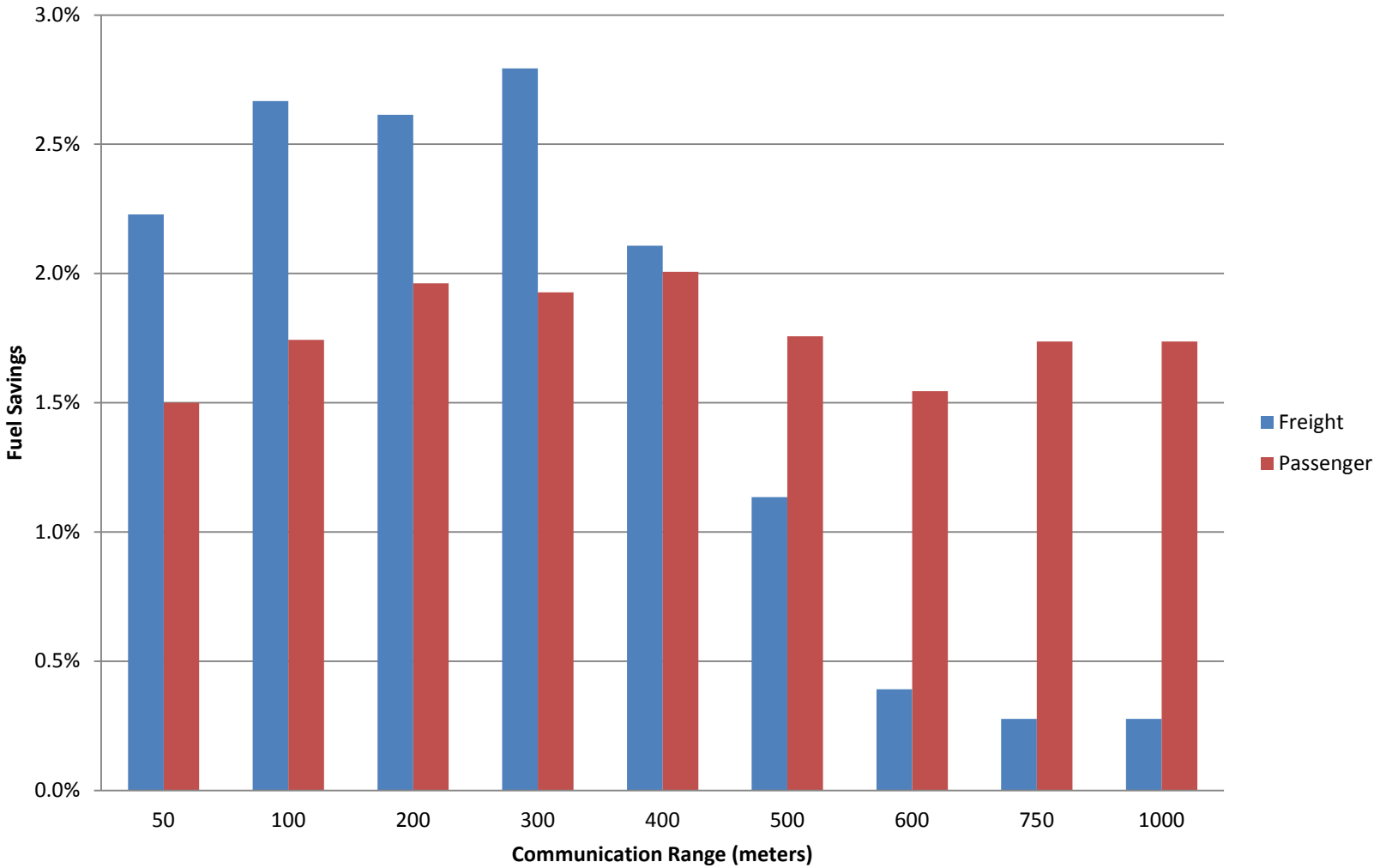
Impact of OBE Penetration Rates



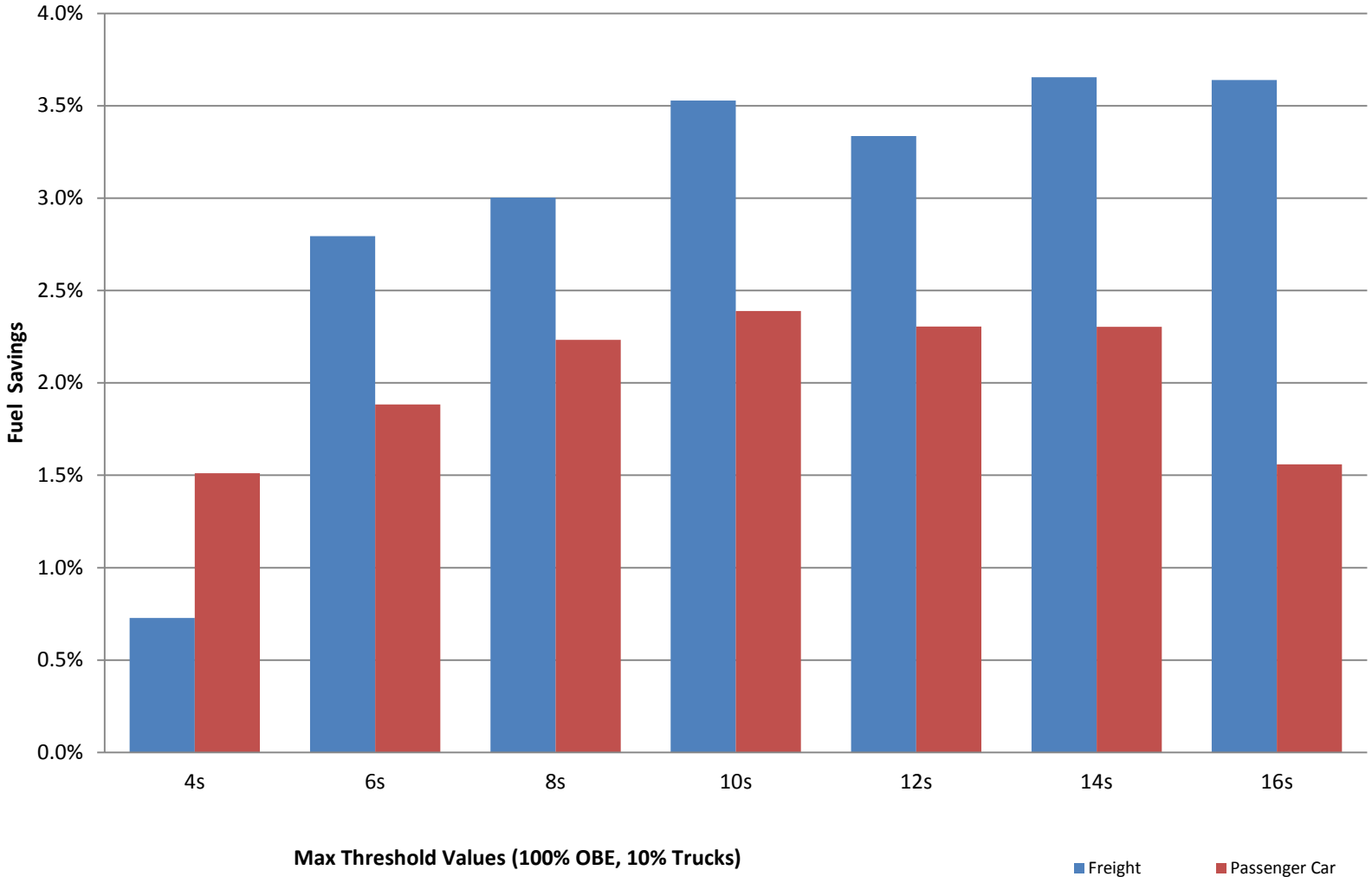
Impact of Truck Percentages



Impact of Communication Distance



Impact of Maximum Extension



Results – A Typical User Snapshot

At about 3.5% savings in Fuel Consumption for 100% penetration, how would this benefit an average user?

- Six mile corridor, average traffic congestion
- Average Medium Freight vehicle, ~8 mpg, diesel costs $4/gallon
- Baseline conditions, vehicles spend **$3** to traverse
- With Signal Priority, vehicles spend **~$2.90** to traverse
- Driving 15,000 arterial miles a year → **$250** savings/year/vehicle
- Fleet Operator (150 vehicles): **$37,500** per year of savings

Conclusions

- The **Eco-Freight Signal Priority** application results in **1% to 4%** fuel savings for freight vehicles, depending on the penetration rate of connected vehicle technology, among other factors, such as congestion
- Passenger vehicles and unequipped freight vehicles in the network also see an improvement in emissions and fuel consumption as they also **benefit from the additional mainline green time** given to freight vehicles
- The application provides the most freight emission/fuel improvements in **undersaturated conditions**, but also improved emissions for the whole system in the saturated conditions due to **additional mainline green time**

Conclusions

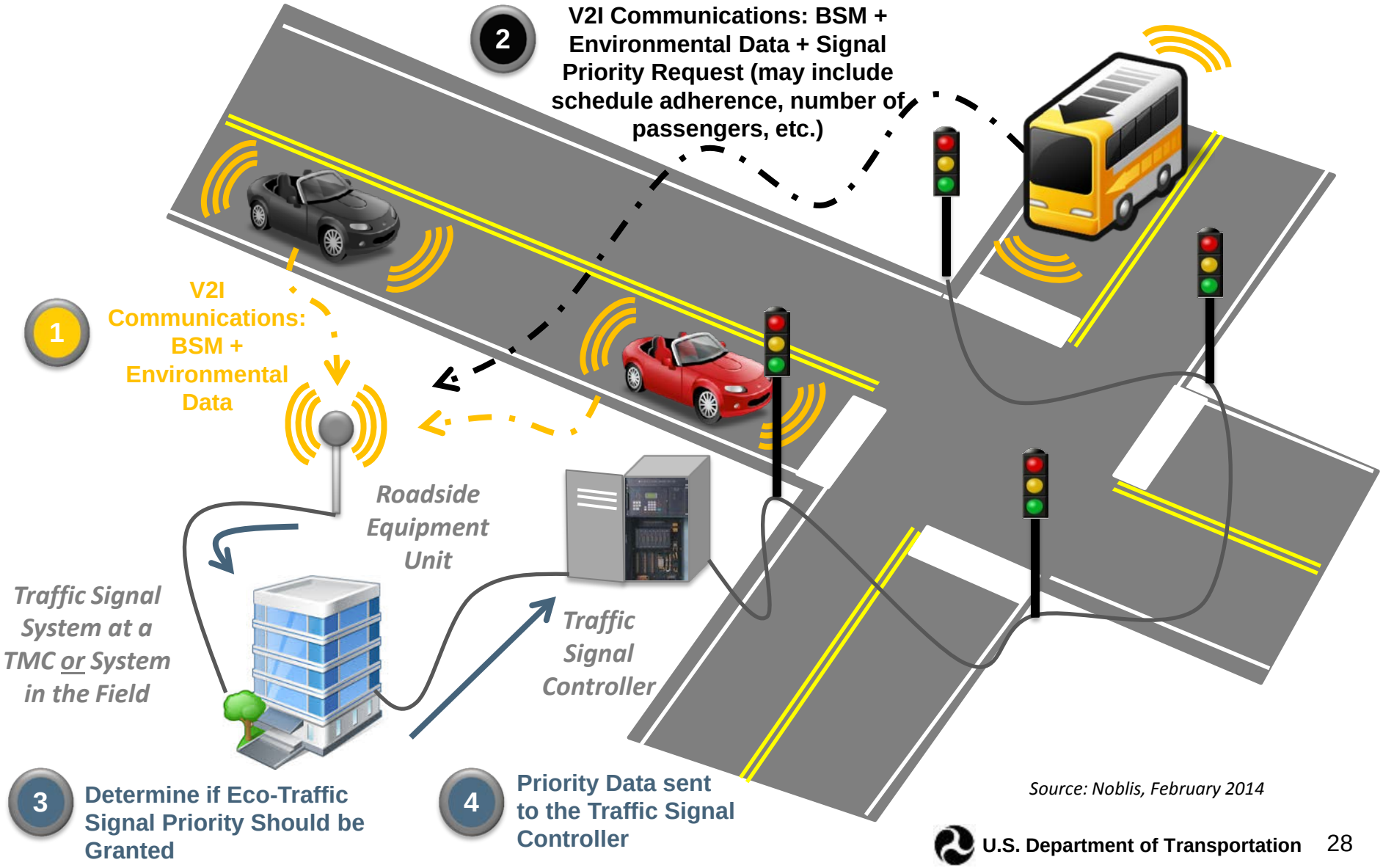
- When granting priority, **the farther** the decision to change the green time is made from the signal, there is less environmental/fuel improvement as it is **harder** to predict queuing and traffic patterns in advance
- Emissions and fuel consumption for freight vehicles **improves** as the maximum green extension or red truncation threshold is **increased**
- When granting priority for environmental objectives using the Eco-Freight Signal Priority application, number of priorities granted is **18%–19% of the total priorities requested** by freight vehicles

