AERIS—Applications for the Environment: Real-Time Information Synthesis

Eco-Lanes Operational Scenario Modeling Report

www.its.dot.gov/index.htm
Final Report—December 2014
Publication Number: FHWA-JPO-14-186

U.S. Department of Transportation

Produced by Booz Allen Hamilton
U.S. Department of Transportation (USDOT)
Intelligent Transportation Systems Joint Project Office (ITS JPO)

Notice

Technical Report Documentation Page

1. Report No. **FHWA-JPO-14-186**	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle AERIS—Applications for the Environment: Real-Time Information Synthesis Eco-Lanes Operational Scenario Modeling Report		5. Report Date December 2014 6. Performing Organization Code
7. Author(s) Balaji Yelchuru, Sean Fitzgerel, Sudeeksha Murari, Matt Barth, Guoyuan Wu, David Kari, Haitao Xia, Sashank Singuluri, Kanok Boriboonsomsin		8. Performing Organization Report No.
9. Performing Organization Name And Address 20 M Street Suite 1000, Washington, DC 20003		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH61-06-D-00006
12. Sponsoring Agency Name and Address U.S. Department of Transportation ITS Joint Program Office-HOIT 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code HOIT-1
15. Supplementary Notes		

16. Abstract

This report constitutes the detailed modeling and evaluation results of the Eco-Lanes Operational Scenario defined by the Applications for the Environment: Real-Time Information Synthesis (AERIS) Program. The Operational Scenario constitutes six applications that are designed to provide environmental benefits to the users of connected vehicle (CV) technology on arterials. In this modeling effort, three of them are modeled, namely, Eco-Lanes Management, Eco-Cooperative Adaptive Cruise Control (Eco-CACC), and Eco-Speed Harmonization (ESH). The applications Eco-Traveler Information and Connected Eco-Driving have been bundled as part of other efforts under the AERIS Program. The applications use the data available in a connected environment and help reduce fuel consumption and emissions by providing driving feedback, speed advice, and platooning and by creating eco-lanes. This report contains the details of the algorithms developed to model the applications, the details of the analysis, and the results of each individual application and the applications applied simultaneously.

17. Key Words AERIS, connected vehicle, eco-lanes, cooperative adaptive cruise control, speed harmonization, microsimulation, modeling, simulation, environmental benefits, emissions estimation, Paramics, and MOVES		18. Distribution Statement	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page)	21. No. of Pages 137	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

Acknowledgements

All research completed over the course of the Applications for the Environment: Real-Time Information Synthesis (AERIS) Project as well as the completion of this document benefitted from the support and regular feedback of the researchers at the Intelligent Transportation Systems (ITS) Joint Program Office (JPO) and the Federal Highway Administration (FHWA).

Table of Contents

List of Figures

List of Tables

Report Summary

Introduction to the AERIS Program

As part of its connected vehicle (CV) research effort, the United States Department of Transportation (USDOT) Intelligent Transportation Systems (ITS) Joint Program Office (JPO) is conducting the Applications for the Environment: Real-Time Information Synthesis (AERIS) Program. The focus of this program is to use CV technology to reduce the environmental impact of road transportation. The AERIS Program consists of various defined applications that are bundled into logical combinations called Operational Scenarios. This report details the modeling, simulation, and evaluation of the Eco-Lanes Operational Scenario.

The AERIS applications are designed to work in a CV environment where vehicles and infrastructure communicate among themselves and with each other to transmit information that can be used for various purposes. Dedicated Short-Range Communication (DSRC) along with other wireless communication means, such as cellular communications, facilitate the transmission of data. The range of the DSRC is approximately 300 meters, while cellular communications provide wide-area coverage (i.e., they have much longer range). In a CV environment, onboard equipment (OBE) in the vehicles is configured to transmit information, such as vehicle speed and location, to the OBEs of other vehicles or the roadside equipment (RSE) located in fixed locations along the roadway. The RSEs can in turn return information to the vehicles, such as Signal Phase and Timing (SPaT) information, as well as other dynamic system attributes. This exchange of information opens a large number of opportunities to derive a variety of benefits, such as reduction of vehicle collisions and reduction of travel times and delays as well as a reduction in fuel consumption and emissions. CV applications are being designed and tested to achieve safety, mobility, and environmental benefits for future traffic systems.

Research is underway to explore the possibilities of deriving environmental benefits from the wealth of real-time data that will become available using CV technology. The objective of the AERIS research program is to generate and acquire environmentally relevant real-time transportation data and use these data to create actionable information that supports and facilitates “green” transportation choices by transportation system users and operators. The AERIS Program adopted a systematic process of incremental tasks that build on each other to develop and evaluate CV applications that may provide environmental benefits.

Before the modeling and evaluation of AERIS applications, three other tasks were carried out as part of this project. The first task was to identify applications that could yield environmental benefit and bundle them into logical groupings of applications—resulting in the development of five Operational Scenarios. The second task of this project was an initial benefit-cost analysis (BCA), which used a detailed model to assess the monetary benefits and costs for each application and bundle of applications. The third task was to prioritize the applications based on criteria such as the potential benefits of the application, likelihood of application deployment, ease of modeling, and availability of data. Based on the results of the selection process, the Eco-Signal Operations, Eco-Lanes, and Low Emissions Zones Operational Scenarios were shortlisted as those eligible for modeling and evaluation. The fourth task was to perform detailed modeling and simulation of the prioritized applications. This report focuses on the modeling and evaluation of the Eco-Lanes Operational Scenario.

Eco-Lanes Applications

The Eco-Lanes Operational Scenario, shown in Exhibit 1 and Exhibit 2, uses CV technologies and applications to reduce fuel consumption, greenhouse gas (GHG), and criteria air pollutant emissions on dedicated freeway lanes called "eco-lanes." The applications within the scenario are designed to reduce inter-vehicle spacing, stop-and-go behavior, and inefficient accelerations and decelerations as well as improve traffic flow along freeways. The Operational Scenario contains seven applications, including Eco-Lanes Management, Eco-Speed Harmonization (ESH), Eco-Cooperative Adaptive Cruise Control (Eco-CACC), Eco-Ramp Metering, Connected Eco-Driving, Wireless Inductive/Resonance Charging, and Eco-Traveler Information. These applications are described below.

Eco-Lanes

Applications for the Environment: Real-Time Information Synthesis

Operational Scenario Description

The Eco-Lanes Operational Scenario includes dedicated freeway lanes – similar to managed lanes – optimized for the environment that encourage use from vehicles operating in eco-friendly ways. The lanes may support:

- Variable speed limits are optimized for the environment based on data collected from vehicles.
- Drivers may opt-in to eco-cooperative adaptive cruise control (ECACC) and vehicle platooning applications.
- Wireless Inductive/Resonance Charging infrastructure embedded in the roadway allows electric vehicles to charge their batteries while the vehicle is in motion.

Potential Benefits

Eco-Speed Harmonization

- In general, Eco-Speed Harmonization performs better at higher traffic volumes and high connected vehicle penetration rates.
- The application provides up to 4.5% fuel reduction.
- Mobility dis-benefits may result from the decreased speed.

Eco-Cooperative Adaptive Cruise Control (ECACC)

- The application provides up to 19% fuel savings on a real-world freeway corridor.
- The application results in up to 42% travel time savings on a real-world freeway corridor.

Eco-Speed Harmonization and ECACC Combined

- When combined, the applications provide up to 22% fuel savings on a real-world freeway corridor; and up to an additional 2% fuel savings when using a dedicated "eco-lane" on the freeway corridor.
- The applications provide up to 33% travel time savings on a freeway corridor.

Operational Scenario Visualization

Dedicated Eco-Lane

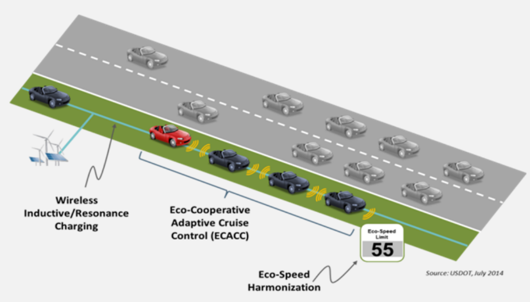


Exhibit 1: Eco-Lanes Operational Scenario

Eco-Lanes Management. This application establishes parameters and defines or geo-fences the eco-lanes boundaries. Eco-lanes parameters may include the types of vehicles allowed in the eco-lanes, emissions parameters for entering the eco-lanes, the number of lanes, and the start and end of the eco-lanes. The application also conveys pre-trip and en route traveler information about eco-lanes to travelers, including information about parameters for vehicles to enter the eco-lanes, current and predicted traffic conditions in the eco-lanes, and geographic boundaries of the eco-lanes.

ESH. This application is similar to current variable speed limit (VSL) applications but uses CV technologies to collect traffic conditions, weather information, and GHG and criteria pollutant information from RSE and vehicles. It then determines dynamic eco-speed limits for a roadway based on areas of traffic congestion, bottlenecks, incidents, special events, and other conditions that may impact the traffic flows. The eco-speed limits in this application can be dynamically changed temporally and spatially, with the key goal of minimizing fuel consumption and pollutant emissions along the roadway.

Eco-CACC. This application leverages CV technology by automatically controlling the speed of a vehicle. It is based on vehicle-to-vehicle (V2V) communications that transmit a leader vehicle’s current speed and acceleration to the vehicle following it, allowing the following vehicle to automatically adjust its speed to maintain a smaller, but safe, headway from the leader vehicle. This application may incorporate other information such as road grade, roadway geometry, and weather conditions to determine the most environmentally efficient trajectory for the subject vehicle. In the long term, the application also may consider the aerodynamic drag reduction effects due to vehicle platooning.

Eco-Ramp Metering. This application determines the most environmentally efficient operation of traffic signals at freeway on-ramps to manage the rate of entering vehicles. This application collects traffic and environmental data to allow on-ramp merge operations that minimize overall emissions, including traffic and environmental conditions on the ramp and on the freeway upstream and downstream of the ramp. Using this information, the application determines a timing plan for the ramp meter based on current and predicted traffic and environmental conditions. The objective for this application is to produce timing plans that reduce overall emissions, including reducing emissions from bottlenecks forming on the freeway as well as emissions from vehicles on the ramp.

Connected Eco-Driving. This application 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, and more local interactions with nearby vehicles. Finally, the application also may 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).

Wireless Inductive/Resonance Charging. This application includes infrastructure deployed along the roadway that uses magnetic fields to wirelessly transmit large electric currents between metal coils placed several feet apart. This infrastructure enables charging of electric vehicles including cars, trucks, and buses. Roadside charging infrastructure supports charging vehicles moving at highway speeds.

Eco-Traveler Information Applications. Eco-Traveler Information applications provide pre-trip and en route multimodal traveler information to encourage transportation choice with reduced environmental impacts. The application collects traffic and environmental data from CV and other sources and uses these data to determine real-time or predicted traffic conditions. This information is provided to travelers so that they can either plan or adjust departure times or mode choice or select an alternative route. Another key component of this application is to provide travelers with transit options to encourage mode shift, including information about transit schedules and real-time transit vehicle arrival and departure times. Traveler information specific to eco-lanes may include parameters for the eco-lanes, travel time or fuel savings comparison between the eco-lanes and general purpose lanes, incident information, availability of wireless inductive/resonance charging in the eco-lanes, vehicle platooning rules and parameters, transit options, and parking information. This information may be disseminated to travelers using websites, 511 systems, dynamic message signs, smart phone applications, and CV technologies.

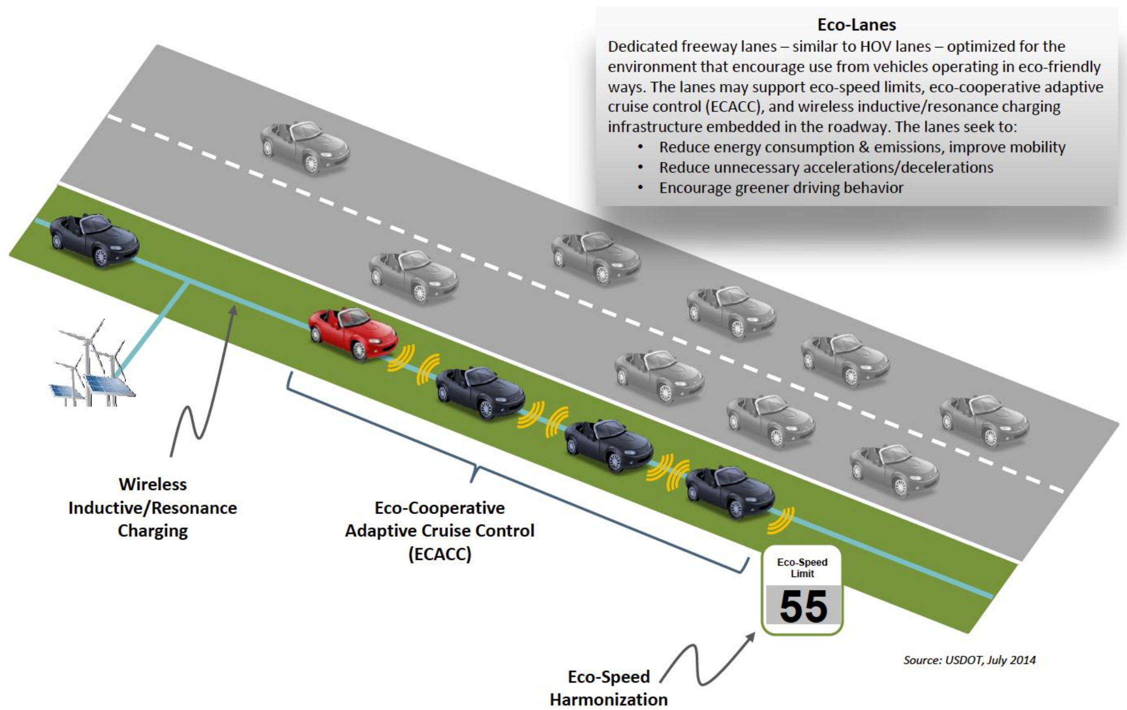


Exhibit 2: Illustration of Eco-Lanes Operational Scenario

In this study, two of the aforementioned applications, the ESH and Eco-CACC, were modeled and evaluated in detail. These efforts are described in the following sections.

Modeling Approach and Performance Measures

The anticipated impacts of the applications were driver and vehicle behavioral changes, such as smoother driving patterns and reduced inter-vehicle gaps along dedicated lanes of the freeways, for the Eco-Lanes Operational Scenario. These specific impacts are best captured using traffic microsimulation tools in which individual vehicles are modeled at high temporal and spatial resolution. A traffic microsimulation tool simulates vehicles and their interactions in a detailed manner. It is possible to record the movements of vehicles for each second they spend on the section of roadway that is used for modeling. For the modeling of the AERIS applications within the Eco-Lanes Operational Scenario, Paramics was used as the microsimulation tool to simulate and analyze the impacts from each of the applications.

Because the anticipated impacts of the Eco-Lanes applications were mostly driving behavior impacts and not travel-demand impacts (e.g., destination choice or route choice), it was determined that the Operational Scenario should be modeled on a freeway-type microsimulation network. As Exhibit 3 shows, one of the networks used in this modeling study is State Route 91 Eastbound (SR-91 E) in Southern California between the Orange County Line and Tyler Street in Riverside, California. SR-91 is a major east-west freeway connecting the beach cities and Inland Empire. For the majority of the freeway, there are five lanes including one high-occupancy vehicle (HOV) lane and four mixed-flow lanes. An existing Paramics model of SR-91 E (only the eastbound lanes were modeled) was used for the modeling because it is a good candidate to suit the needs of the modeling of the Eco-Lanes applications and was readily available and calibrated for use from 2006 validation data.

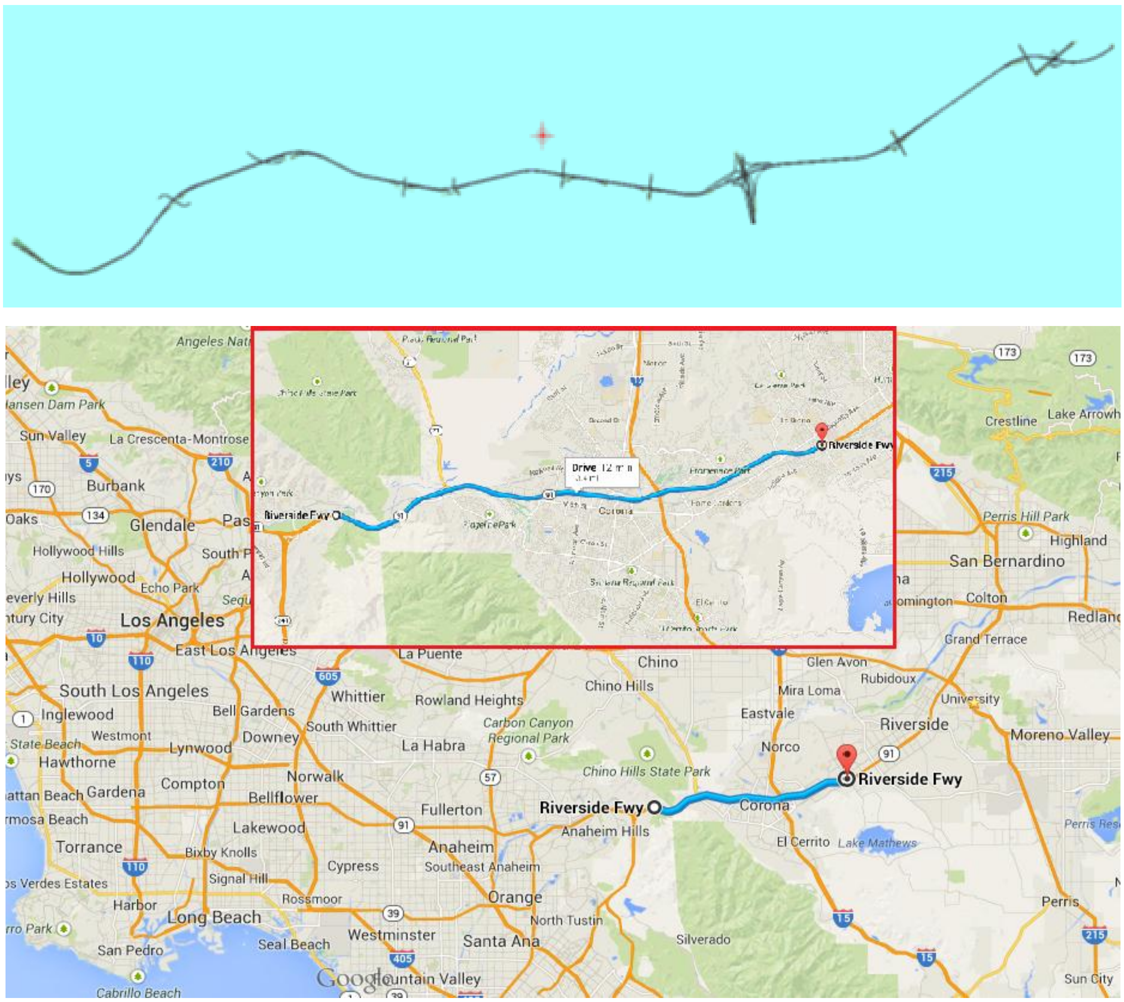


Exhibit 3: SR-91 E in Riverside, California

The Eco-Lanes Operational Scenario applications were modeled individually, then all modeled in combination to test the impact of the entire scenario. The motivation for modeling the applications separately was to characterize each application's benefits thoroughly before cataloging the interactions with the other applications. The steps involved in the process were as follows:

- Assess anticipated behavioral changes of the application,
- Identify the scales for modeling the application,
- Develop an algorithm to model the application,
- Evaluate the application using designated performance measures under several analysis scenarios, and
- Draw conclusions based on the modeling results.

With the Paramics microsimulation tool and the MOtor Vehicle Emissions Simulator (MOVES) emissions estimation tool (developed by the Environmental Protection Agency [EPA]), individual vehicle movements were modeled per the scenario implemented, allowing for fuel consumption and emissions of vehicles to be accurately estimated. Fuel consumption and emissions estimation from MOVES considers driving behavior such as braking and acceleration. Algorithms for each CV application as well as an algorithm for the MOVES real-time environmental simulator were developed and implemented using the application programming interface (API) available with the Paramics microsimulation tool suite, which allowed the application to interact with the simulation engine of the microsimulation model.

Before the start of the modeling, it was important to establish the performance measures using the applications that would be assessed. Performance measures can broadly be classified into environmental and mobility measures. Using the APIs developed for the microsimulation tool as well as the built-in features of the model, many environmental and mobility measures were extracted during the modeling process. Although generating environmental measures is the primary scope of the AERIS analysis, mobility-related measures, such as average travel time, are used to determine the potential mobility impacts of the Eco-Lanes applications.

Environmental measures considered in the analysis include:

- Fuel consumption
- Emissions
    - Carbon dioxide (CO_2)
    - Particulate matter (PM)-10
    - PM-2.5
    - Nitrous oxides (NOx)
    - Volatile organic compounds
    - Hydrocarbons (HC)
    - Carbon monoxide (CO)

Mobility measures considered in the analysis were average travel time.

To properly assess the impacts of the applications of the Eco-Lanes Operational Scenario, it was necessary to develop a baseline model with the assumption that there was no application deployment (i.e., CV penetration rate is zero). This baseline model was developed from the SR-91 E model discussed earlier, which used the MOVES API plugin to estimate the resultant emissions and fuel consumption from the microsimulation model. In addition, overall travel time statistics were collected to help establish the baseline conditions.

From this baseline, the impacts of each of the Eco-Lanes applications could be measured by comparing the resultant emissions along the SR-91 E microsimulation model with the individual applications active against the "baseline" statistics that were collected. To understand the impacts of each of the applications in the simulation, a variety of sensitivity scenarios were generated to characterize the detailed behavior of the application under different conditions. These scenarios included varying vehicle demand of the network, different triggering ranges for the Eco-CACC application, and the CV OBE penetration rate. The increasing levels of OBE penetration help to show the impact of the applications being introduced over the years as the technology is adopted by the vehicle manufacturers and the infrastructure is implemented by the municipalities and other organizations.

Modeling Scenarios

Although certain applications had special parameters that warranted specific sensitivity analyses, several general sensitivity goals were used for the majority of the applications and the combined model. Using these sensitivity parameters allowed for a deeper understanding of the impact of the applications in various situations, allowing for an understanding of the general adoption of the applications. The general parameters were divided into two major groups:

Generic Traffic Simulation Parameter. This parameter helps capture the impact of applications in various traffic conditions normally seen on a freeway corridor.

CV Parameters. These parameters represent the changes in prevalence of CV technology as well as ranges to trigger the technology to simulate not only prevailing scenarios but also possible future changes:

- **OBE Penetration Rate.** These scenarios show the percentage of vehicles on the roadway equipped with CV technology. These scenarios help to gauge the impact of the applications during the years that the vehicle fleet is being introduced to CV technology. Equipped vehicles value percentages used for analysis were 5, 10, 20, 40, 60, 80, and 100.
- **Eco-CACC Triggering Distance.** This distance is the maximum range between the lead vehicle and the following vehicles that can decide to join the platoon. These scenarios help to analyze how the distance would impact the effects of the application and provide recommendations for application-related settings in the future.
- **Eco-CACC Intra-Platoon Clearance**. This clearance is the gap between vehicles of the same platoon. These scenarios help to evaluate the impacts of the application under different inter-vehicle gap settings. Values vary from 5 meters to 20 meters.

Specialized sensitivity analyses were developed for certain applications, and these specialized parameters are discussed in each of the application sections as needed.

ESH Application

An API plugin was developed to implement the mathematics and algorithms of a dynamic environmentally friendly speed limit for the ESH application. The algorithms that were developed use the real-time prevailing conditions of the freeway corridor to return the recommended speed to the vehicle. The algorithm and functions of the API perform the following functions in the microsimulation environment:

- Collection of vehicles' characteristics (e.g., vehicle type) and second-by-second speed data
- Estimation of vehicles' energy consumption and pollutant emissions based on the MOVES model
- Generation of recommended speed limit.

The vehicles communicate with the infrastructure once per second to update the real-time traffic conditions for each roadway segment (500-meters long in this study) and to determine the speed limit for the roadway segments that minimizes fuel use and emissions.

Exhibit 4 shows a depiction of the ESH application.

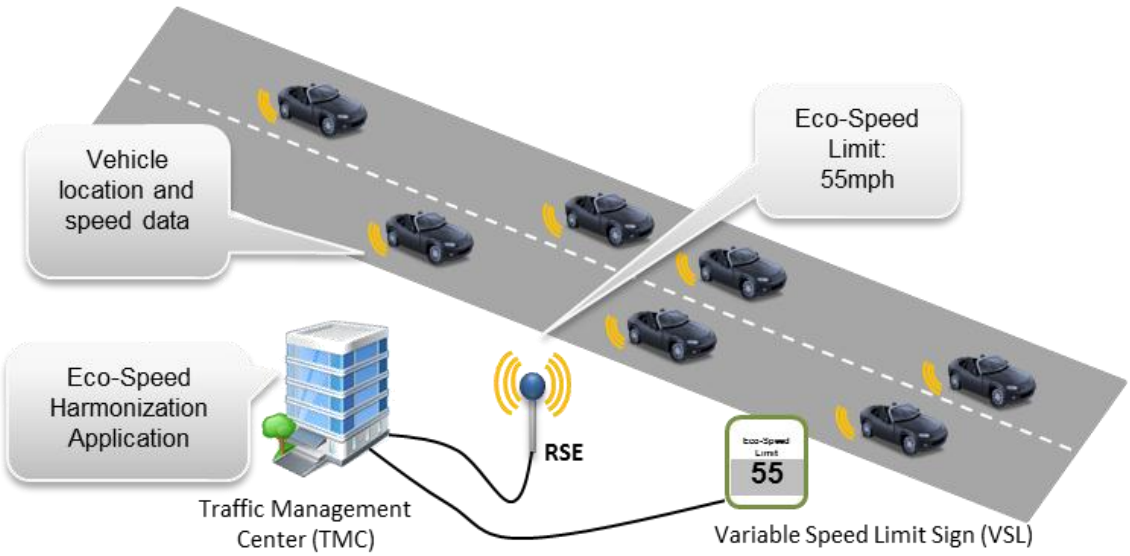


Exhibit 4: ESH Illustrated (Source: USDOT, July 2014)

Exhibit 5 summarizes the overall results from the sensitivity analyses performed, which helps to explain the overall impact of the ESH application. The results are categorized by different performance measures and network models across all scenarios.

Exhibit 5: Range of Energy Benefits of the ESH Application Across Various Scenarios

Network		Range of Energy Benefits									
GHFN	**Volume (vph)**	600	1,200	1,800	2,400	3,000	3,600	4,200	4,800	5,400	6,000
	% Improvement	1.1%	1.5%	1.8%	1.3%	1.1%	1.5%	3.0%	5.0%	4.1%	3.2%
	CV Penetration	5%	10%	20%	40%	60%	80%	100%			
		% Improvement									
	2,400 vph	-0.2%	-0.3%	0.2%	0.6%	0.7%	1.1%	1.3%			
	4,800 vph	1.5%	1.0%	0.6%	1.3%	2.6%	3.9%	5.0%			
SR-91 E	**Volume (vph)**	25,000	28,000	31,000	34,000	37,000					
	% Improvement	4.4%	0.3%	0.1%	1.6%	3.4%					
	CV Penetration	5%	10%	20%	40%	60%	80%	100%			
		% Improvement									
	25,000 vph	0.2%	0.1%	0.9%	2.0%	2.9%	3.1%	4.4%			

Exhibit 6: Range of Mobility Benefits of the ESH Application Across Various Scenarios

Network	Range of Energy Benefits (%)										
GHFN	**Volume (vph)**	600	1200	1800	2400	3000	3600	4200	4800	5400	6000
	% Improvement	-1.0	-0.8	-0.5	-1.0	-1.3	-3.6	-5.6	-0.5	-3.2	-3.0
	CV Penetration	5%	10%	20%	40%	60%	80%	100%			
	% Improvement										
	2,400 vph	-0.2%	-0.3%	-0.3%	-0.3%	-0.5%	-0.5%	-1.0%			
	4,800 vph	2.5%	0.1%	-1.1%	-2.2%	-1.1%	-1.4%	-0.5%			
SR-91 E	**Volume (vph)**	25,000	28,000	31,000	34,000	37,000					
	% Improvement	-1.7%	-0.9%	0.0%	1.3%	-0.5%					
	% Improvement										
	CV Penetration	5%	10%	20%	40%	60%	80%	100%			
	25,000 vph	0.5%	-0.7%	-1.2%	-2.1%	-2.0%	-1.9%	-1.7%			

The benefits provided by the ESH application largely depend on the situation and area in which it is being implemented. The maximum benefits of the application were seen along the upstream of a recurrent bottleneck when the traffic is congested. When the traffic condition is free-flowing, there will be significant penalties on mobility if the ESH application is implemented to favor the environment.

With all of the analyses that were performed, outcomes and conclusions were formed on the performance of the application in various situations. The major conclusions of the application are—

- The application is less effective when the traffic volume is low.
- The results show that the benefits of the application vary with penetration rate. As the penetration rate increases, more and more energy savings can be expected, but the mobility benefits may fluctuate.

Although a lot of useful information was obtained from the sensitivity analyses, additional questions and opportunities to learn more through future research were discovered. Should this application be researched further in future work, the following are opportunities to better understand the application:

- Because the benefits vary with different scenarios, such as congestion levels and location, further research is recommended to develop a more adaptive algorithm whose parameters may be well tuned automatically.
- Additional modules are recommended to develop on the existing algorithm to identify the scenarios when the technology should be turned on and the effective region (in both time and space) to which it should be applied to maximize the benefits in terms of energy.

Eco-CACC Application

Exhibit 7 shows a depiction of the Eco-CACC application.

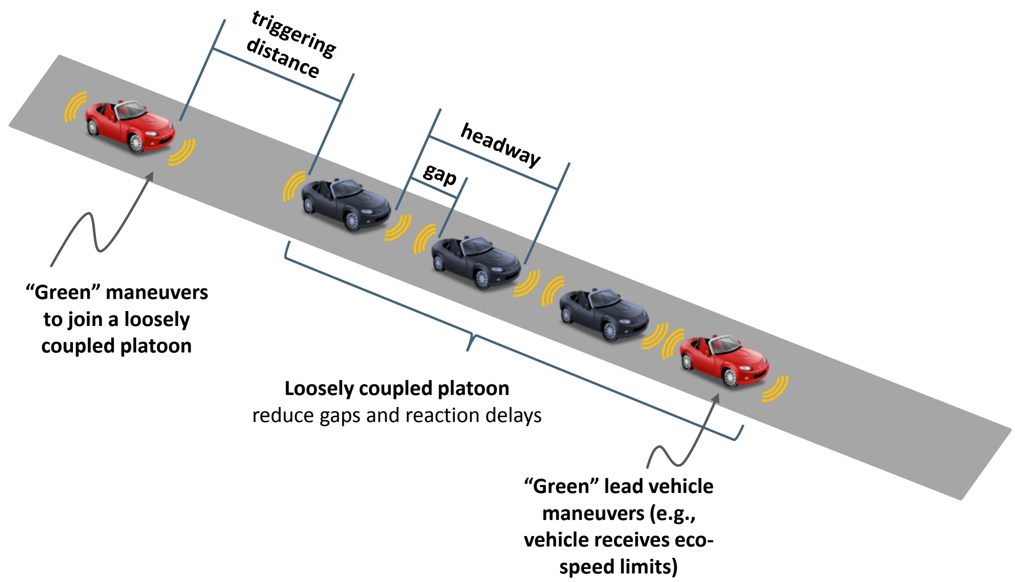


Exhibit 7: Eco-CACC Application Illustrated (Source: USDOT, July 2014)

Exhibit 8 summarizes the overall results from the sensitivity analyses performed across all scenarios, which helps to explain the overall impact of the Eco-CACC application. The results are categorized by the traffic network simulated and reflect network-wide benefits. The volumes listed are totals across all lanes. The first two networks simulated were hypothetical freeway segments, and the final network simulated was the southern California SR-91 E freeway. The first hypothetical freeway segment, referred to as the Generic Hypothetical Freeway Network (GHFN), consisted of three lanes with a single lane drop and without freeway ramps. For the GHFN, Eco-CACC was applied to the two left-most lanes. The second hypothetical freeway segment, referred to as the Intermediate Hypothetical Freeway Network (IHFN), consisted of four lanes, with two pairs of on-ramps and off-ramps; Eco-CACC was applied to the left-most lane. Finally, the third network simulated, the SR-91 E, also restricted Eco-CACC to the left-most lane.

Exhibit 8: Range of Energy Benefits of the Eco-CACC Application Across Various Scenarios

Network		Range of Energy Benefits									Vehicle Clearance (meters)
GHFN	**Volume (vph)**	3,000	3,600	4,200	4,800	5,400	6,000				0
	% Improvement	2.5%	3.0%	12.6%	22.0%	28.1%	31.5%				5
IHFN	**Volume (vph)**	3,000	3,600	4,200	4,800	5,400	6,000	6,600	7,200	7,800	-
	% Improvement	0.3%	0.5%	0.7%	1.1%	1.6%	2.1%	3.8%	5.5%	8.9%	5
SR-91 E	**Volume (vph)**	25,000	28,000	31,000	34,000	37,000					-
	% Improvement	0.1%	0.7%	2.9%	13.9%	19.2%					5
		0.2%	0.7%	2.5%	12.4%	9.2%					15

Exhibit 9: Range of Mobility Benefits of the Eco-CACC Application Across Various Scenarios

Network		Range of Mobility Benefits									Vehicle Clearance (meters)
GHFN	Volume (vph)	3,000	3,600	4,200	4,800	5,400	6,000				-
	% Improvement	-	4.5%	45.0%	58.7%	67.8%	73.0%				5
IHFN	Volume (vph)	3,000	3,600	4,200	4,800	5,400	6,000	6,600	7,200	7,800	-
	% Improvement	-	0.5%	0.6%	0.9%	1.0%	1.5%	2.4%	6.8%	28.6%	5
SR-91 E	Volume (vph)	25000	28000	31000	34000	37000					-
	% Improvement	0.3%	0.6%	4.0%	23.6%	42.8%					5
		0.5%	0.1%	3.6%	22.0%	22.5%					15

With all of the analyses that were performed, outcomes and conclusions were formed on the performance of the application in various situations. The major conclusions of the application are as follows:

- Even the presence of a single Eco-CACC dedicated lane leads to a significant increase in overall network capacity because of a reduction in average headway.
- Vehicle clearance has a significant impact on overall network benefits because of its inverse relationship with overall network capacity.
- Vehicles may maximize their energy savings by choosing the dedicated lane and enabling Eco-CACC. Vehicles that remain outside the dedicated lane still benefit indirectly in terms of travel time and energy.

Although a lot of useful information was obtained from the sensitivity analyses, additional questions and opportunities to learn more through future research were discovered. Should this application be researched further, the following are opportunities to better understand the application:

- Additional testing may be conducted at even higher traffic volumes to more adequately quantify the increase in network capacity resulting from Eco-CACC. In particular, the relationship between vehicle clearance (i.e., headway) and network capacity is of interest.
- More sensitivity analyses on factors such as CV technology penetration rate and number of dedicated lanes may be undertaken on the SR-91 E network.

Combined Modeling of the Eco-Lanes Applications

Exhibit 10 shows the overall design of the combined API plugin elements and their connection with the Paramics microsimulation model. The combination of ESH and Eco-CACC is set up in the plugin to operate under various scenarios. The scenario included in the supplied plugin involves vehicles participating in only one technology at a time. A vehicle can participate in either ESH or Eco-CACC at any given time. However, the plugin may be easily modified to allow vehicles to participate in both applications simultaneously, with Eco-CACC platoon maneuvers being given priority over compliance with ESH speed advice.

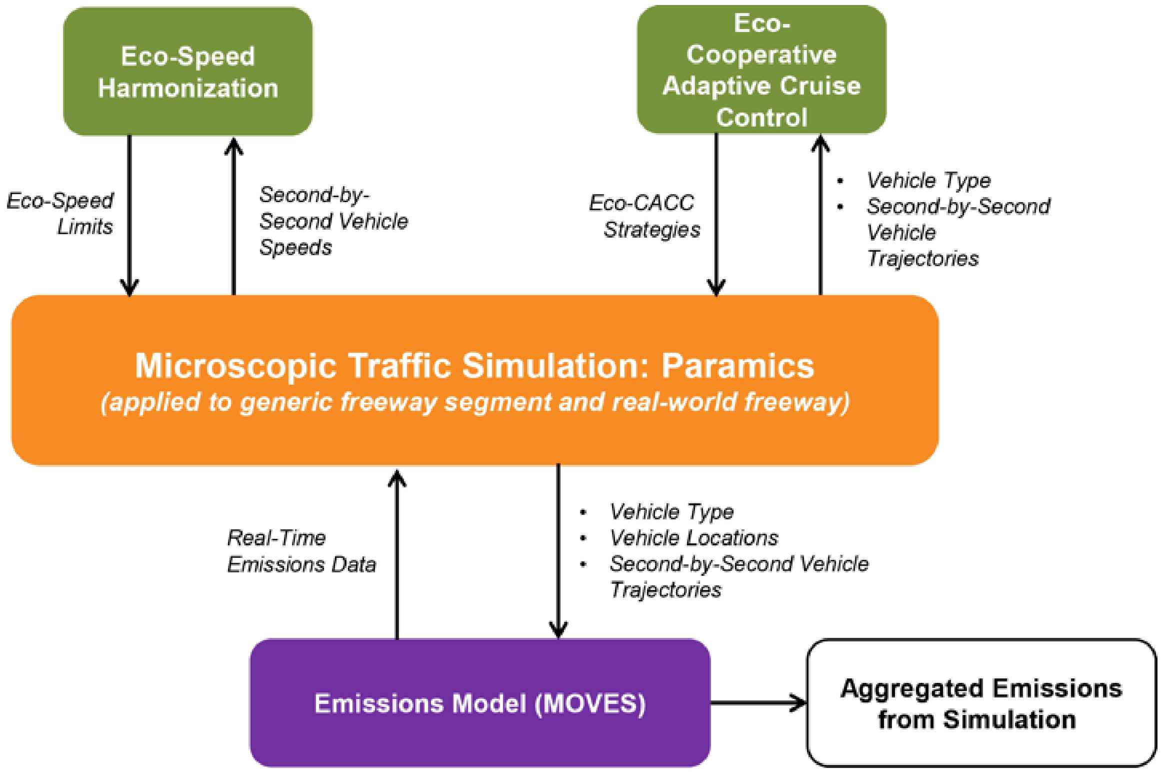


Exhibit 10: Interactions Among the Models and APIs

Exhibit 11 summarizes the overall results from the sensitivity analyses performed across all scenarios, which helps to explain the overall impact of the combined application.

Exhibit 11: Range of Benefits of the Combined Application Across Various Scenarios in Terms of Energy and Travel Time Reduction

Network	Range of Energy Benefits	Range of Mobility Benefits
SR-91 E	4%–22%	-1%–33%

Exhibit 12: Range of Energy Benefits of the Combined Application Across Various Scenarios

Network		Range of Energy Benefits					Vehicle Clearance (meters)
SR-91 E	**Volume (vph)**	25,000	28,000	31,000	34,000	37,000	-
	% Improvement	4.2%	4.4%	7.2%	18.4%	21.6%	5

Exhibit 13: Range of Mobility Benefits of the Combined Application Across Various Scenarios

Network		Range of Mobility Benefits					Vehicle Clearance (meters)
SR-91 E	**Volume (vph)**	25,000	28,000	31,000	34,000	37,000	-
	% Improvement	-1.3%	-0.1%	3.4%	25.3%	33.8%	5

The major conclusions of the application are as follows:

- The combination of ESH and Eco-CACC leads to a slight penalty in travel time and a small benefit in energy relative to Eco-CACC testing.
- The energy savings at lower traffic volumes are higher for the general purpose lanes than the dedicated lane because of the small energy needed for platoon formation.
- At the highest traffic volume, the energy savings are greatest for the dedicated lane because of the increased capacity provided by Eco-CACC.

Explanation of Benefits

The individual modeling and the combined modeling of applications within the Eco-Lanes Operational Scenario all show significant improvements in fuel consumption and the resultant emissions that were analyzed during the modeling process. Although these percentages show a good improvement, the savings may not be easy to understand for the average user or planning organization when envisioning the implementation of this technology. To further break down the benefits of the applications, Exhibit 14 shows each of the applications and how the percentage improvement in fuel consumption translates to financial savings for the driver of the vehicle. For each of the vehicle types, a "typical user" is defined as one who has average mileage and fuel consumption ratings. It is important to remember that there are wide ranges of vehicle types and fuel ratings, so the benefits could be larger or smaller depending on the typical fleet in a given area. However, these numbers show a good "average" that can easily be translated in most of the country.

Exhibit 14: Monetary Savings Snapshot for the Improvement in Fuel Consumption for Each of the Eco-Lanes Applications, for a Typical User

Application	Vehicle Type	Max Fuel Consumption Improvement	Savings per Mile	Savings per Year per Vehicle
ESH	Passenger All	4.4%	$0.008	$65
Eco-CACC	Passenger Freight	9.2%	$0.016	$140

The assumptions used for the calculation of benefits in Exhibit 14 are as follows:

- The average traffic composition is 98-percent light duty vehicles (LDV), including passenger cars and sport utility vehicles (SUV), and 2-percent trucks.

- The miles per gallon for a passenger car are 24 mpg, for an SUV is 17 mpg, and for a truck are 7.3 mpg.
- The average arterial miles traveled by an LDV are 8,250 miles and by a truck are 30,000 miles.
- The average price of fuel per gallon for an LDV is $3.67 and for a truck is $3.95 (diesel).