Potential Future Research

- More sensitivity analyses should be undertaken on a **“grid” type network area** to better understand the effects of Eco-Freight Signal Priority applications on side-street traffic
- A real-time predictive emissions module could be developed to provide the algorithm with a more accurate picture of the **impact of granting or not granting priority** to the freight vehicles
- About 17% of **priorities granted** to freight vehicles **are missed** due to unforeseen queuing or shockwave scenarios. Future improvements to the algorithm could include better arrival time prediction at the intersection

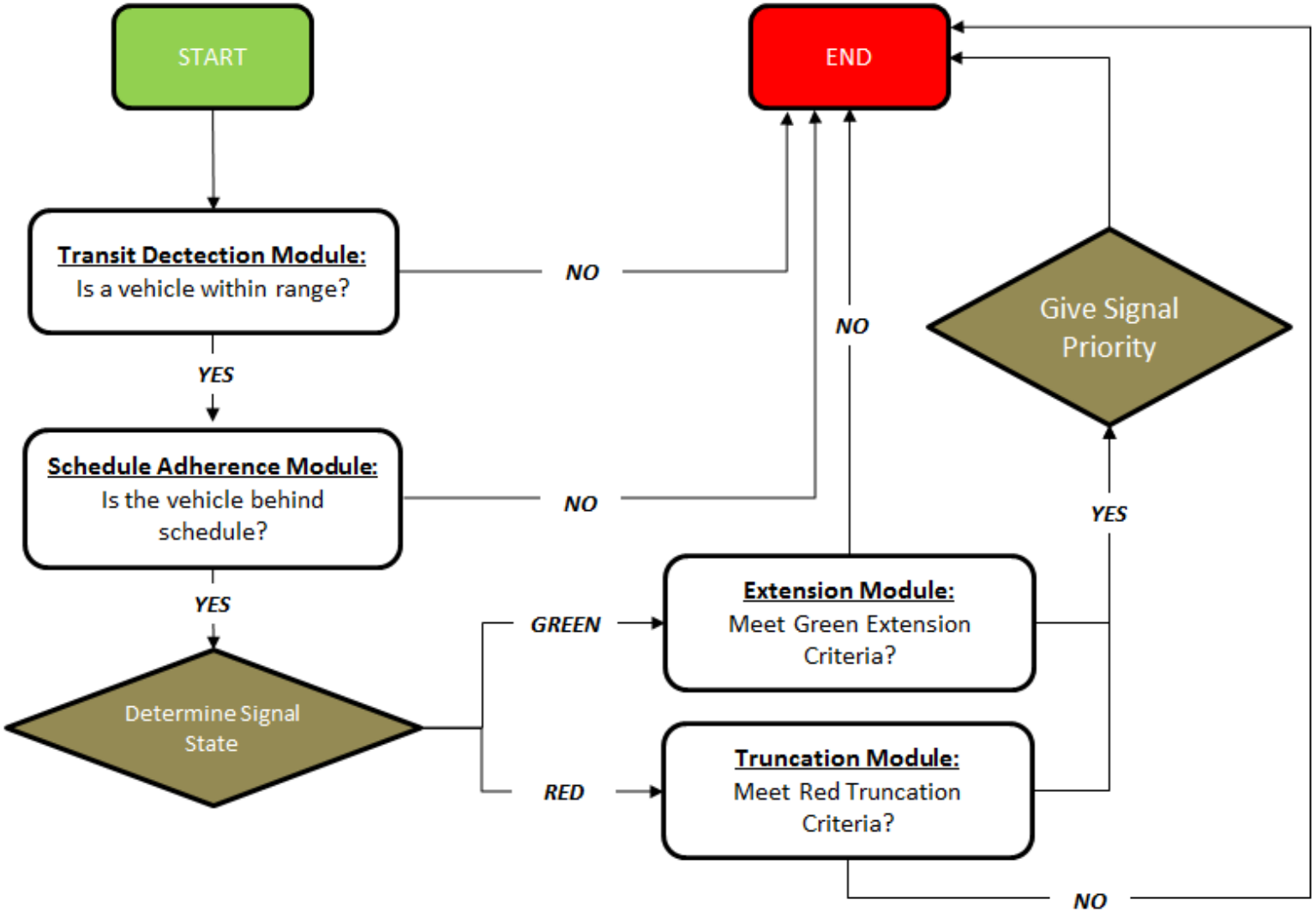
ECO-TRANSIT SIGNAL PRIORITY

Eco-Transit Signal Priority



Source: Noblis, February 2014

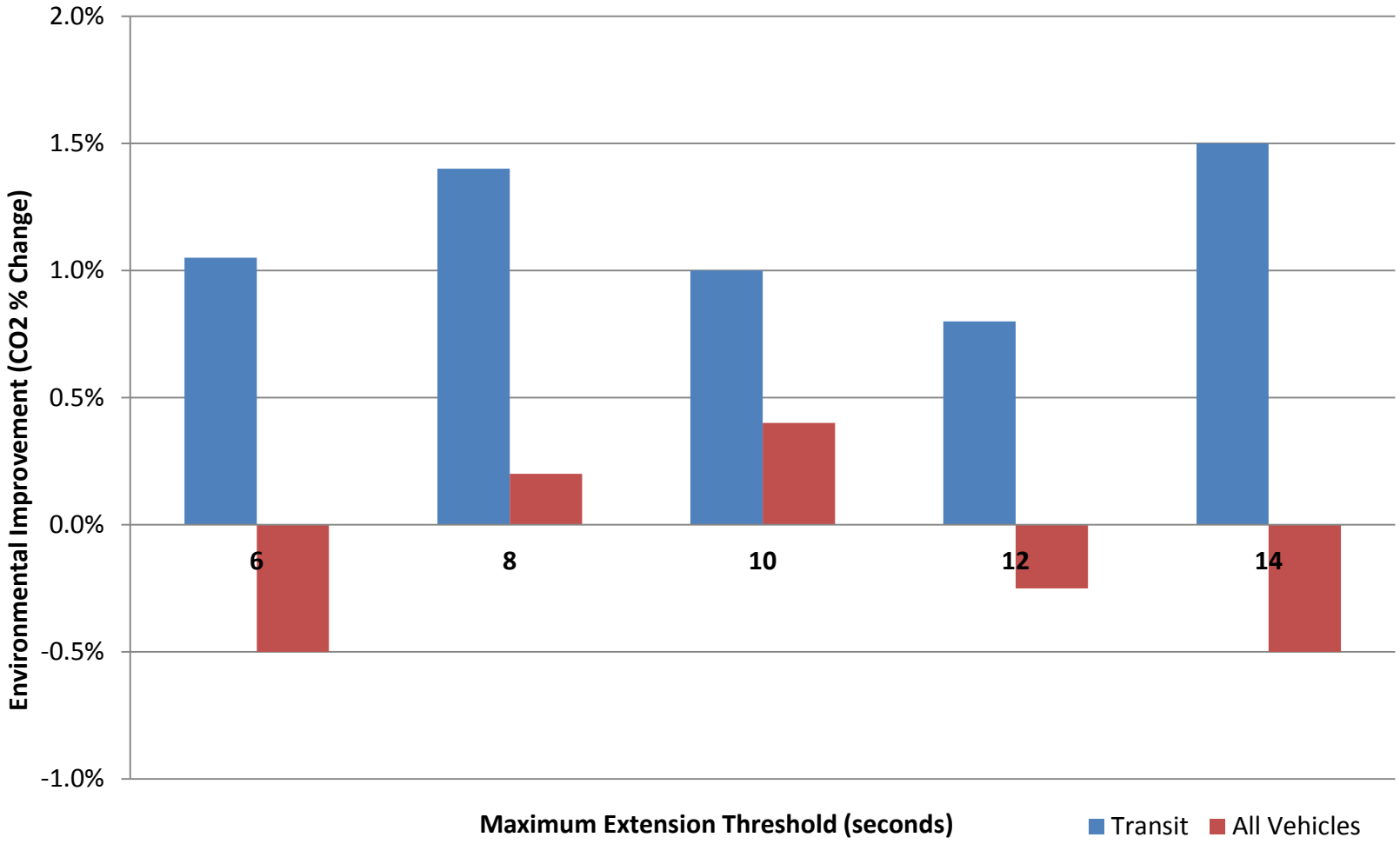
Eco-Transit Signal Priority Algorithm



Modelling Scenarios

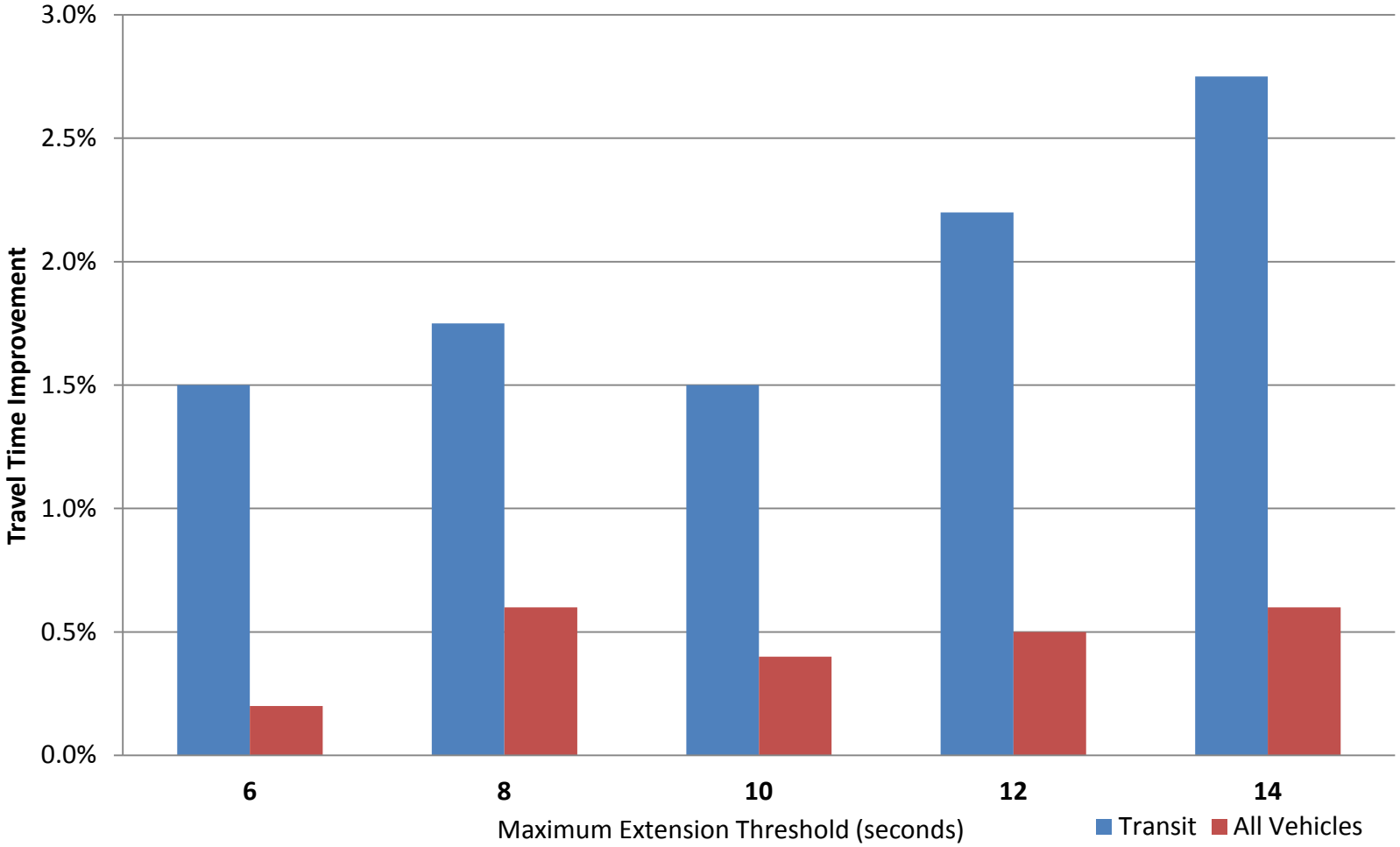
- Sensitivity testing was conducted to understand the impact of the Eco-Transit Signal Priority algorithm across the following models:
  - Baseline Conditions
  - Priority algorithm without schedule adherence