As seen in Exhibit 14, the range of benefits for fuel consumption savings is large and the impact is different for each application.

Conclusions

The results that were obtained from the various sensitivity analyses of the Eco-Lanes applications allow us to draw some conclusions. The modeling exercises allowed for insight into the interactions of the combined applications as well as the performance as standalone applications. Individual application modeling made it possible to characterize an application in detail before proceeding to model several applications together to study their synergies and conflicts.

The majority of the applications in the Eco-Lanes Operational Scenario show greater benefits in energy consumption with higher levels of CV technology. The technology provides the applications with real-time traffic information around the equipped vehicles, which helps them perform better than conventional ITS, such as Adaptive Cruise Control (ACC), with any detrimental side effects to non-CVs falling off quickly in higher levels of implementation.

For the ESH application, the benefits in energy savings vary with traffic conditions and study sites. Significant efforts are required to fine-tune the system parameters, such as the information update frequency and segment length to achieve the most profound benefits in energy while minimizing any penalty in mobility.

For Eco-CACC, the more congested the traffic condition, the more benefits (in both mobility and environmental sustainability) can be expected, primarily because of the increased capacity induced by the application via regulating (reducing) the inter-vehicle spacing.

The addition of ESH on Eco-CACC provides additional energy savings with minimal impact on mobility benefits.

Chapter 1. Introduction

This report is focused on the modeling results for the Applications for the Environment: Real-Time Information Synthesis (AERIS) Program's Eco-Lanes Operational Scenario, with a detailed focus on the development of the scenario framework, algorithm development, and application needs, as well as the modeling and results gained from detailed simulation analysis. The Eco-Lanes Operational Scenario includes dedicated lanes optimized for the environment, referred to as Eco-Lanes. Eco-Lanes are similar to managed lanes; however, these lanes are optimized for the environment using connected vehicle data and can be responsive to real-time traffic and environmental conditions. Eco-Lanes allow an operating entity to change the location of the eco-lanes, the duration of the eco-lanes, the number of lanes dedicated as eco-lanes, the rules for vehicles entering the eco-lanes, and other parameters. These lanes would be targeted towards low emission, high occupancy, freight, transit, and alternative fuel vehicles. Drivers would be able to opt-in to these dedicated eco-lanes to take advantage of eco-friendly applications such as eco-cooperative adaptive cruise control, connected eco-driving, and wireless inductive/resonance charging applications.

The Eco-Lanes Operational Scenario was imagined as a package of seven different freeway-based applications that were designed to operate both individually, as well as combined, in order to meet the AERIS program's objective of reducing the environmental impact of surface transportation. Due to limitations in modeling, budget, and time, only two of the applications within the scenario were modeled and are featured in this report in detail. The individual applications of the Eco-Lanes Operational Scenario are shown in detail in Chapter 2 of this report.

This section of the report serves as a general introduction to the AERIS program goals and objective, as well as the past work completed as a part of the program that has led to the scenarios and applications for modeling that are presented in this report. Chapter 1 also contains an overall view of the document and the information that is contained within.

The AERIS Program

The USDOT ITS JPO is conducting the AERIS Program. The focus of the program is to use CV technology to reduce the environmental impact of road transportation. A CV setting is used to develop applications that modify traveler behavior or directly reduce fuel consumption of vehicles. The primary objective of developing the AERIS applications is to reduce surface transportation's impact on the environment. This project is dedicated to assessing the benefits of implementing applications that maximize environmental benefits. Benefits are assessed by modeling the applications and evaluating them in a simulated CV setting.

The AERIS applications are designed to create significant benefits in terms of reductions in emissions (e.g., GHG emissions, criteria pollutants) and fuel consumption, which could ultimately yield environmental and monetary benefits. Most of the environmental benefits can be realized by improving flow, reducing travel times, and encouraging the use of mass transit, carpooling, and fuel-efficient vehicles. In addition, environmental impacts of surface transportation can be greatly influenced by modifying driving behavior by providing speed or route recommendations and providing incentives to drivers to use fuel-efficient vehicles or other eco-friendly modes.

The main objectives of the AERIS Program are as follows:

- Identify CV applications that could provide environmental impact reduction benefits via reduced fuel use, improved vehicle efficiency, and reduced emissions.
- Facilitate and incentivize “green choices” by transportation service consumers (e.g., system users, system operators, policy decisionmakers).
- Identify V2V, vehicle-to-infrastructure (V2I), and vehicle-to-grid data exchanges via wireless technologies of various types.
- Model and analyze CV applications to estimate the potential environmental impact reduction benefits.
- Develop a prototype for one of the applications to test its efficacy and usefulness.

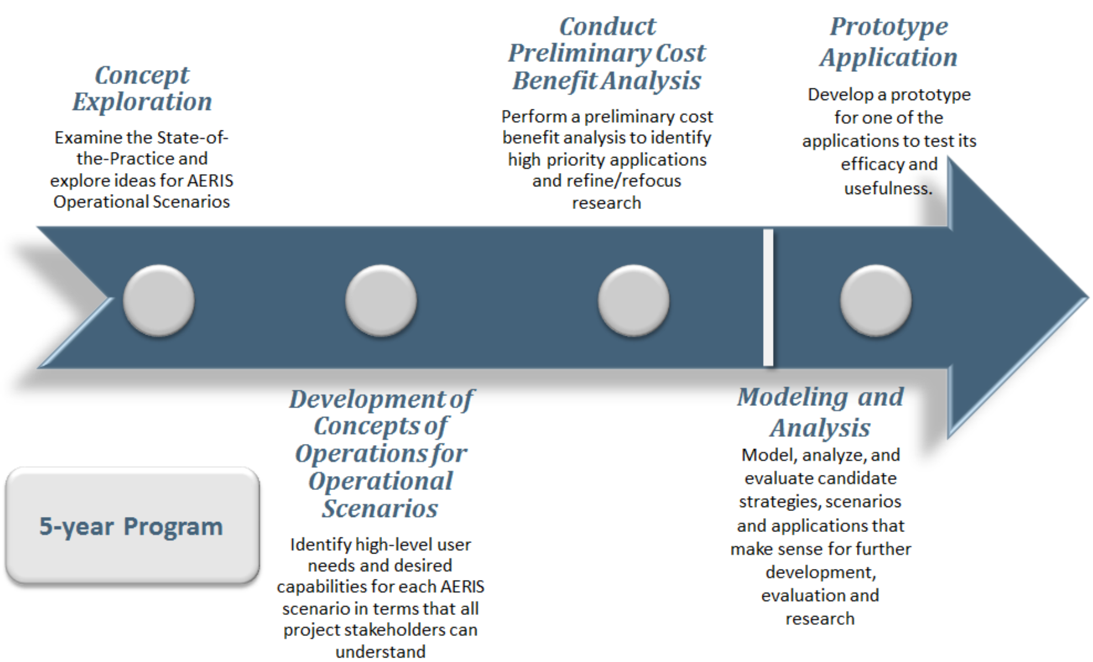


Figure 1: The AERIS Approach (Source: USDOT, AERIS Factsheet http://www.its.dot.gov/factsheets/pdf/AERIS_factsheet.pdf, accessed September 11, 2014)

The AERIS Program is a 5-year program consisting of a phased research approach. Figure 1 illustrates the AERIS research approach:

- **Concept Exploration.** The first step was to examine the state of the practice and explore ideas for AERIS research. Five state-of-the-practice reports were developed as part of this phase investigating (1) environmental applications, (2) assessment of technologies to collect environmental data, (3) environmental models, (4) behavioral and activity-based models, and (5) evaluation of environmental ITS deployments. In addition, six Broad Agency Announcement projects were conducted.

- **Development of Concept of Operations (CONOPS) for Operational Scenarios.** The next phase focused on the identification of environmental applications and the development of CONOPS for three of the five Operational Scenarios. Detailed CONOPS were developed for the Eco-Signal Operations, Eco-Lanes, and Low Emissions Zones Operational Scenarios. CONOPS for the remaining Operational Scenarios will be developed at a later date.
- **Conduct Preliminary BCA.** Once the CONOPS were developed, a preliminary BCA was performed to identify high-priority applications and refine/refocus the research.
- **Modeling and Analysis.** The high-priority applications from the BCA were then selected for more detailed modeling and analysis. The result will be a report that documents the potential benefits that may be possible by implementing AERIS CV applications.
- **Prototype Application.** Finally, the AERIS Program selected one of the AERIS applications for prototyping. The Eco-Approach and Departure at Signalized Intersections application was selected to test its efficacy and usefulness.

Operational Scenario: Definition

The AERIS Program identified five Operational Scenarios or bundles of applications: (1) Eco-Signal Operations, (2) Eco-Lanes, (3) Low Emissions Zones, (4) Eco-Traveler Information, and (5) Eco-Integrated Corridor Management. Each Operational Scenario encompasses a set of applications, which individually achieve environmental benefits. By strategically bundling these applications, the AERIS Program expects that the Operational Scenarios can achieve additional environment benefits greater than those of the individual applications.

Each Operational Scenario also comprises regulatory/policy tools, educational tools, and performance measures. Applications are technological solutions (e.g., software, hardware, interfaces) designed to ingest, process, and disseminate data to address a specific strategy. For example, the Eco-Traffic Signal Priority application may collect data from vehicles, send these data to a local processor to determine whether a vehicle should be granted priority at a signalized intersection and then communicate this priority request to a traffic signal controller.

Identification and Evaluation of Transformative Environmental Applications and Strategies Project

Before the modeling and evaluation of AERIS applications, three other tasks were carried out as part of this project. The first task was to identify applications that could yield environmental benefit and bundle them into Operational Scenarios. This work was completed and is documented in a companion report titled *Identification of the Transformative Concepts and Applications.* The second task was an initial BCA, which used a detailed model that assessed the monetary benefits and costs for each application identified in the aforementioned report. The methodology and results of the BCA are documented in a companion report titled *AERIS Applications for the Environment: Real-Time Information Synthesis Identification and Evaluation of Transformative Environmental Applications and Strategies Project, Initial Benefit-Cost Analysis*. The third task was prioritizing the applications based on criteria such as the benefits of the application, likelihood of deployment, ease of modeling, and data availability. As part of this task, a field experiment was conducted at Turner Fairbank Highway Research Center to evaluate the benefits of the Eco-Approach at Signalized Intersections application. The results and the methodology were documented in reports titled *Identification and Evaluation of Transformative Environmental Applications and Strategies Project, Prioritization Evaluation Report* and *AERIS Field Study Application: Eco-Approach to Signalized Intersections.* The fourth task is to perform detailed modeling and simulation of the prioritized applications. Figure 2 presents the scheme of tasks carried out.

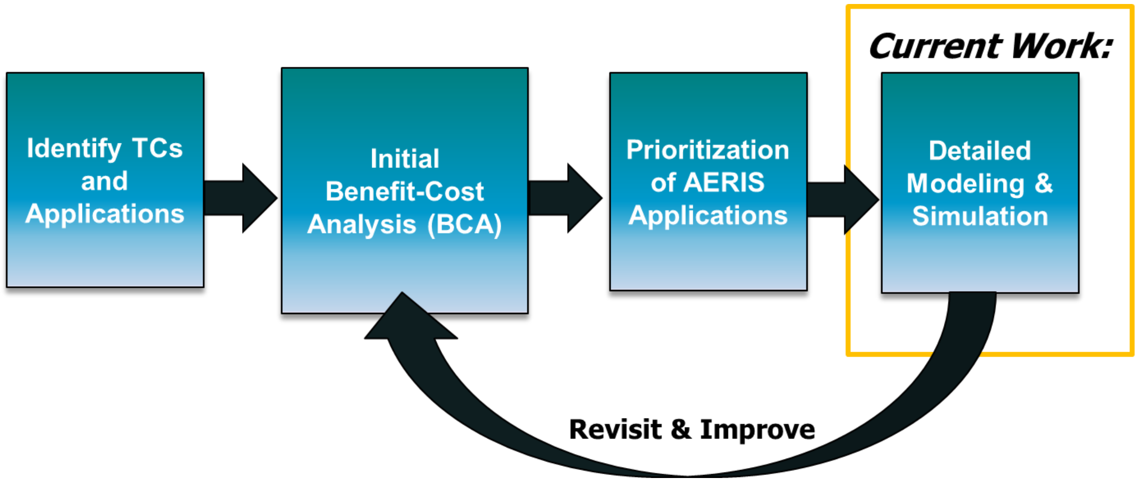


Figure 2: The Role of Modeling and Simulation (Operational Scenatios were referred to as Transformative Concepts or TCs in the past).

Summary of Previous Tasks

Task 1 identified applications and bundled them into five Operational Scenarios, as Figure 3 shows. Each Operational Scenario is a bundle of applications that is individually designed to achieve environmental benefits. The applications are bundled strategically with an expectation that the Operational Scenarios can achieve additional environmental benefits greater than those of the five individual applications:

1. **Eco-Signal Operations.** This Operational Scenario uses CV technologies to decrease fuel consumption and reduce GHGs and criteria air pollutant emissions on arterials by reducing idling, stop-and-go behavior, and unnecessary accelerations and decelerations and improving traffic flow at signalized intersections.
2. **Eco-Lanes.** This Operational Scenario includes dedicated lanes optimized for the environment, referred to as eco-lanes. Eco-lanes are similar to HOV and high-occupancy toll lanes; however, these lanes are optimized for the environment using CV data and can be responsive to real-time traffic and environmental conditions.
3. **Low Emissions Zones.** The AERIS Program seeks to expand on the concept of low emissions zones by investigating the potential of CV technologies to support emissions pricing and incentives for travelers. The purpose of these zones would be to encourage decisions by travelers that help reduce transportation's negative impact on the environment.

4. **Eco-Traveler Information.** This Operational Scenario enables development of new, advanced traveler information applications through integrated, multi-source, multimodal data. Although the AERIS Program may not directly develop specific traveler information applications, an open data/open source approach is intended to engage researchers and the private sector to spur innovation and environmental applications.
5. **Eco-Integrated Corridor Management.** This Operational Scenario includes the integrated operation of a major travel corridor to reduce transportation-related emissions on arterials and freeways. Integrated operations means partnering among operators of various surface transportation agencies to treat travel corridors as an integrated asset, coordinating their operations with a focus on decreasing fuel consumption, GHG emissions, and criteria air pollutant emissions.

Figure 3. AERIS Operational Scenarios (Source: USDOT ITS-JPO, www.its.dot.gov/aeris/pdf/AERIS_Operational_Scenarios011014.pdf, accessed April 13, 2014)

In Task 2, the applications were subject to a BCA on a national scale. The BCA model was developed to assess the benefits and costs of each application on a national scale for a period extending through 2055. Most of the steps of the BCA required substantial input from the AERIS team including stakeholders (e.g., Transit Administration) and CV experts (e.g., researchers). The AERIS team collaborated closely to ensure consensus on the baseline assumptions, benefit categories, and cost assumptions. In addition, the approach and assumptions were vetted within the ITS JPO. The baseline assumptions were used to provide a benchmark against which the relative results for each of the applications were compared. The BCA was conducted in two parallel work streams, one for benefit estimation and the other for cost estimation. The results of benefit and cost estimations were then input into the model, which extrapolated results to the entire nation and provided results for each year in the analysis.

Task 3 was prioritization of applications for modeling. To determine the priority order for modeling the AERIS Operational Scenarios, a set of preliminary screening questions were considered. The following key questions pertaining to modeling were considered:

Are environmental and transportation data required to model the Operational Scenario readily available or easy to collect? The availability and quality of environmental and transportation data greatly impact the ability to model an application, the scale at which the application may be modeled, and the level of effort required to assemble the needed data. Specific data requirements may include vehicle emission information, signal information, and traffic volumes for model validation.

Are algorithms in place—or could they be developed with minimal effort—to model the applications in the Operational Scenario? The availability and readiness of algorithms are important to the accuracy of modeling and evaluating the benefits of the applications and their Operational Scenarios; however, the lack of algorithms does not necessarily mean that the application does not have the potential to provide significant environmental benefits. The availability of algorithms was considered as a part of the prioritization.

Could the Operational Scenario be accurately modeled using existing behavioral, traffic simulation, or environmental models? Similar to the need for algorithms, the ability to use existing behavioral, traffic simulation, and environmental models is significant in evaluating the benefits of the applications and Operational Scenarios. The modeling feasibility was considered as part of the prioritization.

Each application was scored using several factors that affect its modeling/testing. Each factor was weighted and the total weighted scores of the applications within each of the Operational Scenarios were averaged to assign a score for each Operational Scenario. The Eco-Signal Operations Operational Scenario was chosen to be modeled first, followed by Eco-Lanes and Low Emissions Zones. The other Operational Scenarios were not considered for modeling owing to the complexity of modeling the applications or the lack of data to model the applications.

Document Overview

This document includes the following six chapters and three appendixes:

1. **Chapter 1** provides the background and overview for AERIS modeling activities.
2. **Chapter 2** presents an overview of the Eco-Lanes applications.
3. **Chapter 3** presents the common modeling elements for the Eco-Lanes applications testing scenarios including performance measures, the hypotheses to be tested, a description of the modeling region, data and tool needs, how the model was calibrated, and the modeling approach.
4. **Chapters 4 and 5** describe how the ESH and Eco-CACC applications were modeled and how scenarios were tested. These chapters present the algorithms developed and used, the hypotheses to be tested, the modeling approach, and the results and findings of the

modeling efforts. It also presents and suggests topics for future research. For each of the applications, the following aspects are described:

- **Hypotheses**. This section presents the hypotheses and their justification on the anticipated benefits of each application that were made as part of the analysis plan.
- **Algorithm.** This section describes the algorithm used to implement the AERIS application.
- **Modeling Approach.** This section describes how the model was created to test the AERIS application's hypotheses and how performance measures were generated from the model.
- **Scenarios.** This section describes the scenarios modeled.
- **Modeling Results.** This section presents the results of the modeling efforts along with a discussion of the benefits of the AERIS application revealed by the model.
- **Findings and Opportunities for Future Research.** This section details qualitative findings and suggests topics for future research.

5. **Chapter 6** describes the combined modeling results when both the ESH and Eco-CACC applications were applied to the real-world network, SR-91 E freeway segment.
6. **Appendix A** provides a list of acronyms used in the report.
7. **Appendix B** presents a variety of potential controller algorithms for the ECACC.
8. **Appendix C** provides the BCA used to estimate the magnitude of the environmental benefits of AERIS applications over the future years.

Chapter 2. Eco-Lanes Applications

This chapter describes the AERIS Eco-Lanes Operational Scenario and its associated applications that seek to decrease fuel consumption and emissions by smoothing traffic flow along dedicated freeway lanes. The Eco-Lanes Operational Scenario uses CV technologies to fulfill the aforementioned tasks. Figure 4 illustrates the Eco-Lanes Operational Scenario as envisioned by the AERIS Program.

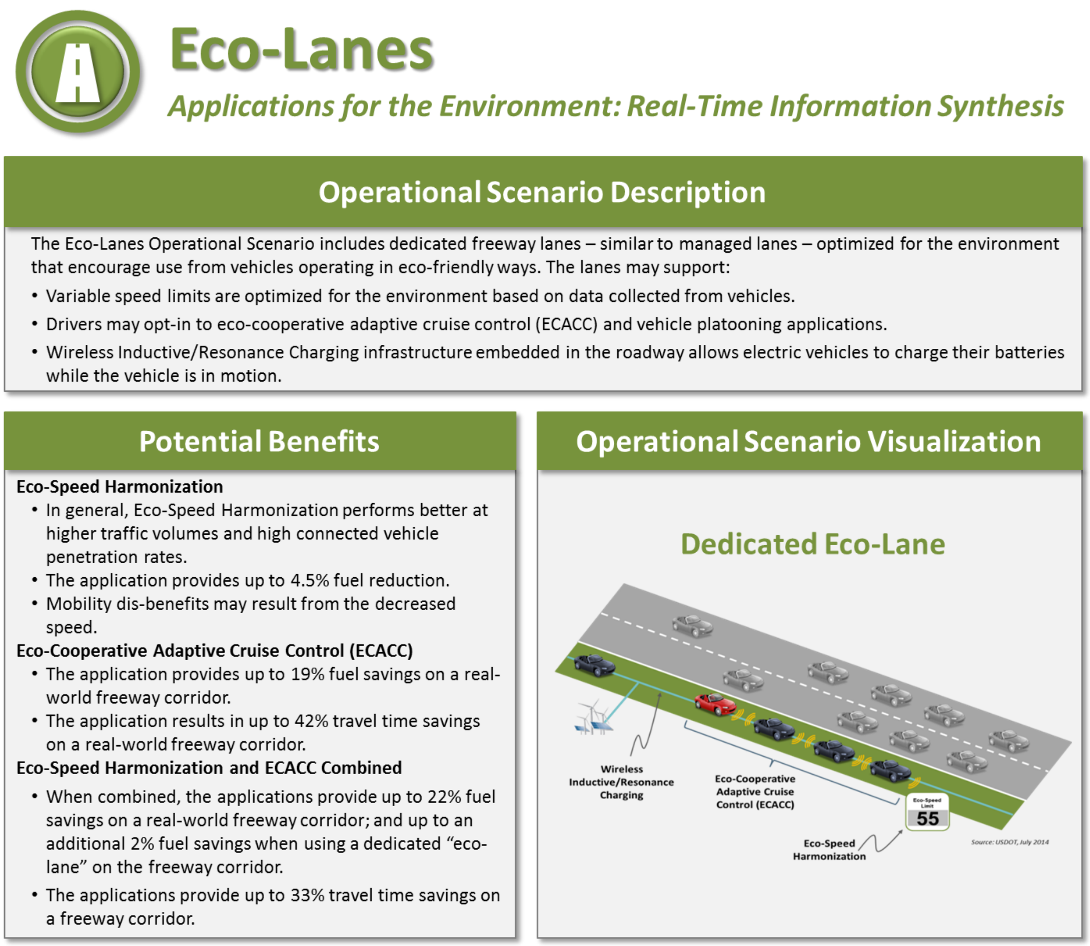


Figure 4. Eco-Lanes Operational Scenario (Source: USDOT ITS-JPO, www.its.dot.gov/aeris/pdf/AERIS_Operational_Scenarios011014.pdf, accessed August 13, 2014)

The Eco-Lanes Operational Scenario consists of seven applications that are carried out on the dedicated freeway lanes. These applications include Eco-Lanes Management, ESH, Eco-CACC, Eco-

Ramp Metering, Connected Eco-Driving, Wireless Inductive/Resonance Charging, and Eco-Traveler Information applications. This report is focused on the modeling and evaluation of two of the aforementioned applications—ESH and Eco-CACC. These two applications are described in greater detail here.

ESH

This application determines eco-speed limits based on traffic conditions, weather information, and GHG and criteria pollutant information. The purpose of speed harmonization is to dynamically change speed limits on links that approach areas of traffic congestion, bottleneck, incidents, special events, and other conditions that affect flow. 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. When tuned for the environment, eco-speed limits can be broadcast by RSE units and received by OBE units or displayed on VSL signs located along the roadway. Information also can be disseminated via cellular data channels. This ESH application is similar to the current VSL application; however, the speed recommendations specifically target the reduction of emissions and fuel consumption along the roadway.

Eco-CACC

The Eco-CACC application is an extension of the ACC concept. Eco-CACC includes longitudinal automated vehicle control while considering eco-driving strategies. In addition to feedback loops used in ACC, which use forward-looking sensors to derive distance and speed information of the immediate preceding vehicle, other preceding vehicles' speed, acceleration, and location are used, provided from the CV technology. These data are transmitted from the preceding vehicles 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 preceding vehicle. The Eco-CACC application can incorporate other information, such as road grade, roadway geometry, and road weather information, to help determine the most environmentally efficient vehicle trajectories. In a sense, Eco-CACC creates loosely coupled platoons, where two or more vehicles travel with small gaps, which could reduce aerodynamic drag, depending on the following distances. This operation relies on V2V communication that allows vehicles to accelerate or brake with minimal lag to maintain the platoon with the lead vehicle. The reduction in drag results in reduced fuel consumption, greater fuel efficiency, and less pollution for vehicles. This application is applicable to all vehicle classes.

Chapter 3. Common Modeling Elements

Eco-Lanes Modeling Region Description

The Eco-Lanes applications are targeted at providing environmental benefits on freeways. This section describes the networks or subsets of networks that were used for testing the various Eco-Lanes applications. A microscopic traffic simulation model was used and applied to freeway corridors for the Eco-Lanes applications, allowing for the evaluation of system operations and short-term driving behavior. Table 1 illustrates an assessment of how much each application influences the overall trip chain. The scale of modeling is determined based on the parts of the trip affected by the application.

Table 1: Influence of Applications on Trip Chain and Recommended Modeling Scale

Application	Trip Chain Affected						Recom-mended Modeling Scale	Comments
	Destination Choice	Mode Choice	Time-of-Day Choice	Route Choice	Lane Choice	Driving Behavior		
Eco-Speed Harmonization					◔	●	Corridor Simulation	Changes in driving behavior are expected. Corridor simulation is sufficient to capture effects of application.
Eco-Cooperative Adaptive Cruise Control				◔	◑	●	Corridor Simulation	Route choice impact is likely to be minimal. Primary changes are likely to be seen in driving behavior and speed profiles.

Legend:

◔ – Application has only a possible influence on the particular trip chain element.

◑ – Application has a probable influence on the particular trip chain element.

● – Application has only a definite influence on the particular trip chain element.

As the modeling details of the Eco-Lanes applications were developed, several freeway network implementations were used. Initially, a fairly simple GHFN was used and then additional features were introduced to this network. Finally, a real-world network was used to test the final Eco-Lanes applications on a real-world corridor. The networks are described in more detail here.

GHFN

A GHFN with three lanes was used for the initial analyses. In the middle of this network, a two-lane section was inserted to trigger a recurring congestion region that propagates upstream. This section was intentionally created to evaluate the algorithmic response to recurrent bottleneck scenarios. With this network, it was possible to adjust the overall traffic volume and the freeway speed limit to elicit different operational details. Figure 5 shows the layout of the freeway model. The total length of the corridor was about 6 miles, with a 5.44-mile upstream stretch, a 0.62-mile downstream stretch, and a 0.16-mile lane-drop (from three lanes to two lanes) area. It is noted that only one vehicle type (i.e., passenger car) was modeled for this network.

When modeling the Eco-CACC application on the GHFN, platoon formation was permitted on every segment and lane except for the lane before the lane-drop. Because of the presence of platoons on the middle lane, vehicles near the lane-drop area used the developed merging protocol to change lanes from the bottom lane to the middle lane.

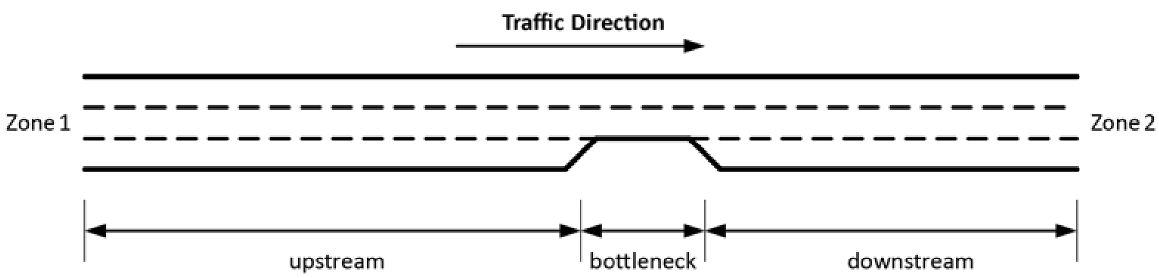


Figure 5: Layout of GHFN: 6.5 Mile with Lane-Drop

IHFN

Several of the Eco-Lanes applications (in particular Eco-CACC) will consist of different lateral maneuvers between lanes. To better understand the effect of these lateral maneuvers, a more complex hypothetical freeway network segment was created. This IHFN segment is similar to the GHFN; however, it also contains on-ramp/off-ramp pairs in addition to dedicated lanes (e.g., an eco-lane). With this addition, it was possible to see the weaving effects of traffic while merging into the dedicated lane (i.e., the left-most lane), which permits equipped vehicles to form Eco-CACC platoons. In addition, the IHFN was used as a test bed to apply heterogeneous route-based platoon formation as well as the platoon-splitting algorithm. Heterogeneous route-based platoon formation involves vehicles with different destinations participating in the same platoon. Figure 6 illustrates the IHFN. The segment is 3.72 miles long, including two pairs of on-ramps/off-ramps with a separation distance of 1.24 miles. Figure 6 provides a closer look at the on-ramps and off-ramps. In total, there are four lanes, including the left-most dedicated lane. For simplicity, only passenger cars were used in this model.

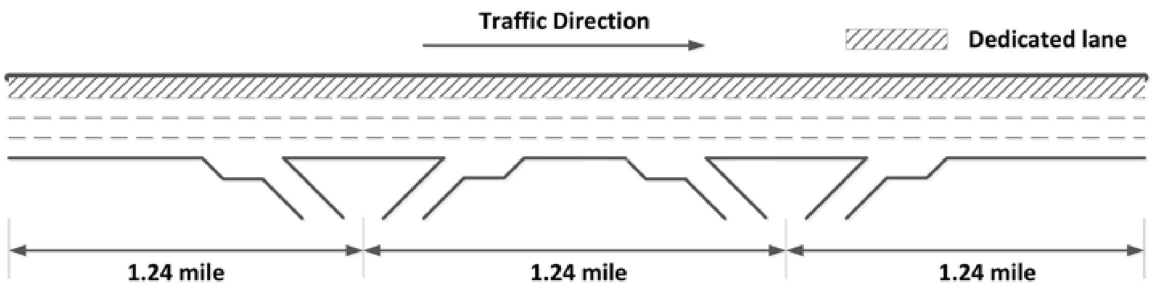


Figure 6: IHFN with One Dedicated Eco-Lane and Two Pairs of On-Ramps/Off-Ramps

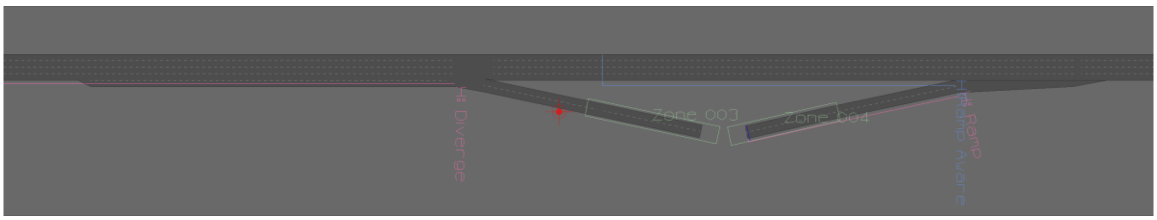


Figure 7: Screenshot of the First On-Ramp/Off-Ramp Pair

California SR-91 Eastbound Network

As previously described, it is necessary to simulate a real-world corridor in this modeling study to see if the Eco-Lanes applications would be deployable in the near-term future. For this real-world corridor, SR-91 E in Southern California was used, consisting of a 15-mile corridor between the Orange County Line and Tyler Street in Riverside, California. SR-91 is a major east-west freeway connecting the beach cities and the Inland Empire of Southern California. For the majority of the freeway corridor, there are five lanes total, currently consisting of one HOV lane and four mixed-flow, general purpose lanes. The simulated corridor has nine pairs of on-ramps/off-ramps. There are a total of 13 origin zones and 12 destination zones. The speed limit on the facility is 60 miles per hour (mph) for certain stretches and 65 mph for other parts of the corridor. Traffic conditions fall into level of service C to F during the peak hours. Traffic demands, origin-destination (O-D) patterns, and driving behavior were calibrated to a typical weekday for summer 2006. The screenshot of SR-91 E corridor model in Paramics is already illustrated in the Report Summary (see Exhibit 3). Figure 8 details the layout of the interchange between SR-91 E and I-15.

Network Modification for the Eco-CACC

To simplify the application development of Eco-CACC, two modifications were applied to the original SR-91 E network: (1) converting the buffer-separated dedicated lane configuration to a continuous-access dedicated lane configuration; and (2) simplifying the overall fleet mix by consolidating all the different vehicle types into a single passenger vehicle type.

For consistency, the same modifications were applied to evaluate the ESH application.

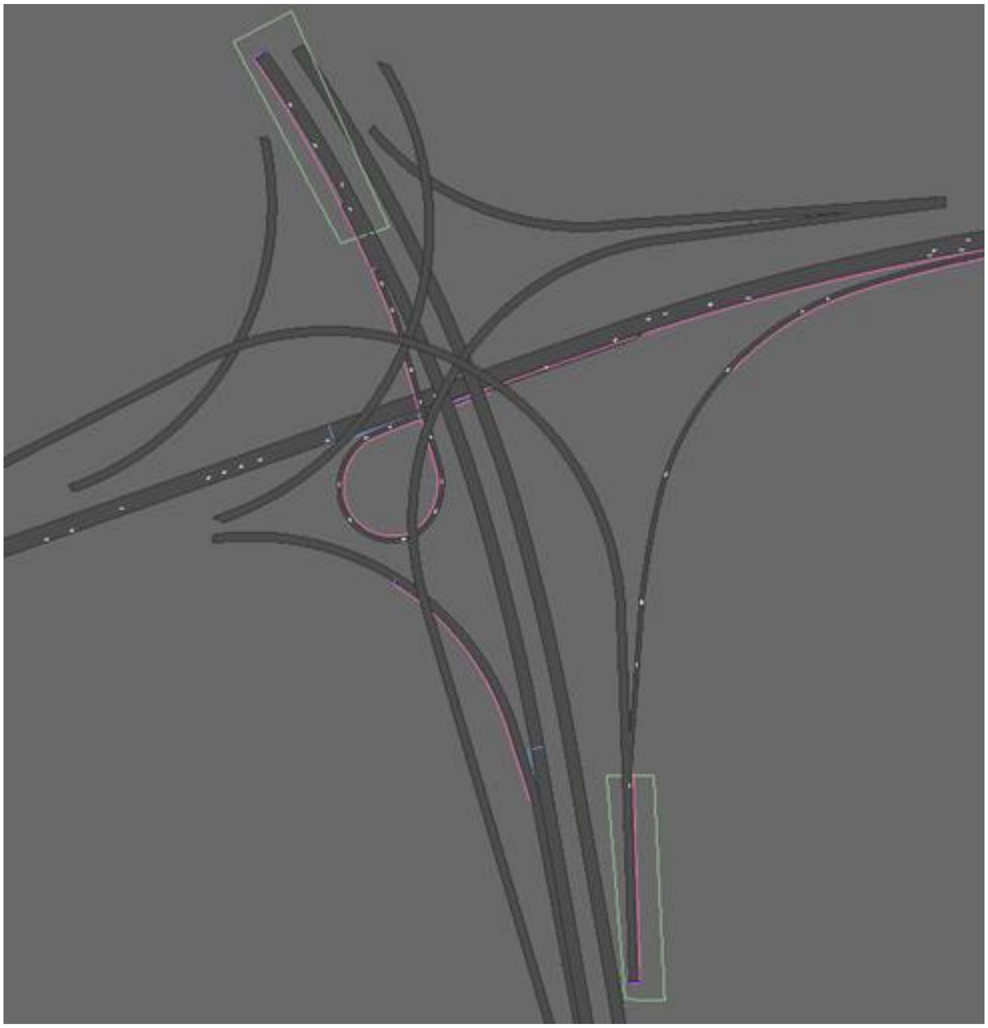


Figure 8: Screenshot of SR-91 and I-15 Interchange

Table 2: Summary of Network Models Used in Each Eco-Lanes Application summarizes the model usage for ESH, Eco-CACC, and the combined application, respectively.

Table 2: Summary of Network Models Used in Each Eco-Lanes Application

Application	GHFN	IHFN	SR-91 E
ESH	X	-	X
Eco-CACC	X	X	X
Combined	-	-	X

Model Calibration

The SR-91 E model network was originally coded in Paramics by the Bourns College of Engineering—Center for Environmental Research and Technology at the University of California at Riverside and was used in previous research to evaluate the impacts of HOV lane configuration on the system-wide fuel consumption and pollutant emissions, as documented in the Boriboonsomsin and Barth report (2006). According to the report, traffic demands, vehicle mix, O-D patterns, and driver behavior in the model were calibrated to the field data collected on a typical weekday in the summer of 2006.

Modeling Approach

This section describes the overall modeling approach used to analyze the environmental impacts of the Eco-Lanes Operational Scenario. The individual applications were modeled separately and the application-specific approach for each is used for modeling.

The key modeling needs to evaluate the environmental benefits of each of the Eco-Lanes applications were identified in the *Eco-Lanes Analysis Plan*, dated September 2013. In addition, the functions of the application that are not considered for modeling were identified for each application in that report.

Figure 9 presents the modeling framework adopted to model Eco-Lanes applications. In this figure, the light blue boxes indicate user inputs, purple boxes indicate output results from the traffic simulation, and the green boxes indicate calculated environmental parameters. The modeling tools used are a combination of a traffic microsimulation tool and emissions tool, coded as an API in the Paramics environment. Initially, the identified network (i.e., links, nodes, and their characteristics) was coded in the microsimulation tool. In addition, travel demand, O-D patterns, and vehicle fleet mix are required inputs to the traffic microsimulation. The O-D trip tables are used to create volume inputs for the microsimulation. Finally, the overall network was calibrated for the baseline traffic, matching field data. The key calibration parameters were driving behavior model parameters, such as driver reaction time and mean target headway.

Quadstone's Paramics traffic microsimulation software was used to model the Eco-Lanes applications. Paramics supports the development and implementation of plugins to model V2V and V2I communications. The tool was used to simulate the movement of individual vehicles and their interactions, including detailed speed profiles that can be used to estimate emissions and fuel consumption. In terms of defining the area of analysis, Paramics requires parameter inputs on the sub-area of the overall network and the traffic control within that sub-area. In addition, the vehicle O-D pairs are defined for the sub-area, thereby defining the travel demand fractions. These input parameter sets are illustrated on the left side of Figure 9. Similarly, each vehicle type and vehicle fuel type must be defined as well as general modeling parameters such as the simulation numerical seed, the length of the simulation run, and other parameters.

With the use of its built-in API, Paramics supports the implementation of plugins that can be developed to enable users to interface with its core simulation engine to perform specific tasks. Two plugins are needed for Eco-Lanes applications:

- Algorithm for implementing the applications

- Vehicle operating mode (OpMode) aggregator

The native outputs from the Paramics model generally need to be reduced and broken down to be used in further analyses. For Paramics to quickly and efficiently build a useful input file for the emissions model, the vehicle OpMode aggregator plugin serves as a direct virtual interface between the traffic microsimulation tool and the emissions modeling tool.

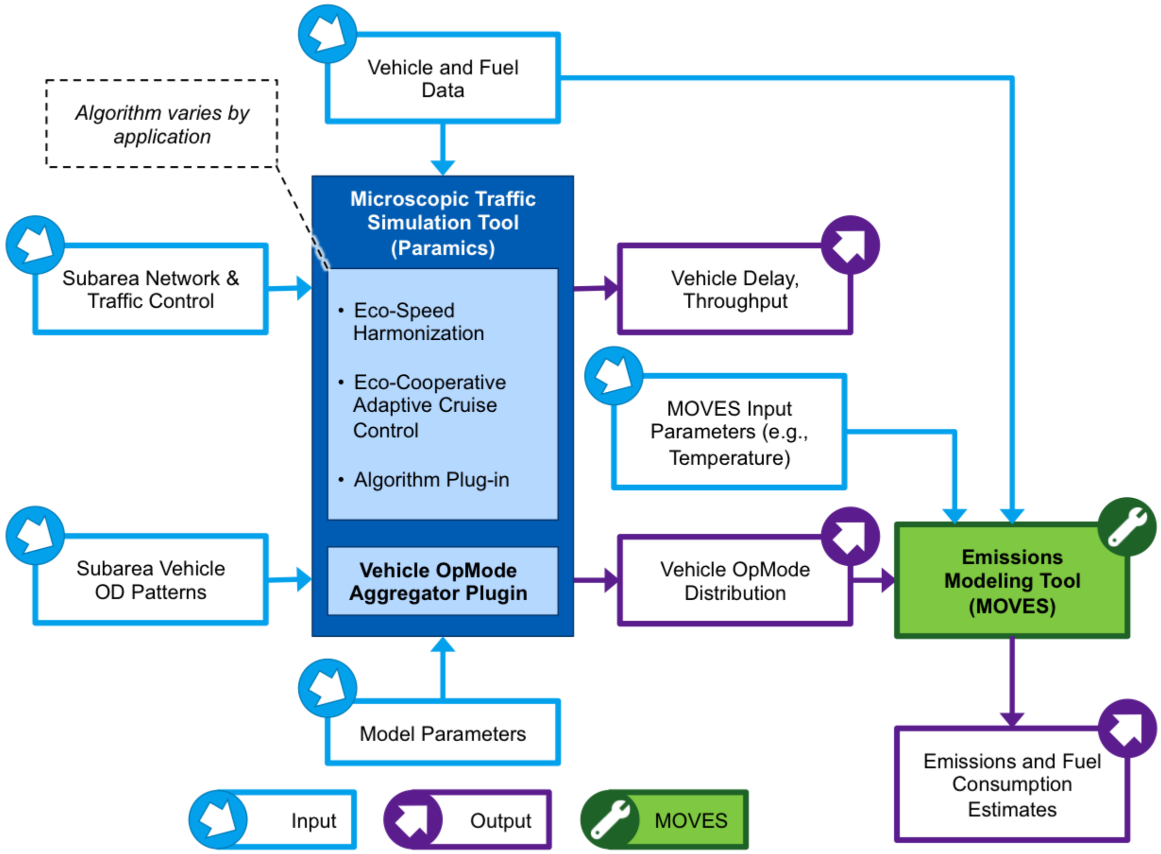


Figure 9: Modeling Framework for Eco-Lanes Applications

A number of tools estimate emissions at various scales that range from macro to micro. There are several microscale vehicle emission models that are commonly used in the United States; for this project, the EPA MOVES model was used.