  - Priority algorithm with schedule adherence
- Environmental impact was measured by comparing, across all vehicles and transit vehicles separately, changes to:
  - Emissions levels (Level of CO_2)
  - Delay experienced by vehicles on the network
- Variables investigated within the sensitivity testing:
  - Communication distance and Maximum extension time provided
  - Bus Frequency
  - Level of Demand

Impact of Maximum Extension Time on Emissions



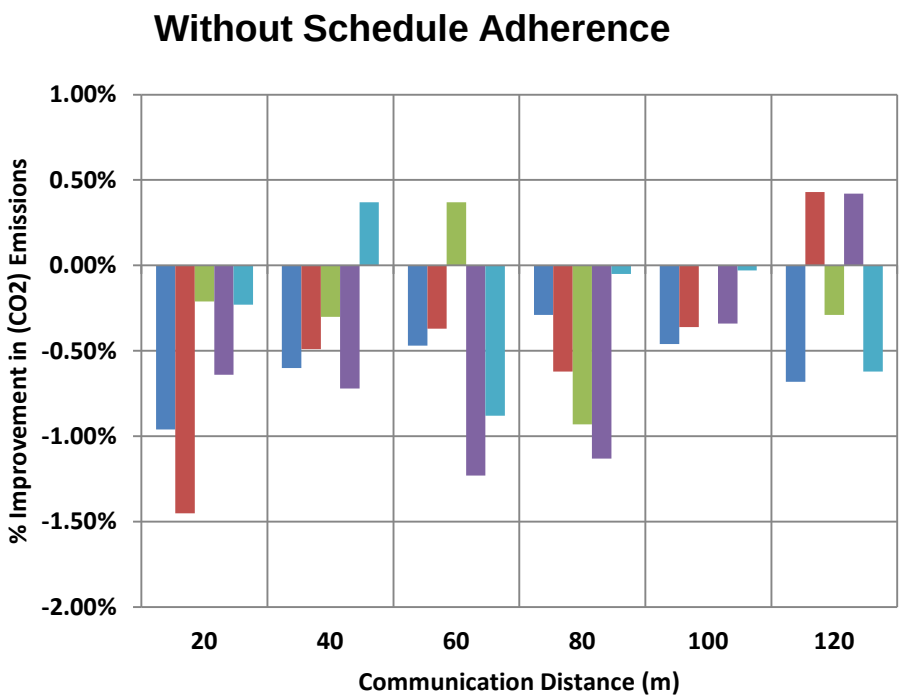
***Graph presents results for communication distance of 120m with bus scheduling adherence**

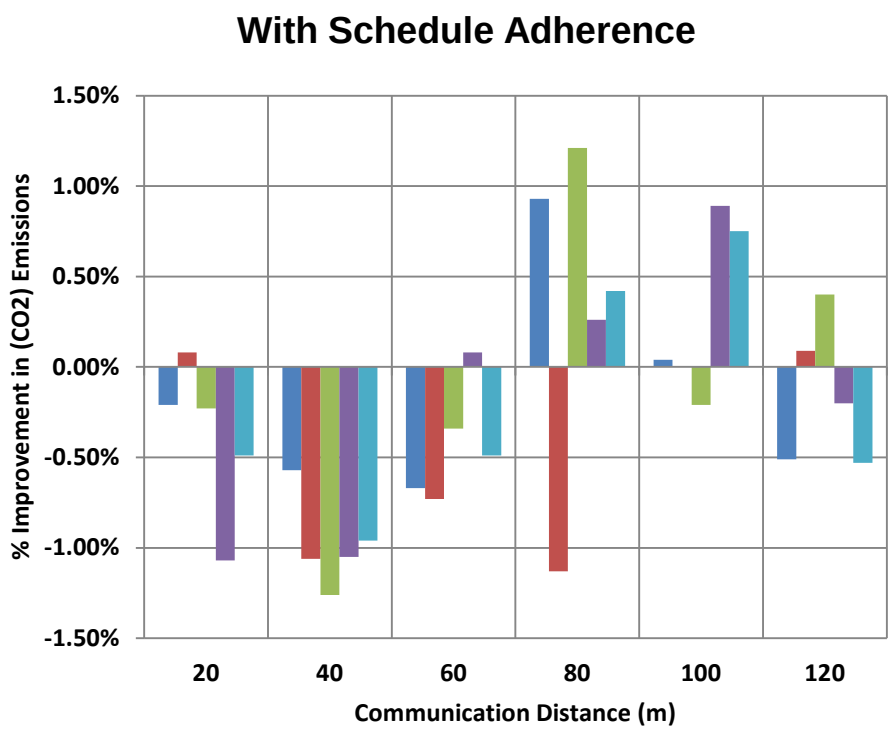
Impact of Maximum Extension Time on Mobility



***Graph presents results for communication distance of 120m with bus scheduling adherence**

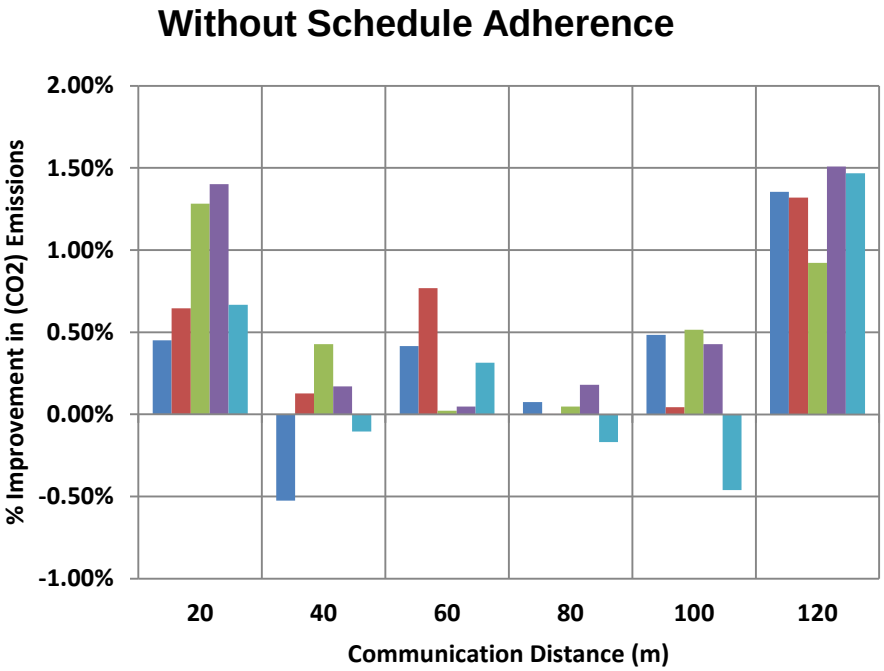
Impact of Schedule Adherence Restriction on Emissions (All Vehicles)

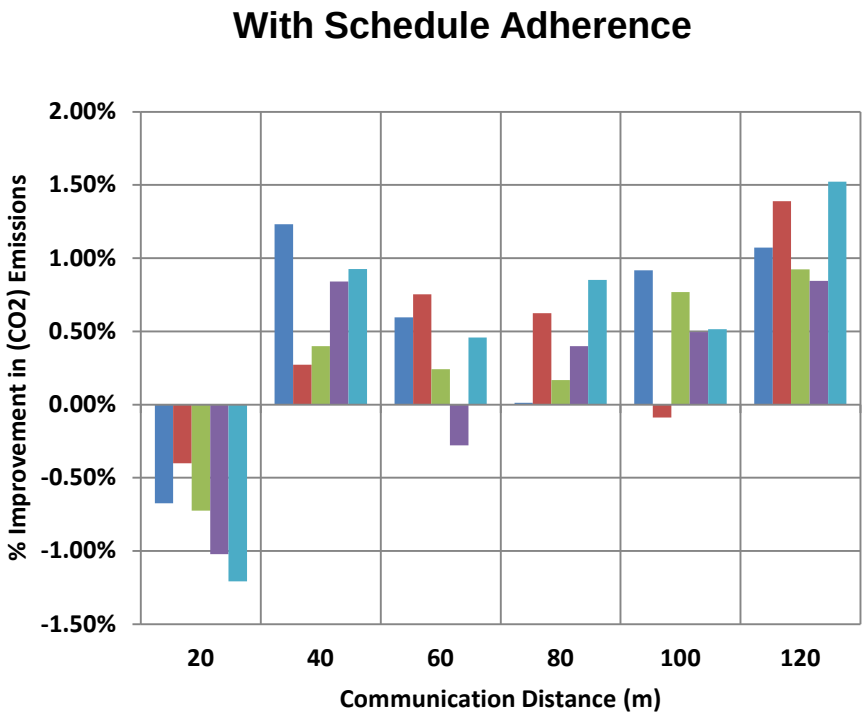




- Max Extension Time: 6 secs
- Max Extension Time: 8 secs
- Max Extension Time: 10 secs
- Max Extension Time: 12 secs
- Max Extension Time: 14 secs