MOVES is the latest vehicle emission-modeling tool developed by EPA. The tool estimates macro-, meso-, and micro-scalmacroe vehicle emissions and includes several features, such as the ability to estimate particulate and air toxic emissions, for a variety of vehicle types. MOVES was selected for analysis because of its ability to model emissions for future-year vehicles.

Three general approaches can be used to link traffic model outputs to MOVES:

1. **Through Link Average Speeds.** The traffic model outputs the average speed for each roadway link in the network, which is used as direct input to MOVES. MOVES will then generate emission estimates for the default vehicle OpMode distribution based on typical

driving cycles for each average speed bin. The default MOVES OpMode distributions vary by roadway type. Therefore, the emissions vary by roadway type.

2. **Through Link Driving Cycles.** Fine-grained traffic models, such as microsimulation models, output the driving cycles (i.e., second-by-second speed profiles) on roadway links. All or a subset of these driving cycles are used as direct inputs to MOVES or are aggregated into a set of representative driving cycles before use as inputs to MOVES. MOVES then computes vehicle OpMode distribution cycles and subsequently generates the emission estimates.
3. **Through Link-Specific Vehicle Operating Mode Distribution.** The vehicle OpMode distribution created from vehicle driving cycles is used as an input for MOVES. MOVES then generates emission estimates based on the vehicle OpMode distribution. Alternatively, MOVES outputs emission rate look-up tables for each OpMode to estimate emissions.

Among the three approaches, the last approach is the most accurate because it uses OpMode profiles of all the vehicles to estimate emissions. This approach was used to estimate the environmental benefits of the Eco-Signal Operations applications. In addition, MOVES requires general user inputs, such as ambient temperature and other parameters (blue input box feeding the MOVES model). The vehicle OpMode aggregator Paramics plugin does the following:

- Generates second-by-second speed profiles for each vehicle in the simulation
- Calculates the corresponding second-by-second vehicle-specific power values (which is one of the indicators of vehicle emission levels)
- Determines the vehicle OpMode as defined by MOVES
- Creates vehicle OpMode distributions as an output

Figure 10 illustrates this procedure.

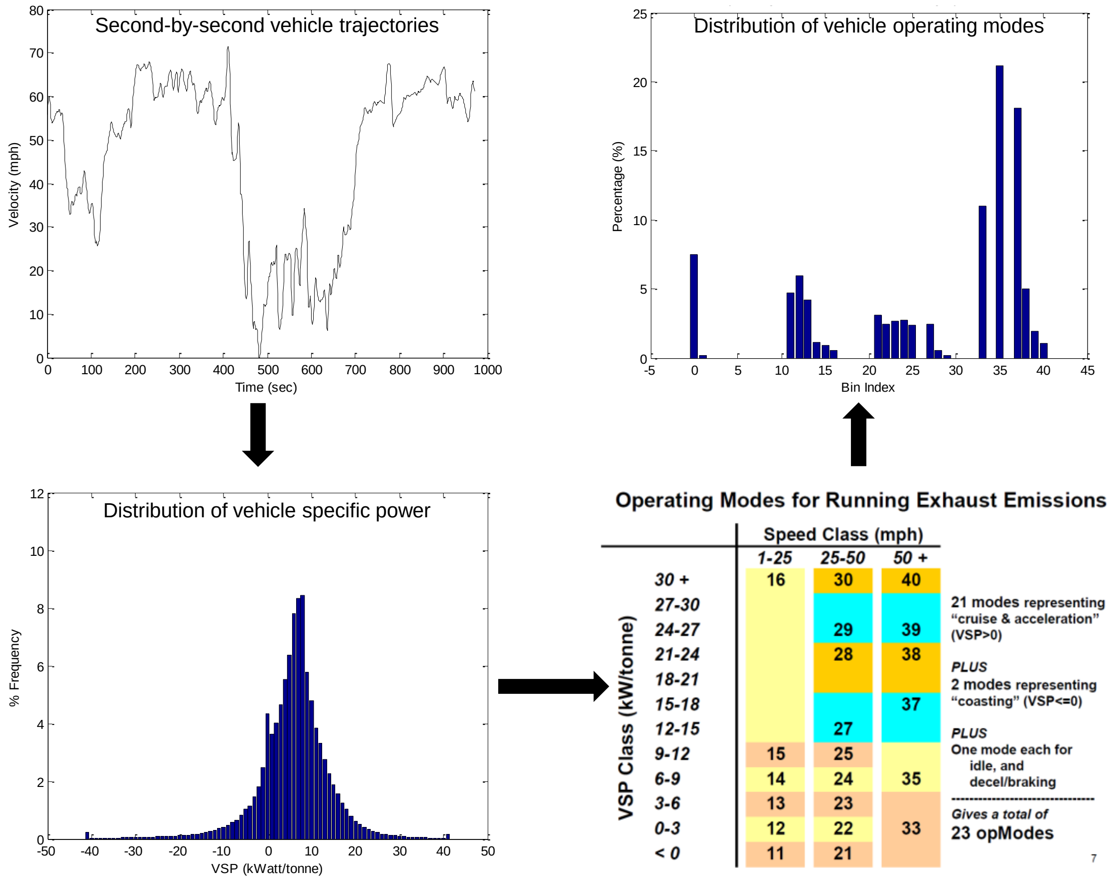


Figure 10: Procedure for Creating Vehicle OpMode Distribution

The vehicle fleet mix data, along with other available input data, such as fuel type, ambient temperature, and vehicle age distribution, are input into MOVES to generate emission rates by vehicle OpMode for each vehicle type. These emission rates are then applied to the vehicle OpMode distributions to estimate emissions for the scenario simulated. This process was used to estimate emissions for both the baseline scenario and the scenario where the Eco-Lanes applications are implemented. The emission results from both scenarios are compared to determine benefits of the applications.

Analysis Scenarios

Analysis scenarios were designed specifically for each application to test them by varying certain parameters. The parameters were divided into three categories.

Levels of Congestion. This parameter corresponds to different levels of traffic demand. It helps capture the impact of applications in various traffic conditions normally seen on a corridor (i.e., different congestion levels):

- **Traffic Demand.** Traffic demand varies greatly from light traffic to flow at capacity or beyond, depending on networks and applications. For example, when ESH was modeled using the GHFN, the traffic demands range from 600 vehicles per hour (vph) to 6,000 vph with a 600 vph increment. The impact of traffic demand on the performance of applications is very important for analysis.

Penetration Rates. In this study, we mainly focused on the following:

- **OBE Penetration Rate.** The OBE penetration rate is the percentage of vehicles on the roadway that are equipped with CV technology. All applications were modeled with varying OBE penetration rates (i.e., 5, 10, 20, 40, 60, 80, and 100 percent). These scenarios help capture the impact of data transmitted from the CVs.

Application-Specific Parameters. These parameters are specific to individual applications. For the Eco-CACC, scenarios with different triggering distances were modeled:

- **Eco-CACC Triggering Distance.** For the Eco-CACC application, the triggering distance is the inter-vehicle clearance threshold where the platoon can be formed. Values of 20, 30, and 40 meters were simulated.
- **Eco-CACC Intra-platoon Clearance.** For the Eco-CACC application, the intra-platoon clearance represents the physical distance between two consecutive vehicles within the same platoon. The distance is measured between the front bumper of one vehicle to the rear bumper of the next vehicle ahead in the platoon. Values of 5 and 15 meters were simulated.

Table 3: Summary of Modeled Scenarios for Each Eco-Lanes Application summarizes all the modeled scenarios (with respect to the parameter set) for each application (i.e., ESH, Eco-CACC, and the combined model).

Table 3: Summary of Modeled Scenarios for Each Eco-Lanes Application

Application	Network	Generic Parameter: Traffic Demand	Generic Parameter: OBE Penetration Rate	Application-Specific Parameter: Triggering Distance	Application-Specific Parameter: Intra-platoon Clearance
ESH	**GHFN**	X	X	N/A	N/A
	SR-91 E	X	X	N/A	N/A
Eco-CACC	**GHFN**	X	X	X	X
	IHFN	X	-	-	-
	SR-91 E	X	-	-	X
Combined	**SR-91 E**	X	-	-	-

Performance Measures

The performance measures that were used for the evaluation of the Eco-Lanes applications are presented here. Performance measures can be broadly classified into environmental and mobility measures. Although generating environmental measures is the primary scope of analysis, mobility-related measures, such as average travel time, are used to determine the potential mobility impacts of the Eco-Lanes applications.

Environmental measures considered in the analysis include:

- Fuel consumption
- Emissions:
  - CO_2
  - PM-10
  - PM-2.5
  - NOx
  - Volatile organic compounds
  - HC
  - CO

Mobility measures considered in the analysis include the average travel time for all vehicles in the network.

Microsimulation outputs are used to compute most of the performance measures using the MOVES plugin. The mobility measures are used only to examine whether the performance has been affected adversely. All the applications are evaluated based on benefits achieved in terms of the fuel consumption and emissions.

Chapter 4. ESH Application

This chapter summarizes the application and results of modeling the ESH application for two freeway traffic networks (i.e., GHFN and SR-91 E, as Chapter 3 shows) using the Paramics (version 6.9.3) microscopic traffic simulation software and MOVES 2010b. Sensitivity analyses were performed on the following parameters to evaluate the environmental and mobility benefits that result from the introduction of this application:

- Traffic volume
- Penetration rate of Eco-CACC technology

A description of the ESH application in general (including the application hypothesis) as well as a detailed explanation of the ESH algorithm in presented in this section. Next, the modeling approach and scenarios are presented, followed by detailed modeling results from the application analyses. The remainder of this section is dedicated to observations, discussions, and conclusions.

Application Description

With the availability of real-time traffic information and other information (e.g., roadway grade and road weather conditions), speed limits at particular locations and times can be dynamically provided to drivers, allowing them to reduce unnecessary stop-and-go driving while meeting specific driving requirements (e.g., travel time), as Figure 11 shows. For drivers, it is not realistic to make a significant sacrifice to travel time to gain marginal environmental benefits. It also cannot be assumed that the reduction in travel time automatically saves energy. The speed advice can be disseminated through at least two channels: (1) the traffic management center (TMC) provides a speed recommendation using VSL signs to all vehicles to harmonize speed of the entire roadway segment, or (2) each individual vehicle optimizes its speed limit within each roadway segment based on data (i.e., traffic conditions) collected from infrastructure-based sensors and data coming from downstream CVs; the information is provided via in-vehicle display. Please note that in the following modeling efforts, it is assumed that the driver compliance rate is 100 percent and the recommended speed limit can be instantly and exactly followed by each individual equipped vehicle.

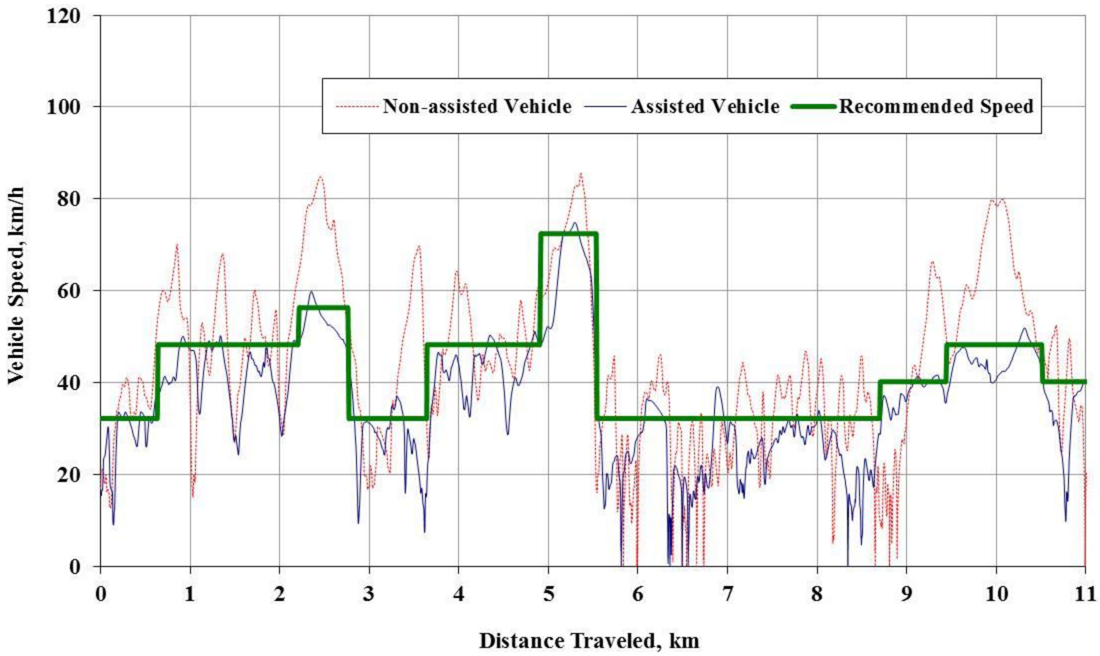


Figure 11: Example Vehicle Trajectories with and without ESH Assistance

The red trajectory represents a vehicle traveling in congestion with significant stop-and-go activity. The blue trajectory represents a vehicle that follows a dynamic speed limit (green line). Both trajectories have similar travel times but different energy consumption.

This ESH application can be implemented in a variety of ways, depending on how the dynamic set speed (i.e., recommended speed) is determined. In this study, the research team developed the set speed determination algorithm based on the average speed of a downstream link or segment, which can be directly measured and estimated using CV technology. For link *i*, within the *k*-th time interval $k \cdot \Delta T$, the average link speed is:

$$\bar{V}_i(k \cdot \Delta T) = \begin{cases} V^{ff}, & no\ vehicle\ within\ k \cdot \Delta T\ along\ link\ i \\ \frac{Vehicle\ miles\ traveled\ within\ k \cdot \Delta T\ along\ link\ i}{Vehicle\ hours\ spent\ within\ k \cdot \Delta T\ along\ link\ i}, & otherwise \end{cases} \quad (1)$$

where V^{ff} is the free-flow speed or speed limit of that roadway segment. With the measured average speed along the downstream link *i*, a simple speed control law can be developed to determine the recommended speed for vehicle *j*, within the (*k*+1)-th time interval $(k+1) \cdot \Delta T$, using a linear regression model:

$$V_j^{ctrl}((k+1) \cdot \Delta T) = a \cdot \bar{V}_i(k \cdot \Delta T) + b\ , \quad (2)$$

where a and b are two controlled parameters, representing the slope and intercept of the linear function, respectively. Based on the simulation data collected from previous research, a candidate set of parameters a and b can be determined by the least square fitting, as Figure 12 shows. Each data point represents the best controlled case (i.e., control speed along y-axis) in terms of energy savings when the average link speed was measured at the value along the x-axis. As explained in the following content, it turns out that such control strategy is sensitive to the network model and traffic condition.

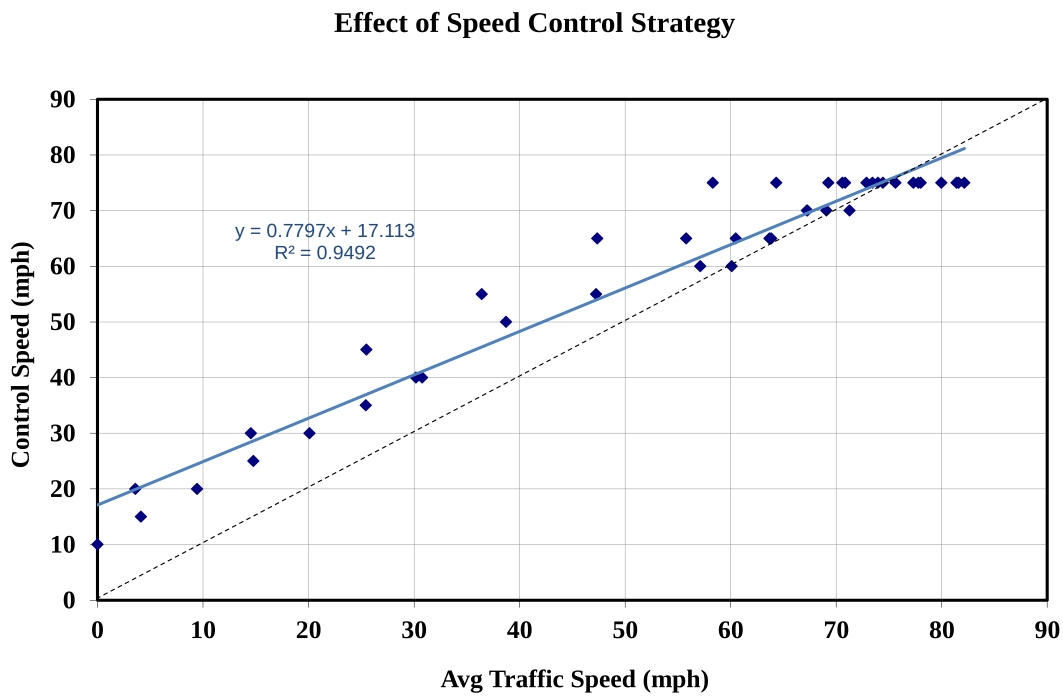


Figure 12: A Candidate Strategy for the Control Speed Determination

Further investigation of the proposed linear regression-based control algorithm may reveal that if $0 < a < 1$, then the control speed of the upstream links (or segments) will converge to the equilibrium speed at $b/(1-a)$ (i.e., the intersection between the linear function $y = ax + b$ and $y = x$), as Figure 13 shows. In addition, the convergence rate largely depends on the slope of linear function. By carefully tuning the equilibrium speed as well as the slope parameter, savings in network-wide energy consumption can be expected with minimum penalty on mobility.

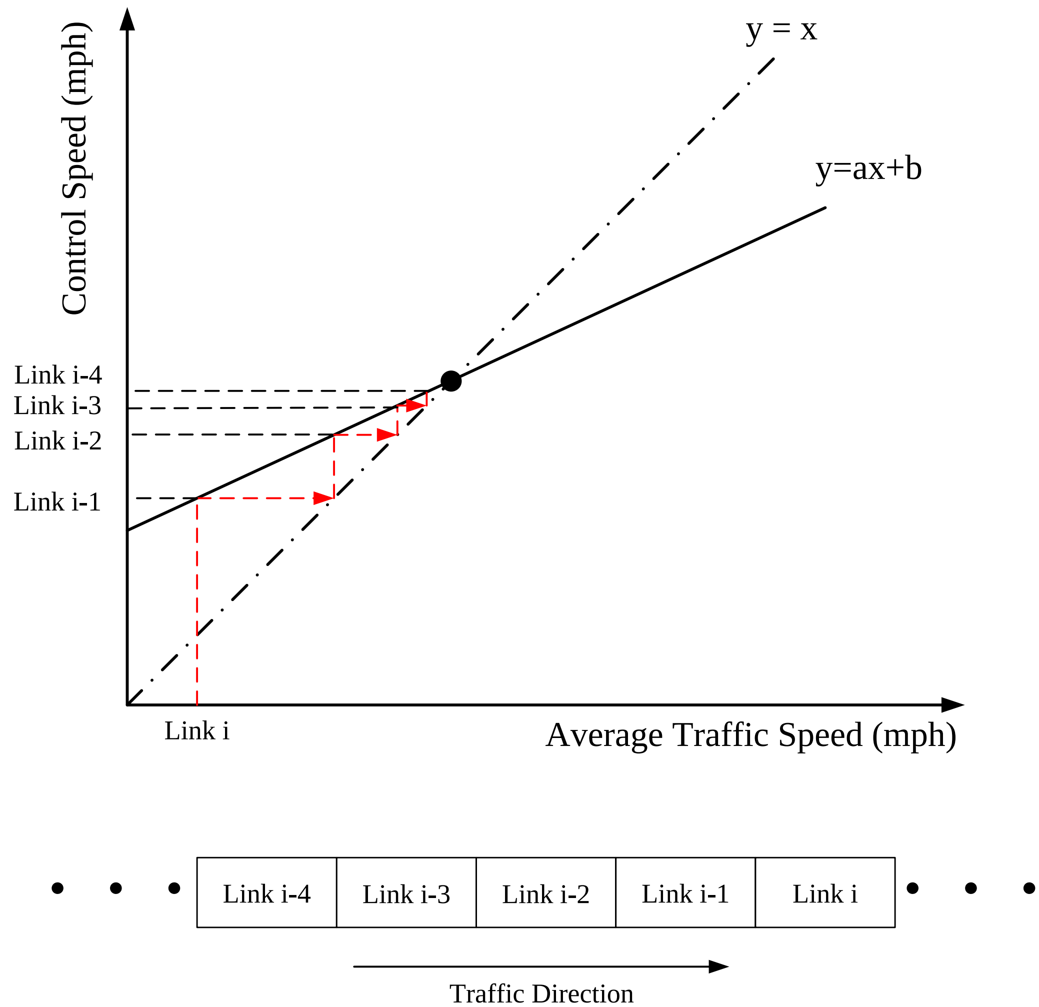


Figure 13: Illustration of the Effects of Proposed Speed Control Algorithm in the ESH Application

Hypothesis

The following hypotheses are made for the ESH application:

- Dissemination of downstream traffic information (e.g., congestion) along the upstream links/segments may smooth out the shockwave propagation and encourage less aggressive deceleration maneuvers. Such smoothing effects will result in a reduction of energy consumption and pollutant emissions by as much as 5 percent (in this study) with 100-percent penetration rate of OBE (and 100-percent compliance rate as well). System parameters have been finely tuned to achieve minimum impacts on mobility at the same time, across multiple congestion levels.
- Speed variations across different lanes may be significantly removed because of the speed regulating effect of the ESH application. This effect may further discourage the occurrence of (discretionary) lane change maneuvers. However, the impacts of

mandatory lane change maneuvers (e.g., because of lane-drop or leaving the mainline) may be deteriorated in the simulation scenario where the surrounding traffic speed is homogeneous.

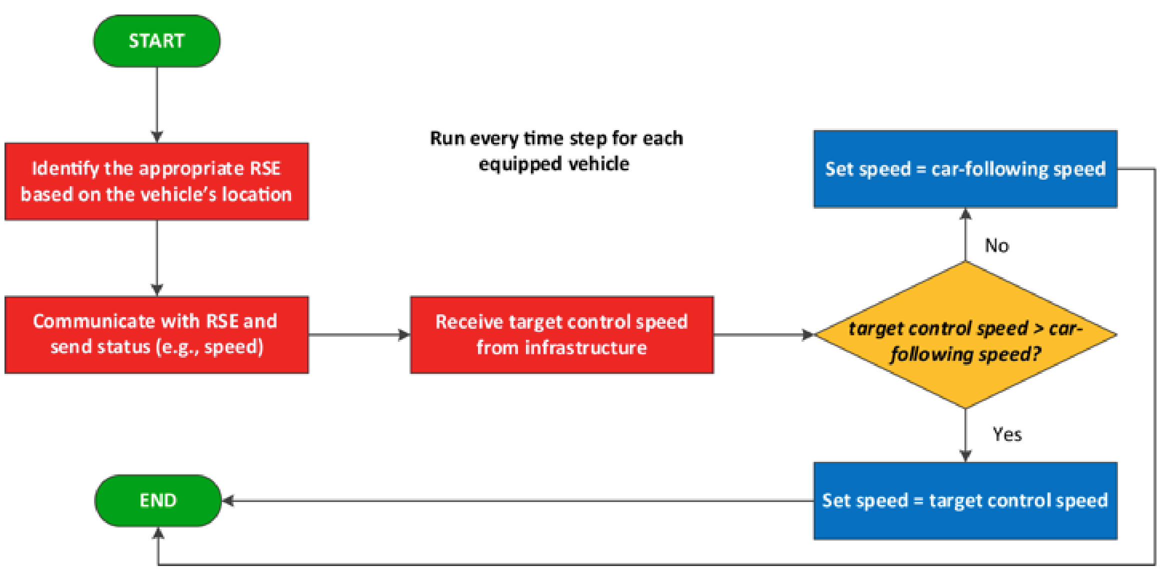
- The benefits in energy savings are expected to decrease under partial penetration rate of CV technology. But the mobility impact does not need to follow a monotonic trend across the whole spectrum of penetration rate.

Algorithm

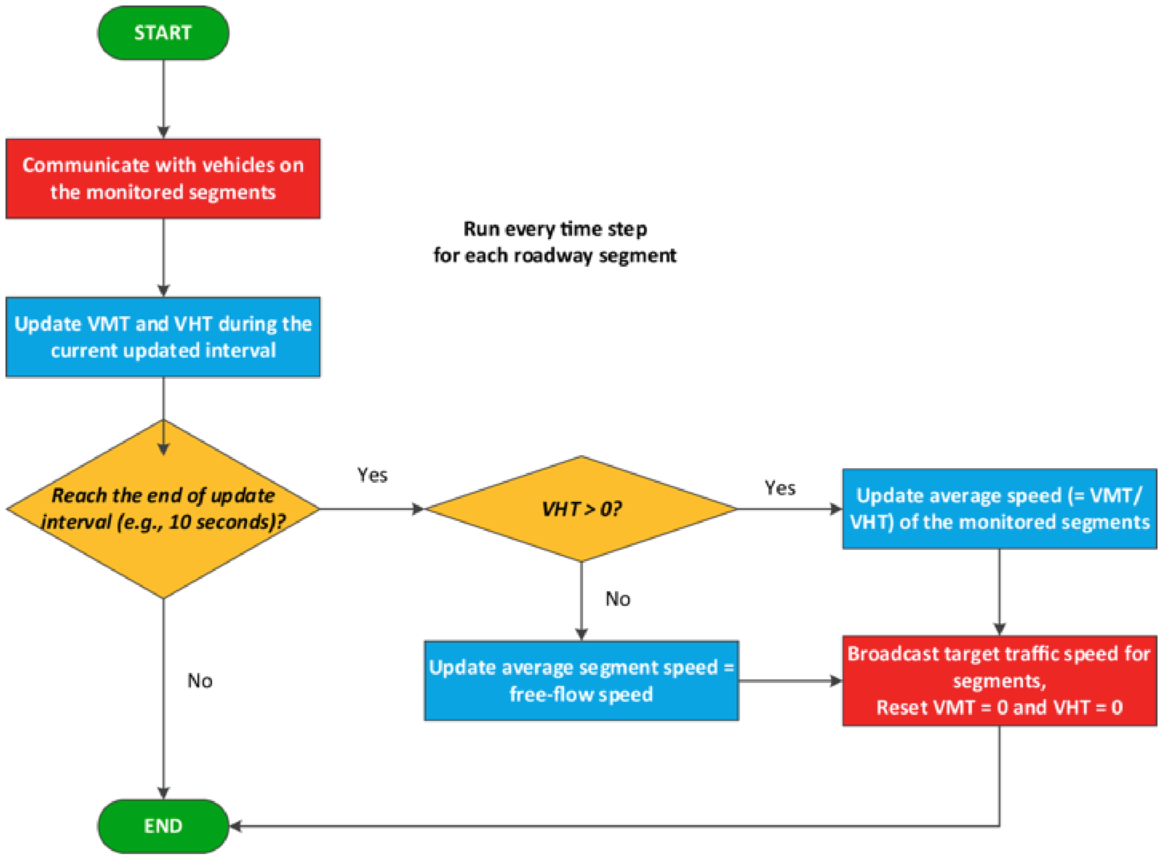
To test the ESH application's impact on the vehicles as part of the Eco-Lanes Operational Scenarios, an API was coded in Paramics to implement the ESH algorithm.

Figure 14 presents the flowchart of the application module. At each time step, the equipped vehicle can use its location to identify the associated RSE of the link or segment along which it is travelling and the one of the exact downstream link or segment. The subject vehicle can communicate with the downstream RSE by receiving any speed recommendation obtained from the proposed ESH algorithm. Based on the car-following constraint, the vehicle can determine its set speed for the next time step. At the same time, it sends its real-time information (e.g., instantaneous speed) to the RSE of current link, such that the RSE can calculate the link average speed.

At each time step, the RSE communicates with equipped vehicles along the upstream link or segment by broadcasting the recommended speed limit. In the meantime, it receives the information from equipped vehicles traveling on the same link and keeps updating the link average speed at a user-defined frequency that may vary with scenarios in the following modeling efforts. The segment length was another user-defined system parameter in the simulation and was chosen as 500 meters in this study. If the link average speed is higher than some threshold (i.e., the link is not congested at all), there is no need to trigger the application for the upstream links.



(a) For individual equipped vehicle



(b) For each RSE

Figure 14: Flowchart of ESH Module

Modeling Approach and Scenarios

As mentioned, the performance of the proposed ESH algorithm is sensitive to the network model as well as traffic condition. Significant effort was applied to fine-tuning the system parameters to achieve desirable energy savings without too much penalty on mobility. There is no single set of parameters that can satisfactorily work for all the networks (i.e., GHFN and SR-91 E) and simulation scenarios tested in this report.
More specifically, the system parameters to be fine-tuned in this study include the following:

- **Equilibrium Speed**. As Figure 13 illustrates, this term largely depends on the value of regression function parameters, a and b. It represents the speed to which the control speeds of upstream links (or segments) will converge under steady traffic demands.
- **Slope of Regression Line**. As Figure 13 illustrates, this term is responsible for the convergence rate at which the control speeds of upstream links (or segments) will approach the equilibrium speed.
- **Information Updating Frequency**. This parameter controls the length of time interval between two consecutive updates of link average speed estimation.

- **Application Triggering Threshold**. This quantity is in charge of activation and deactivation of the ESH application along the upstream links/segments. In other words, if the current link average speed is higher than the triggering threshold, the application will be deactivated. Otherwise, the upstream traffic speed will be controlled by the application.
- **Link/Segment Length**. This term determines the spatial span where the application can cause significant effects. In this study, the segment length was chosen as 500 meters.

As stated in Chapter 3, the ESH application was tested on two networks (i.e., GHFN and SR-91 E). Regarding the sensitivity analysis, the application effectiveness was evaluated for a variety of congestion levels as well as OBE penetration rates. The following section will present the simulation results in detail.

Results

Network 1: Hypothetical Freeway Segment with Lane-Drop

For the hypothetical freeway segment with the lane-drop area, two sensitivity analyses were conducted:

1. Traffic volume, which varies from 600 vph to 6,000 vph with a constant O-D profile and increment of 600 vehicles.
2. Penetration rate of vehicles participating in the ESH application, which varies from 5 percent to 100 percent. More specifically, the levels include 5, 10, 20, 40, 60, 80, and 100 percent.

The simulation time was 1 hour, with additional time to allow all vehicles to exit the network. A single vehicle type was used during the simulations. In addition, to avoid significant penalty on mobility when the traffic condition is free-flowing, the application mainly took effect along the upstream sections of congestion regions where the average speed was below a user-defined threshold (e.g., 45 mph).

Traffic Volume Sensitivity Analysis

For the traffic volume sensitivity analysis, comparison between 0-percent penetration rate (i.e., “baseline”) and 100-percent penetration rate were conducted over a variety of traffic volumes: 600; 1,200; 1,800; 2,400; 3,000; 3,600; 4,200; 4,800; 5,400; and 6,000 vph. Figure 14 presents the relative changes in average energy consumption and travel time under different traffic demands after the application of ESH technology. Table 4 further details the reduction in pollutant emissions as a result of the implementation of the ESH application.

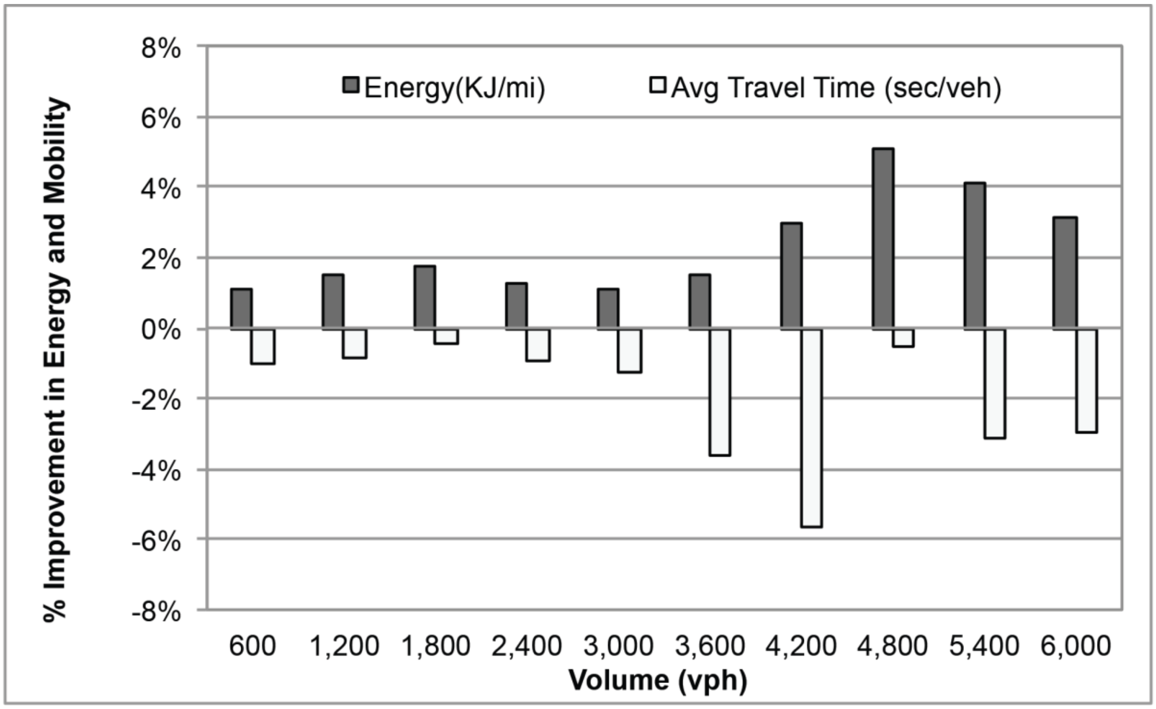


Figure 15: Relative Changes in Average Travel Time and Energy Consumption versus Traffic Volume When Applying ESH Technology (GHFN)

Table 4: Percentage of Improvement of ESH Over Baseline, Traffic Volume Sensitivity Analysis Results (GHFN)

Volume (vph)	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM-2.5 (g/mi)	Avg_TT (s/veh)
600	1.1%	1.1%	10.5%	4.1%	1.9%	7.2%	-1.0%
1,200	1.5%	1.5%	12.7%	5.2%	2.4%	8.8%	-0.8%
1,800	1.8%	1.8%	12.8%	5.6%	2.7%	9.6%	-0.5%
2,400	1.3%	1.3%	9.4%	4.0%	2.1%	6.6%	-1.0%
3,000	1.1%	1.1%	7.6%	3.1%	2.0%	6.6%	-1.3%
3,600	1.5%	1.5%	6.8%	2.1%	3.3%	5.6%	-3.6%
4,200	3.0%	3.0%	9.0%	3.0%	8.3%	12.6%	-5.6%
4,800	5.0%	5.0%	9.9%	5.5%	10.2%	11.9%	-0.5%
5,400	4.1%	4.1%	9.4%	4.0%	11.7%	14.1%	-3.2%
6,000	3.2%	3.2%	9.0%	2.5%	12.9%	13.7%	-3.0%

The traffic volume sensitivity analysis, which Figure 6 and Table 4 shows, indicates that the ESH provides the most significant benefits in terms of energy savings as well as pollutant emissions reduction when the traffic is heavily congested (between 4,200 vph and 6,000 vph). In particular, because the parameters were calibrated for the scenario where the traffic volume is 4,800 vph and penetration rate is 100 percent, the most profound benefits can be observed at this congestion level. At the same time, the mobility (average travel time, in this study) may be changed on the order of 5 percent. When the traffic volume is low, minimal impacts of the ESH application can be expected because of the little disturbance or variation in speed distribution at free-flow traffic state.

ESH Penetration Rate Sensitivity Analysis

For a vehicle to participate in the ESH application, it is assumed that it has CV technology capable of communicating and receiving information from infrastructure. Please note that the ESH concept may be also implemented (without accessing the very detailed real-time traffic information) by using conventional ITS technology. Simulating the increasing CV OBE technology rates helps to understand how the application would operate over the years as the technology becomes more prevalent along the roadways. A total of seven zero-penetration rates of ESH technology were simulated at two selected ranges of traffic volumes (i.e., 2,400 vph and 4,800 vph), representing lightly congested and heavily congested traffic conditions, respectively. The penetration rates tested were 5, 10, 20, 40, 60, 80, and 100 percent. Figure 16 and Figure 17 illustrate the relative changes in average energy consumption and travel time over a variety of penetration rates when the traffic volumes are 2,400 vph and 4,800 vph, respectively.

Table 5 and Figure 16 show more details in relative savings of other criteria pollutant emissions. Please note that very small negative energy impacts (less than 0.3 percent) may result from random noise in the simulation.

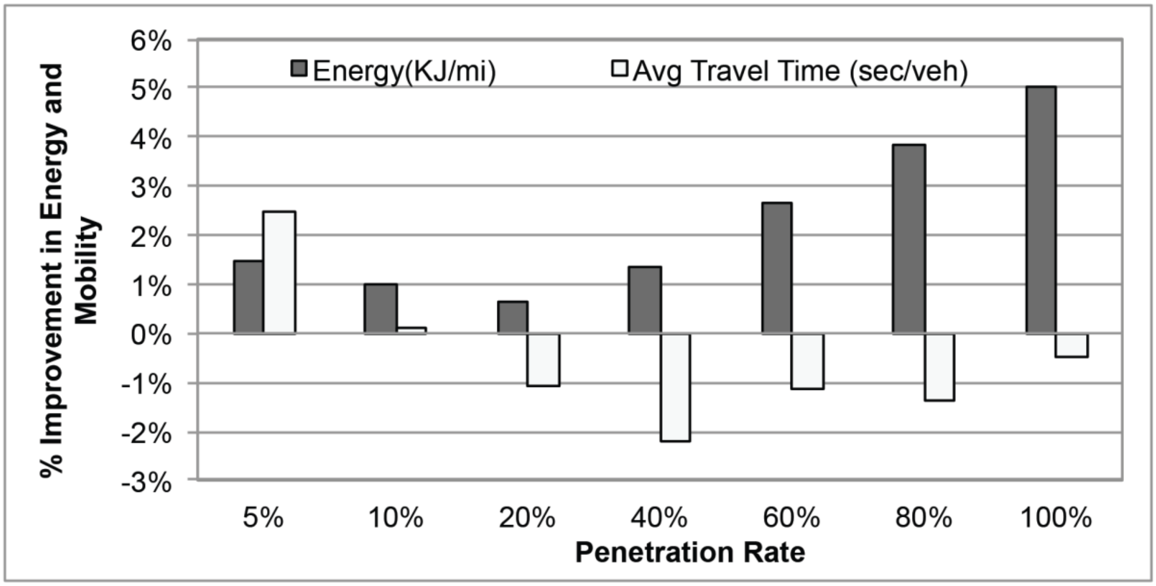


Figure 16: Average Travel Time and Energy Percentage Savings versus Penetration Rate When Traffic Volume Is 2,400 vph (GHFN)

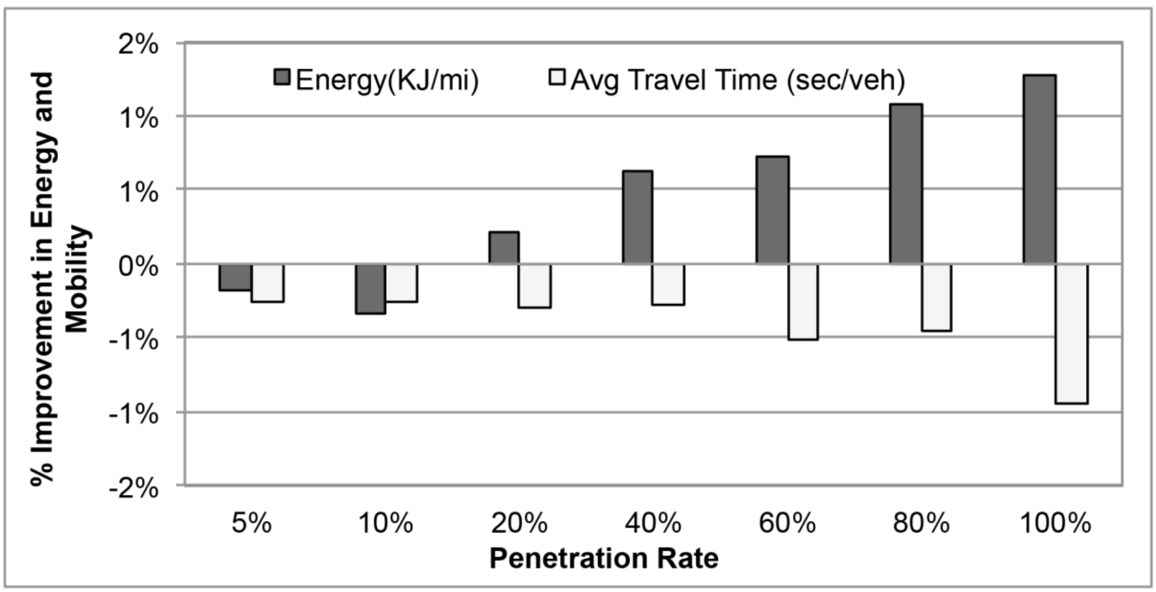


Figure 17: Average Travel Time and Energy Percentage Savings versus Penetration Rate When Traffic Volume Is 4,800 vph (GHFN)

Table 5: Percentage of Improvement of ESH Over Baseline, Penetration Rate Sensitivity Analysis Results When Traffic Volume Is 2,400 vph (GHFN)

Penetration Rate	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	Avg_TT (s/veh)
5%	-0.2%	-0.2%	-0.7%	-0.5%	-0.2%	-0.6%	-0.2%
10%	-0.3%	-0.3%	-1.7%	-0.9%	-0.4%	-2.1%	-0.3%
20%	0.2%	0.2%	1.1%	0.4%	0.4%	0.5%	-0.3%
40%	0.6%	0.6%	3.8%	1.7%	0.9%	2.7%	-0.3%
60%	0.7%	0.7%	5.9%	2.5%	1.2%	4.8%	-0.5%
80%	1.1%	1.1%	8.6%	3.8%	1.7%	6.5%	-0.5%
100%	1.3%	1.3%	9.4%	4.0%	2.1%	6.6%	-1.0%

Table 6: Percentage Improvement of ESH Over Baseline, Penetration Rate Sensitivity Analysis Results When Traffic Volume Is 4,800 vph (GHFN)

Penetration Rate	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	Avg_TT (s/veh)
5%	1.5%	1.5%	1.3%	1.6%	0.9%	2.0%	2.5%
10%	1.0%	1.0%	1.4%	0.6%	1.4%	3.1%	0.1%
20%	0.6%	0.6%	1.5%	0.2%	1.8%	3.2%	-1.1%
40%	1.3%	1.3%	3.8%	1.0%	4.1%	6.3%	-2.2%
60%	2.6%	2.6%	5.8%	2.6%	5.8%	8.0%	-1.1%
80%	3.9%	3.9%	7.9%	3.9%	8.4%	10.6%	-1.4%
100%	5.0%	5.0%	9.9%	5.5%	10.2%	11.9%	-0.5%

The sensitivity analyses on the penetration rate of ESH technology, which Figure 16 and Figure 17 as well as

Table 5 and

Penetration Rate	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	Avg_TT (s/veh)
5%	-0.2%	-0.2%	-0.7%	-0.5%	-0.2%	-0.6%	-0.2%
10%	-0.3%	-0.3%	-1.7%	-0.9%	-0.4%	-2.1%	-0.3%
20%	0.2%	0.2%	1.1%	0.4%	0.4%	0.5%	-0.3%
40%	0.6%	0.6%	3.8%	1.7%	0.9%	2.7%	-0.3%
60%	0.7%	0.7%	5.9%	2.5%	1.2%	4.8%	-0.5%
80%	1.1%	1.1%	8.6%	3.8%	1.7%	6.5%	-0.5%
100%	1.3%	1.3%	9.4%	4.0%	2.1%	6.6%	-1.0%

Table 6, indicate that the higher the penetration rate, the greater the benefits in energy would be. However, when the penetration rate is lower than 10 percent, the trend is less consistent and reliable. However, the benefits in mobility are more variable across different penetration rates (especially in heavily congested condition) compared with the benefits in energy.

A more indepth analysis reveals that when the traffic volume is 2,400 vph, the traffic condition along the upstream of the lane-drop area is mostly free-flowing, except for the occasional shockwave that results from merging maneuvers of vehicles from the bottom lane. The ESH application has minimal impacts on both energy and mobility. When the traffic volume is 4,800 vph (heavily congested), the shockwave smoothing effect of the ESH application can be observed. However, the choice of system parameters can significantly affect its performance. As mentioned, the system parameters were tuned to favor the case where the traffic volume is 4,800 vph.

Network 2: SR-91 E Freeway

For the SR-91 E freeway network, a comparative study was conducted over the “calibrated” traffic volume. The total traffic volume (“calibrated”) entering the network was around 25,000 vehicles. The simulation time was 2 hours, with separate demand profiles used for each hour, which helped to simulate the real-world changing traffic conditions to better test the resiliency of the application. For consistency with the Eco-CACC application evaluation, a single vehicle type was used during the simulations. Note that the ESH technology was applied across all the lanes, including the single dedicated lane (HOV lane) and general purpose lanes, in the following simulation study.

Traffic Volume Sensitivity Analysis

To understand how the traffic volume impacts the effectiveness of the ESH for a real-world corridor, scenarios with four other mainline traffic volumes (i.e., 28,000, 31,000, 34,000, and 37,000 vehicles, respectively) were simulated. Figure 8 presents the relative changes in average energy consumption and travel time under different traffic demands when applying the proposed ESH technology. Table 7 further shows the relative improvement in other criteria pollutant emissions because of the introduction of the application over different traffic volumes.

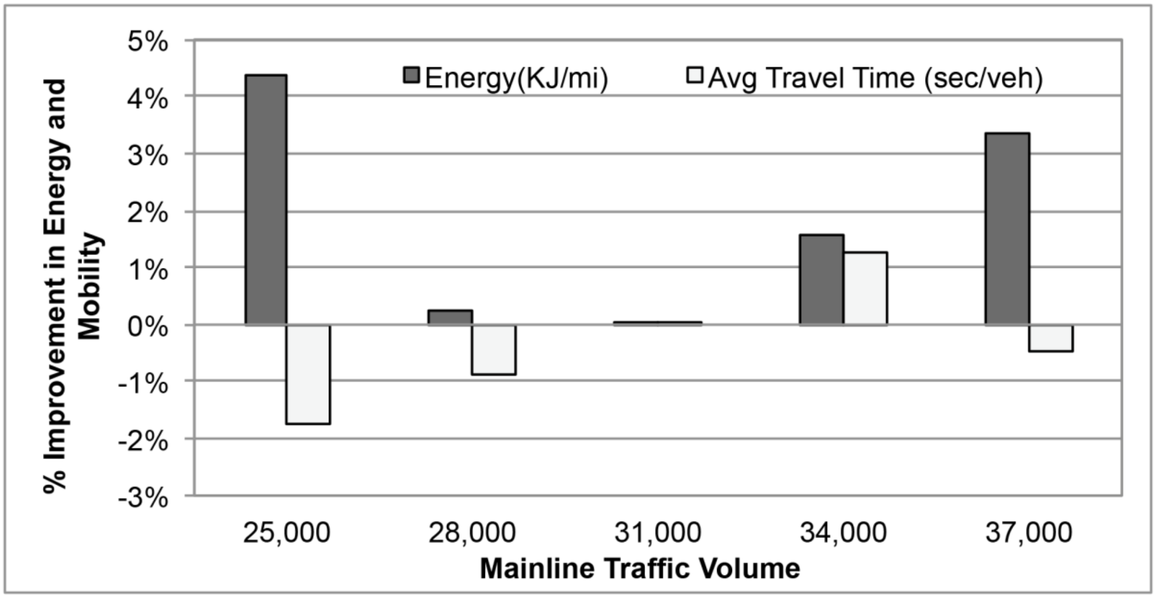


Figure 18: Relative Changes in Average Travel Time and Energy Consumption versus Traffic Volume When Applying ESH Technology (SR-91 E)

As Figure 18 and Table 7 show, the application of ESH to the SR-91 E freeway may lead to energy savings of as much as 4.4 percent and average travel time reduction in the range between -1.7 percent and 1.3 percent, under different traffic volumes. The system parameters were tuned for different traffic volumes (i.e., 25,000 vehicles and 34,000 vehicles) of the network under the assumption of a 100-percent OBE penetration rate. Compared with the results from the hypothetical freeway network, the trend in energy savings and mobility changes become much less consistent. One of the potential explanations is the entangled impacts of many other factors (such as the existence of on-ramps/off-ramps) in the complex real-world model of SR-91 E.

Table 7: Percentage Improvement of ESH Over Baseline, Traffic Volume Sensitivity Analysis Results (SR-91 E)

Volume	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	Avg_TT (s/veh)
25000	4.36%	4.36%	15.21%	7.20%	7.10%	9.51%	-1.73%
28000	1.30%	1.30%	6.40%	0.29%	4.50%	-1.86%	-8.05%
31000	-2.03%	-2.03%	1.20%	-7.78%	4.47%	-10.49%	-21.14%
34000	-1.52%	-1.52%	15.87%	-5.14%	12.95%	19.70%	-26.95%
37000	2.16%	2.16%	20.70%	0.58%	17.03%	29.68%	-10.57%

ESH Penetration Rate Sensitivity Analysis

In addition to the sensitivity analysis with increasing traffic volume along the mainline, simulation tests for different levels of CV OBE penetration rates under the “calibrated” volume (i.e., 25,000 vehicles) were also conducted. Figure 19 and

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
3000	3931.2886	282.5413	2.4089	0.1117	0.6645	0.00924	364.8120
3600	3961.6475	284.7232	2.4384	0.1127	0.6702	0.009306	367.6145
4200	3947.5324	283.7087	2.4337	0.1129	0.6644	0.009421	370.9136
4800	3938.3956	283.0520	2.4466	0.1132	0.6613	0.009452	372.7430
5400	3922.1737	281.8861	2.4518	0.1135	0.6557	0.009438	376.2061
6000	3939.0579	283.0995	2.5621	0.1157	0.6582	0.009903	395.0078

Table 12: Percent Improvement of Eco-CACC Over Baseline, Traffic Volume Sensitivity Analysis Results present the benefits from the ESH application over various technology penetration rates (from 5 percent to 100 percent) in terms of energy consumption, pollutant emissions, and mobility. The system parameters were fine-tuned for 25,000 vehicles (with 100-percent technology penetration rate).

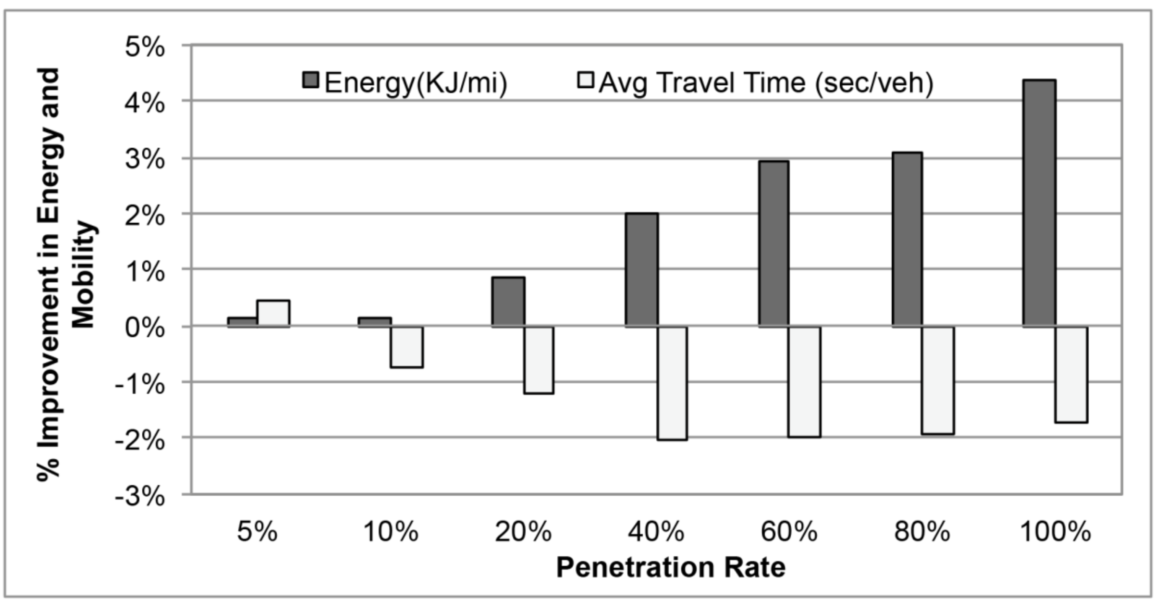


Figure 19: Average Travel Time and Energy Percentage Savings versus Penetration Rate When Total Traffic Volume Is Around 25,000 Vehicles (SR-91 E)

Table 8: Percent Improvement of ESH Over Baseline, Penetration Rate Sensitivity Analysis Results When "Calibrated" Volume (SR-91 E)

Penetration Rate	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	Avg_TT (s/veh)
5%	0.15%	0.15%	0.01%	-0.06%	0.34%	-0.31%	0.46%
10%	0.11%	0.11%	-0.56%	-0.60%	0.51%	-1.38%	-0.72%
20%	0.88%	0.88%	1.67%	0.54%	1.76%	0.34%	-1.22%
40%	1.97%	1.97%	5.21%	2.21%	3.54%	2.65%	-2.05%
60%	2.94%	2.94%	8.40%	3.71%	5.13%	4.29%	-1.99%
80%	3.07%	3.07%	10.98%	4.87%	5.32%	6.23%	-1.94%
100%	4.36%	4.36%	15.21%	7.20%	7.10%	9.51%	-1.73%

As can be observed from Figure 19 and Table 8, savings in energy consumption increase (from 0.1 percent to 4.4 percent) as the growth of technology penetration rate under the "calibrated" traffic volume increases. This is consistent with the results from GHFN. In terms of the mobility, average travel times do not exhibit a monotonic trend over the penetration rate, but the relative changes are all within the range of 2.1 percent.

Findings and Opportunities for Future Research

Observations and Conclusions

Modeling and simulation results of the proposed ESH application indicate that the application is sensitive to the network geometry and traffic conditions. System parameters need to be carefully selected to achieve desirable benefits in energy/emissions without penalizing the mobility. The key system parameters include equilibrium speed, slope of regression line, information updating frequency, application triggering threshold, and link/segment length. The simulation study was conducted under the best set of parameters that were determined by the research team after a detailed calibration process.
More specific observations are summarized as follows:

- Compared with the results from more complex networks, such as SR-91 E, the trend of benefits in terms of energy/emissions reduction due to the application of ESH is more consistent for simple networks (e.g., GHFN). A hypothesis is that there are much more influential factors (such as the existence of multiple weaving sections or bottlenecks) in the complex real-world model, which may suffer from more dimensions of noise. In contrast to the energy savings, the changes in mobility are more variable regardless of networks.
- The application is sensitive to the traffic condition (e.g., congestion level). Based on the parameter settings in this study, it can be observed that the most significant

benefits in terms of energy savings and emissions reduction can be obtained when the traffic is heavily congested (such as 4,800 vph in GHFN and 37,000 vehicles in SR-91 E). When the traffic volume is low, minimal technology impacts can be expected because of the little disturbance or variation in speed distribution at free-flow traffic state. However, by carefully tuning the system parameters, the network model with light traffic can still benefit from the application in terms of energy savings at a certain expense of mobility (e.g., 25,000 vehicles in SR-91 E).

- Sensitivity analyses show that the trend of energy benefits is consistent with respect to the change in technology penetration rate. The higher the penetration rate, the greater the benefits in energy savings would be. However, when the penetration rate is lower than 10 percent, such a trend is less consistent and reliable. However, the benefits in mobility are more variable across different technology penetration rates (especially under heavily congested traffic conditions).

Recommendations

Based on the findings from the modeling efforts of the ESH application, the research team provides the following recommendations for future research:

- There are opportunities to further enhance the ESH algorithm such that it can be more adaptive to different networks and traffic conditions. A significant amount of effort was made to calibrate the algorithm’s parameters to favor specific scenarios. However, such a set of parameters usually fail to work for other situations.
- A more comprehensive decisionmaking module/layer should be developed on the proposed ESH algorithm to determine the switch on/off of the ESH algorithm. In addition, after determining that the application should be engaged, another module should be built to evaluate the temporal and spatial ranges where the application should be applied.

Chapter 5. Eco-CACC Application

This chapter summarizes the application and results of modeling the Eco-CACC application for several freeway traffic networks using the Paramics (version 6.9.3) microscopic traffic simulation software and MOVES 2010b. A series of progressively complex networks were simulated, culminating in simulating Eco-CACC for the SR-91 E freeway in Southern California (see Chapter 3). The SR-91 E freeway was chosen because data on network geometry, traffic demand, and congestion levels were readily available, permitting calibration of the baseline scenario. Sensitivity analyses were performed on the following parameters to evaluate the environmental and mobility benefits that resulted from the introduction of this application:

- Traffic volume
- Penetration rate of Eco-CACC technology
- Triggering distance
- Intra-platoon clearance.

A description of the Eco-CACC application is provided, followed by a detailed presentation of the selected Eco-CACC algorithm. Next, the selected freeway networks are presented, followed by simulation results. The remainder of the section is devoted to observations, discussions, and conclusions.

Application Description

The Eco-CACC application is an extension of ACC that incorporates V2V as well as infrastructure-to-vehicle communication to provide mobility and environmental benefits to platoons of vehicles. Like ACC, Eco-CACC provides longitudinal control of a vehicle but still requires a driver to provide lateral control to the vehicle. Conventional ACC relies on sensors and actuators to detect and regulate the gap between the ego-vehicle (The term “ego-vehicle” will be used in the remainder of the text to denote a particular reference vehicle [the “self”-vehicle] being discussed in contrast to vehicles behind or in front of the current vehicle) and the vehicle directly ahead, whereas Eco-CACC adds communicated information from the vehicle directly ahead, and possibly the platoon leader, to permit shorter following gaps than are possible for ACC. Additional information from the infrastructure on network geometry and real-time traffic conditions further allows the speed of platoon leaders to be regulated to provide optimal environmental benefits for entire platoons.

Hypothesis

Several hypotheses can be made concerning individual vehicle performance, lane performance, and overall network performance for the Eco-CACC application. The following hypotheses are based on 100-percent penetration of Eco-CACC technology, with the presence of a single dedicated lane for platoons, and platoon clearance of 15 meters:

- In general, platoon formation decreases inter-vehicle spacing, which results in an increase in roadway capacity. The increase in roadway capacity will be evident at sufficiently high traffic volumes, providing substantial network benefits in as much as 20-percent reduced travel time and 10-percent reduced energy consumption.
- Individual vehicles will expend a small amount of energy in the initial platoon formation maneuver. At very low traffic volumes, a small penalty of less than 5 percent in energy and emissions may be present relative to a non-platoon baseline. In contrast, at higher traffic volumes, vehicles in platoons may experience energy consumption reductions of as much as 20 percent.
- Furthermore, because of the increase in network capacity, vehicles not participating in platoons will receive moderate indirect benefits of as much as 10-percent energy savings.
- As a result of the increased capacity in the dedicated lane, the non-dedicated lanes will receive an indirect benefit in terms of energy because of vehicles changing lanes into the dedicated lane.

A similar set of hypotheses for the case of platoon clearance at 5 meters may be summarized as further increasing roadway capacity as well as the accompanying mobility, energy, and emissions savings.

Partial CV penetration is expected to decrease the aforementioned savings by a factor roughly equivalent to the penetration rate itself (e.g., the benefits for a 60-percent penetration rate will be approximately 60 percent of a 100-percent penetration rate).

Algorithm

To aid the subsequent Eco-CACC description, we first define several terms used within the context of platooning, as Table 9 shows. The term “ego-vehicle” will be used in the remainder of the text to denote a particular reference vehicle (the “self”-vehicle) being discussed in contrast to vehicles behind or in front of the current vehicle.

Table 9: ITS Eco-CACC Definitions

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

The first half of the bumper pair refers to the bumper of the preceding vehicle and the second half of the bumper pair refers to the bumper of the current vehicle (behind the preceding vehicle).

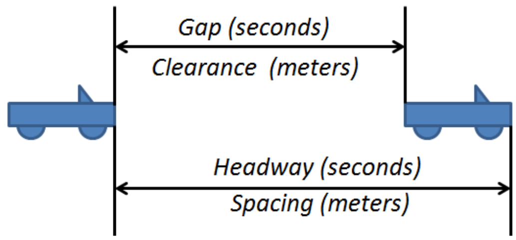


Figure 20: Illustration of Definitions

The core of the Eco-CACC algorithm is the definition of vehicle roles within a state machine, as Figure 20 shows. A state machine is a representation of a system in which each possible behavior, or “state,” is explicitly defined, along with the conditions that trigger transitions between states. The state machine may be viewed as a complete directed graph, in which any state is directly reachable from the current state. A vehicle is defined as leading a platoon (leader), following a platoon leader (follower), or not currently in a platoon (“none”). Unequipped vehicles are considered permanently part of the “none” state. OBE-equipped CVs in the “none” state may transition to being a follower if there is a vehicle ahead that is sufficiently close. Alternatively, an equipped vehicle in the “none” state may become a leader if a vehicle behind the ego-vehicle is within range to trigger platoon formation behavior. A follower may transition to the “none” state by either dropping off the tail of the platoon or by changing lanes. In addition, a follower vehicle may become a leader if the vehicle ahead was a leader and changed lanes. A leader may become a follower if the leader is overtaken by an equipped vehicle. Finally, a leader may transition to the “none” state if they transfer leadership to the vehicle directly behind the ego-vehicle.

The outer loop of conditions relates to maneuvers that occur within the platoon’s lane and are referred to as longitudinal maneuvers. The inner loop of conditions relates to maneuvers that occur in preparation or during vehicle lane changing and are referred to as lateral maneuvers.

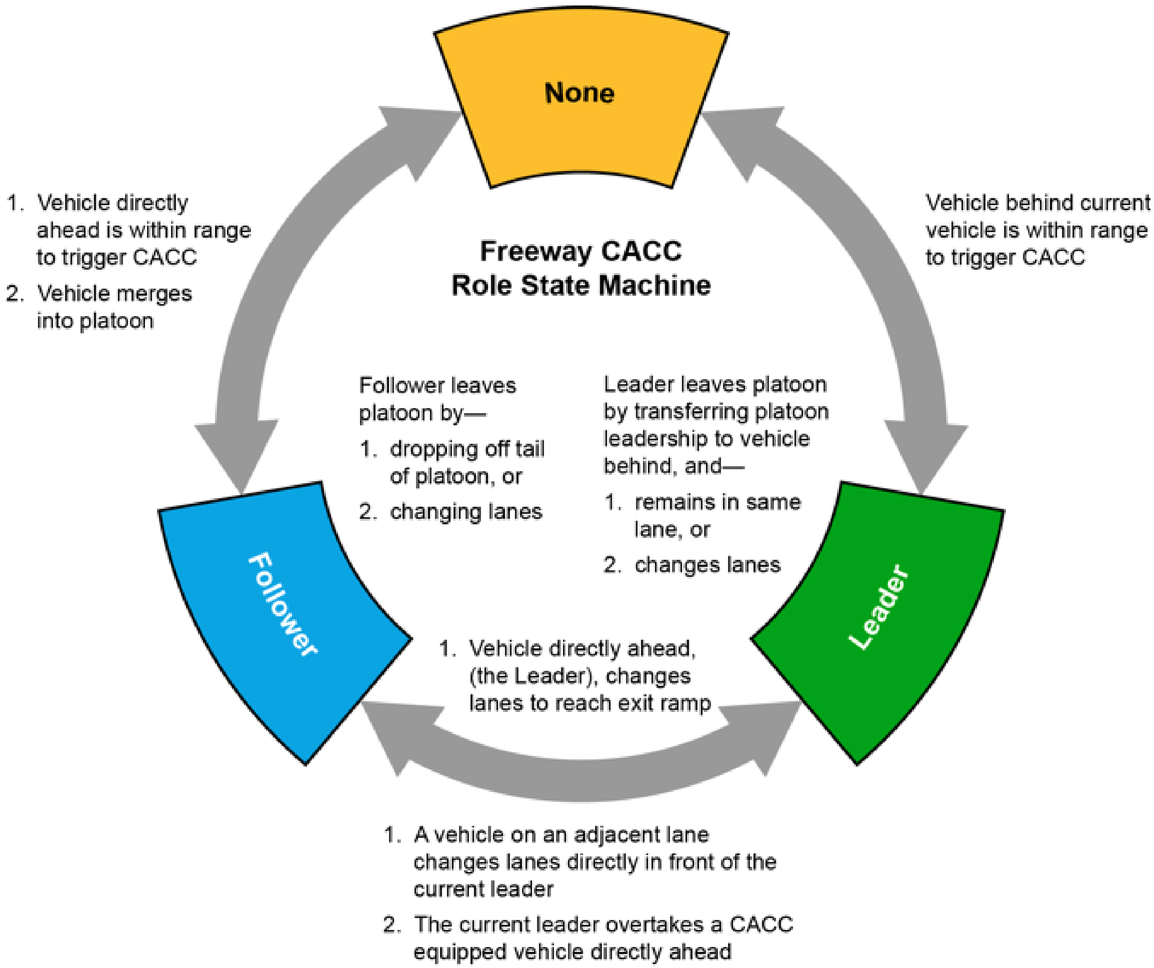


Figure 21: Freeway CACC Role State Machine

Figure 22 shows how the state diagram (in Figure 21) can be developed as an algorithm for the Eco-CACC application for the Eco-Lanes concept. The state flow diagram may be considered a three-stage process. In the first stage, if a vehicle is in a platoon and is approaching a freeway exit, a platoon-splitting protocol is executed. In the second stage, if an equipped vehicle is approaching a lane-drop area with an adjacent platoon in the target lane, a platoon-merging (single vehicle with platoon) protocol is executed. In the final stage, the vehicle state is updated based on proximity to surrounding equipped vehicles. Please note that the first two stages take priority over the third stage and result in changing the state of the ego-vehicle. After conducting a sensitivity analysis, the distance threshold referenced in Figure 22 was set to 40 meters and is hereafter referred to as “triggering distance.”

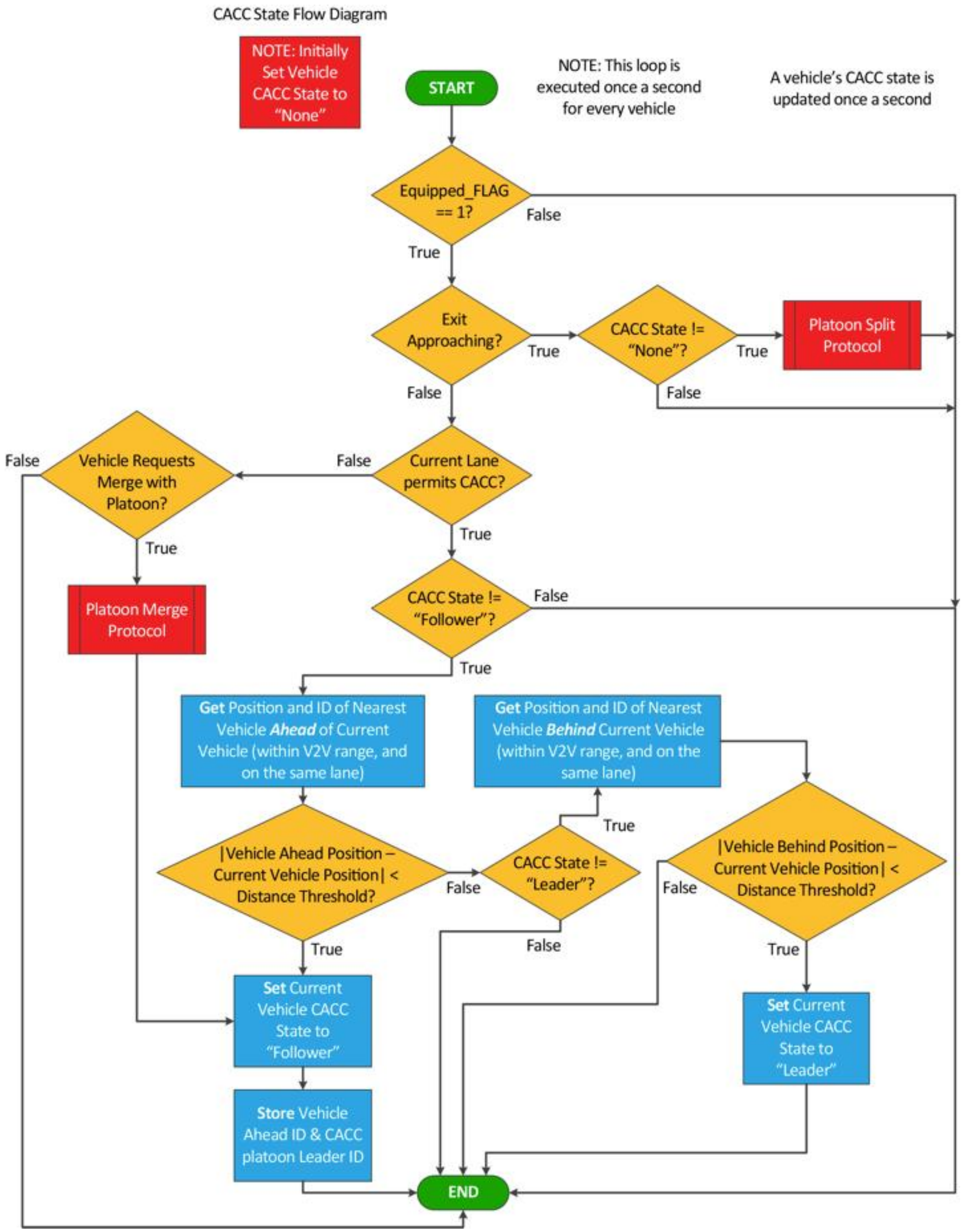


Figure 22: Freeway CACC State Flow Diagram

Vehicles within the leader or “none” states are permitted to be controlled by the simulation software. However, vehicles within the follower state have their own kinematics controlled by a gap controller. Numerous different gap controllers exist and are typically grouped in the general categories of spatial or temporal gap control. Spatial gap controllers seek to control the inter-vehicle distance between the ego-vehicle and the preceding vehicle. Temporal gap controllers seek to control the time between the ego-vehicle and the preceding vehicle. For the purposes of visualization, a spatial regulator was selected. As Figure 23 shows, the selected spatial regulator also incorporates the constraints of maximum acceleration and minimum deceleration. These acceleration constraints are not set by vehicle capabilities but for safety and driver comfort/acceptance during maneuvers. The presented spatial regulator makes use of proportional control to regulate the error term (target clearance) using two parameters, R1 and R2. R1 is inversely related to the spatial gap closing rate, when the ego-vehicle is initially closing the gap. R2 is inversely related to the spatial gap opening rate and is used if the ego-vehicle overshoots the specified target clearance. The greater R1 or R2, the longer the vehicle will take to achieve the specified target clearance. For the simulation results presented in this report, R1 was selected to be 2, and R2 was selected to be 0.5. R2 is deliberately selected as lower than R1 for safety purposes. The remaining parameters were set as follows: Target clearance was set variously as 5 meters or 15 meters. Maximum acceleration and minimum deceleration were set to 3.5 meters and -7.5 meters per second squared, respectively. Several additional controllers are shown in Appendix B for reference.

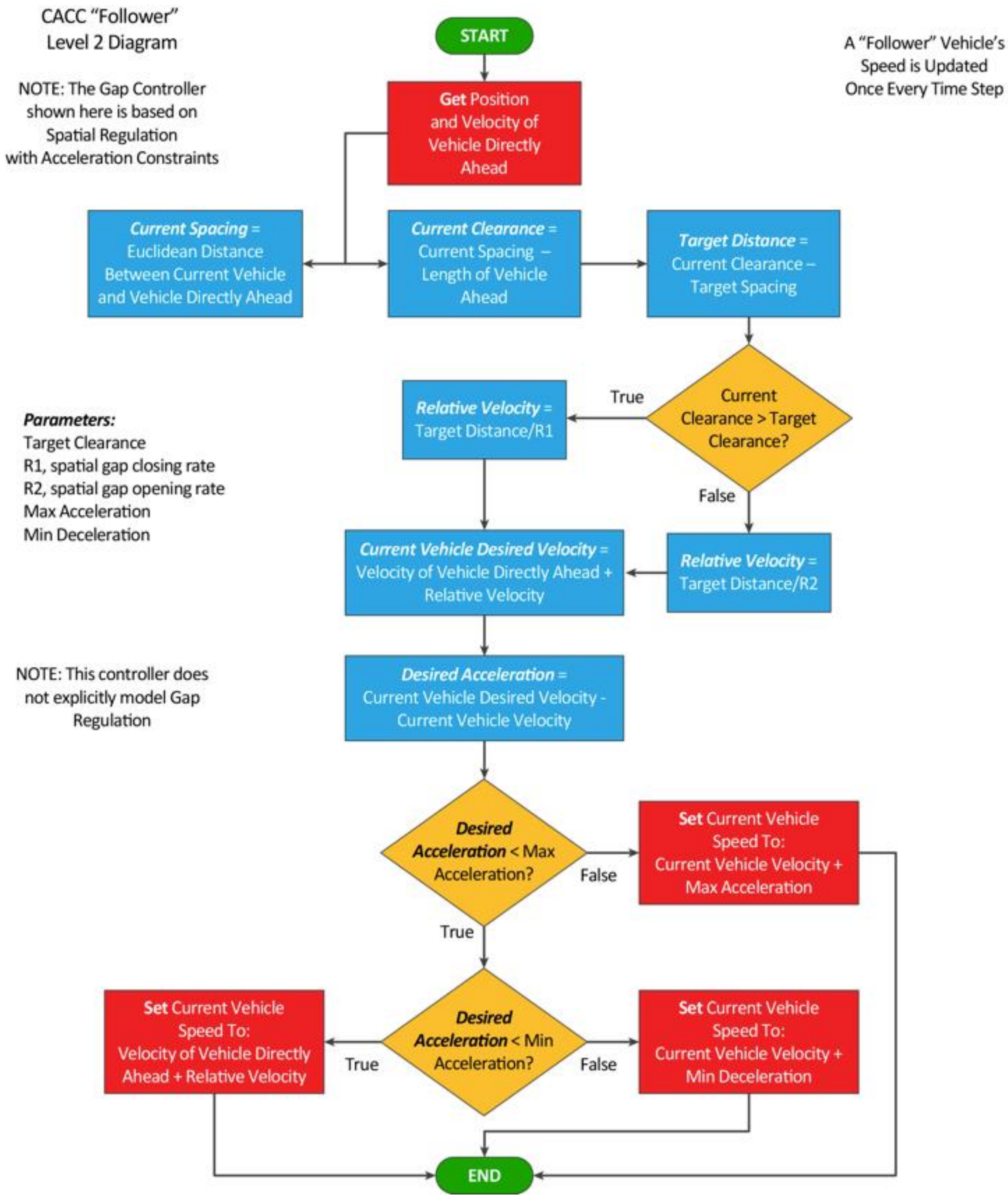


Figure 23: CACC Follower Level-2 Diagram, Spatial Regulator with Acceleration Constraints

Cooperative Maneuver Protocols

Depending on the initial set of assumptions, a variety of maneuvering protocols may be formed. For the purposes of this report, maneuvers are conducted on the individual vehicle level. Rather than having an entire platoon change lanes synchronously, the platoon is first split, and each vehicle changes lanes independently. No restrictions in terms of permitted vehicles are placed on the initial platoon formation (other than the vehicles being equipped for Eco-CACC). As a result, vehicles with different destinations are permitted to participate in the same platoon. The selected heterogeneous route-based platoon formation is in contrast to homogeneous route-based platoon formation, in which only vehicles with the same destination (freeway exit) are permitted to participate in a given platoon. In homogenous route-based platoon formation, platoons may leave the freeway as a platoon. However, for heterogeneous route-based platoon formation, individual vehicles must leave their platoon to reach their desired exit. The developed splitting protocol that Figure 22 shows is based on heterogeneous route-based formation.

As Figure 22 shows, the splitting protocol is executed when a vehicle in a platoon is close to its desired exit. Depending on where a vehicle is located in the platoon, one of three cases is performed. In each case, the splitting maneuver is a two-stage process. The first stage involves a relative longitudinal positioning of one or more vehicles. The second stage involves a lateral maneuver. The relative longitudinal positioning stage is accomplished by using the same controller used for following behavior (see Figure 23) with a modulation of the target clearance parameter. The lateral maneuver of changing lanes is assumed to be executed by a human driver.

If a vehicle is the leader of the platoon, platoon leadership is passed on to the vehicle behind the current leader. Before starting the maneuver, the vehicle behind the current leader must acknowledge the leadership transfer request. Once the request is accepted, the vehicle behind the current leader increases its relative clearance with respect to the current leader by changing its target clearance parameter. As soon as the new target clearance is achieved by the vehicle behind the leader, the leader is free to change lanes and switches off its participation flag. By switching off its participation flag, the vehicle communicates to other vehicles that it does not desire to currently be a part of a platoon. In this case, the ego-vehicle prevents reformation of additional platoons (involving the ego-vehicle) on the way to its exit. The first column of Figure 24 shows the case of a leader leaving its platoon.

The second column of Figure 24 shows the case of a vehicle at the tail of a platoon leaving its platoon. The tail of the platoon essentially drops off the back of the platoon before changing lanes.

The final two columns of Figure 24 show the case of a vehicle between the leader and the tail of a platoon leaving its platoon. The relative longitudinal positioning is applied to the ego-vehicle as well as the vehicle directly behind the ego-vehicle. The rationale behind having both vehicles participate in the first stage of the maneuver is to create a safety gap both in front of and behind the ego-vehicle before control is transferred back to the human driver. The additional clearance not only contributes to enhanced safety but also helps the human driver to make the desired lane change.

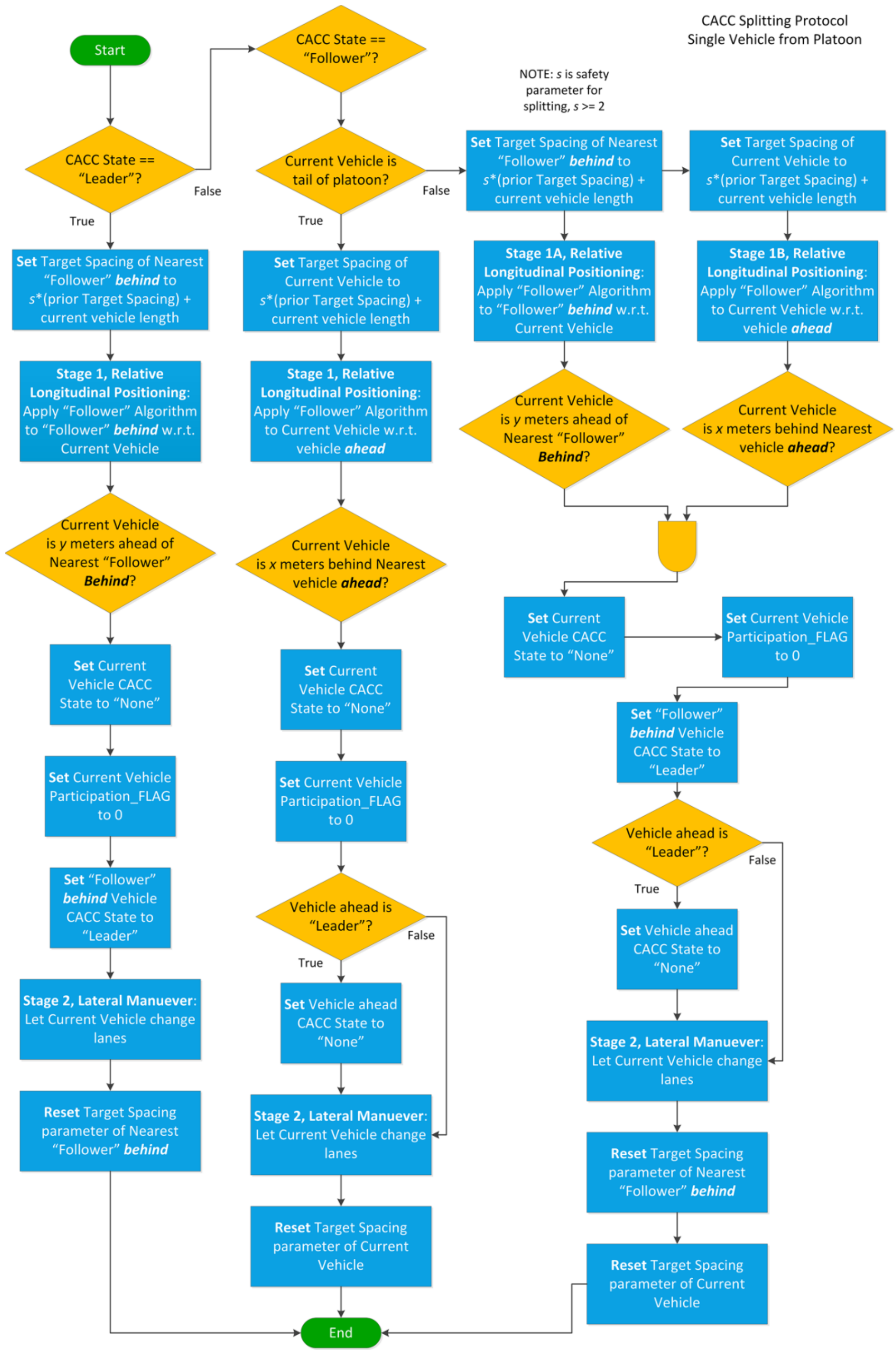


Figure 24: CACC Splitting Protocol, Level-2 Diagram

If an equipped vehicle is approaching a lane-drop area with an adjacent platoon in the target lane, the platoon-merging protocol that Figure 26 shows is executed. The maneuver is based on recognition of the two nearest vehicles in the adjacent lane. Once again, the maneuver is a two-stage process consisting of a relative longitudinal positioning stage and a lateral maneuver stage. The relative longitudinal stage involves two vehicles changing their relative positioning with respect to the nearest vehicle ahead of the ego-vehicle in the adjacent target lane. As seen in Figure 25a, vehicles 1 and 2 are part of a platoon and vehicle 3 is a vehicle attempting to merge with the platoon between vehicles 1 and 2. Vehicle 2 increases its target clearance with respect to vehicle 1 to allow sufficient room for vehicle 3 to merge with the platoon. Vehicle 3 also drops sufficiently behind vehicle 1. Vehicle 3's knowledge of its longitudinal position relative to vehicle 1 is a combination of diagonal radar units, Global Positioning System, and CV technology. Once the relative positioning phase is complete (Figure 25b), the driver of vehicle 3 changes lanes and transfers longitudinal control to the Eco-CACC controller (Figure 25c). The term "Eco-CACC controller" refers to the physical device present on an equipped vehicle, which controls brake and throttle actions in response to the Eco-CACC algorithm previously introduced.