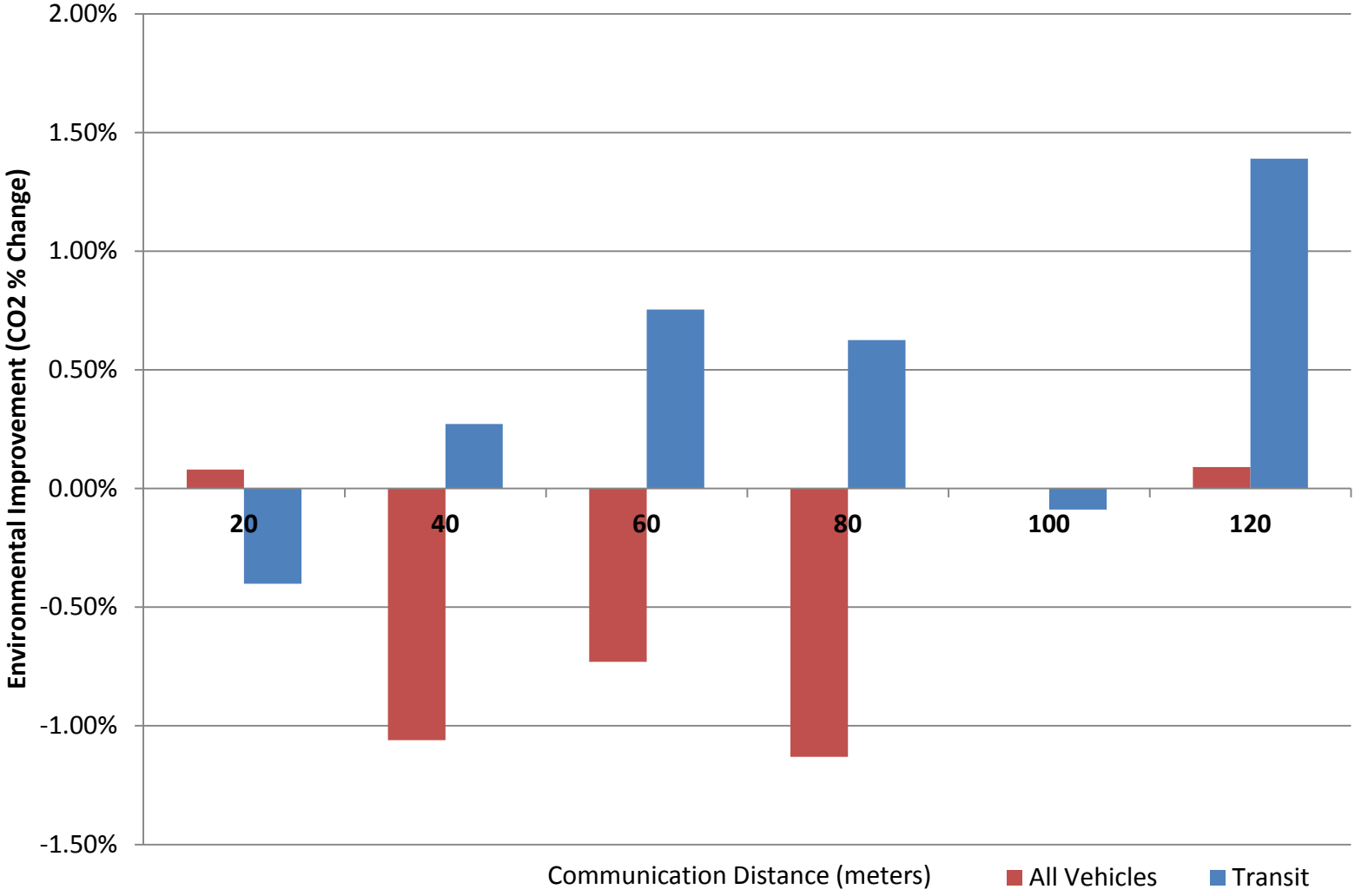
Impact of Schedule Adherence Restriction on Emissions (Transit)





- Max Extension Time: 6 secs
- Max Extension Time: 8 secs
- Max Extension Time: 10 secs
- Max Extension Time: 12 secs
- Max Extension Time: 14 secs

Impact of Communication Distance on Emissions



***Graph presents results for maximum extension time of 8s with bus schedule adherence**

Results – A Typical User Snapshot

At about 2% savings in Fuel Consumption for 100% penetration, how would this benefit an average user?

- Six mile corridor, average traffic congestion
- Average Transit vehicle, ~10 mpg, diesel costs $4/gallon
- Baseline conditions, vehicles spend **$2.40** to traverse
- With Signal Priority, vehicles spend **~$2.35** to traverse
- Driving 20,000 arterial miles a year → **$165** savings/year/vehicle
- Fleet Operator (200 vehicles): **$33,000** per year of savings

Conclusions

- When only looking at transit vehicles, the Eco-Transit Signal Priority application improves the level of emissions and fuel consumption by about **1% to 2%**, depending on the scenario, such as congestion level or communication distance.
- The Eco-Transit Signal Priority application does not provide a significant improvement in the level of emissions and delay for the other vehicles on the network. However, there are some scenarios that provide minimal improvements, on the order of **1% to 2%**, across the network.
- The travel time improvements were observed in many of the scenarios, on the order of **1% to 3%**, with increasing communication distance, resulting in larger improvements.

Conclusions

- Using the **schedule adherence** aspect of the application has a smaller improvement in the resultant emissions since priorities would be denied more often, but improves the overall transit performance
- As the **bus frequency** increases in the network, there are no additional savings found for emissions or fuel consumption when compared to the baseline, which means the application would have similar impacts in **different levels of transit demand**
- Implementation of the priority algorithm, in general, results in reduced emissions levels and improvement in the environmental measures for buses, however in some cases it was found to be detrimental for other vehicles and the overall network.

Potential Future Research

- Only **green extension** and **red truncation** were used in the application algorithm. In further investigation, more options may be applied such as **phase insertion** and phase rotation.
- Future investigations should consider **passenger throughput** as a measure for the transit vehicle as criteria for assessing a priority request.
- **Trajectory planning algorithm** used to make priority determinations can be improved to better estimate the arrival time of buses at intersections.

CONNECTED ECO-DRIVING APPLICATION

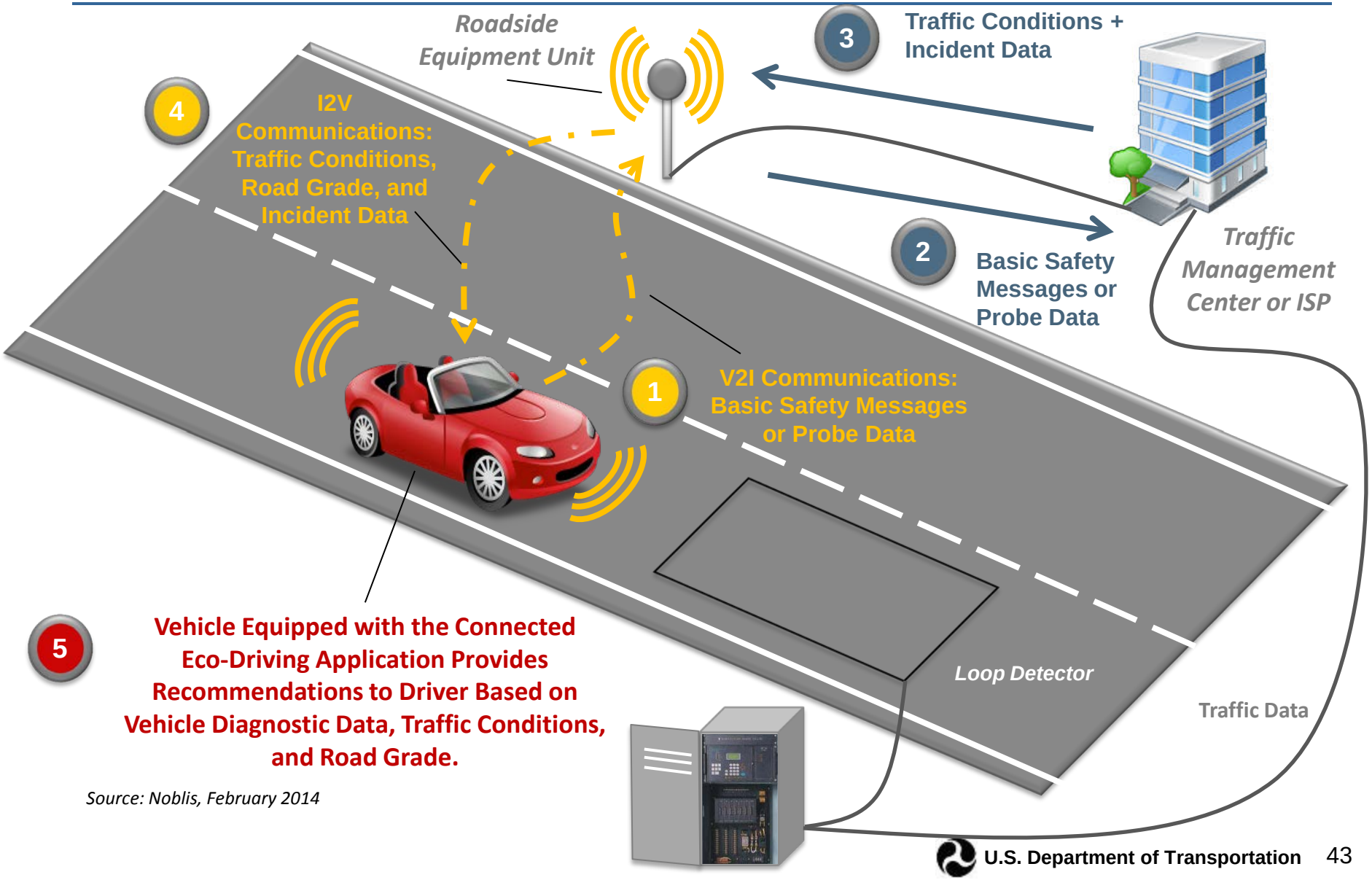
Presentation Overview

- Connected Eco-Driving Concept
- Components of Connected Eco-Driving Application
- Simulation Modeling Setup
- Preliminary Simulation Results
- Conclusions and Future Work

Connected Eco-Driving Concept

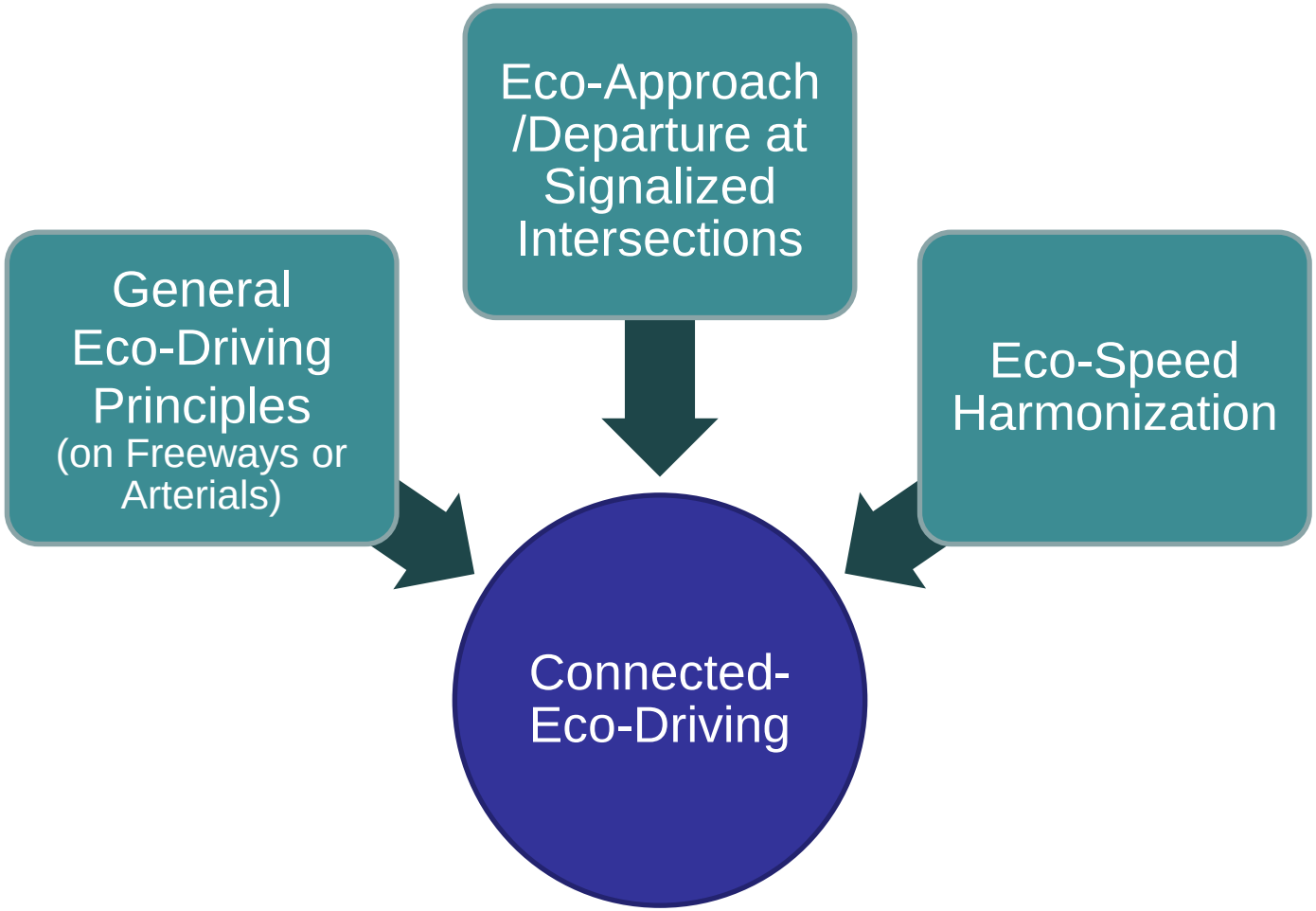
- General Idea
  - To provide customized real-time driving advice to drivers, based on prevailing traffic conditions and local interactions with nearby vehicles on different types of roadway
- Goal
  - Influence driver behavior to save fuel and reduce emissions, without affecting mobility
- Advice may include:
  - Recommended driving speeds (including acceleration/deceleration)
  - Feedback to drivers (online or off-line) on their driving behavior
  - Vehicle-assisted strategies (e.g., adjust speed according to traffic and signals, change gear, switch power sources (hybrid vehicles), etc.)
  - Advice can be applied on an individual vehicle basis or to traffic as a whole

Connected Eco-Driving

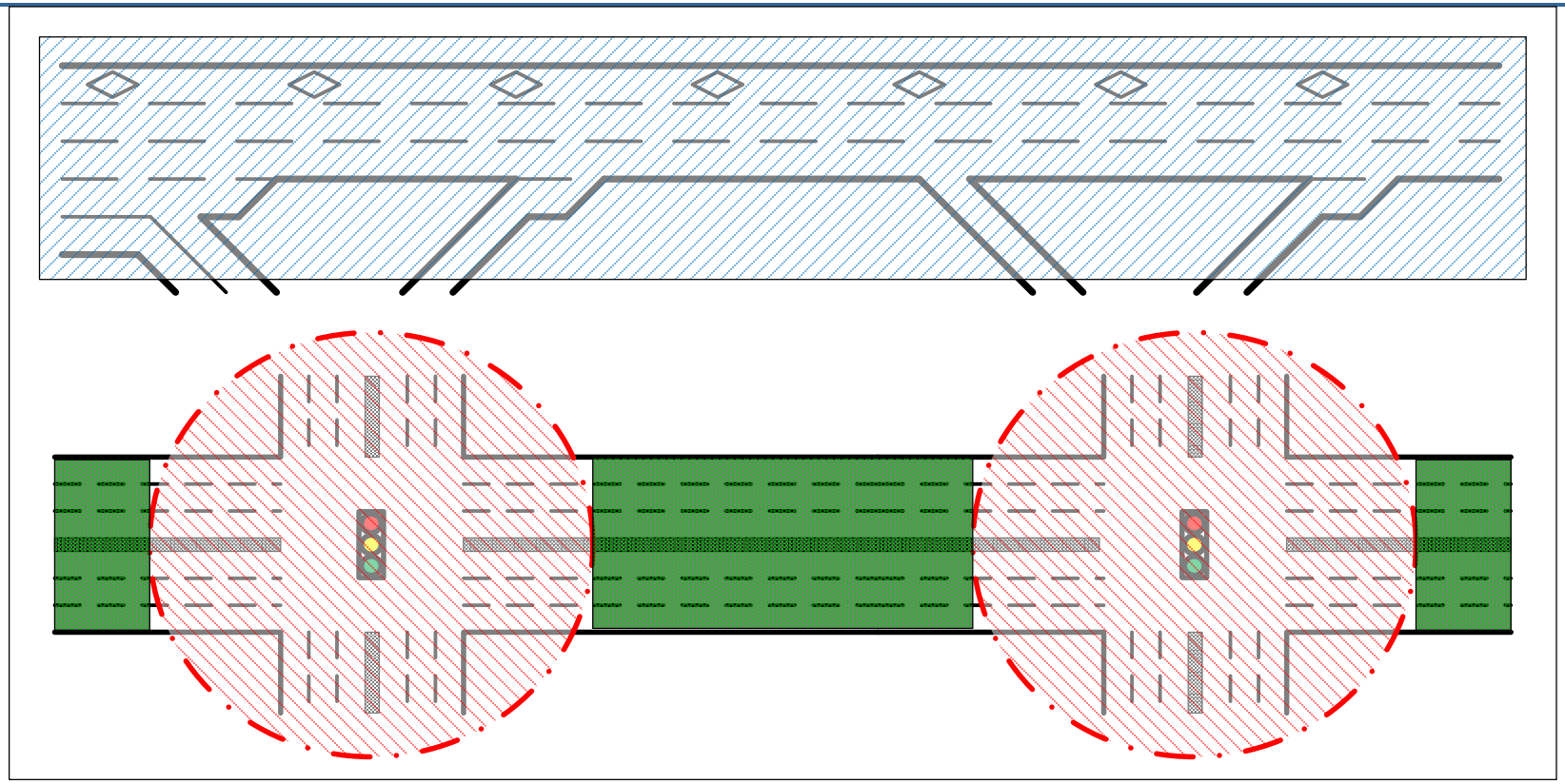


Source: Noblis, February 2014

Components of Connected Eco-Driving



Effective Region of Each Component



Eco-speed harmonization for freeways

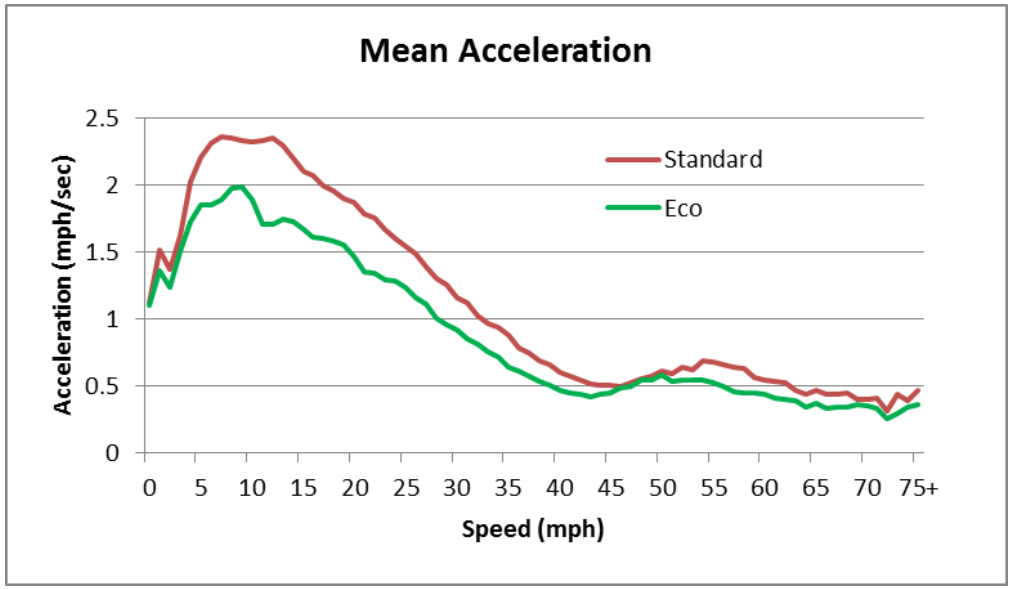
Eco-speed harmonization for arterials (out of intersection communication range)

Eco-approach and departure (within intersection communication range)

General eco-driving principles applied to the entire network

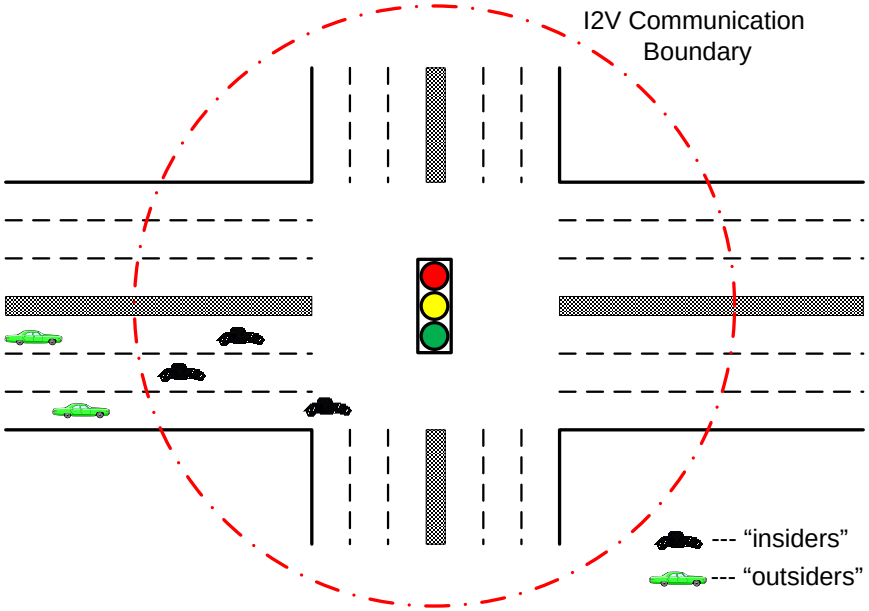
Applying Eco-Driving Principles

- At all locations and conditions, we apply general eco-driving principles, based on training and real-time MPG feedback
- In the modeling effort, real-world speed-acceleration profiles for eco-driving are used to represent this module
- These speed-acceleration profiles modify the car-following logic used in the microsimulation tool