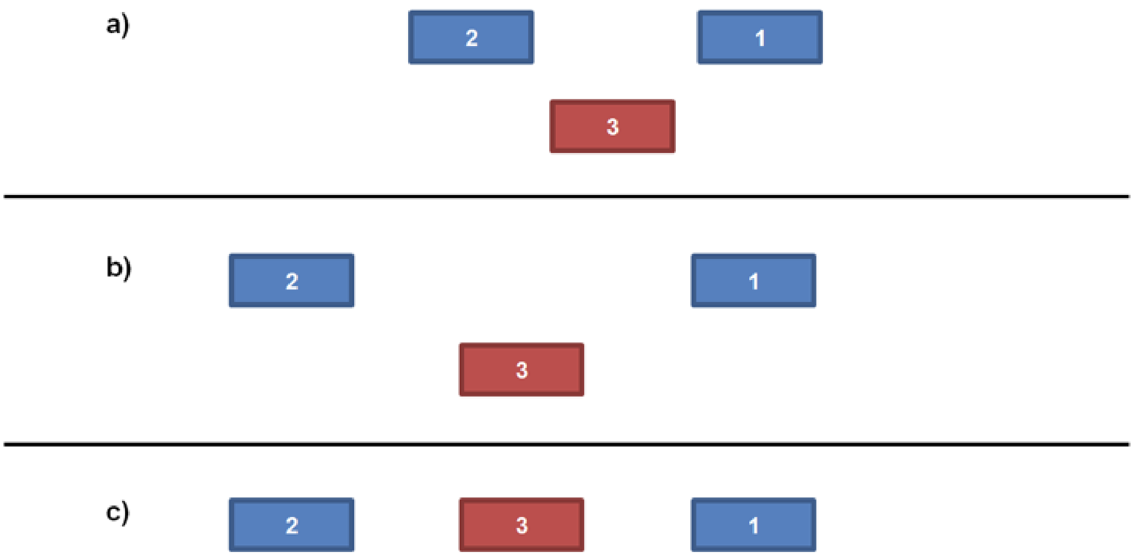


Figure 25: CACC Merging Protocol: a) Before Stage 1, b) Completion of Stage 1, c) Completion of Stage 2

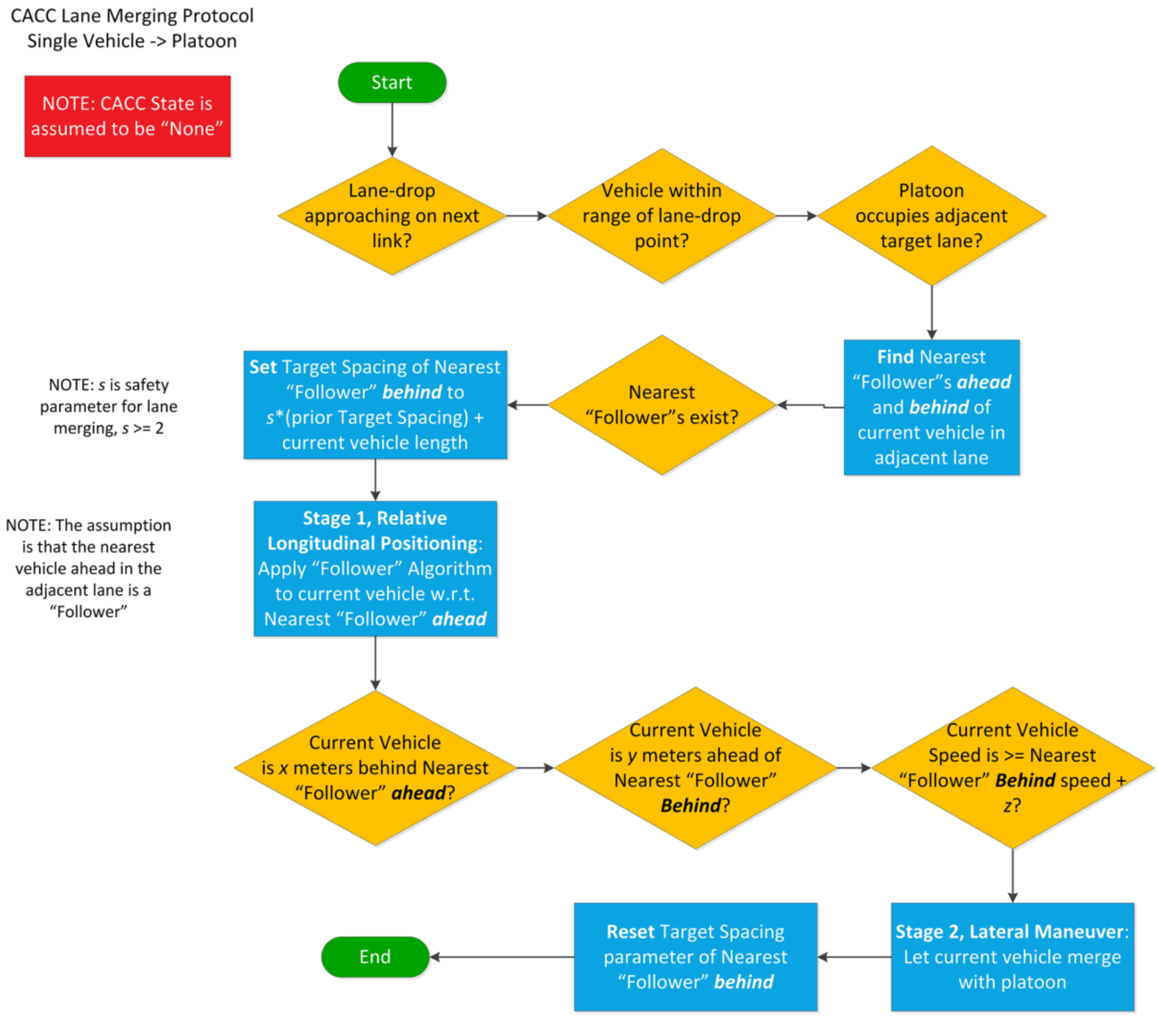


Figure 26: CACC Lane Merging Protocol, Level-2 Diagram

Modeling Approach and Scenarios

Two main approaches exist for modeling CACC behavior within the microscopic traffic simulator. The first approach is to alter simulation parameters, such as headway and reaction time, to mimic the desired behavior of achieving lower gaps between vehicles. The second approach is to explicitly model CACC behavior using a state machine and vehicle controllers. The first approach has the advantage of being quickly and easily implemented within microscopic simulation. The second approach has the advantage of permitting direct control over vehicles within platoons and modeling more complex vehicle interactions. In terms of accurately modeling real-world behavior, explicitly modeling platoon behavior is superior to indirectly mimicking platoon behavior. As a result, the second approach was selected and serves as the basis for the following Eco-CACC algorithm.

Results

Network 1: Hypothetical Freeway Segment with Lane-Drop

For the hypothetical freeway segment with the lane-drop area, a series of four sensitivity analyses were conducted:

- Traffic volume
- Penetration rate of Eco-CACC technology
- Triggering distance
- Intra-platoon clearance.

All of the sensitivity analyses shared the following parameters: The total hourly traffic volume entering the network varied between 3,000 vehicles and 6,000 vehicles total in increments of 600. A constant demand profile was used, meaning that the vehicular demand is constant over time along the roadway. The simulation time selected was 1 hour, with additional time to allow all vehicles to enter and exit the network. A single light-duty vehicle type was used during the simulations. Unless otherwise stated, the following results are network-wide results including all vehicles across all lanes.

Traffic Volume Sensitivity Analysis

For the traffic volume sensitivity analysis, penetration rates of 100 percent and 0 percent were tested over the following traffic volumes: 3,000; 3,600; 4,200; 4,800; 5,400; and 6,000 vph. The triggering distance, or distance threshold when vehicles will trigger platoon-forming behavior, was set at 40 meters or less. The vehicle clearance parameter was set at 5 meters.

The traffic volume sensitivity analyses, which Figure 27 through Figure 30 and Table 10 through Table 12 show, indicate that the baseline capacity of the freeway segment was roughly 3,600 vph. After 3,600 vph, the baseline performance in terms of travel time and energy degraded. In contrast, even at the highest volume tested, 6,000 vph, the applied Eco-CACC algorithm and merging protocol maintained free-flow conditions present at lower volumes. Further testing at higher volumes is necessary before drawing conclusions on the limit of the capacity improvement provided by CACC. The results provided indicate that the capacity is improved by at least two-thirds. A maximum savings of more than 70 percent and 30 percent were achieved in travel time and energy, respectively. It should be noted that the significant difference in results between the baseline and the Eco-CACC algorithm are the result of the combination of the core Eco-CACC algorithm and the merging protocol. The simultaneous increase in traffic density and vehicle cooperation leads to the maintenance of free-flow traffic at higher volumes than are normally possible for today’s freeways.

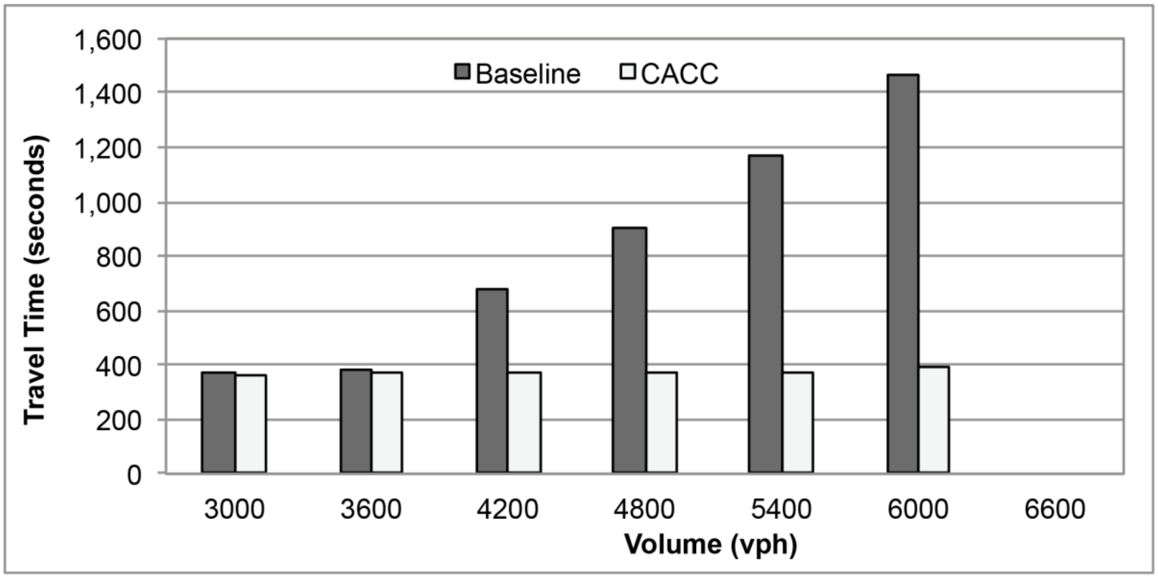


Figure 27: Average Travel Time versus Traffic Volume for 0-Percent and 100-Percent Penetration Rates

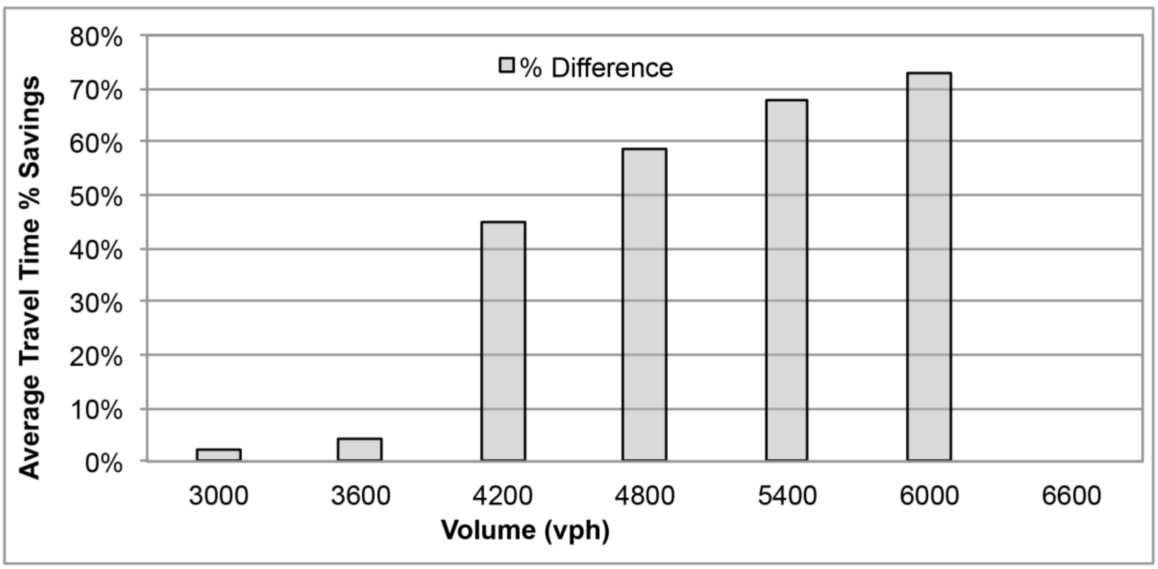


Figure 28: Average Travel Time Percent Savings versus Traffic Volume for 100-Percent versus 0-Percent Penetration Rates

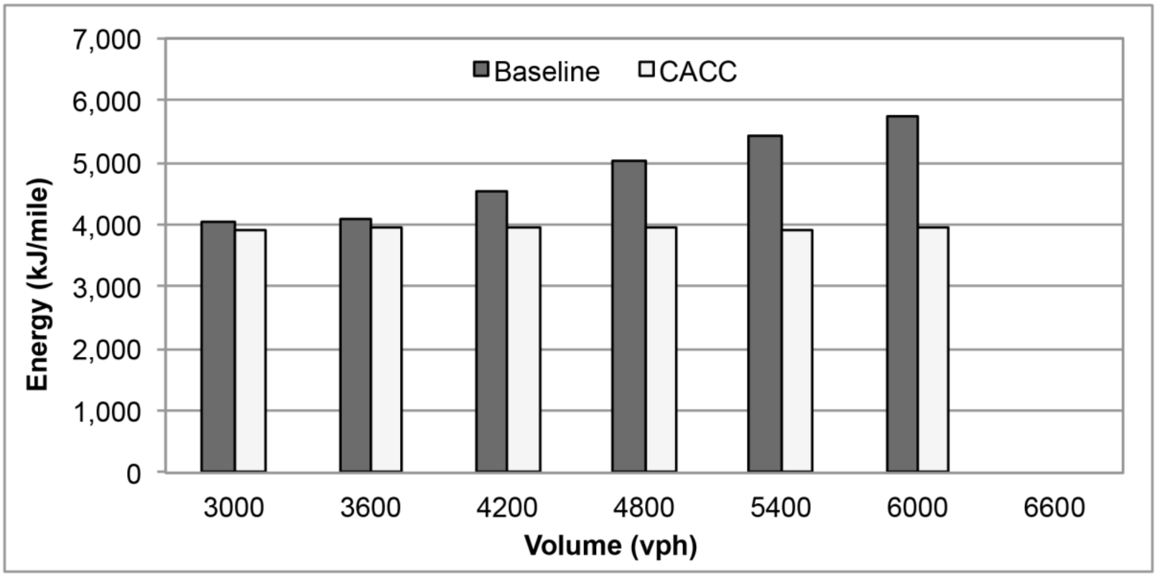


Figure 29: Energy versus Traffic Volume for 0-Percent and 100-Percent Penetration Rates

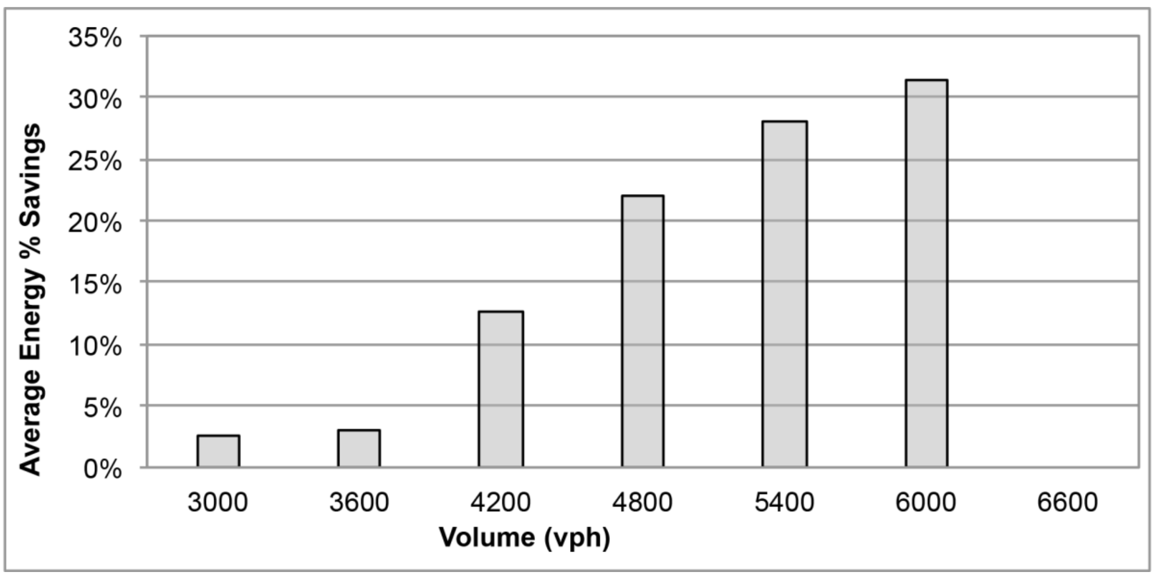


Figure 30: Energy Percent Savings versus Traffic Volume for 100-Percent versus 0-Percent Penetration Rates

Table 10: Baseline, Traffic Volume Sensitivity Analysis Results

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
3000	4032.1786	289.7922	2.5689	0.1173	0.6829	0.009716	372.6657
3600	4084.5152	293.5536	2.6508	0.1208	0.6877	0.009911	384.8094
4200	4517.4448	324.6678	3.1275	0.1623	0.5977	0.008662	674.6607
4800	5048.5277	362.8366	3.5383	0.1939	0.5917	0.008679	902.0285
5400	5451.7048	391.8128	3.8299	0.2153	0.6018	0.008873	1167.4204
6000	5749.5646	413.2199	4.0465	0.2313	0.6086	0.009009	1462.9594

Table 11: Eco-CACC, Traffic Volume Sensitivity Analysis Results

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
3000	3931.2886	282.5413	2.4089	0.1117	0.6645	0.00924	364.8120
3600	3961.6475	284.7232	2.4384	0.1127	0.6702	0.009306	367.6145
4200	3947.5324	283.7087	2.4337	0.1129	0.6644	0.009421	370.9136
4800	3938.3956	283.0520	2.4466	0.1132	0.6613	0.009452	372.7430
5400	3922.1737	281.8861	2.4518	0.1135	0.6557	0.009438	376.2061
6000	3939.0579	283.0995	2.5621	0.1157	0.6582	0.009903	395.0078

Table 12: Percent Improvement of Eco-CACC Over Baseline, Traffic Volume Sensitivity Analysis Results

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
3000	2.50%	2.50%	6.23%	4.78%	2.70%	4.90%	2.11%
3600	3.01%	3.01%	8.01%	6.72%	2.54%	6.10%	4.47%
4200	12.62%	12.62%	22.18%	30.46%	-11.16%	-8.76%	45.02%
4800	21.99%	21.99%	30.85%	41.64%	-11.76%	-8.91%	58.68%
5400	28.06%	28.06%	35.98%	47.28%	-8.95%	-6.37%	67.77%
6000	31.49%	31.49%	36.68%	49.99%	-8.15%	-9.92%	73.00%

Eco-CACC Penetration Rate Sensitivity Analysis

A vehicle with Eco-CACC technology is assumed to have sensors, controllers, and CV technology capable of communicating and receiving information from surrounding vehicles and infrastructure. A total of seven non-zero penetration rates of Eco-CACC technology were simulated at the aforementioned range of traffic volumes. The penetration rates tested were 5 percent, 10 percent, 20 percent, 40 percent, 60 percent, 80 percent, and 100 percent. The triggering distance was set at 40 meters and the vehicle clearance parameter was set at 5 meters.

The penetration rate of Eco-CACC technology sensitivity analyses, which Figure 31 and Figure 32 and Table 13 and Table 14 show, indicate that the higher the penetration rate, the greater the benefits. The benefits in capacity improvement appear to be positively correlated with the penetration rate. The higher the penetration rate, the greater the benefit in capacity improvement would be, and vice versa. Furthermore, the results also appear to indicate a lower and upper threshold for penetration rate in terms of performance. Penetration rates less than or equal to 10 percent have little benefit as a result of the sparsity of platoons. However, penetration rates greater than or equal to 60 percent have similar performance (within the range of tested volumes).

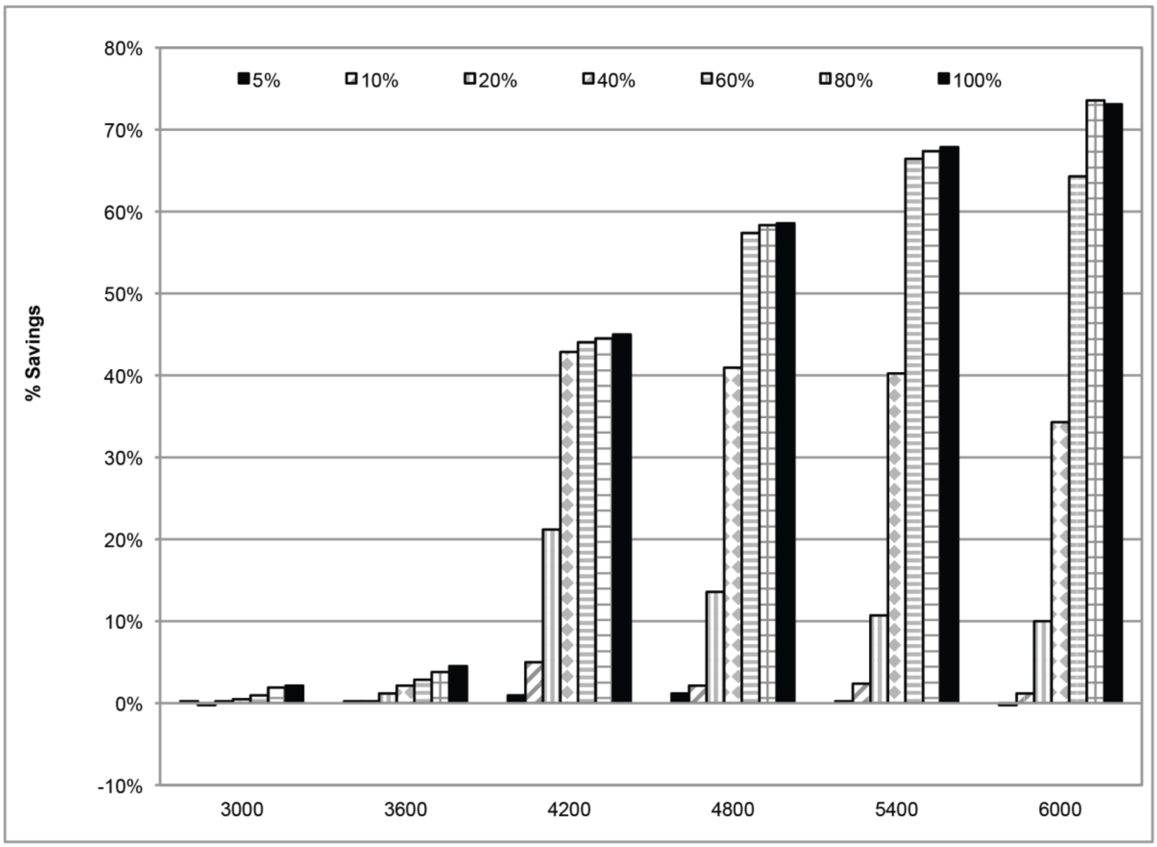


Figure 31: Average Travel Time Percent Savings versus Traffic Volume and Penetration Rate

Table 13: Travel Time Percent Improvement of Eco-CACC Over Baseline, Penetration Rate Sensitivity Analysis Results

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
3000	2.50%	2.50%	6.23%	4.78%	2.70%	4.90%	2.11%
3600	3.01%	3.01%	8.01%	6.72%	2.54%	6.10%	4.47%
4200	12.62%	12.62%	22.18%	30.46%	-11.16%	-8.76%	45.02%
4800	21.99%	21.99%	30.85%	41.64%	-11.76%	-8.91%	58.68%
5400	28.06%	28.06%	35.98%	47.28%	-8.95%	-6.37%	67.77%
6000	31.49%	31.49%	36.68%	49.99%	-8.15%	-9.92%	73.00%

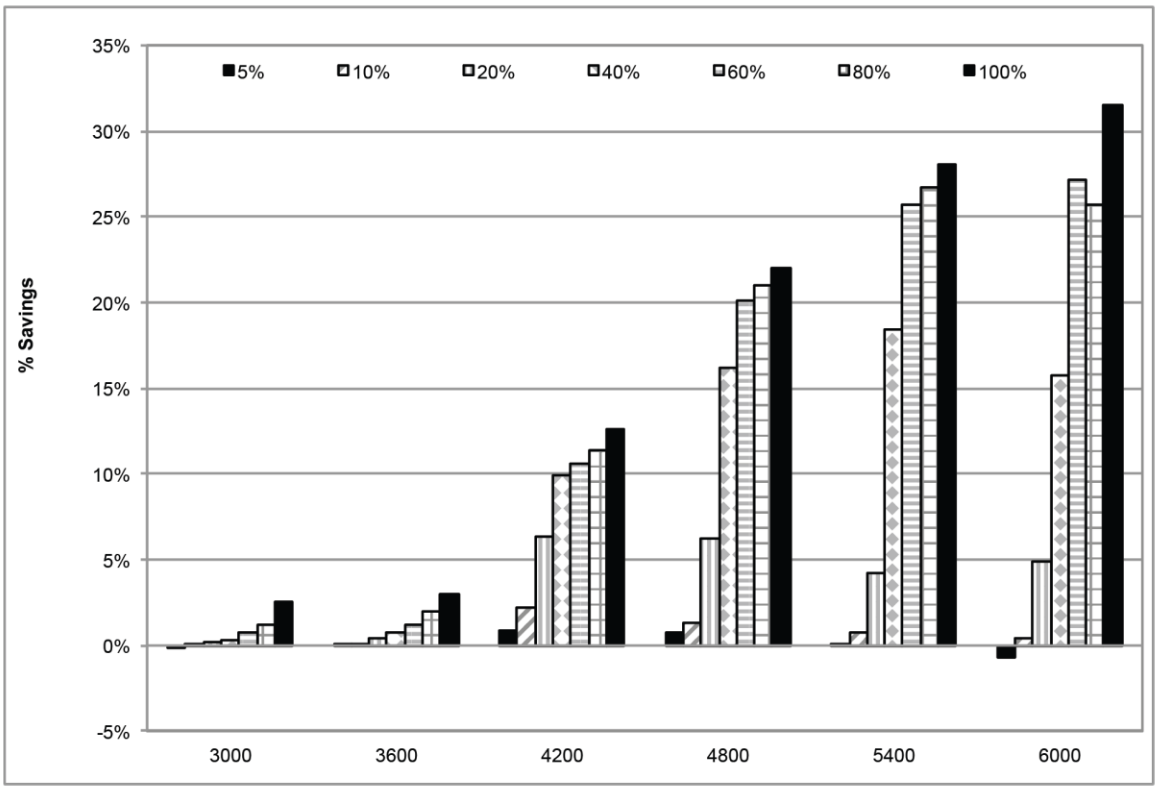


Figure 32: Energy Percent Savings versus Traffic Volume and Penetration Rate

Table 14: Energy Percent Improvement of Eco-CACC Over Baseline, Penetration Rate Sensitivity Analysis Results

Volume (vph)	5%	10%	20%	40%	60%	80%	100%
3000	-0.02%	0.06%	0.15%	0.33%	0.77%	1.20%	2.50%
3600	0.00%	0.07%	0.37%	0.74%	1.22%	1.98%	3.01%
4200	0.84%	2.17%	6.34%	9.95%	10.56%	11.44%	12.62%
4800	0.81%	1.33%	6.25%	16.23%	20.12%	20.99%	21.99%
5400	0.01%	0.78%	4.26%	18.41%	25.74%	26.76%	28.06%
6000	-0.68%	0.46%	4.95%	15.78%	27.11%	25.69%	31.49%

Triggering Distance Sensitivity Analysis

Triggering distance is the inter-vehicular clearance at which a vehicle will attempt to join a platoon ahead. Three triggering distances (20 meters, 30 meters, and 40 meters) were simulated at the aforementioned volumes. The vehicle clearance parameter was set at 5 meters and the penetration rate of Eco-CACC technology was set to 100 percent.

The triggering distance sensitivity analyses, which Figure 33 and Figure 34 show, indicate that there are only small improvements in increasing triggering distance. Recall that the triggering distance is the inter-vehicular distance at which an Eco-CACC–equipped vehicle will elect to begin closely following the vehicle ahead. In a real-life scenario, this parameter may be set manually by a driver. Depending on the ratio of triggering distance to a driver's normal car-following distance, a driver may need to drive closer to a vehicle to trigger platoon formation. In simulation, the observed car-following distance was roughly 25 meters. As a result, when the triggering distance was set to 20 meters, very few platoons formed before the lane-drop area. As a result of the disturbance of vehicles changing lanes in the lane-drop area, approaching vehicles slowed down, leading to car-following distances of less than 20 meters, and therefore triggering platoon formation. In contrast, the selection of triggering distances greater than 20 meters, such as 30 meters and 40 meters, led to platoon formation immediately after vehicle insertion into the network. These smaller platoons increased in size when passing through the lane-drop area. In summary, increasing the triggering distance influenced how early a vehicle joined a platoon, the overall length of platoons, and, to a small degree, the number of vehicles involved in platooning behavior. Therefore, despite the small benefit apparent in Tables 5-15 and 5-16, the underlying fundamental vehicle behavior is significantly different among the tested triggering distances in simulation.

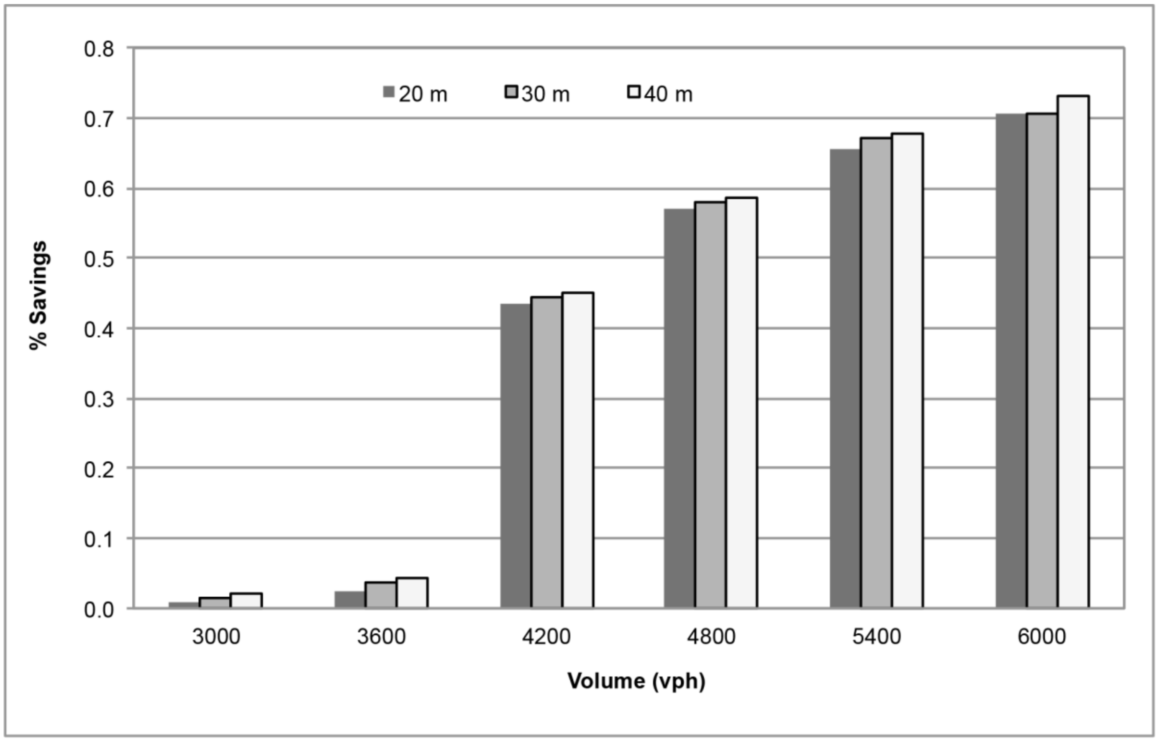


Figure 33: Average Travel Time Percent Savings versus Traffic Volume and Triggering Distance

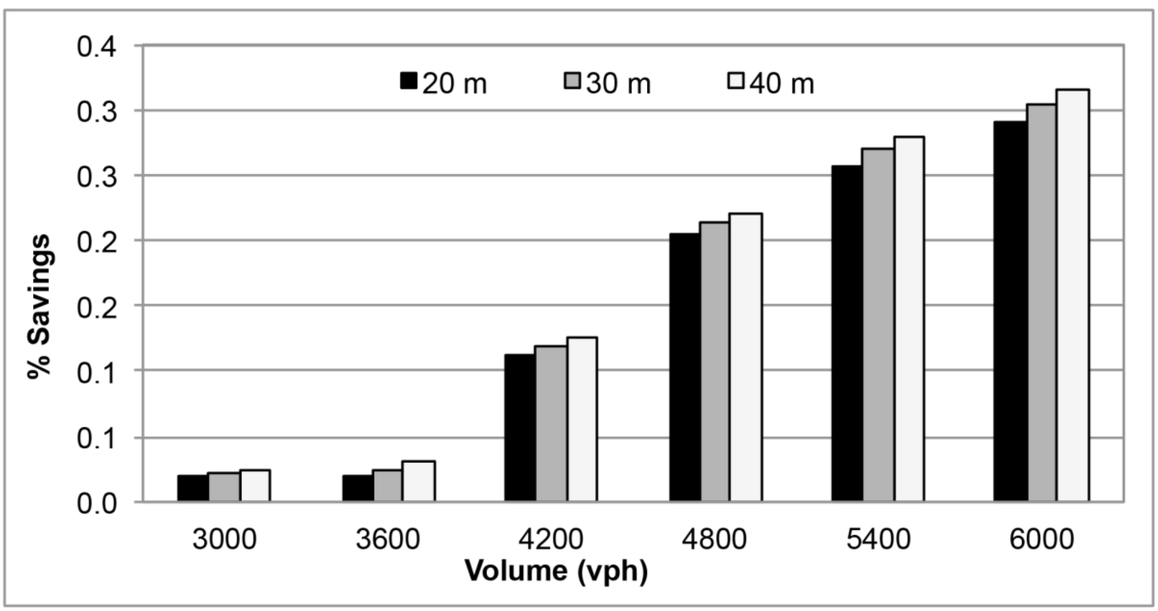


Figure 34: Energy Percent Savings versus Traffic Volume and Triggering Distance

Table 15: Travel Time Percent Improvement of Eco-CACC Over Baseline, Triggering Distance Sensitivity Analysis Results

Volume (vph)	20 m	30 m	40 m
3000	0.73%	1.51%	2.11%
3600	2.42%	3.60%	4.47%
4200	43.45%	44.45%	45.02%
4800	56.99%	58.10%	58.68%
5400	65.67%	67.22%	67.77%
6000	70.62%	70.69%	73.00%

Table 16: Energy Percent Improvement of Eco-CACC Over Baseline, Triggering Distance Sensitivity Analysis Results

Volume (vph)	20 m	30 m	40 m
3000	1.95%	2.21%	2.50%
3600	1.92%	2.44%	3.01%
4200	11.20%	11.85%	12.62%
4800	20.45%	21.42%	21.99%
5400	25.74%	27.08%	28.06%
6000	29.08%	30.47%	31.49%

Intra-Platoon Clearance Sensitivity Analysis

Intra-platoon clearance is the clearance between vehicles travelling in the same platoon. Intra-platoon clearances of 5 meters, 10 meters, 15 meters, and 20 meters were simulated at each of the aforementioned volumes. A triggering distance of 40 meters was selected along with a penetration rate of Eco-CACC technology of 100 percent.

The intra-platoon clearance sensitivity analyses, which Figure 35 and Figure 36 and Table 17 and

Volume (vph)	5 m	10 m	15 m	20 m
3000	2.11%	1.85%	1.60%	1.33%
3600	4.47%	4.11%	3.81%	3.43%
4200	45.02%	44.80%	44.56%	44.23%
4800	58.68%	58.44%	58.21%	58.07%
5400	67.77%	67.52%	67.31%	66.94%

Volume (vph)	5 m	10 m	15 m	20 m
6000	73.00%	72.69%	72.65%	72.11%

Table 18 show, indicate that there is very little performance drop as the intra-platoon clearance is increased. However, increasing the intra-platoon clearance does lower the achievable traffic density, therefore lowering the achievable capacity. Increasing intra-platoon clearance led to increases in average platoon size and length (the number of vehicles within a platoon and the distance between the leader and the tail of the platoon, respectively). To fully observe the effects of platoon growth, no restraints were placed on the maximum platoon length. Future work should consider maximum platoon lengths. The case of 15-meter intra-platoon clearance corresponds roughly to a 0.6-second gap. Larger gaps allow CACC controllers more time to respond to emergency situations. In conclusion, there is a slight tradeoff between overall capacity improvement and level of safety.

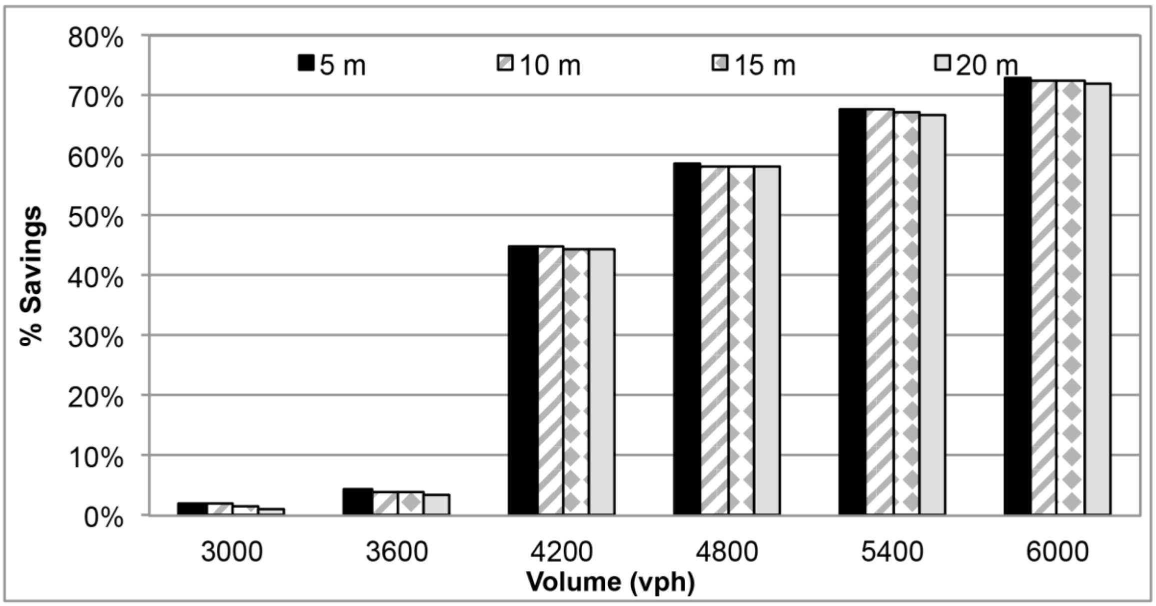


Figure 35: Average Travel Time Percent Savings versus Traffic Volume and Intra-Platoon Clearance

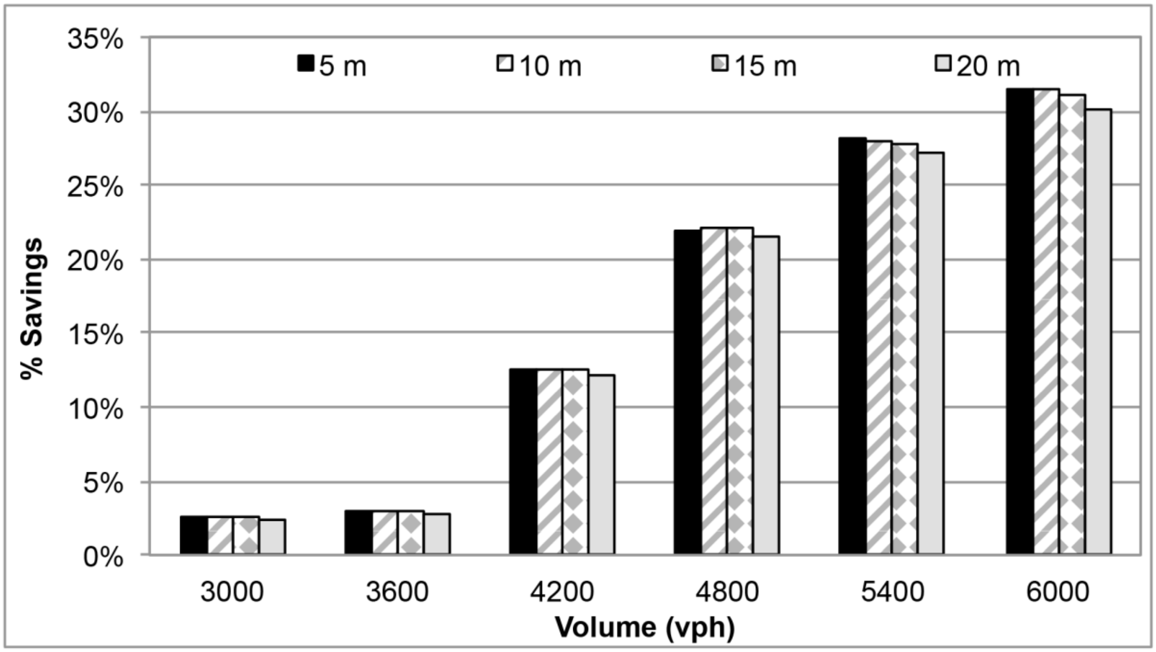


Figure 36: Energy Percent Savings versus Traffic Volume and Intra-Platoon Clearance

Table 17: Travel Time Percent Improvement of Eco-CACC Over Baseline, Intra-Platoon Clearance Sensitivity Analysis Results

Volume (vph)	5 m	10 m	15 m	20 m
3000	2.11%	1.85%	1.60%	1.33%
3600	4.47%	4.11%	3.81%	3.43%
4200	45.02%	44.80%	44.56%	44.23%
4800	58.68%	58.44%	58.21%	58.07%
5400	67.77%	67.52%	67.31%	66.94%
6000	73.00%	72.69%	72.65%	72.11%

Table 18: Energy Percent Improvement of Eco-CACC Over Baseline, Intra-Platoon Clearance Sensitivity Analysis Results

Volume (vph)	5 m	10 m	15 m	20 m
3000	2.50%	2.55%	2.53%	2.47%
3600	3.01%	3.00%	3.00%	2.84%
4200	12.62%	12.46%	12.49%	12.17%

Volume (vph)	5 m	10 m	15 m	20 m
4800	21.99%	22.04%	22.00%	21.50%
5400	28.06%	27.96%	27.76%	27.18%
6000	31.49%	31.53%	31.11%	30.06%

Network 2: Hypothetical Freeway Segment with On-Ramps/Off-Ramps and a Dedicated Lane ("Eco-Lane")

For the hypothetical freeway segment with on-ramps/off-ramps, a sensitivity analysis for traffic volume was conducted. The total hourly traffic volume entering the network varied between 3,000 vehicles and 7,800 vehicles total in increments of 600. A constant demand profile was used. The simulation time selected was 1 hour, with additional time to allow all vehicles to enter and exit the network. A single vehicle type, in this case a single occupant vehicle, was used during the simulations. The left-most lane was set as a dedicated "eco-lane" for Eco-CACC platoons. This "eco-lane" was designed to operate much like an HOV lane but restricted to "eco-vehicles" rather than HOVs. Vehicles in platoons that are close to their desired exit initiate the platoon-splitting protocol. The platoon-merging protocol is not applied to the network because of the absence of lane-drops. In addition to the traffic volume sensitivity analysis, an analysis of network savings versus dedicated lane savings is provided. Finally, a section on the benefits of mainstream vehicles choosing the dedicated lane is included. Unless otherwise stated, the following results are network-wide results including all vehicles across all lanes.