Eco-Speed on Arterials

- For vehicles within the “Intersection Zone” (i.e., within SPaT communication range):
  - Previously developed **Eco-Approach and Departure module** applied
- For vehicles outside the “Intersection Zone”:
  - **Eco-speed harmonization module** applied



Eco-Approach and Departure

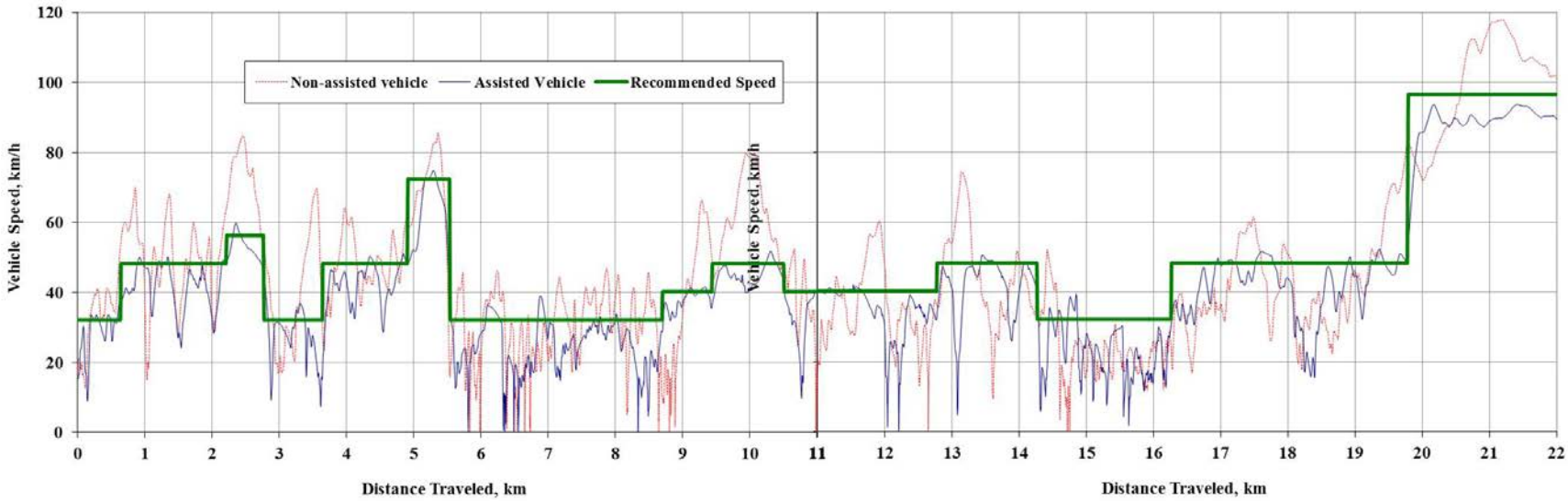
- Eco-Approach
  - Provides drivers recommended speed profiles that encourage "green" approaches to signalized intersections
  - Utilizes traffic signal phase and timing (SPaT) information sent from road-side equipment (RSE) through wireless communication

- Eco-Departure
  - Provides drivers recommended speed profiles that encourage "green" departures from signalized intersections
  - Instead of targeting speed limit, *utilizes real-time downstream traffic information through wireless communication*

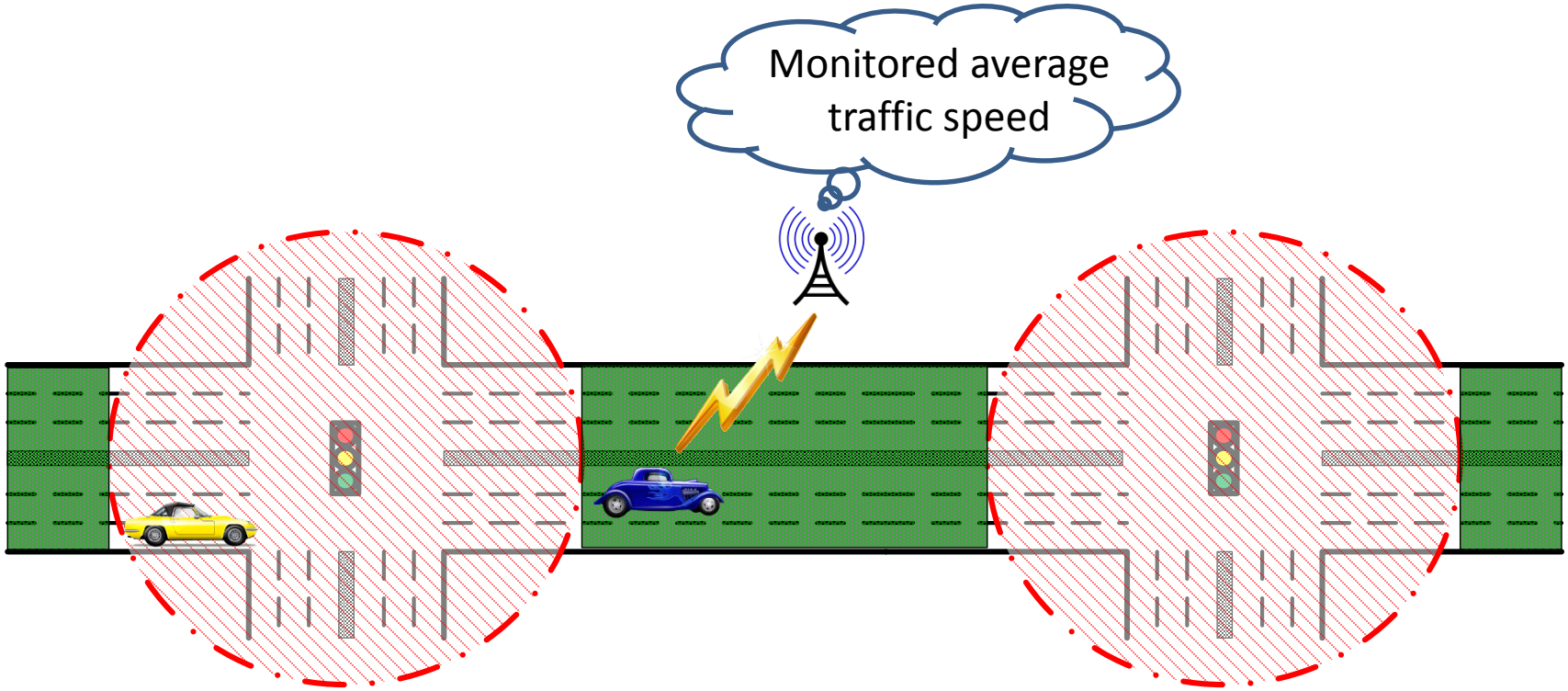
Reference 1: M. Barth, S. Mandava, K. Boriboonsomsin, and H. Xia "Dynamic ECO-Driving for Arterial Corridors", *Proceedings of the IEEE Forum of Integrated Sustainable Transportation*, Vienna Austria, 6/2011, 7 pp.
Reference 2: H. Xia, K. Boriboonsomsin and M. Barth, "Dynamic eco-driving for signalized arterial corridors and its indirect network-wide energy/emissions benefits", Journal of Intelligent Transportation Systems: Technology, Planning, and Operations, 17(1), 2013, pp. 31 – 41

Eco-Speed Harmonization

- Basic Idea
  - To dynamically provide speed advice to vehicles as a whole to reduce unnecessary stop-and-go maneuvers without adversely affecting mobility (e.g., travel time)
  - Speed advice is based on localized traffic information
  - Freeway example:



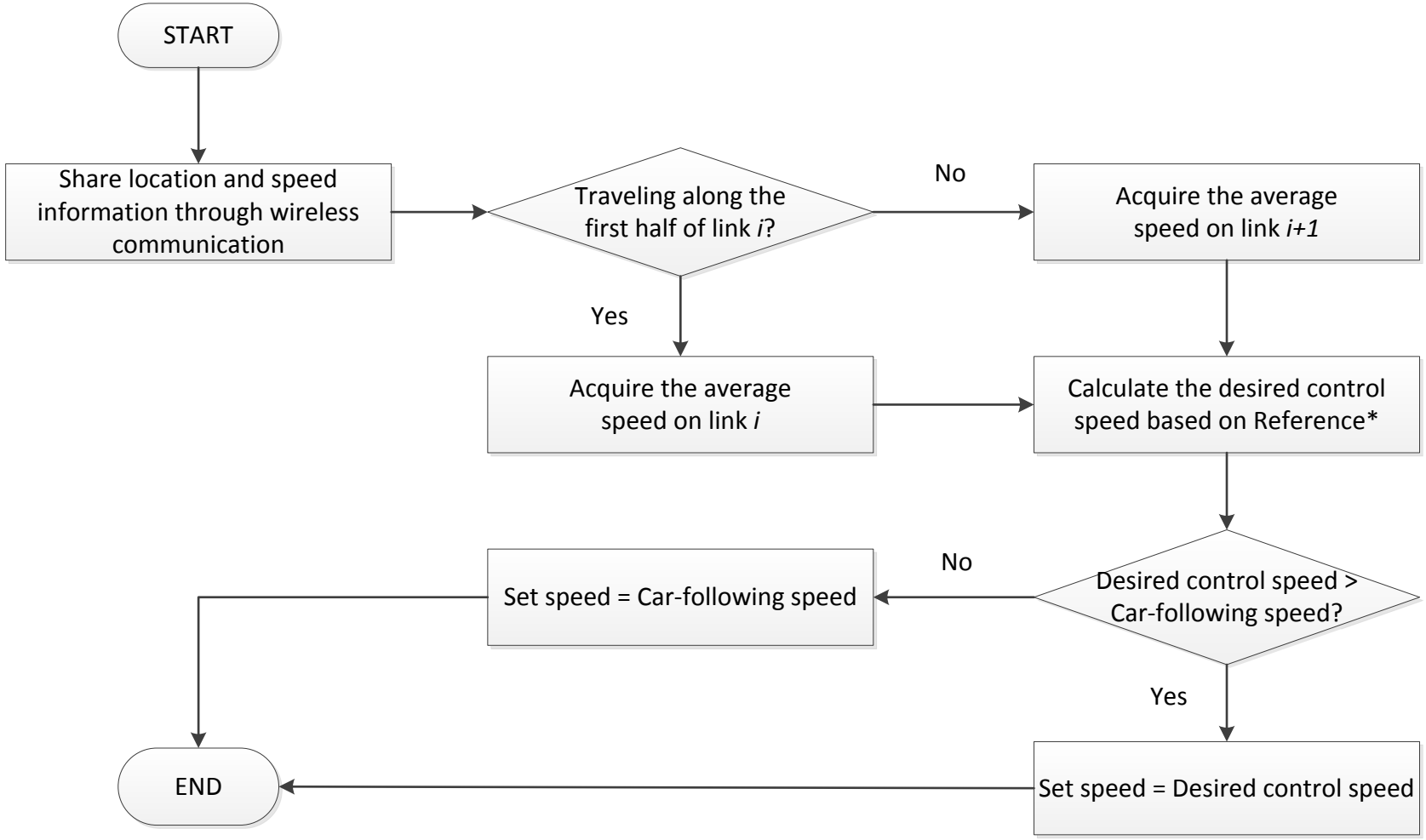
Arterial Eco-Speed Harmonization Concept