Traffic Volume Sensitivity Analysis

For the traffic volume sensitivity analysis, penetration rates of 100 percent and 0 percent were tested over the following traffic volumes: 3,000; 3,600; 4,200; 4,800; 5,400; 6,000; 6,600; 7,200; and 7,800 vph. The triggering distance, or distance threshold when vehicles will trigger platoon-forming behavior, was set at 40 meters. The vehicle clearance parameter was set at 5 meters.

The traffic volume sensitivity analyses for network 2, which Figure 37 through Figure 40 and Table 19 through **Error! Reference source not found.** show, indicate that there is only a small improvement in terms of travel time and energy at volumes less than or equal to 6,600 vph. There is a significant improvement at volumes greater than 6,600 vph, around 28 percent for travel time and 9 percent for energy at 7,800 vph. Even the presence of a single dedicated lane led to an increase in overall network capacity. The roadway sections immediately before on-ramps led to platoon formation as vehicles would change lanes to the left to better accommodate vehicles entering the freeway. Benefits for volumes less than 6,600 vph were 0 percent to 2 percent for travel time and 0 percent to 4 percent for energy.

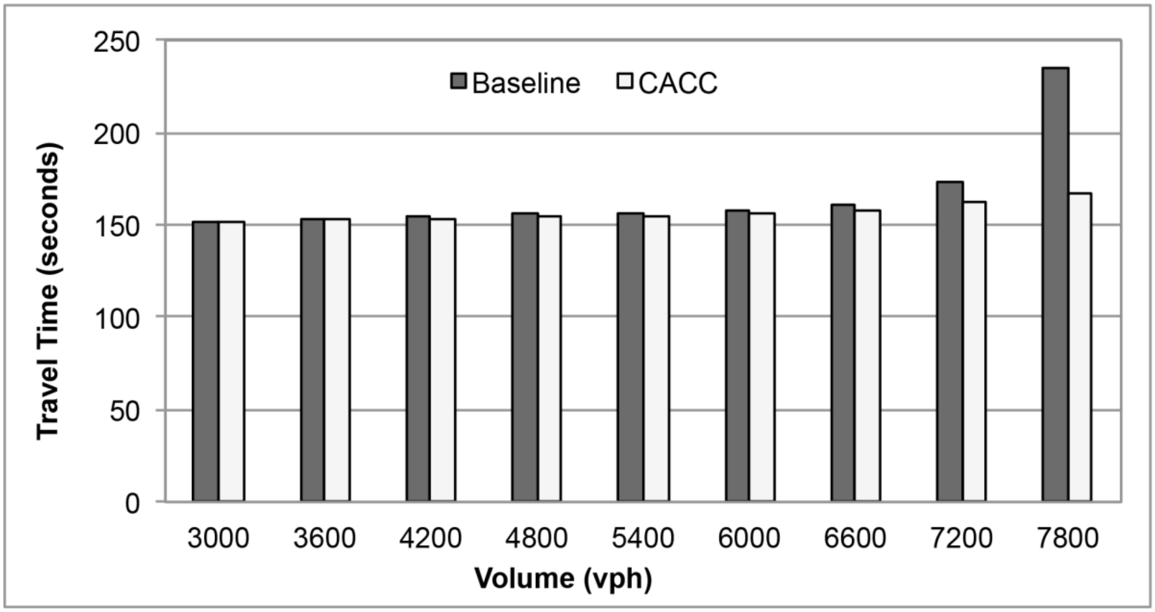


Figure 37: Average Travel Time versus Traffic Volume for 0-Percent and 100-Percent Penetration Rates

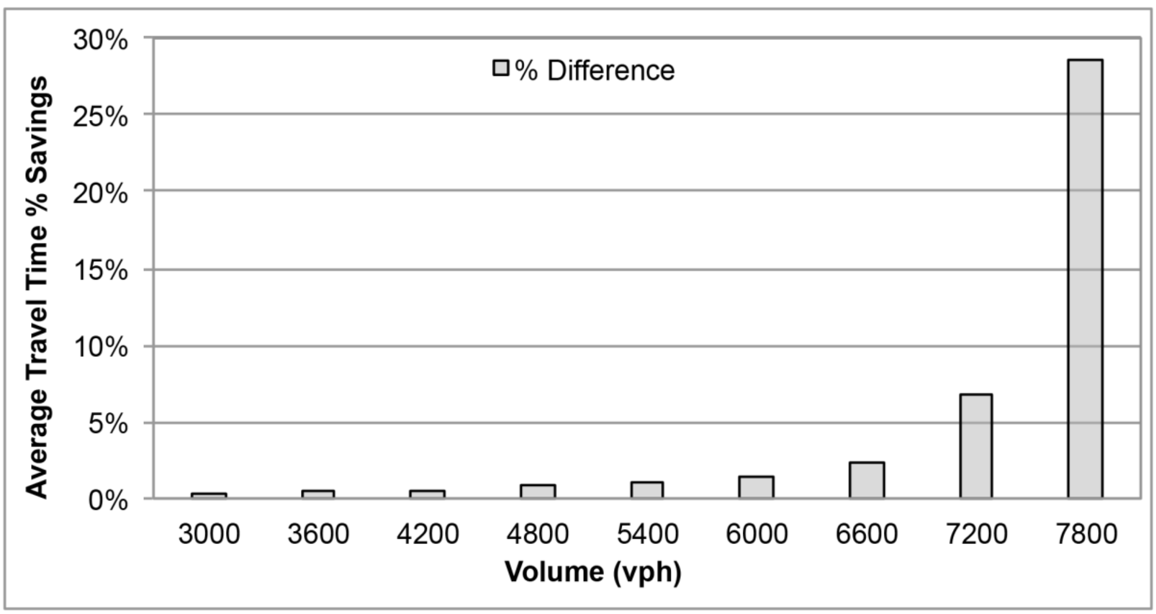


Figure 38: Average Travel Time Percent Savings versus Traffic Volume for 100-Percent versus 0-Percent Penetration Rates

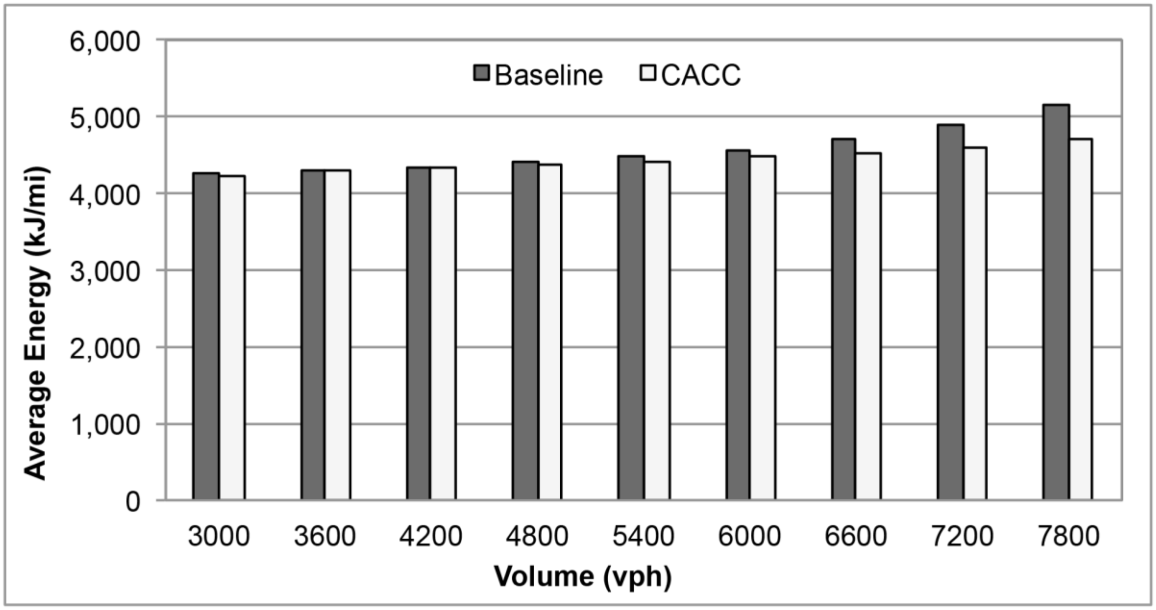


Figure 39: Energy versus Traffic Volume for 0-Percent and 100-Percent Penetration Rates

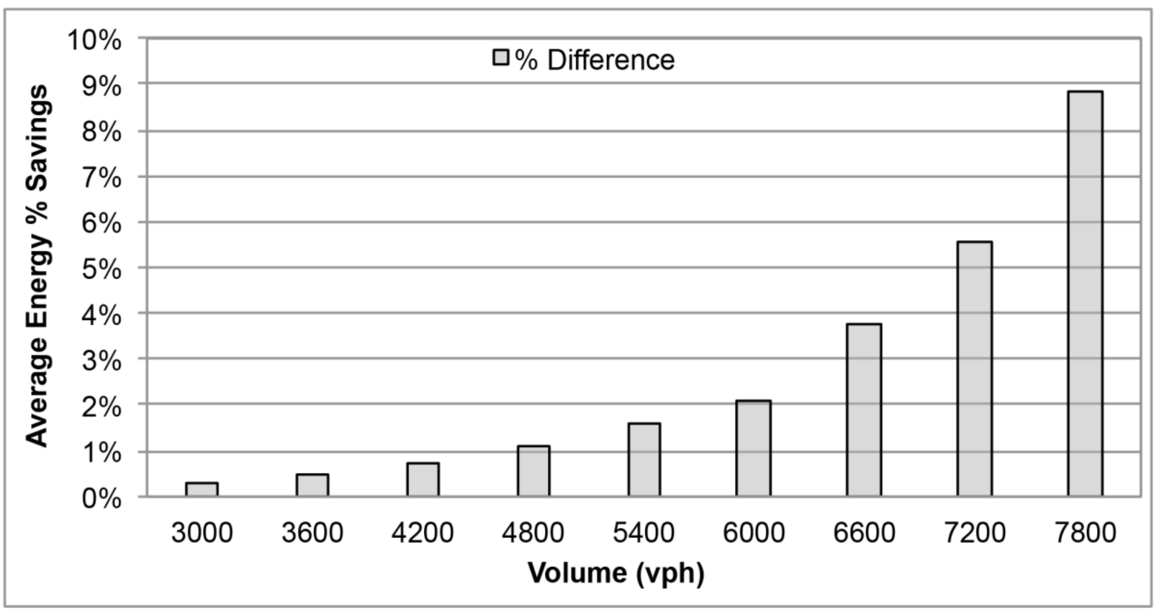


Figure 40: Energy Percent Savings versus Traffic Volume for 100-Percent versus 0-Percent Penetration Rates

Table 19: Baseline, Traffic Volume Sensitivity Analysis Results

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
3000	0.30%	0.30%	1.34%	0.79%	0.25%	1.38%	0.38%
3600	0.50%	0.50%	1.72%	1.07%	0.46%	2.03%	0.53%
4200	0.72%	0.72%	3.23%	1.82%	0.75%	2.99%	0.57%
4800	1.12%	1.12%	4.53%	2.69%	1.18%	4.93%	0.89%
5400	1.62%	1.62%	5.48%	3.36%	1.83%	5.31%	1.02%
6000	2.09%	2.09%	6.99%	4.46%	2.35%	8.09%	1.48%
6600	3.75%	3.75%	11.04%	7.43%	4.29%	12.01%	2.43%
7200	5.54%	5.54%	14.07%	10.97%	5.71%	17.36%	6.83%
7800	8.86%	8.86%	14.41%	16.29%	5.92%	15.49%	28.55%

Traffic Network Savings versus Dedicated Lane Savings

The average energy savings considering the entire network (Figure 41) differs from the average energy savings experienced in the dedicated lane. Energy data for the dedicated lane was defined as the aggregation of energy data for vehicles while they were in the dedicated lane. Therefore, if a vehicle changes lanes into the dedicated lane, energy data is accumulated as long as the vehicle remains in the dedicated lane. If a vehicle changes lanes from the dedicated lane, that vehicle no longer contributes energy data to the dedicated lane analysis. Note that vehicles with different routes use the dedicated lane. Furthermore, based on the aforementioned definition, there is no corresponding dedicated lane travel time definition due to lane changes and diverse routes. In addition to showing the dedicated lane savings, Figure 41 also shows the average savings for the remaining three lanes. Figure 42 shows the relative benefit of choosing the dedicated lane over a non-dedicated lane.

The additional analysis of benefits that Figure 41 through Figure 44 show provides insight into the operation of the algorithms applied to the network. At relatively low traffic volumes, the vehicles on the dedicated lane expended slightly more energy than vehicles in the baseline scenario because of acceleration during platoon formation. The overall network energy savings were around 0 percent due to the balance of a 4-percent cost in energy on the dedicated lane and a 1-percent reduction in energy on the remaining lanes. At higher volumes, the dedicated lane energy savings increased to a maximum of 14 percent. In addition, the indirect benefit of non-dedicated lane energy savings reached roughly 4 percent at the highest volume. Therefore, the benefits in preserving relatively free-flow traffic outweigh the small energy costs associated with conducting automated maneuvers.

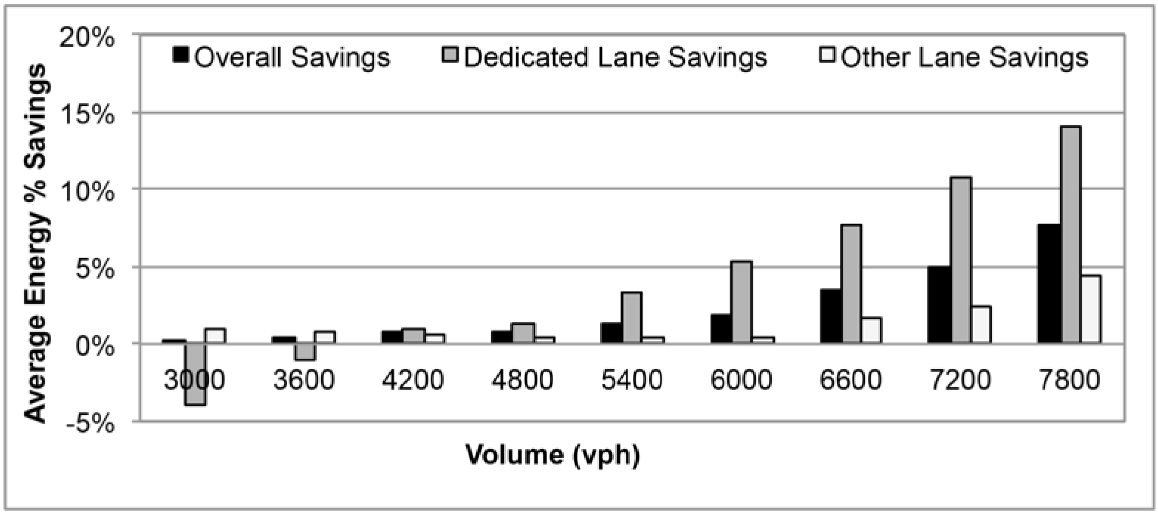


Figure 41: Dedicated Lane Energy Savings versus Traffic Volume

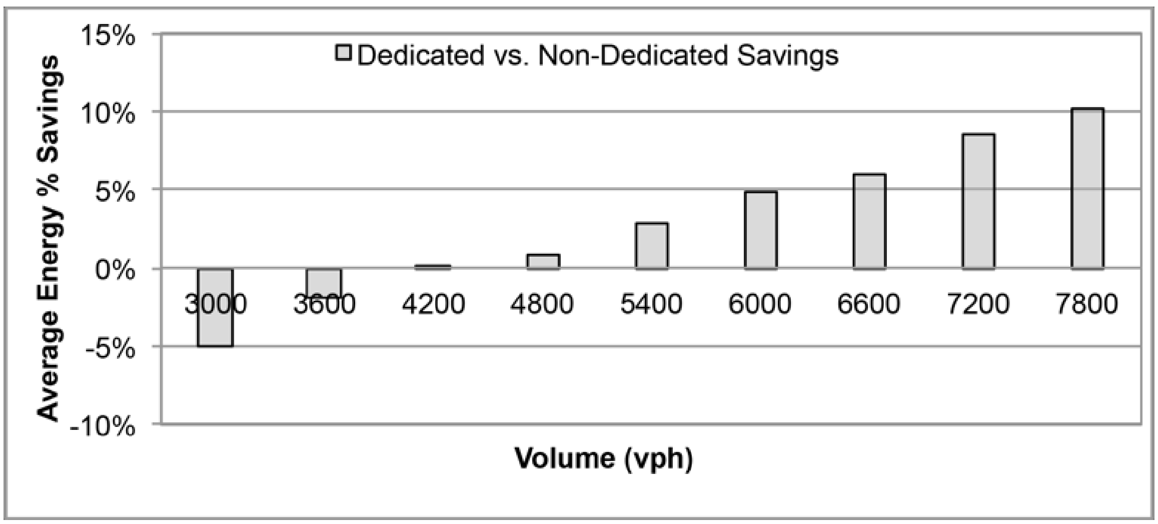


Figure 42: Relative Benefit of Dedicated Lane versus Non-Dedicated Lane Savings

Benefits for Mainstream Vehicles Choosing the Dedicated Lane

In addition to aggregating data by lane, data may also be aggregated for vehicles following a specific route. The selected route that made the most use of the dedicated lane was the mainstream route. The mainstream route was defined as the only route not including on-ramps or off-ramps. Along the mainstream route, data collection was further divided among vehicles that chose to use the dedicated lane and vehicles that did not choose the dedicated lane. Figure 43 shows the relative travel time and energy benefits of choosing the dedicated lane versus a non-dedicated lane. Part of the reason energy savings are negative at most volumes is because of the additional energy required for vehicles to change lanes into the dedicated lane due to congestion on non-dedicated lanes. To isolate the benefits vehicles obtain in the dedicated lane, an additional experiment was conducted in which the vehicles that started and remained in the dedicated lane were compared with all other vehicles with the same route. Figure 44 shows these results.

The apparent discrepancy in energy savings between Figure 43 and Figure 45 may be attributed to vehicles expending energy changing lanes into the dedicated lane due to congestion on non-dedicated lanes. Isolating for vehicles that start and end in the dedicated lane reveals that these individual vehicles obtain a 6-percent to 10-percent savings in travel time and a -2-percent to 5-percent savings in energy relative to other vehicles along the same route (Figure 43). The small negative energy savings at lower traffic volumes is the result of additional energy being expended to conduct automated maneuvers. At higher traffic volumes, the energy rate increases more quickly for non-dedicated lanes than the dedicated lane, thereby outweighing the energy costs of automated maneuvering. A visual comparison of Figure 42 and Figure 43 reveals that vehicles that start in the dedicated lane have a benefit over vehicles that wait to change lanes into the dedicated lane because of congestion.

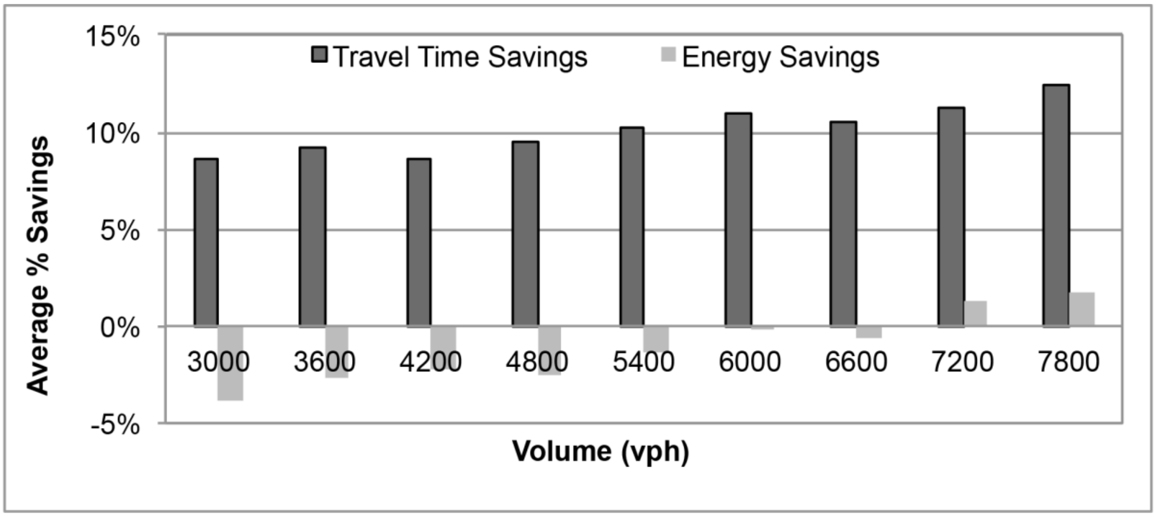


Figure 43: Average Benefits for Mainstream Vehicles Choosing the Dedicated Lane

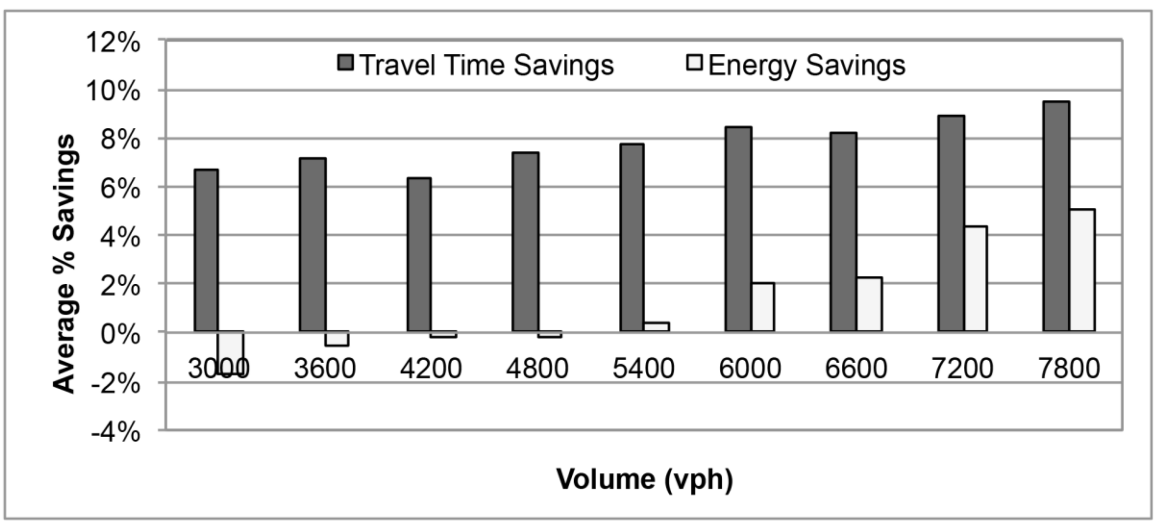


Figure 44: Average Benefits for Mainstream Vehicles Starting in the Dedicated Lane

Network 3: SR-91 E Freeway with Dedicated Lane ("Eco-Lane")

For the SR-91 E freeway, a sensitivity analysis for traffic volume was conducted. The total hourly traffic volume entering the network was varied between 25,000 vehicles and 37,000 vehicles total in increments of 3,000. A constant demand profile was used. The simulation time selected was 2 hours, with separate profiles used for each hour. The case of 25,000 vehicles was based on calibration of real-world data. A single vehicle type was used during the simulations. The left-most lane was set as a dedicated lane for Eco-CACC platoons. The number of mainstream lanes varies between four and six. Vehicles in platoons that are close to their desired exit initiate the platoon-splitting protocol. The platoon-merging protocol is not applied to the network because of the absence of lane-drops. Unless otherwise stated, the following results are network-wide results including all vehicles across all lanes.

Traffic Volume Sensitivity Analysis

For the traffic volume sensitivity analysis, penetration rates of 100 percent and 0 percent were tested over the following traffic volumes: 25,000; 28,000; 31,000; 34,000; and 37,000 vehicles. The triggering distance, or distance threshold when vehicles will trigger platoon-forming behavior, was set at 40 meters. Two values were used for the vehicle clearance parameter. The vehicle clearance parameter was first set at 5 meters to assess the maximum possible benefit of applying CACC to a real-world traffic network. Next, the vehicle clearance parameter was set to 15 meters to reflect a realistic deployment scenario.

As Figure 45 through Figure 58 and Table 20 through

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
25000	4312.2076	309.9178	3.8214	0.1400	0.7512	0.0142	411.8914
28000	4313.1120	309.9828	3.8400	0.1401	0.7529	0.0141	449.8930
31000	4378.0505	314.6500	4.0398	0.1446	0.7664	0.0150	480.3299
34000	4583.5199	329.4169	4.6079	0.1595	0.7997	0.0172	547.9909
37000	5224.1798	375.4609	5.7884	0.2000	0.8899	0.0245	792.3982

Table 25 shows, the application of Eco-CACC to a single dedicated lane on the SR-91 E freeway led to significant savings at the highest tested volumes. Although additional testing needs to be conducted at different volumes, the initial results indicate that a single dedicated lane makes little to no difference in terms of travel time and energy at relatively low volumes. Just as with network 2 (i.e., IHFN), there was a substantial increase to overall capacity for network 3. When the vehicle clearance parameter was set to 5 meters, the benefits ranged from 0 percent to 42 percent for travel time and 0 percent and 19 percent for energy. Likewise, when the vehicle clearance parameter was set to 15 meters, the benefits ranged from 0 percent to 24 percent for travel time and 0 percent to 13 percent for energy. The results indicate that the primary difference between vehicle following distances of 5 meters and 15 meters is the resulting increase in capacity. The results at the highest volume tested (37,000 vehicles) indicate that the system was within its capacity for the 5-meter test but beyond its capacity for the 15-meter test. Consequently, additional testing must be conducted at higher volumes to quantify the difference in capacity between vehicle clearance of 5 meters and 15 meters.

It is important to note that the results shown do not represent the maximum achievable benefits possible for applying Eco-CACC in a single dedicated lane. Additional testing at higher traffic volumes is necessary to ascertain the new capacity for a given traffic network. The increase in capacity is related to the increase in traffic density caused by platooning. One remarkable feature of the aforementioned results is that the application of Eco-CACC to only a single lane still caused a substantial increase in network capacity. The application of Eco-CACC to more than one lane should result in even more dramatic increases in roadway capacity.

Part 1: Vehicle Clearance Parameter of 5 Meters

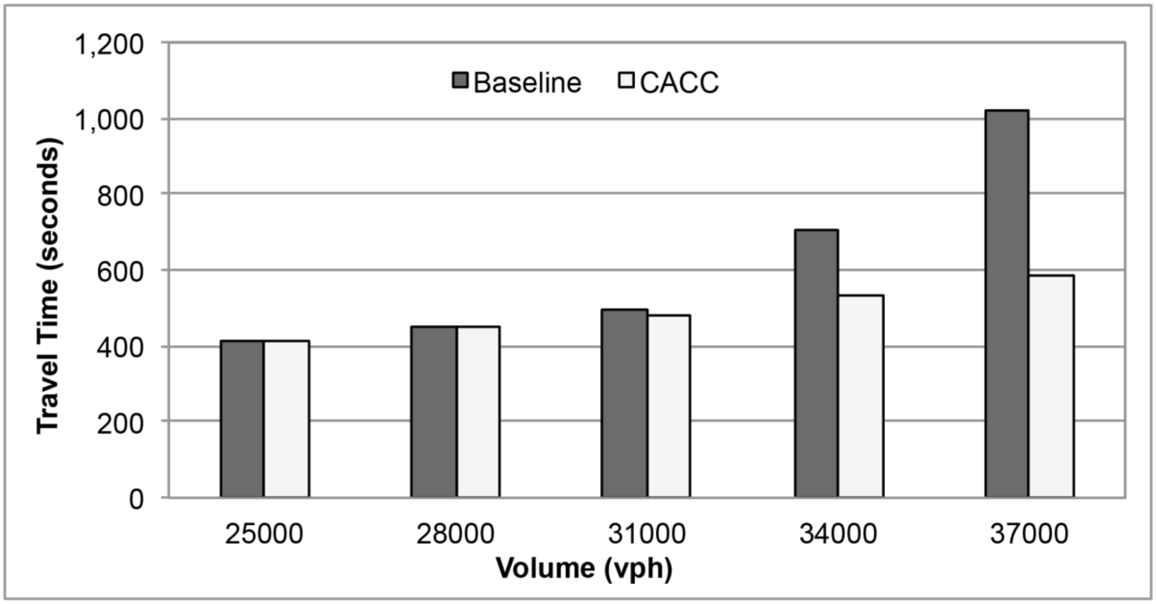


Figure 45: Average Travel Time versus Traffic Volume for 0-Percent and 100-Percent Penetration Rates, 5m Vehicle Clearance

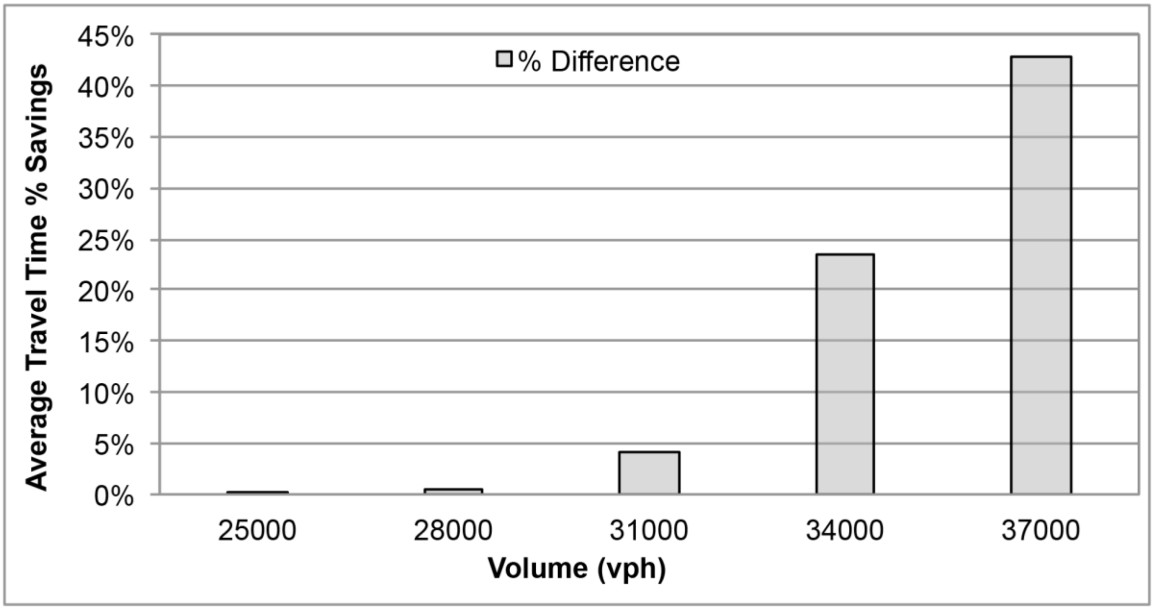


Figure 46: Average Travel Time Percent Savings versus Traffic Volume for 100-Percent versus 0-Percent Penetration Rates, 5m Vehicle Clearance

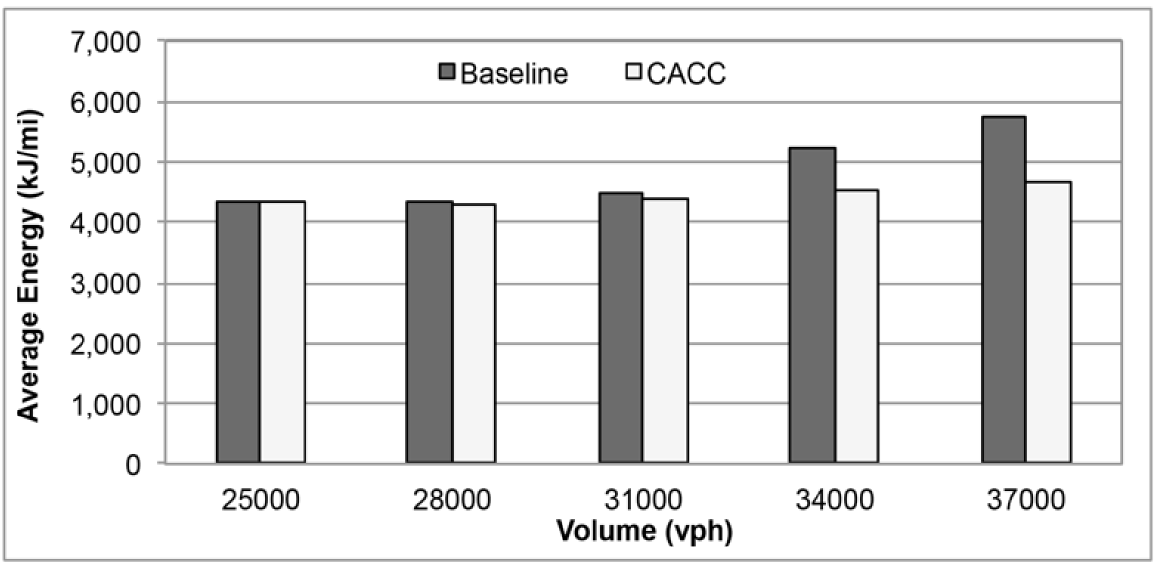


Figure 47: Traffic Volume for 0-Percent and 100-Percent Penetration Rates, 5m Vehicle Clearance

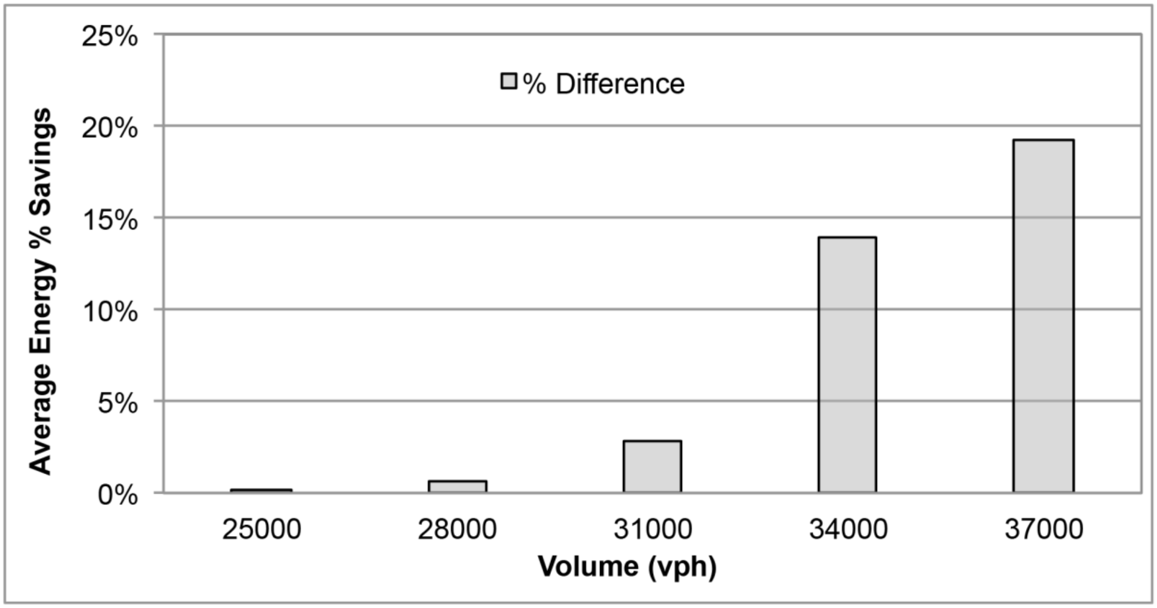


Figure 48: Energy Percent Savings versus Traffic Volume for 100-Percent versus 0-Percent Penetration Rates, 5m Vehicle Clearance

Table 20: Baseline, Traffic Volume Sensitivity Analysis Results

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
25000	4320.6885	310.5274	3.8453	0.1404	0.7533	0.0143	413.8942
28000	4341.5825	312.0290	3.9371	0.1421	0.7579	0.0145	450.1636
31000	4491.1921	322.7814	4.4314	0.1538	0.7859	0.0166	498.2444
34000	5235.4219	376.2688	5.9993	0.2046	0.8833	0.0245	702.3228
37000	5754.3728	413.5655	6.5284	0.2355	0.9220	0.0274	1022.4019

Table 21: Eco-CACC, Traffic Volume Sensitivity Analysis Results, 5m Vehicle Clearance

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
25000	4317.8101	310.3205	3.8630	0.1407	0.7530	0.0144	412.7937
28000	4310.7868	309.8157	3.9166	0.1411	0.7535	0.0143	447.6072
31000	4362.7826	313.5526	4.1373	0.1456	0.7653	0.0150	478.1213
34000	4509.7201	324.1130	4.5656	0.1566	0.7885	0.0166	536.5902

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
37000	4648.5840	334.0931	5.0162	0.1670	0.8161	0.0184	584.4299

Table 22: Percent Improvement of Eco-CACC Over Baseline, Traffic Volume Sensitivity Analysis Results, 5m Vehicle Clearance

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
25000	0.07%	0.07%	-0.46%	-0.20%	0.04%	-0.45%	0.27%
28000	0.71%	0.71%	0.52%	0.72%	0.59%	1.56%	0.57%
31000	2.86%	2.86%	6.64%	5.32%	2.61%	9.21%	4.04%
34000	13.86%	13.86%	23.90%	23.43%	10.72%	32.32%	23.60%
37000	19.22%	19.22%	23.16%	29.07%	11.49%	33.04%	42.84%

Part 2: Vehicle Clearance Parameter of 15 Meters

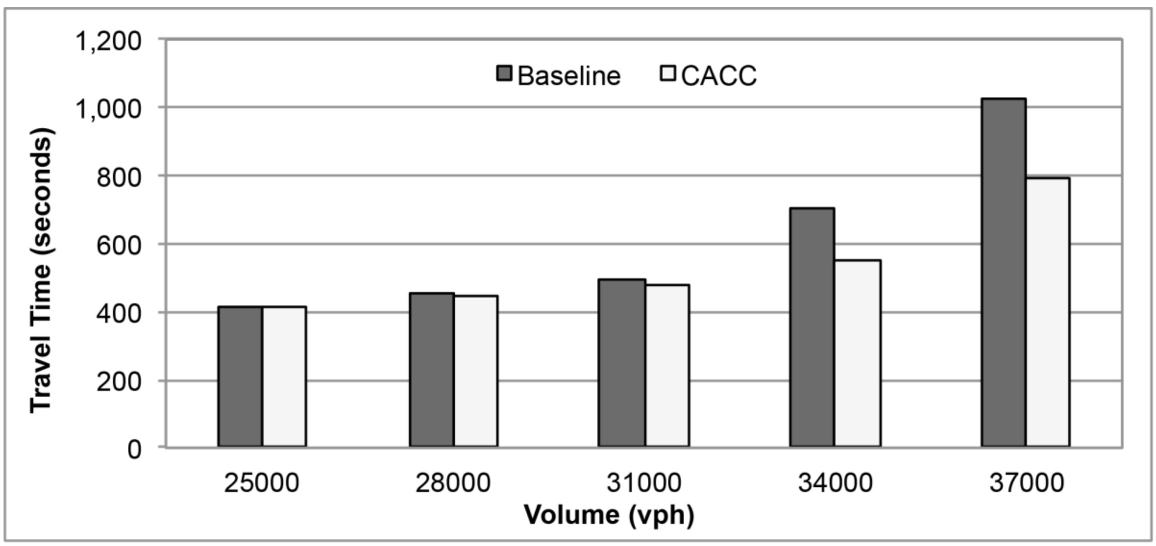


Figure 49: Average Travel Time versus Traffic Volume for 0-Percent and 100-Percent Penetration Rates, 15m Vehicle Clearance