Eco-approach and departure (within intersection communication range)

Eco-speed harmonization for arterials (out of intersection communication range)

Flow-Chart of Eco-Speed Harmonization



*** Reference:** M. Barth and, K. Boriboonsomsin "Energy and emissions impacts of a freeway-based dynamic eco-driving system", Transportation Research Part D, Vol. 14, 2009, pp. 400 - 410

Summary of Networks and Modules Combination

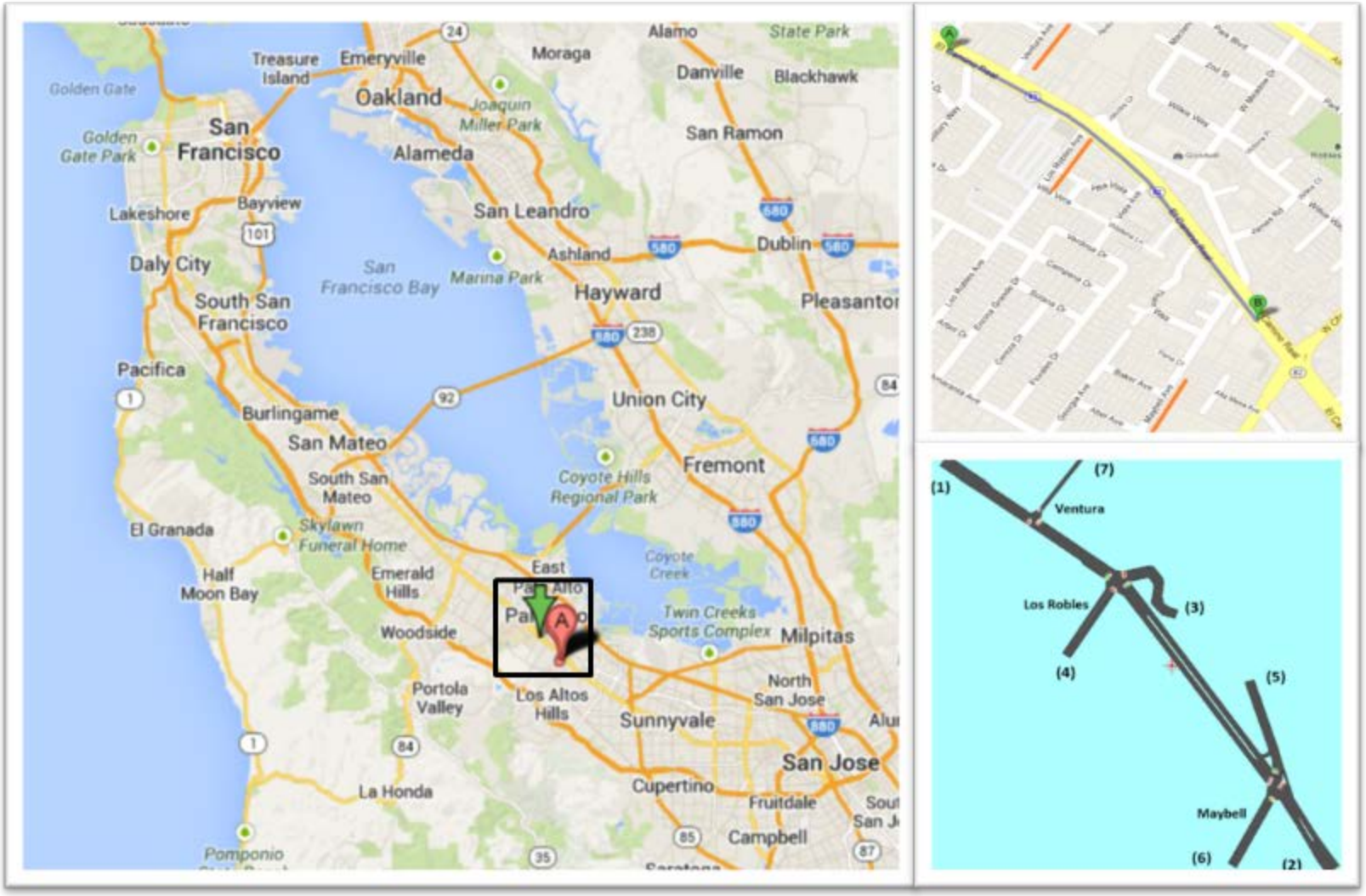
- Hypothetical Freeway Segment
  - Scenario 1: Eco-Speed Harmonization (freeway) and using Eco-Driving Principles
- Three-Intersection El Camino Real
  - Scenario 1: Eco-Approach/Departure alone
  - Scenario 2: Eco-Approach/Departure with Arterial Eco-Speed Harmonization and using Eco-Driving Principles
- SR-91 E Freeway Corridor
  - Scenario 1: Eco-Speed Harmonization (freeway) and using Eco-Driving Principles

Traffic Simulation Modeling

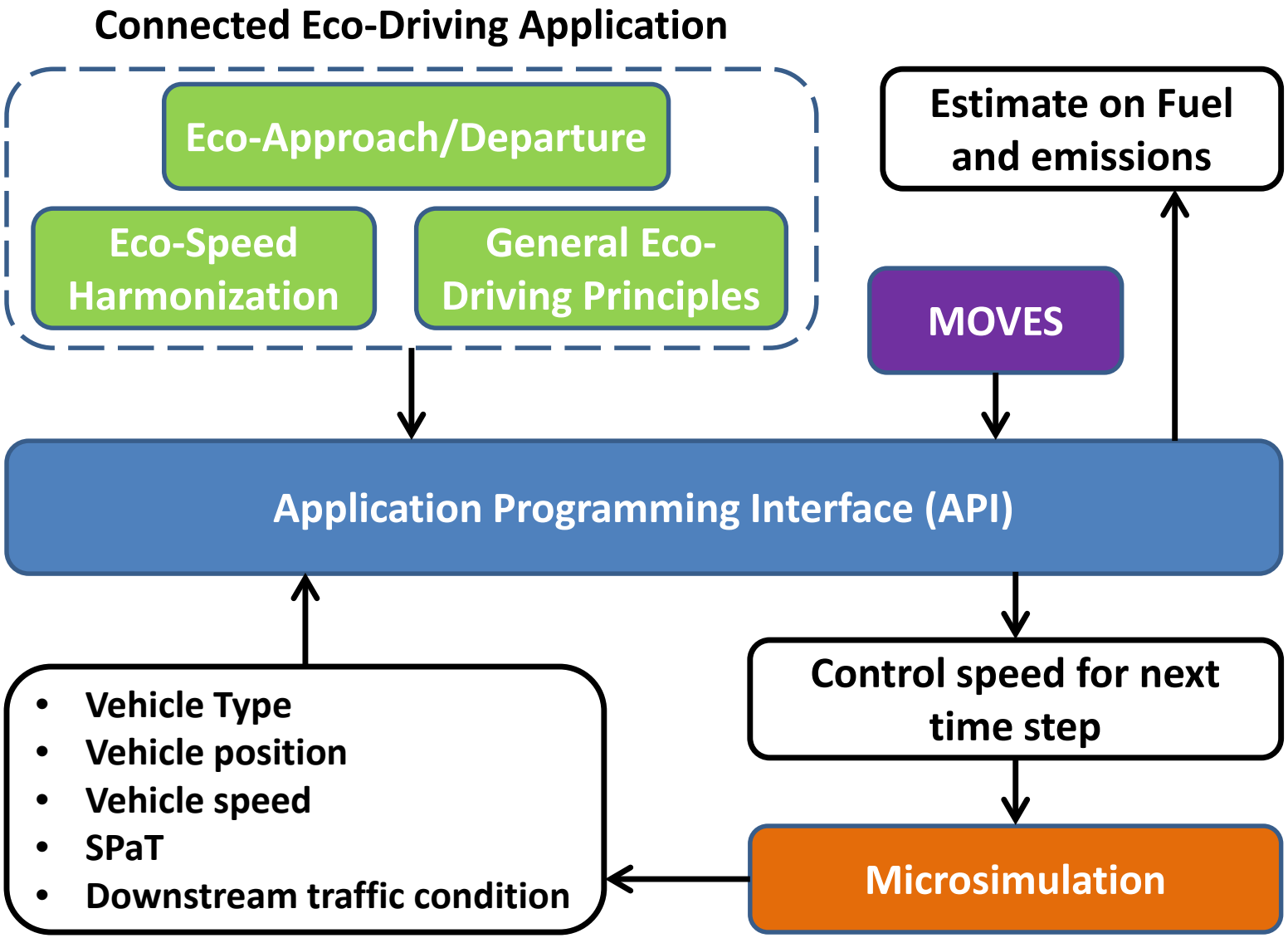
- Objectives
  - Understand model performance under different traffic conditions and roadway networks
  - Evaluate benefits (in particular energy/emissions) from the Connected Eco-Driving application

- Setup
  - Paramics traffic simulation model with API plug-ins (energy/emissions models, eco-approach and departure, eco-speed harmonization)
  - Simulation parameters (e.g., car-following, acceleration profiles) calibrated using field data and based on eco-driving data
  - Modeling initially focused on a “generic freeway segment”
  - Modeling focused on El Camino Real network (Palo Alto, CA) with real-world traffic and network data