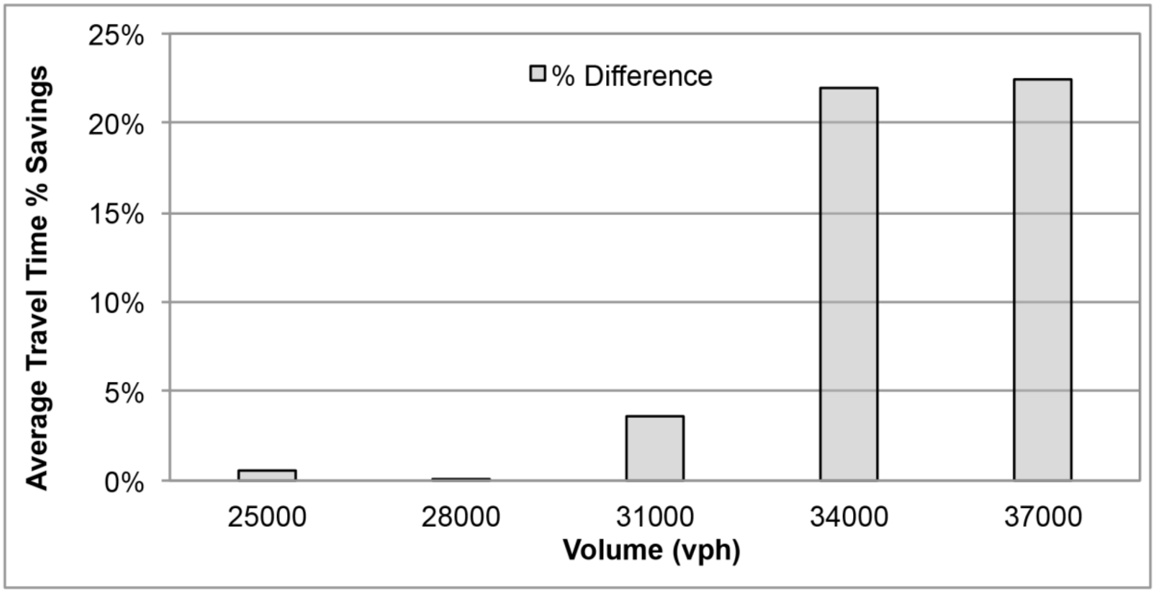


Figure 50: Average Travel Time Percent Savings versus Traffic Volume for 100-Percent versus 0-Percent Penetration Rates, 15m Vehicle Clearance

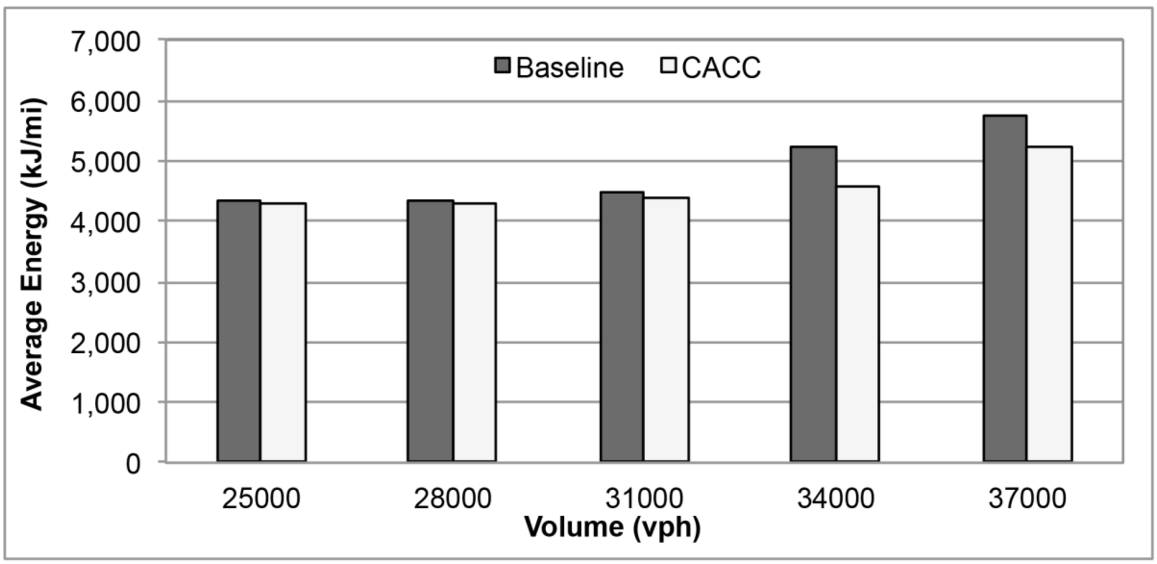


Figure 51: Energy versus Traffic Volume for 0-Percent and 100-Percent Penetration Rates, 15m Vehicle Clearance

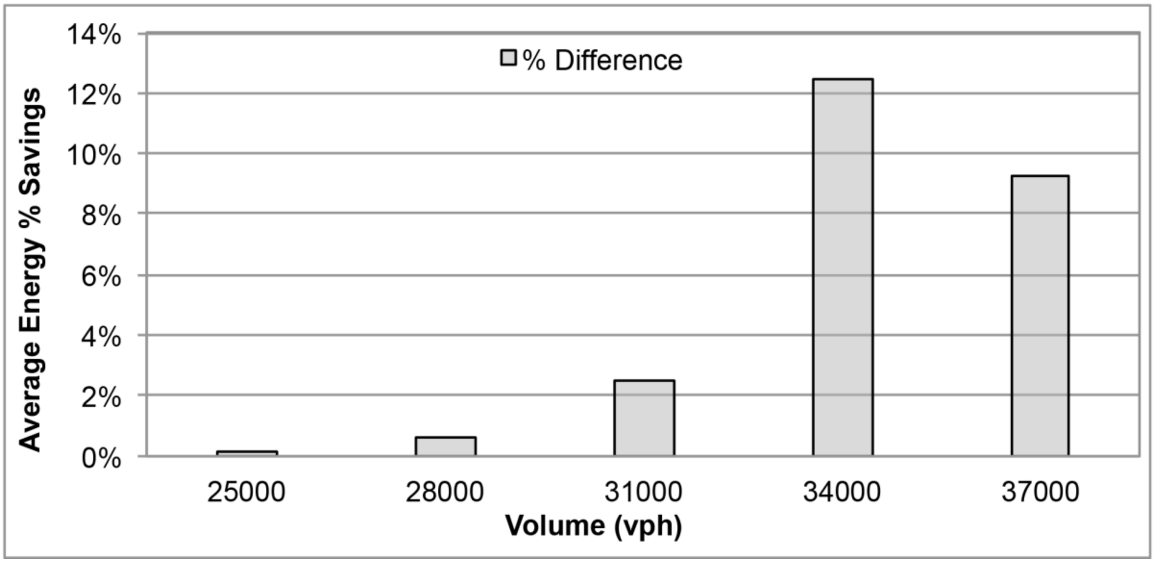


Figure 52: Energy Percent Savings versus Traffic Volume for 100-Percent versus 0-Percent Penetration Rates, 15m Vehicle Clearance

Table 23: Baseline, Traffic Volume Sensitivity Analysis Results

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
25000	4320.6885	310.5274	3.8453	0.1404	0.7533	0.0143	413.8942
28000	4341.5825	312.0290	3.9371	0.1421	0.7579	0.0145	450.1636
31000	4491.1921	322.7814	4.4314	0.1538	0.7859	0.0166	498.2444
34000	5235.4219	376.2688	5.9993	0.2046	0.8833	0.0245	702.3228
37000	5754.3728	413.5655	6.5284	0.2355	0.9220	0.0274	1022.4019

Table 24: Eco-CACC, Traffic Volume Sensitivity Analysis Results, 15m Vehicle Clearance

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
25000	4312.2076	309.9178	3.8214	0.1400	0.7512	0.0142	411.8914
28000	4313.1120	309.9828	3.8400	0.1401	0.7529	0.0141	449.8930
31000	4378.0505	314.6500	4.0398	0.1446	0.7664	0.0150	480.3299
34000	4583.5199	329.4169	4.6079	0.1595	0.7997	0.0172	547.9909
37000	5224.1798	375.4609	5.7884	0.2000	0.8899	0.0245	792.3982

Table 25: Percent Improvement of Eco-CACC Over Baseline, Traffic Volume Sensitivity Analysis Results, 15m Vehicle Clearance

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
25000	0.20%	0.20%	0.62%	0.26%	0.28%	0.69%	0.48%
28000	0.66%	0.66%	2.47%	1.44%	0.66%	2.43%	0.06%
31000	2.52%	2.52%	8.84%	5.96%	2.48%	9.64%	3.60%
34000	12.45%	12.45%	23.19%	22.01%	9.46%	29.93%	21.97%
37000	9.21%	9.21%	11.33%	15.08%	3.48%	10.54%	22.50%

Traffic Network Savings versus Dedicated Lane Savings

The average energy savings considering the entire network (Figure 8) differs from the average energy savings experienced in the dedicated lane. Energy data for the dedicated lane was defined as the aggregation of energy data for vehicles while they were in the dedicated lane. Therefore, if a vehicle changes lanes into the dedicated lane, energy data is accumulated as long as the vehicle remains in the dedicated lane. If a vehicle changes lanes from the dedicated lane, that vehicle no longer contributes energy data to the dedicated lane analysis. Note that vehicles with different routes use the dedicated lane. Furthermore, based on the aforementioned definition, there is no corresponding dedicated lane travel time definition due to lane changes and diverse routes. In addition to showing the dedicated lane savings, Figure 41 and Figure 43 also show the average savings for the remaining lanes. Figure 42 and Figure 44 show the relative benefit of choosing the dedicated lane over a non-dedicated lane.

The results also demonstrate that for the tested traffic volumes, the dedicated lane is the most energy efficient lane. In fact, the dedicated lane was 3 percent to 12 percent more energy efficient than the non-dedicated lanes and 3 percent to 26 percent more energy efficient relative to the average baseline scenario lane. In addition to the direct benefits that Eco-CACC brings to participating vehicles, other vehicles and lanes indirectly benefited. The non-dedicated lanes saw a reduction in energy consumption ranging from 0 percent to 16 percent.

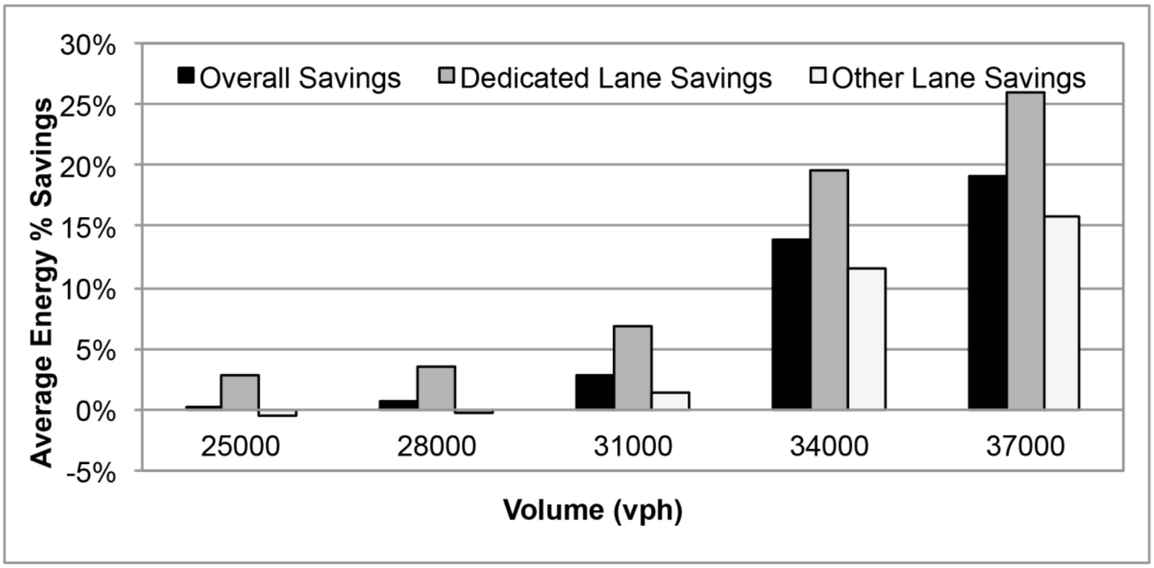


Figure 53: Dedicated Lane Energy Savings versus Traffic Volume, 5m Vehicle Clearance

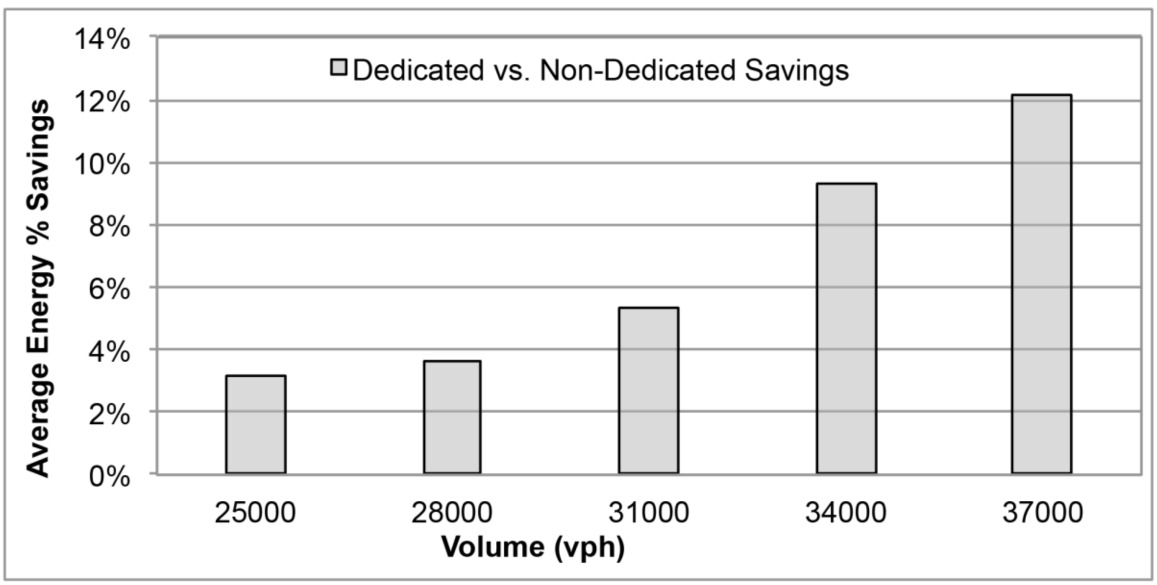


Figure 54: Relative Benefit of Dedicated Lane versus Non-Dedicated Lane Savings, 5m Vehicle Clearance

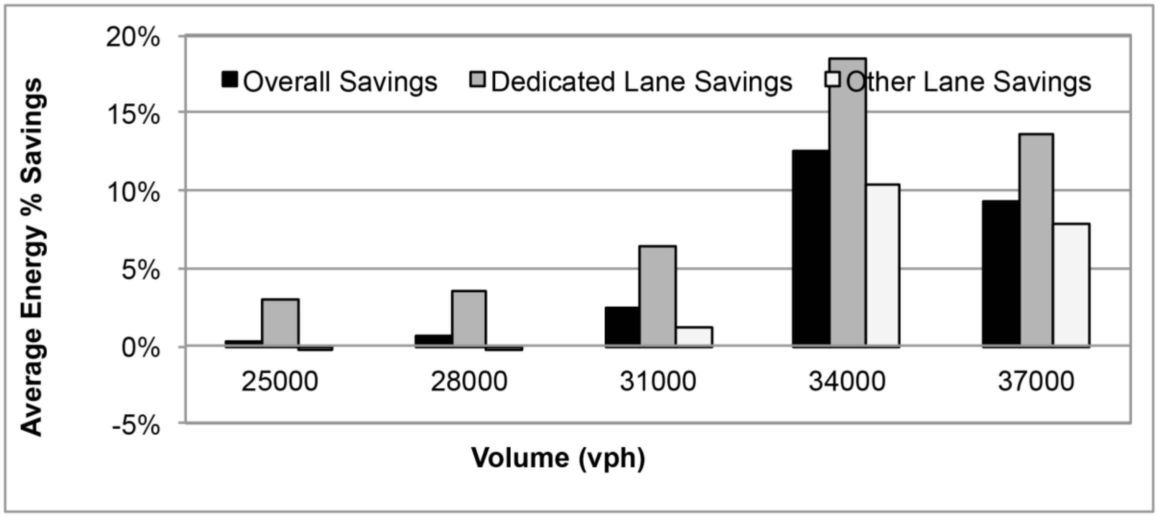


Figure 55: Dedicated Lane Energy Savings versus Traffic Volume, 15m Vehicle Clearance

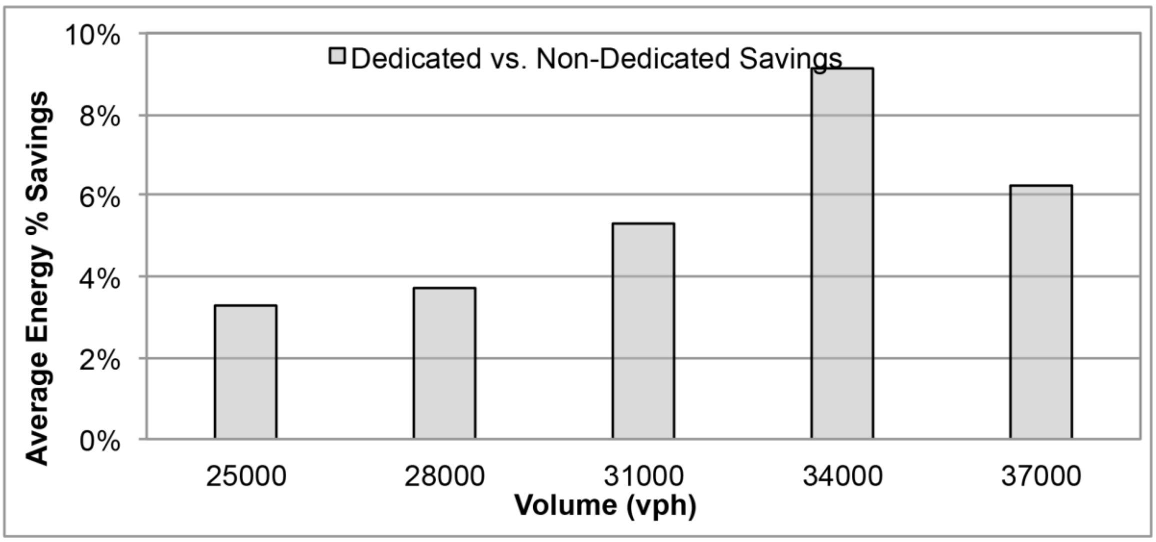


Figure 56: Relative Benefit of Dedicated Lane versus Non-Dedicated Lane Savings, 15m Vehicle Clearance

Benefits for Mainstream Vehicles Choosing the Dedicated Lane

In addition to aggregating data by lane, data may also be aggregated for vehicles following a specific route. The selected route that made the most use of the dedicated lane was the mainstream route. The mainstream route was defined as the only two routes not including on-ramps or off-ramps. Along the mainstream route, data collection was further divided among vehicles that chose to use the dedicated lane and vehicles that did not choose the dedicated lane. Figure 57 and Figure 58 show the relative travel time and energy benefits of choosing the dedicated lane versus a non-dedicated lane.

Equipped vehicles that chose to use the dedicated lane obtained a 10 percent to 19 percent benefit in reduced travel time, with a -1 percent to 5 percent benefit in energy savings.

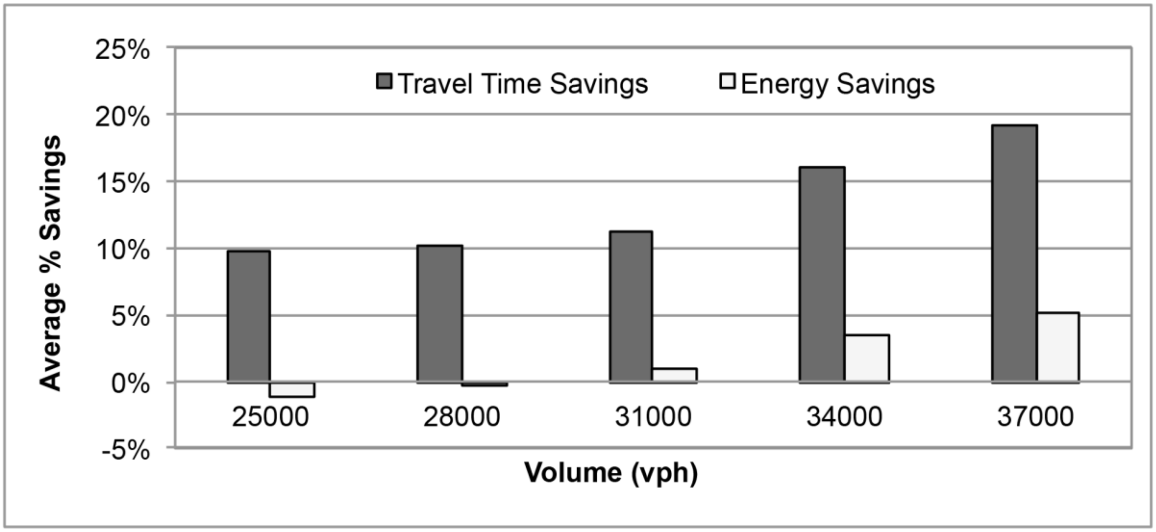


Figure 57: Average Benefits for Mainstream Vehicles Choosing the Dedicated Lane, Relative to Mainstream Vehicles Using General-Purpose Lanes, 5m Vehicle Clearance

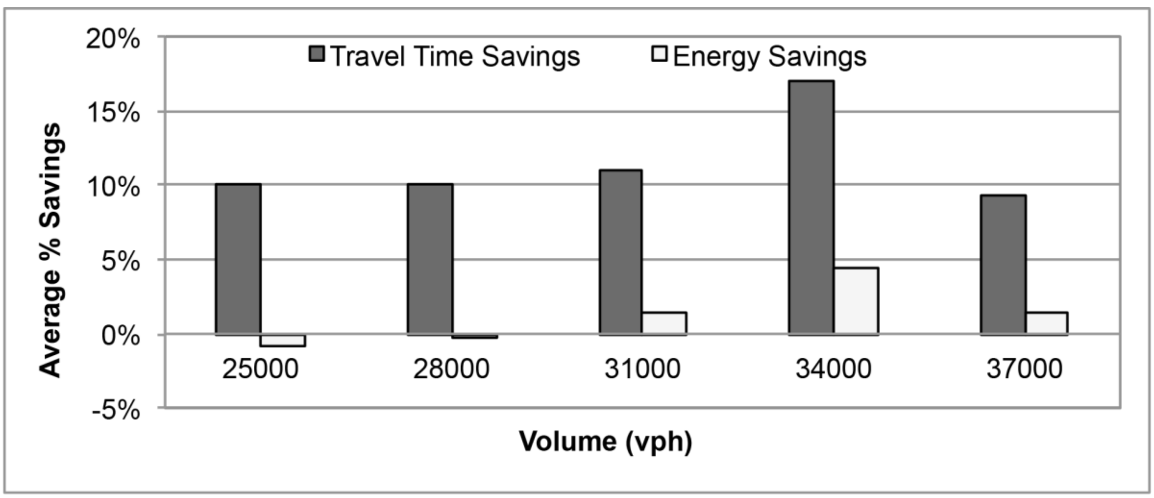


Figure 58: Average Benefits for Mainstream Vehicles Choosing the Dedicated Lane, Relative to Mainstream Vehicles Using General-Purpose Lanes, 15m Vehicle Clearance

Analysis of Number of Eco-CACC Eco-Lanes

Recall that network 1 (GHFN) consisted of two or three lanes, including a lane-drop, and that the two left-most lanes were set as dedicated lanes. As a result of the selection of two dedicated lanes, a merging protocol specifically designed to work with a single lane-drop was used in conjunction with the core Eco-CACC algorithm. The combination of the two algorithms proved to be highly effective, leading to benefits in travel time and energy more than 70 percent and 30 percent, respectively. Furthermore, the initial baseline capacity of approximately 3,600 vph was increased by two-thirds to 6,000 vph, with additional capacity benefits likely at higher volumes (greater than 6000 vph). In fact, to properly quantify the increase in capacity, a new plugin will need to be written that inserts platoons of vehicles, rather than inserting individual vehicles, into the network to achieve the desired hourly insertion rate. The selection of only a single dedicated lane for network 1 would have removed the necessity of applying the merging protocol. Future work involves testing the hypothesis that a single dedicated lane would be worse than two dedicated lanes with the merging protocol.

Network 2 (IHFN) consisted of four lanes with the left-most lane set as a dedicated lane. Because of the presence of off-ramps, a platoon-splitting protocol was implemented in addition to the Eco-CACC core. Another hypothesis that will be tested in future work is that the presence of two or more dedicated lanes is better than a single dedicated lane. Including more than one dedicated lane for network 2 will involve another layer of interaction and cooperation, namely inter-platoon interaction and cooperation. The developed protocols described in the “Algorithm” section of this chapter include intra-platoon cooperation, in which vehicles within a single platoon accommodate the merging or departure of a vehicle into or from a platoon. Inter-platoon cooperation may involve two or more platoons splitting to permit a vehicle to reach its desired exit.

Network 3 (SR-91 E) consisted of four to six mainstream lanes with the left-most lane set as a dedicated lane. Once again, the platoon-splitting protocol was included along with the Eco-CACC core. Because of the absence of lane-drops, the inclusion of the platoon-merging protocol was unnecessary. Based on the results for all three networks, it appears that the ratio of the number of dedicated lanes to total lanes is a significant factor in determining overall benefits. Accordingly, future work will consider conducting a sensitivity analysis on the number of dedicated Eco-CACC lanes within the SR-91 E freeway network. For each number of dedicated lanes, different auxiliary technologies may need to be applied to work in conjunction with Eco-CACC based on network geometry. The inclusion of all lanes as dedicated lanes will necessitate the creation of a merging protocol designed around on-ramps. The differences in relative speeds and the finite space of an on-ramp mean the new merging protocol will likely be more complex than the developed lane-drop merging protocol.

Findings and Opportunities for Future Research

Network 1: GHFN with Lane-Drop

As mentioned previously, a series of four sensitivity analyses were conducted for network 1 concerning—

a) Traffic volume
b) Penetration rate of Eco-CACC technology
c) Triggering distance
d) Intra-platoon clearance.

a) Traffic Volume

Summary

- A maximum savings of more than 70 percent and 30 percent were achieved in travel time and energy, respectively.
- The results provided indicate that the capacity is improved by at least two-thirds.

Conclusions

- Platooning increases traffic density and roadway capacity.
- The simultaneous increase in traffic density and vehicle cooperation leads to the maintenance of free-flow traffic at higher volumes than are normally possible for today's freeways.

Future Work

- Additional testing may be conducted at even higher traffic volumes to more adequately quantify the increase in network capacity resulting from Eco-CACC. In particular, the relationship between vehicle clearance (i.e., headway) to network capacity is of interest.

b) Penetration Rate of Eco-CACC Technology

Summary

- The higher the penetration rate, the greater the benefits in capacity improvement.

Conclusions

- The benefits in capacity improvement, travel time, and energy appear to be positively correlated with the penetration rate.
- Penetration rates less than or equal to 10 percent have little benefit because of the sparsity of platoons.
- Penetration rates greater than or equal to 60 percent have similar performance to a 100-percent penetration rate scenario (within the range of tested volumes).

Future Work

- A penetration rate sensitivity analysis may be conducted for both networks 2 and 3.
- Additional areas of interest include exploring and defining behavioral interactions between equipped and unequipped vehicles.

c) Triggering Distance

Summary

- Increasing the triggering distance results in a benefit of less than 3 percent for travel time and energy with respect to the baseline.

Conclusions

- Increasing the triggering distance influences how early a vehicle joins a platoon, the overall length of platoons, and, to a small degree, the number of vehicles involved in platooning behavior.
- Increasing triggering distance does not have a significant impact on overall network benefits.

Future Work

- Although triggering distance does not have a significant impact on overall network benefits, triggering distance in conjunction with various controller parameters and designs (see Appendix B) may have a moderate impact on individual vehicle performance.

d) Intra-Platoon Clearance

Summary

- Increasing the intra-platoon clearance results in a penalty of less than 1 percent for travel time and 2 percent for energy with respect to the baseline.

Conclusions

- Increasing intra-platoon clearance leads to increases in average platoon size and length (the number of vehicles within a platoon and the distance between the leader and the tail of the platoon, respectively).
- There is a slight tradeoff between overall capacity improvement and level of safety.

Future Work

- Although intra-platoon clearance does not have a significant impact on overall network benefits for the hypothetical freeway segment, the results may differ significantly on real-world networks such as the SR-91 E. The relationship between headway and overall network capacity is of particular interest.

Network 2: IHFN with a Dedicated Lane

Summary

- Benefits for volumes less than 6600 vph were 0 percent to 2 percent for travel time and 0 percent to 4 percent for energy.
- There is a significant improvement at volumes greater than 6600 vph, around 28 percent for travel time and 9 percent for energy at 7800 vph.
- At higher volumes, the dedicated lane energy savings increased to a maximum of 14 percent. In addition, the indirect benefit of non-dedicated lane energy savings reached roughly 4 percent at the highest volume.

Conclusions

- Even the presence of a single dedicated lane leads to a significant increase in overall network capacity.
- Vehicles may maximize their energy savings by choosing the dedicated lane. Vehicles that remain outside the dedicated lane still benefit indirectly in terms of travel time and energy.

Future Work

- Although the dedicated lane is the most energy efficient, it is not feasible for all drivers (under a 100 percent penetration rate scenario) to attempt to use the same lane at once. Additional research may be conducted to determine whether natural human decisionmaking is sufficient in preventing overcrowding of the dedicated lane, and whether an optimal lane selection strategy could substantially improve on human decision lane choices.

Network 3: SR-91 E Freeway with Dedicated Lane

Summary

- When the vehicle clearance parameter was set to 5 meters, the benefits ranged from 0 percent to 42 percent for travel time and 0 percent to 19 percent for energy.
- Likewise, when the vehicle clearance parameter was set to 15 meters, the benefits ranged from 0 percent to 24 percent for travel time and 0 percent to 13 percent for energy.
- The dedicated lane was 3 percent to 12 percent more energy efficient than the non-dedicated lanes, and 3 percent to 26 percent more energy efficient relative to the average baseline scenario lane.

Conclusions

- Even the presence of a single dedicated lane leads to a significant increase in overall network capacity.
- Vehicle clearance has a significant impact on overall network benefits because of its inverse relationship with overall network capacity.
- Vehicles may maximize their energy savings by choosing the dedicated lane. Vehicles that remain outside of the dedicated lane still benefit indirectly in terms of travel time and energy.

Future Work

- The application of Eco-CACC to more than one lane may result in even more dramatic increases in roadway capacity. The ratio of the number of dedicated eco-lanes to the total number of lanes may likely be one of the determining factors in terms of maximum possible benefits.
- Additional testing at higher volumes is necessary to quantify the differences in capacity between the 5-meter and 15-meter intra-platoon clearance parameter values.

Chapter 6. Combined Modeling of ESH and Eco-CACC

The combined modeling of the two applications within the Eco-Lanes Operational Scenario includes simulating both ESH and Eco-CACC on the SR-91 E freeway segment. The ESH application is described in Chapter 4, and the Eco-CACC application is described in Chapter 5. There are several ways the two technologies may be combined within a given network. The primary parameter involved with integrating ESH and Eco-CACC is in selecting which lanes are permitted for one or more of the technologies. Within the scope of the project, a single dedicated lane was reserved exclusively for Eco-CACC and the remaining general purpose lanes were set as ESH lanes. All vehicles are assumed to be equipped with both ESH and Eco-CACC technology.

Hypothesis

The hypothesis is that the combination of ESH with Eco-CACC will provide small energy benefits in the range of 0 percent to 5 percent added to the benefits shown for the independent Eco-CACC results. The mobility benefits are expected to fall within the range of plus or minus 5 percent savings added to the independent Eco-CACC results.

Algorithm

The combined application uses the algorithms detailed in Chapters 4 and 5. The ESH portion is similar to the independent ESH modeling with the exception that it is not applied to the left-most lane. In addition, several parameters in the ESH algorithm were modified to account for the increased capacity resulting from the combination with Eco-CACC. Specifically, the interval parameter was set to 60 seconds, the segment length was set to 500 meters, and the speed threshold was set to 70 mph. The parameters “a” and “b” in the linear equation referenced were set to 0.7797 and 7.6503, respectively. The Eco-CACC portion is identical to the independent Eco-CACC modeling. The specific parameters used are described in the results section.

Modeling Approach and Scenarios

The combined modeling used the same SR-91 E freeway network used for independently testing ESH and Eco-CACC.

Results

Network 3: SR-91 E Freeway with Dedicated Eco-CACC Lane and General Purpose ESH Lanes

A set of experiments similar to the ones presented in Chapter 5 concerning Eco-CACC applied to network 3 were repeated for testing the combined modeling on network 3. A single sensitivity analysis for traffic volume was conducted. The total hourly traffic volume entering the network varied between 25,000 vehicles and 37,000 vehicles total in increments of 3,000. A constant demand profile was used. The simulation time selected was 2 hours, with separate profiles used for each hour. The case of 25,000 vehicles was based on calibration of real-world data. A single light-duty vehicle type was used during the simulations. The left-most lane was set as a dedicated lane for Eco-CACC platoons and the remaining lanes were set as ESH lanes. All vehicles were permitted to use the dedicated lane. Vehicles in platoons that are close to their desired exit initiate the platoon-splitting protocol. The platoon-merging protocol is not applied to the network because of the absence of lane-drops. Unless otherwise stated, the following results are network-wide results including all vehicles across all lanes.

Traffic Volume Sensitivity Analysis

For the traffic volume sensitivity analysis, penetration rates of 100 percent and 0 percent were tested over the following traffic volumes: 25,000; 28,000; 31,000; 34,000; and 37,000 vph. The triggering distance, or distance threshold when vehicles will trigger platoon-forming behavior, was set at 40 meters. The vehicle clearance parameter was set at 5 meters.

As Figure 59 through Figure 62 and Table 26 through

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
25000	4.24%	4.24%	12.87%	6.55%	6.47%	9.23%	-1.27%
28000	4.41%	4.41%	12.30%	6.64%	6.40%	9.15%	-0.10%
31000	7.17%	7.17%	19.93%	12.49%	9.21%	18.82%	3.36%
34000	18.39%	18.39%	34.76%	30.08%	16.99%	38.88%	25.33%
37000	21.61%	21.61%	29.99%	30.41%	17.92%	36.16%	33.77%

Table 29 show, the combination of Eco-CACC on a dedicated lane and ESH on the remaining lanes leads to significant energy and mobility savings relative to the baseline scenarios for higher traffic volume tests. The benefits ranged from 4 percent to 22 percent savings for energy and -1 percent and 33 percent savings for travel time. With the exception of the highest volume tested, the benefits of the combined modeling over just Eco-CACC applied to a single dedicated lane were 4 percent to 5 percent for energy and -1.5 percent to 1.5 percent for travel time. Additional testing, accompanied by further parameter tuning and algorithm modification, needs to be conducted to verify the effect of incorporating ESH at high traffic volumes on travel times. In a deployment scenario, parameters may need to be adjusted based on current traffic volume estimates. Irrespective of a slight penalty to the benefits of travel time, the results indicate that the further addition of ESH to Eco-CACC does slightly increase the overall energy benefits.