Region of Modeling: El Camino Real in Northern California

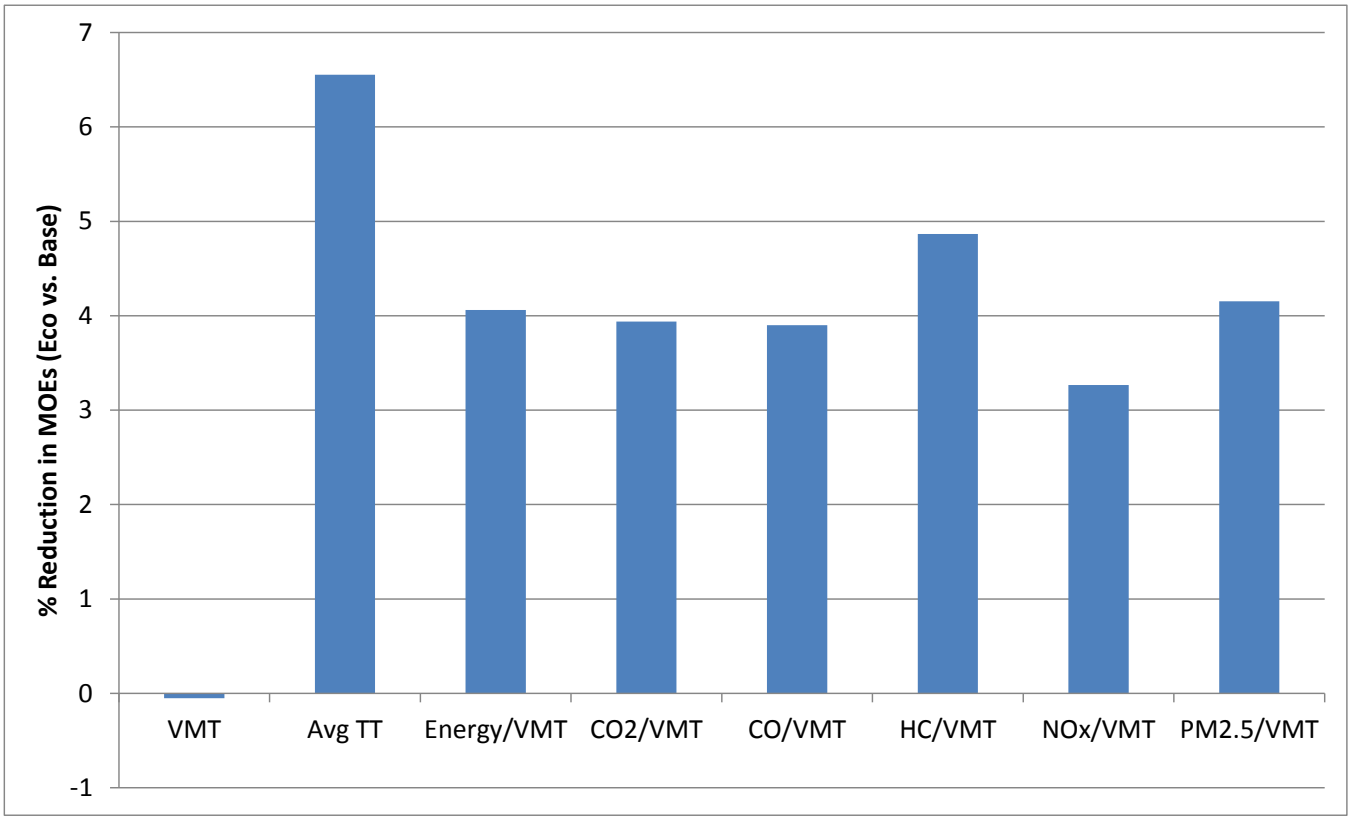


Modeling Tools and Interaction



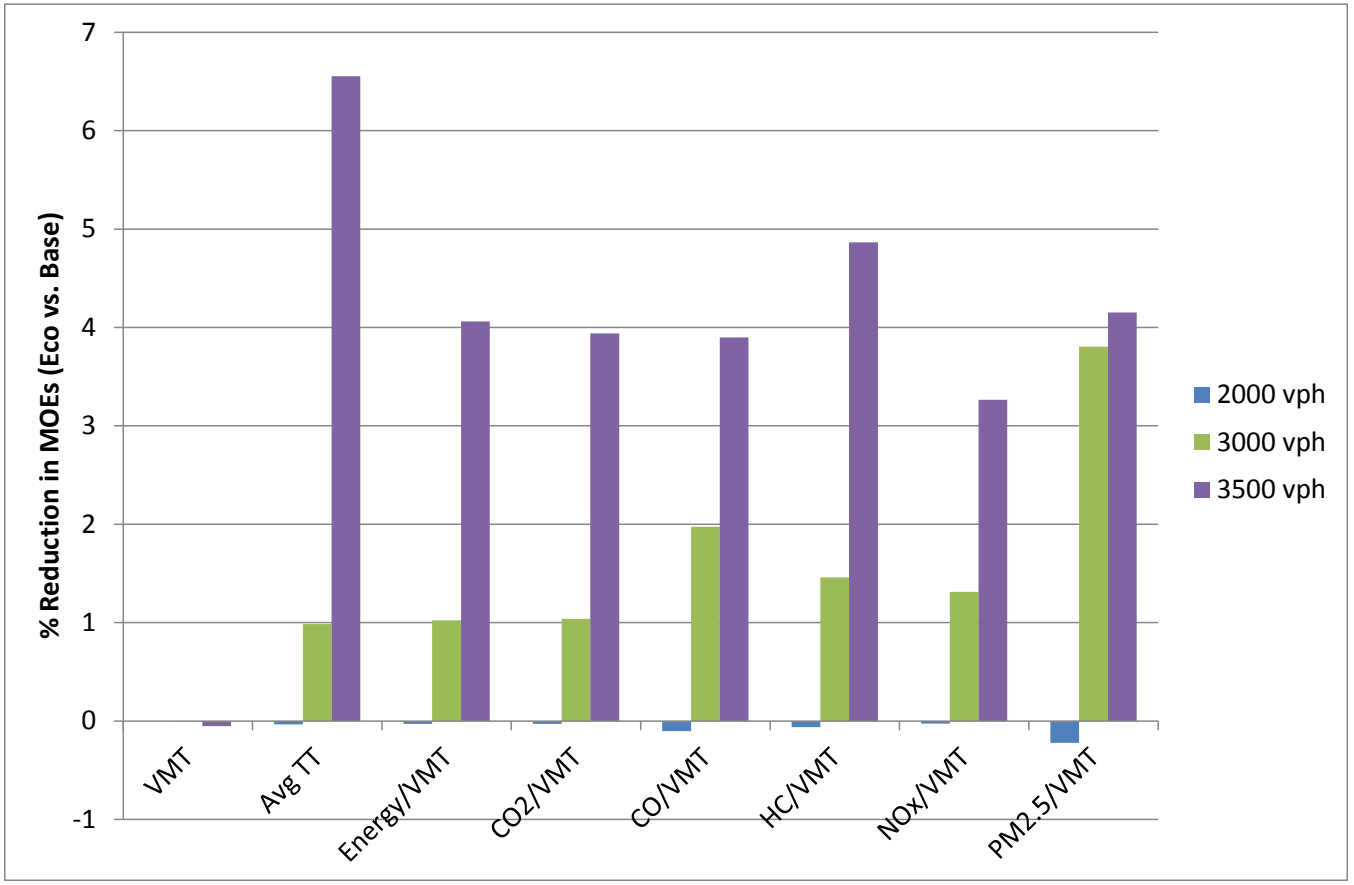
Preliminary Modeling Results: Hypothetical Freeway Segment

- For freeway, both eco-speed harmonization and eco-driving feedback modules are activated
- Evaluate benefits for various MOEs



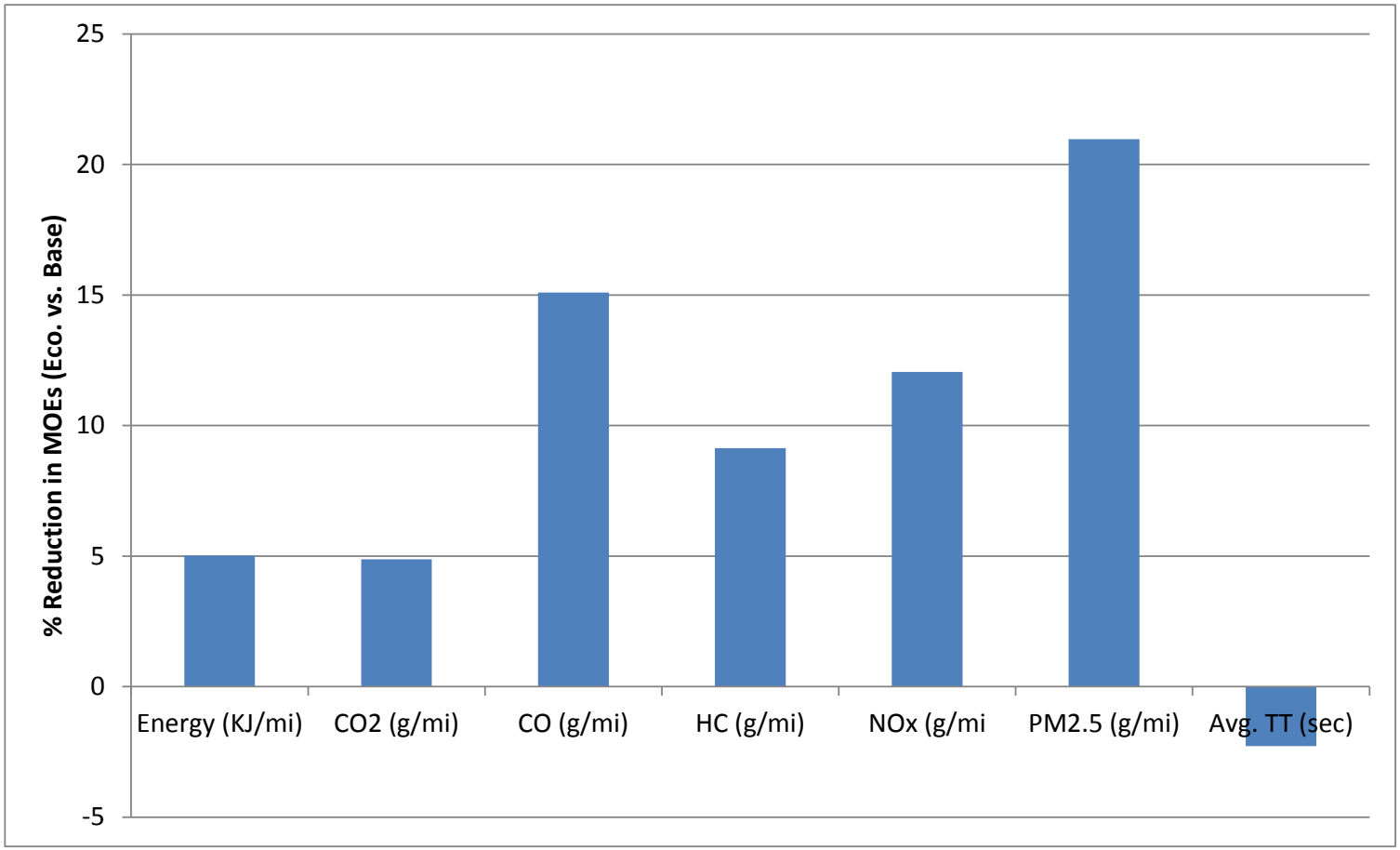
Sensitivity Analysis: Hypothetical Freeway Segment

- MOEs improvements under different congestion levels



Preliminary Modeling Results: El Camino Real Network

- Results for v/c = 0.77 (baseline demand)



Conclusions and Future Work

- **Conclusions:**
  - For the hypothetical freeway segment, connected eco-driving application (freeway speed harmonization with eco-driving principles) provides up to **4% fuel savings** and more than **6% travel time reduction**, depending on the traffic conditions
  - For arterial network (arterial speed harmonization with eco-driving principles and eco-approach/departure) , around **5% fuel savings** can be achieved but **travel time** increases by **2%**

- **Future Work:**
  - Conduct more sensitivity analysis on individual connected eco-driving components and different combinations
  - Perform sensitivity analysis on other parameters (e.g., penetration rate)
  - Evaluate on a larger network (interconnected arterial and freeway segments)

Research Team

Booz Allen Hamilton

- Balaji Yelchuru (Principal Investigator)
- Sean Fitzgerel
- Sudeeksha Murari

University of New South Wales

- Travis Waller (Principal Investigator)
- Vinayak Dixit
- Kasun Wijayaratna (Graduate Student)
- Tuo Mao (Graduate Student)

University of California, Riverside

- Matt Barth (Principal Investigator)
- Guoyuan Wu (Research Faculty)
- Haitao Xia (Graduate Student)

AERIS Research Team Partners

Upcoming AERIS Webinar

Reissue:

Preliminary Eco-Traffic Signal Timing Modeling Results

Wednesday, March 12th, 2014 at 1:00 pm EST

Registration

Persons planning to participate in the webinar should register online at

www.itsa.org/aerisfall2013

For more information on the AERIS program:

http://www.its.dot.gov/aeris/