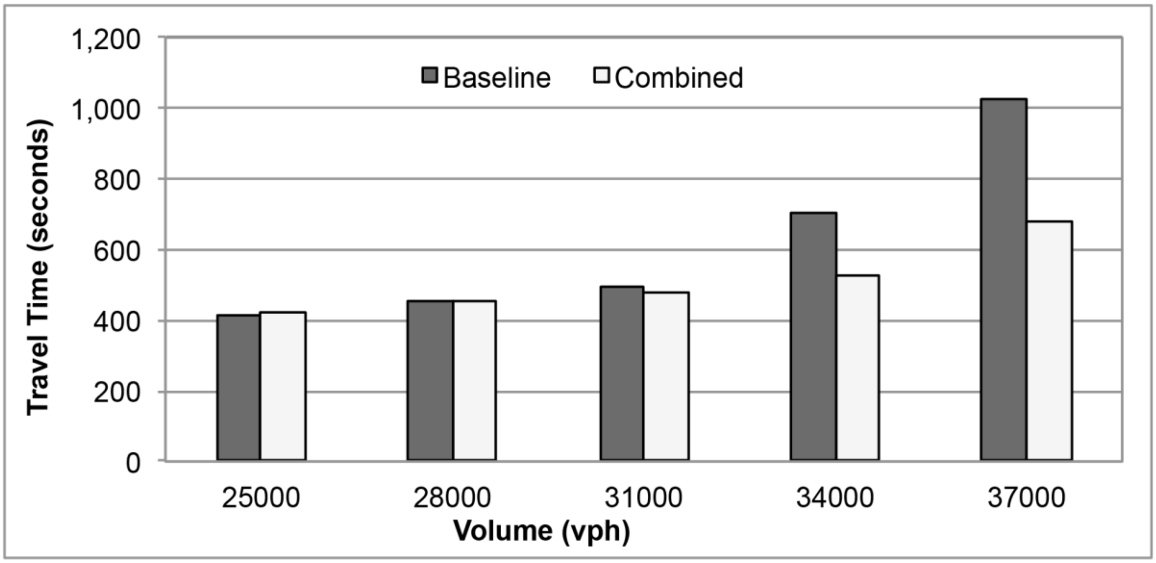


Figure 59: Average Travel Time versus Traffic Volume for 0-Percent and 100-Percent Penetration Rates, 5m Vehicle Clearance

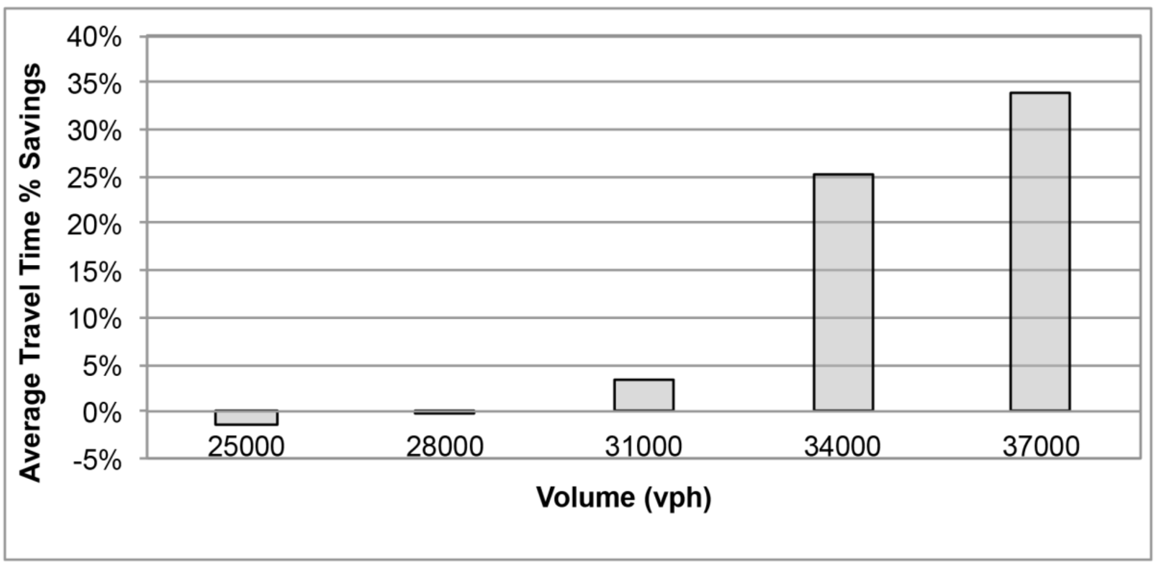


Figure 60: Average Travel Time Percent Savings versus Traffic Volume for 100-Percent versus 0-Percent Penetration Rates, 5m Vehicle Clearance

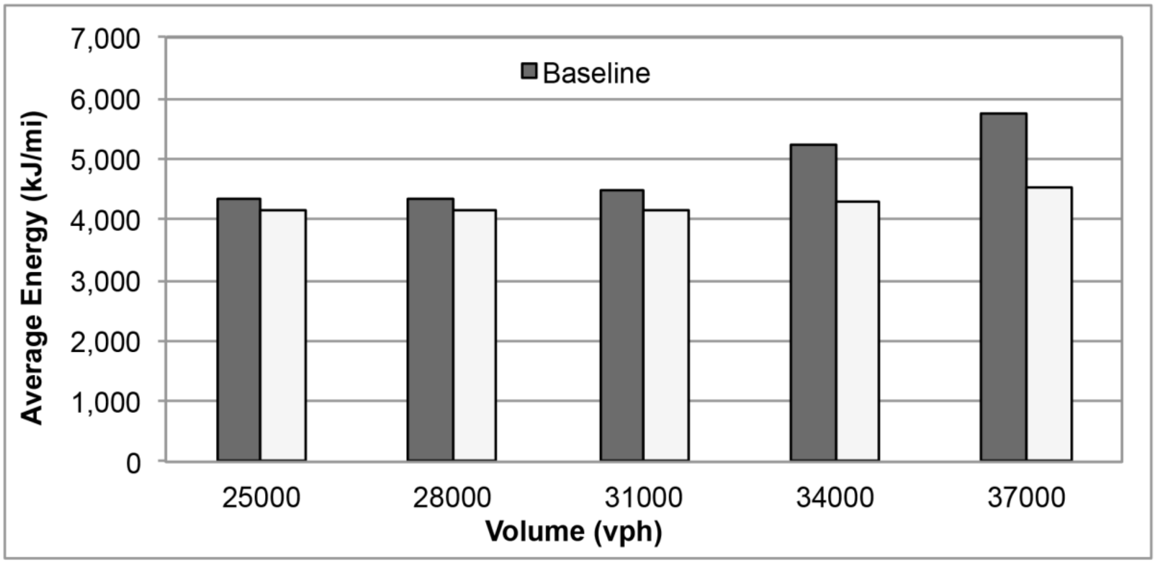


Figure 61: Energy versus Traffic Volume for 0-Percent and 100-Percent Penetration Rates, 5m Vehicle Clearance

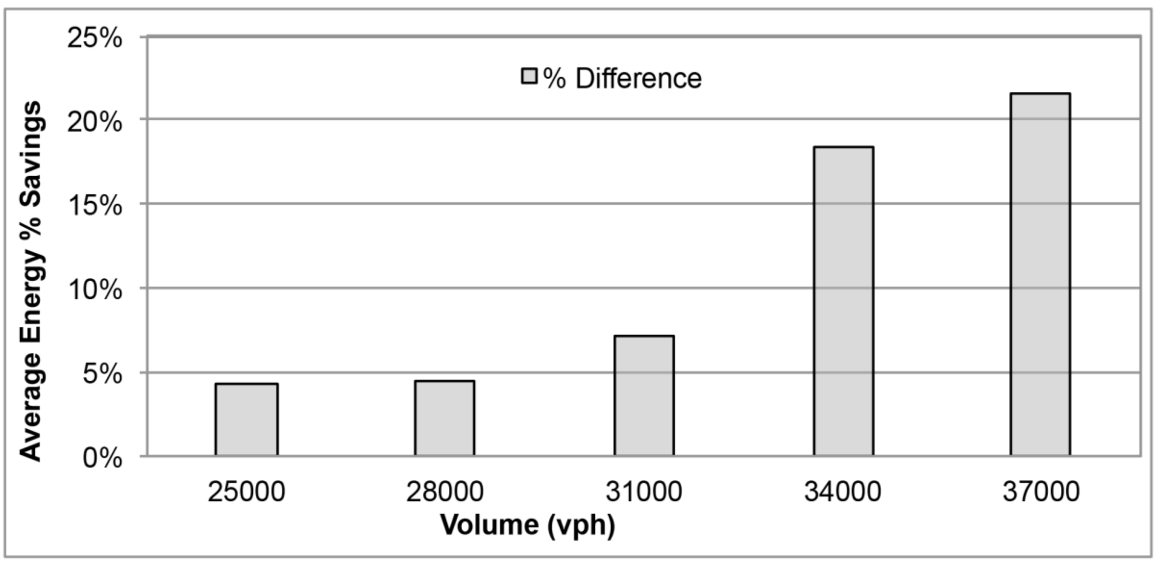


Figure 62: Energy Percent Savings versus Traffic Volume for 100-Percent versus 0-Percent Penetration Rates, 5m Vehicle Clearance

Table 26: Baseline, Traffic Volume Sensitivity Analysis Results

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
25000	4320.6885	310.5274	3.8453	0.1404	0.7533	0.0143	413.8942
28000	4341.5825	312.0290	3.9371	0.1421	0.7579	0.0145	450.1636
31000	4491.1921	322.7814	4.4314	0.1538	0.7859	0.0166	498.2444
34000	5235.4219	376.2688	5.9993	0.2046	0.8833	0.0245	702.3228
37000	5754.3728	413.5655	6.5284	0.2355	0.9220	0.0274	1022.4019

Table 27: Combined Modeling, Traffic Volume Sensitivity Analysis Results, 5m Vehicle Clearance

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
25000	4137.5371	297.3642	3.3504	0.1312	0.7045	0.0130	419.1689
28000	4150.2801	298.2801	3.4527	0.1327	0.7095	0.0132	450.6334
31000	4169.1533	299.6365	3.5482	0.1346	0.7135	0.0134	481.5282
34000	4272.5162	307.0651	3.9142	0.1430	0.7332	0.0150	524.4014
37000	4510.8661	324.1951	4.5703	0.1639	0.7567	0.0175	677.1665

Table 28: Percent Improvement of Combined Modeling Over Baseline, Traffic Volume Sensitivity Analysis Results, 5m Vehicle Clearance

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
25000	4.24%	4.24%	12.87%	6.55%	6.47%	9.23%	-1.27%
28000	4.41%	4.41%	12.30%	6.64%	6.40%	9.15%	-0.10%
31000	7.17%	7.17%	19.93%	12.49%	9.21%	18.82%	3.36%
34000	18.39%	18.39%	34.76%	30.08%	16.99%	38.88%	25.33%
37000	21.61%	21.61%	29.99%	30.41%	17.92%	36.16%	33.77%

Table 29: Relative Percent Improvement of Combined Modeling Over Eco-CACC, Traffic Volume Sensitivity Analysis Results, 5m Vehicle Clearance

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
25000	4.17%	4.17%	13.33%	6.75%	6.43%	9.68%	-1.54%
28000	3.70%	3.70%	11.78%	5.92%	5.80%	7.59%	-0.67%
31000	4.31%	4.31%	13.29%	7.17%	6.60%	9.61%	-0.68%
34000	4.53%	4.53%	10.86%	6.65%	6.27%	6.56%	1.74%
37000	2.39%	2.39%	6.83%	1.34%	6.44%	3.12%	-9.07%

Traffic Network Savings versus Dedicated Lane Savings

The average energy savings considering the entire network (Figure 63) differs from the average energy savings experienced in the dedicated lane. Energy data for the dedicated lane was defined as the aggregation of energy data for vehicles while they were on the dedicated lane. Therefore, if a vehicle changes lanes into the dedicated lane, energy data is accumulated as long as the vehicle remains in the dedicated lane. If a vehicle changes lanes from the dedicated lane, that vehicle no longer contributes energy data to the dedicated lane analysis. Note that vehicles with different routes use the dedicated lane. Furthermore, based on the aforementioned definition, there is no corresponding dedicated lane travel time definition due to lane changes and diverse routes. In addition to showing the dedicated lane savings, Figure 63 shows the average savings for the remaining lanes. Figure 64 shows the relative benefit of choosing the dedicated lane over a non-dedicated lane.

As Figure 63 shows, at lower traffic volumes, the general purpose lanes experience a greater energy savings than the dedicated lane. However, at the highest traffic volume, the dedicated lane experiences a greater energy savings than the general purpose lanes. The energy savings at lower traffic volumes are higher for the general purpose lanes than the dedicated lane because of the small energy needed for platoon formation. At the highest traffic volume, the energy savings are greatest for the dedicated lane as result of the increased capacity provided by Eco-CACC.

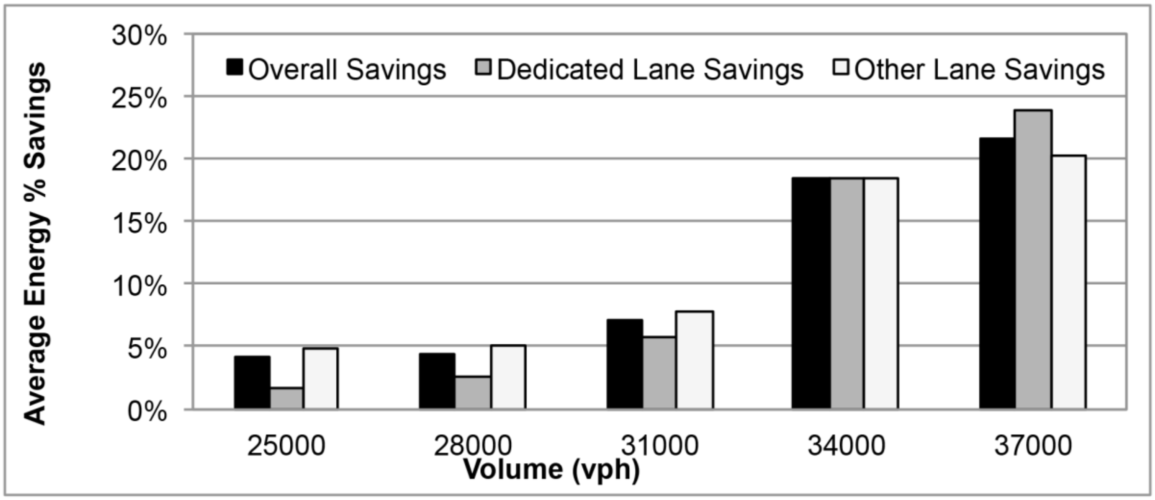


Figure 63: Dedicated Lane Energy Savings versus Traffic Volume, 5m Vehicle Clearance

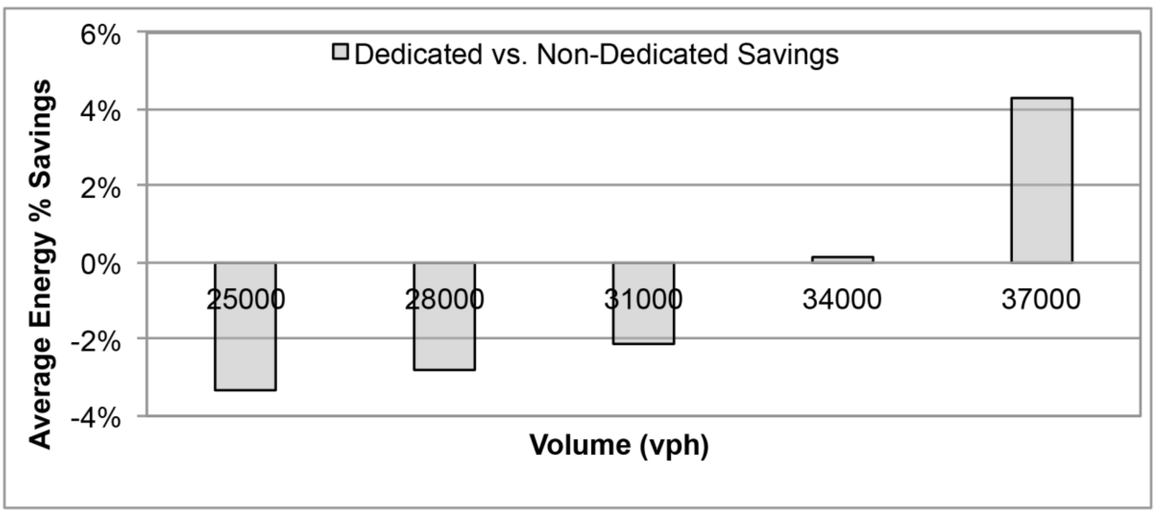


Figure 64: Relative Benefit of Dedicated Lane versus Non-Dedicated Lane Savings, 5m Vehicle Clearance

Benefits for Mainstream Vehicles Choosing the Dedicated Lane

In addition to aggregating data by lane, data may also be aggregated for vehicles following a specific route. The selected route that made the most use of the dedicated lane was the mainstream route. The mainstream route was defined as the only two routes not including on-ramps or off-ramps. Along the mainstream route, data collection was further divided among vehicles that chose to use the dedicated lane and vehicles that did not choose the dedicated lane. Figure 65 shows the relative travel time and energy benefits of choosing the dedicated lane versus a non-dedicated lane.

As Figure 65 shows, vehicles that choose the dedicated lane receive a travel time benefit of more than 10 percent with a slight energy penalty of at most -3 percent relative to mainstream vehicles that do not use the dedicated lane. Conversely, vehicles that remain in the general purpose lanes receive a slight energy benefit, accompanied with a moderate loss in terms of potential travel time savings. It should be noted that the dedicated lane savings for vehicles choosing the dedicated lane are indeed positive relative to the no-technology baseline. Both the dedicated lane and the general purpose lanes experience significant energy and travel time savings because of the combination of ESH and Eco-CACC, as

Volume (vph)	Energy (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM2.5 (g/mi)	VHT (s/veh)
25000	4137.5371	297.3642	3.3504	0.1312	0.7045	0.0130	419.1689
28000	4150.2801	298.2801	3.4527	0.1327	0.7095	0.0132	450.6334
31000	4169.1533	299.6365	3.5482	0.1346	0.7135	0.0134	481.5282
34000	4272.5162	307.0651	3.9142	0.1430	0.7332	0.0150	524.4014
37000	4510.8661	324.1951	4.5703	0.1639	0.7567	0.0175	677.1665

Table 28 and Figure 63 show. On top of the base network-level benefits and because of the variation in benefits between the dedicated lane and the general purpose lanes, drivers can choose whether they want to maximize their benefits in terms of travel time or energy depending on observed traffic conditions and driver preference. The results that Figure 65 show indicate that the indirect energy benefit CACC provides to the general purpose lanes plus the small energy benefits provided by ESH actually slightly outweigh the CACC energy benefits (minus the energy expenditure involved with platoon formation) in the dedicated lane itself.

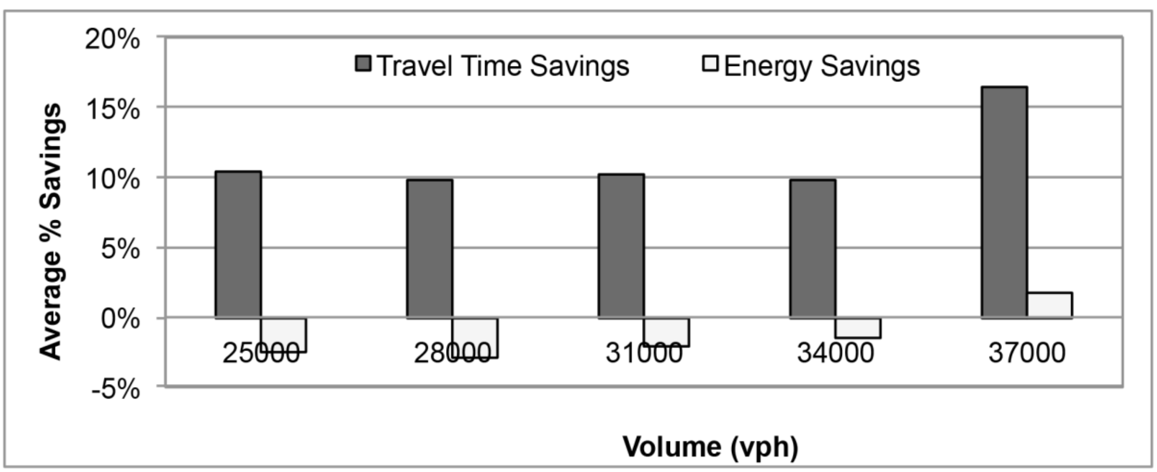


Figure 65: Average Benefits for Mainstream Vehicles Choosing the Dedicated Lane Relative to Mainstream Vehicles Using General-Purpose Lanes, 5m Vehicle Clearance

Findings and Opportunities for Future Research

Summary

- The overall network benefits ranged from 4 percent to 22 percent savings for energy and -1 percent to 33 percent savings for travel time.
- With the exception of the highest volume tested, the benefits of the combined modeling over just Eco-CACC applied to a single dedicated lane were 4 percent to 5 percent for energy and -1.5 percent and 1.5 percent for travel time.
- At lower traffic volumes, the general purpose lanes experience a greater energy savings than the dedicated lane. In contrast, at the highest traffic volume, the dedicated lane experiences a greater energy savings than the general purpose lanes.
- Vehicles that choose the dedicated lane receive a travel time benefit of more than 10 percent with a slight energy penalty of at most -3 percent relative to vehicles that do not select a dedicated lane.

Conclusions

- The combination of ESH and Eco-CACC leads to a slight penalty in travel time and a small benefit in energy relative to Eco-CACC testing.
- The energy savings at lower traffic volumes are higher for the general purpose lanes than the dedicated lane because of the small energy needed for platoon formation.
- At the highest traffic volume, the energy savings are greatest for the dedicated lane because of the increased capacity provided by Eco-CACC.
- Based on observed traffic conditions and driver preference, drivers can choose whether they want to maximize their benefits in terms of travel time or energy by choosing an appropriate lane (either the dedicated lane with Eco-CACC or the general purpose lanes with ESH).

Future Work

- Additional parameter selection and algorithm design for the ESH component of combined modeling is necessary before drawing any definitive conclusions on the application of ESH along with Eco-CACC.
- Additional parameter requirements could be considered related to the types of vehicles that will be allowed to use the eco-lane(s).
- Further research may be conducted on applying ESH and Eco-CACC on a single lane and perhaps ultimately even applying the two technologies together across all lanes.
- One potential scenario is a vehicle equipped with only one of the two technologies (e.g., a vehicle equipped for ESH but not for Eco-CACC). More complex vehicle interactions may be necessary to ensure driver safety.

Appendix A. List of Acronyms

Acronym	Definition
AERIS	Applications for the Environment: Real-Time Information Synthesis
ACC	Adaptive Cruise Control
API	Application Programming Interface
BAA	Broad Agency Announcement
BCA	Benefit-Cost Analysis
CACC	Cooperative Adaptive Cruise Control
CO	Carbon Monoxide
CO_2	Carbon dioxide
CV	Connected Vehicle
Eco-CACC	Eco-Cooperative Adaptive Cruise Control
ESH	Eco-Speed Harmonization
GHFN	Generic Hypothetical Freeway Network
GHG	Greenhouse Gases
GPS	Global Positioning System
HC	Hydrocarbons
IHFN	Intermediate Hypothetical Freeway Network
HOV	High-Occupancy Vehicle
ITS	Intelligent Transportation System
KPH	kilometers per hour
LOS	Level of Service
MOVES	MOtor Vehicle Emission Simulator
MOE	Measure of Effectiveness
NO_X	Nitrous Oxides
OBE	On-board Equipment
OD	Origin-Destination
PATH	Partners for Advanced Transportation TecHnology
PM	Particulate Matter

Acronym	Definition
RNG	Random Number Generator
RSE	Roadside Equipment
SCAG	Southern California Association of Governments
SH	Speed Harmonization
SPaT	Signal Phase and Timing
TC	Transformative Concept
TMC	Traffic Management Center
UCR	University of California Riverside
V/C	Volume to Capacity Ratio
VHT	Vehicle–Hours Traveled
VMT	Vehicle Miles Traveled
VPH	Vehicles per Hour
VSL	Variable Speed Limit

Appendix B. Candidates of Eco-CACC Controllers

There are at least three defining features of any CACC controller: 1) the regulator type (e.g., spatial or temporal), 2) the controller structure (e.g., P, PD, or PID), and 3) the constraints incorporated. In Table 30, the controller structure is assumed to be based on proportional control. Future work will look at comparing various control structures.

Table 30: Eco-CACC Controller Options

<table>
<tr><th>Constraints \ Regulator Type</th><th>Spatial</th><th>Temporal</th></tr>
<tr><td>No Constraints</td><td>Figure B.1</td><td>Figure B.3</td></tr>
<tr><td>+ Acceleration Constraints</td><td>Figure B.2</td><td rowspan="2">Figure B.4</td></tr>
<tr><td>+ Spatial Constraints</td><td>n/a</td></tr>
</table>

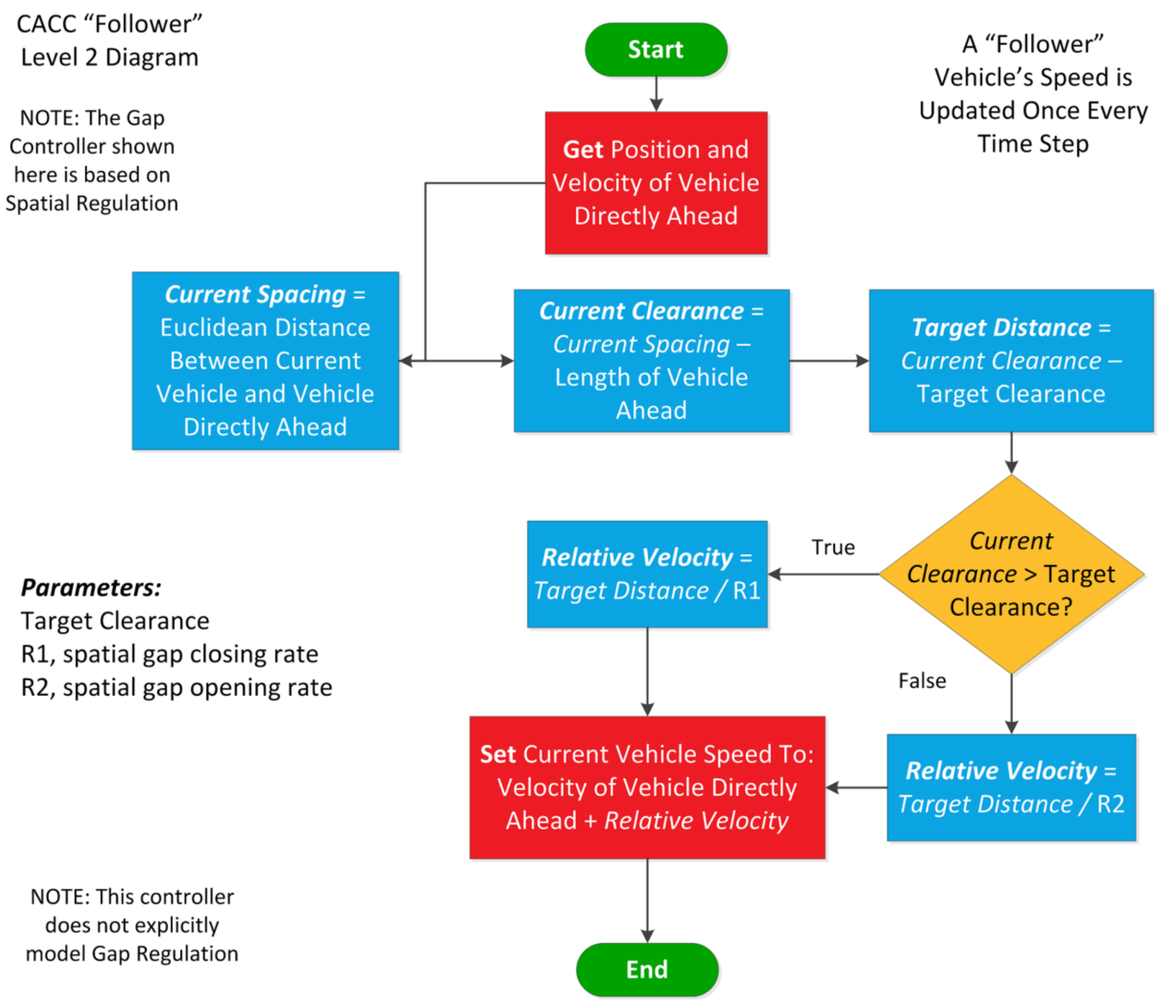


Figure 66: Spatial Regulator

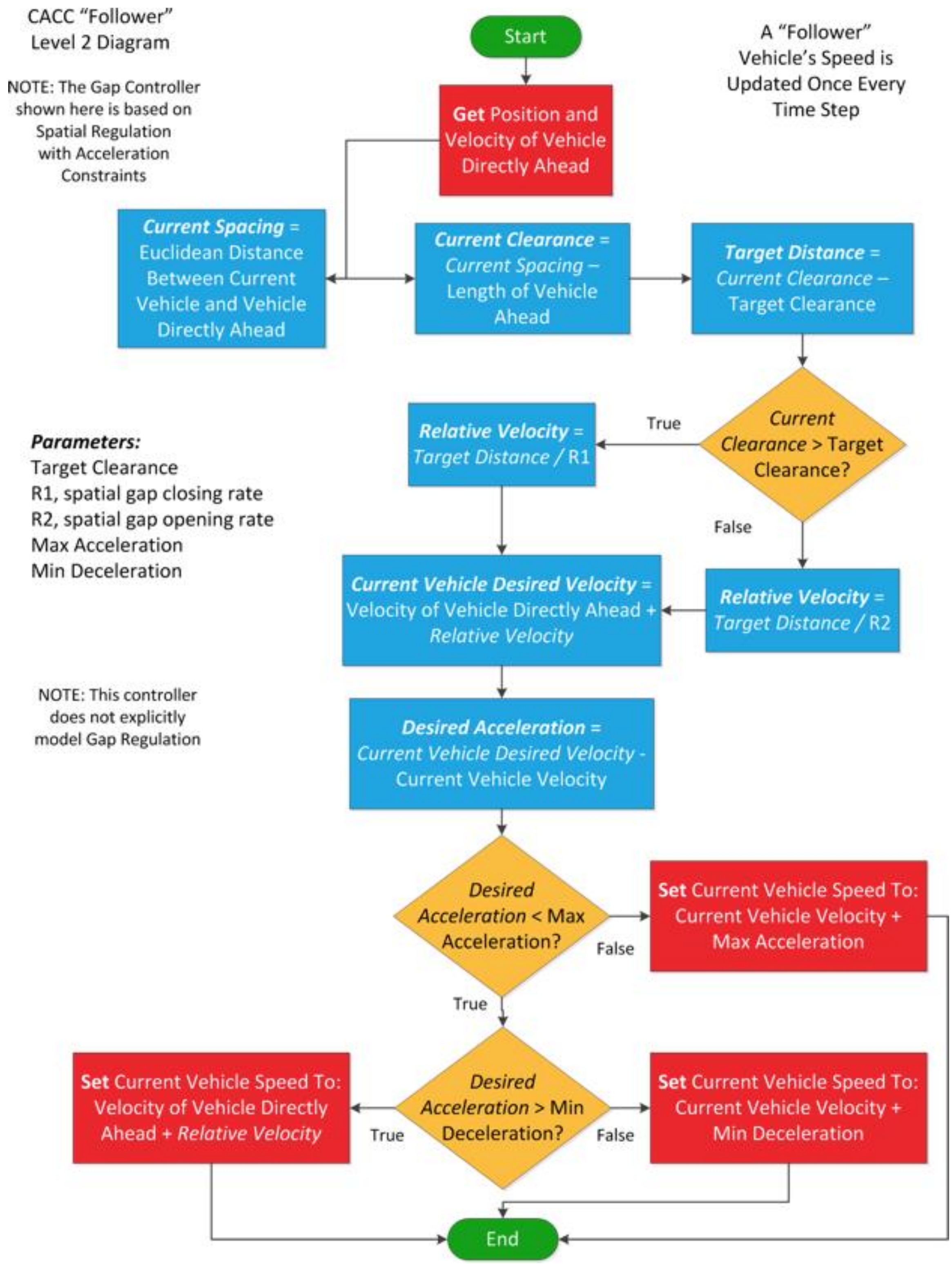


Figure 67: Spatial Regulator with Acceleration Constraints

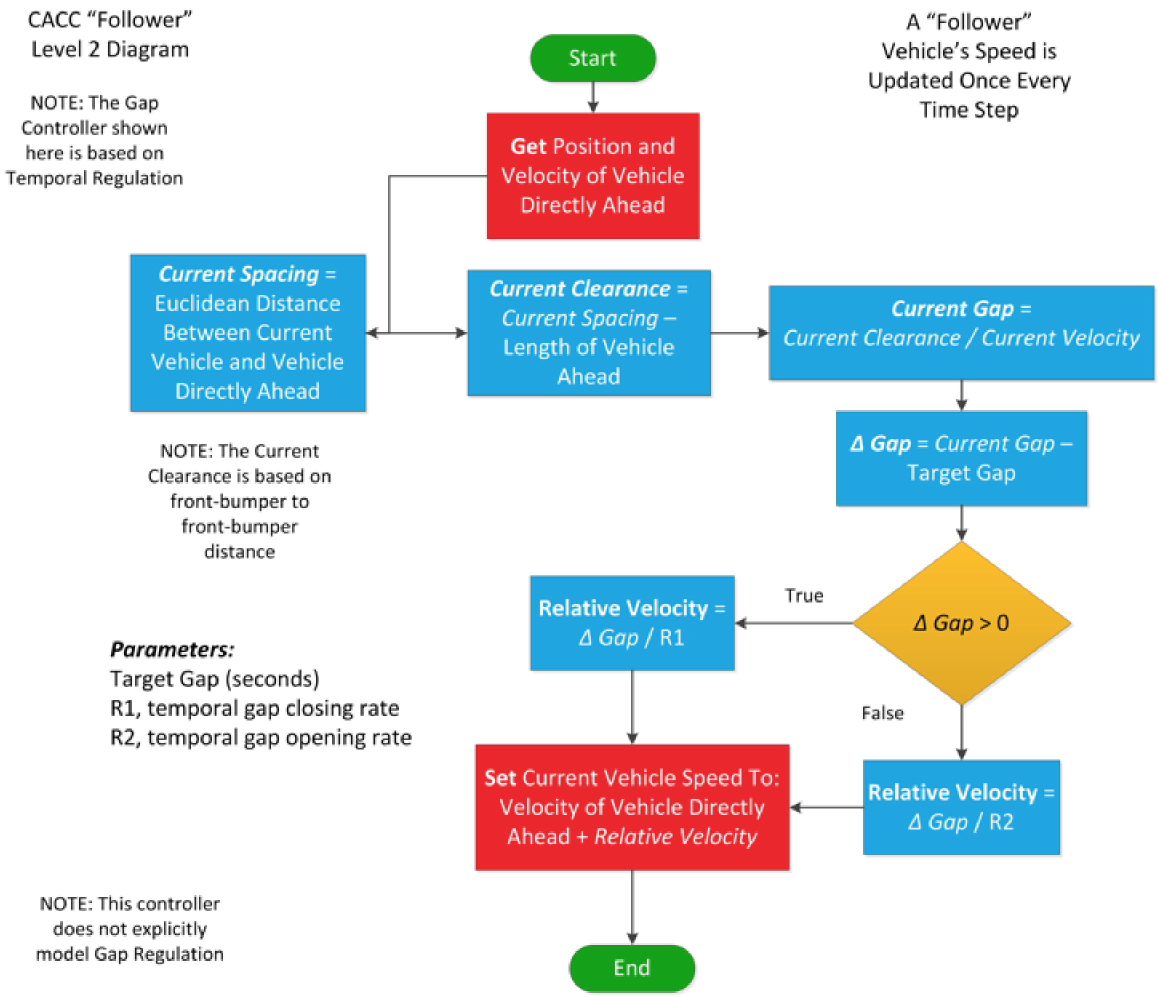


Figure 68: Temporal Regulator

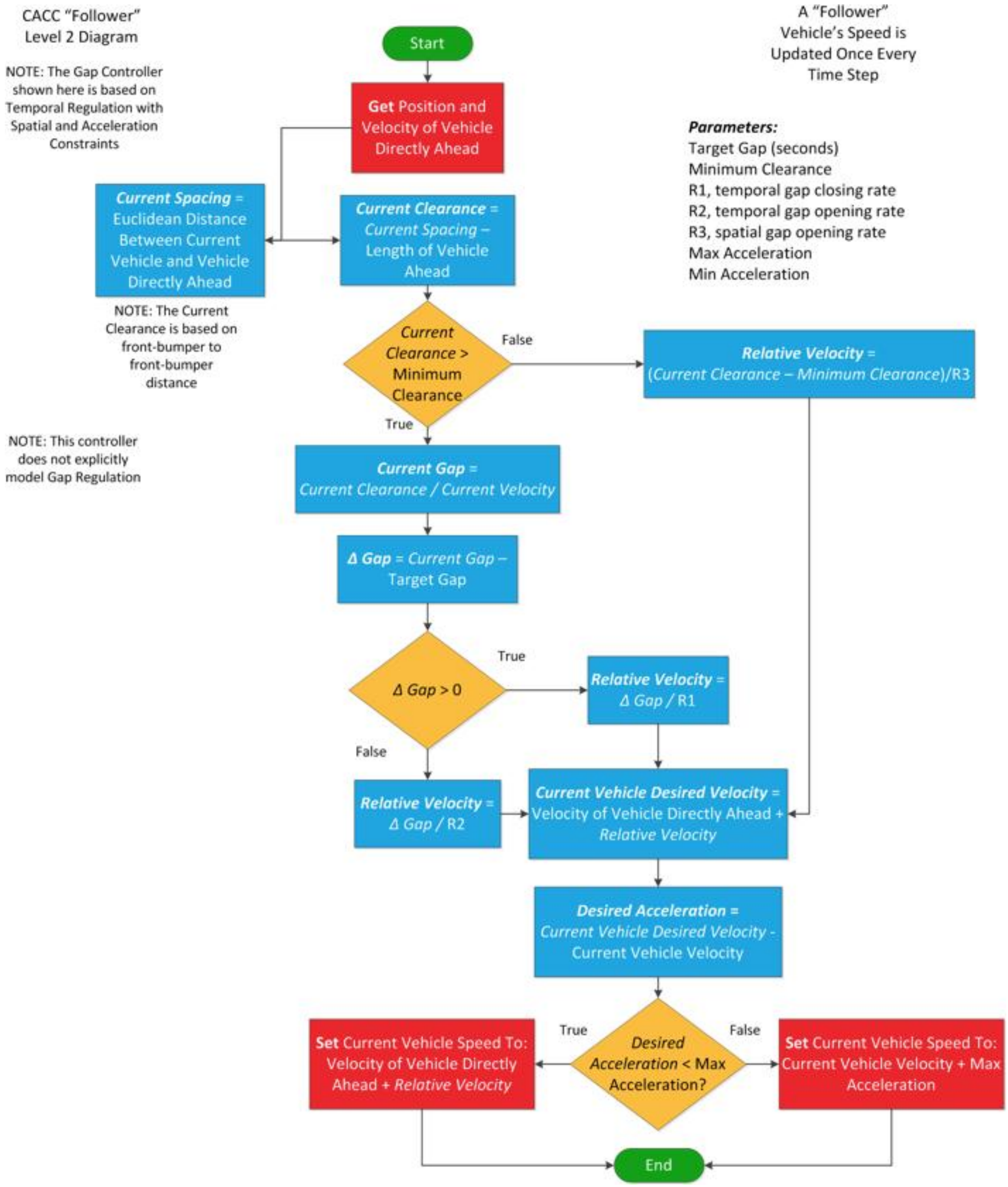


Figure 69: Temporal Regulator with Spatial and Acceleration Constraints

Appendix C. Benefit-Cost Analysis

The purpose of the BCA described in this appendix is to estimate the magnitude of the environmental benefits (i.e., GHG and criteria pollutant emission reductions and reduced fuel use) of the AERIS Program in future years. The BCA evaluates the applications individually and as a bundle. This section documents the methodology and results of the BCA of the Eco-Lanes Operational Scenario. Before building the model for the BCA of AERIS applications, several assumptions were made. The approach, assumptions, and results of the BCA are presented in the following sections.

BCA Approach

A brief summary of the approach to developing the BCA model is presented in the following sections.

Overall Approach. Figure 70 illustrates the overall approach of the BCA. Many of the following steps required substantial input from the AERIS team, including stakeholders (e.g., Federal Transit Administration) and CV experts (e.g., CV researchers); the AERIS team collaborated closely to ensure consensus on the baseline assumptions, benefit categories, and cost assumptions. In addition, the approach and cross-cutting assumptions were vetted within the ITS JPO. The baseline assumptions are used for each of the subsequent steps of the BCA and provide a benchmark against which to compare the relative results for each of the applications. The BCA was conducted in two parallel work streams, one for benefit estimation and the other for cost estimation. The results of benefit and cost estimations were then input into the model, which extrapolated results to the entire nation and provided results for each year in the analysis.

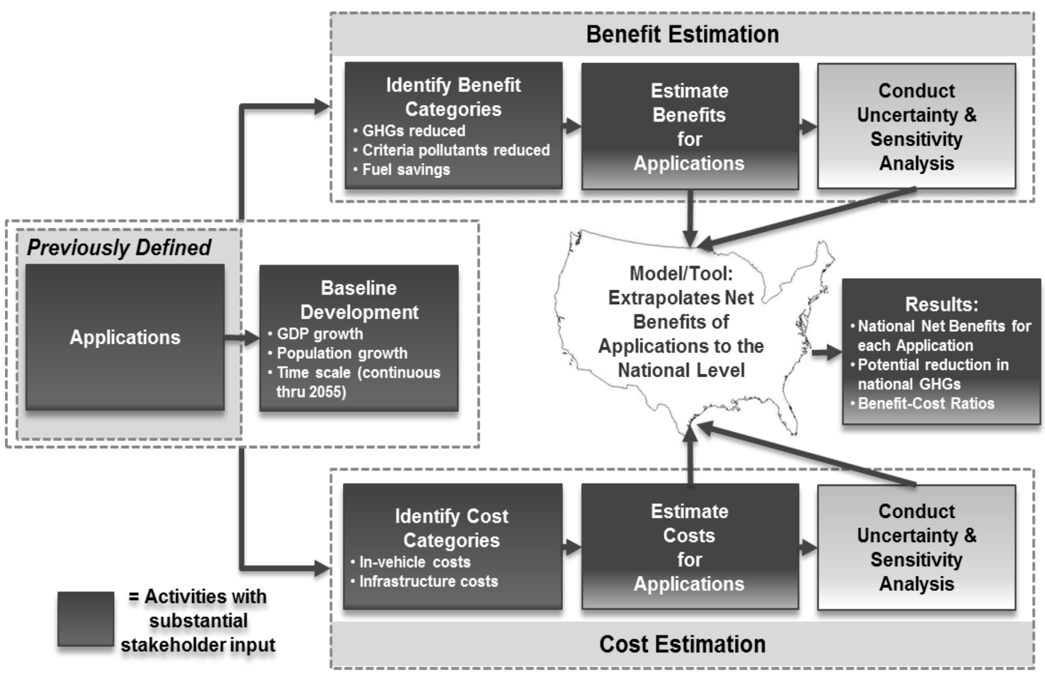


Figure 70: BCA Approach

Key Assumptions. Multiple assumptions impacted the results of the analysis. Significant assumptions are—

- Only incremental costs attributable to AERIS were considered, so the CV infrastructure was assumed to already be in place.
- Only the following environmental benefits were considered: GHG reductions, criteria pollutant reductions, and fuel savings.
- Mobility (i.e., travel time savings) and safety benefits were not investigated.
- Cost data were derived from the ITS Cost-Benefit Database.
- The benefits were estimated using the modeling results.
- In most cases, the most conservative assumptions (i.e., cautious, limited assumptions) were used.

A number of variables had a significant impact on the estimate of benefits:

- **OBE Deployment Rate.** OBEs connect vehicles by receiving and transmitting information; they enable the use of an application. The number of vehicles with OBEs will have a direct impact on the potential benefits that can be realized by an application.
- **RSE Deployment Rate.** Traffic signal-based applications require RSEs at signals to receive and transmit data; RSEs enable the use of these applications. The number of road junctions with RSEs will directly impact the potential benefits that can be realized by the signal-based applications.
- **AERIS Application Deployment Rate.** In addition to the ability to communicate via OBEs and RSEs, the applications will have to be deployed or purchased. Not every jurisdiction or vehicle owner will purchase the application, and deployment will likely occur in a phased manner. The deployment of the applications will directly impact the potential benefits that can be realized by an application at the national level.
- **AERIS Application Compliance Rate.** Even if the ability to communicate is enabled and the application is deployed, there is a third factor, known as the compliance rate, which impacts the benefits of an application. There are two types of compliance—agency and driver. For those applications with components installed within the infrastructure, the jurisdiction may decide to enable or disable the application under certain circumstances; the proportion that it is expected to be turned on is defined as the Agency Compliance Rate. Similarly, for those applications that provide advice to the driver, the driver has the choice of whether to comply (i.e., the Driver Compliance Rate). These two factors directly impact the potential benefits that an application may yield at the national level.
- **Fuel Price Projection.** The price of fuel (motor gasoline) is a significant factor in the baseline scenario. The price is used to quantify the value of a gallon of fuel saved for benefit estimation. In addition, the price of fuel is correlated with the vehicle miles traveled (VMT), which is an important variable in the baseline scenario. The higher the price of fuel, the less VMT and the smaller the potential for benefit realization from the applications.

Baseline Development. A baseline scenario with projections of vehicle and transportation infrastructure (e.g., traffic signals), behavior (e.g., public transit ridership), and technology (e.g., vehicle fuel efficiency) was developed to evaluate the world without AERIS through 2055 for the entire United States. The baseline scenario includes assumptions about the deployment of OBE, RSE, and applications. However, these applications are assumed to be used to support only safety, mobility, and security system management goals and exclude environmental benefits. In addition, there are a number of other factors that will influence the impacts of applications in the future, including the price of fuel, the amount of VMT, and the fuel efficiency of vehicles. These are included in the baseline. Thus, the baseline scenario is used to measure the relative performance of the individual applications to reduce GHG and criteria emissions and reduce fuel consumption.

Benefit Estimation. This BCA focused on the environmental benefits; therefore, the mobility (i.e., travel time savings) and safety benefits or disbenefits are not assessed. The focus is air-related environmental benefits, namely GHG and criteria pollutant emissions (such as nitrous oxides). Reducing GHG and criteria air pollutant emissions has direct and indirect benefits, and their value (including health impacts, visibility, and climate change) is captured in the monetary valuation of the benefit categories. In addition, the direct benefits of fuel savings are evaluated in the BCA. Once the benefit categories were identified, estimation of those categories was conducted in the high-level steps described next for each application. Modeling results were used to estimate unit benefits that each application might realize. The values were normalized to a unit basis depending on the type of application (e.g., gallons per VMT). The unit benefits were assigned a monetary value based on the social and monetary costs associated with the benefit categories.

Cost Estimation. The cost estimation process was conducted by exercising four high-level steps and was repeated for each application. The first step was to identify the individual cost elements required to enable the functionality of each application. A number of the infrastructure- and technology-related costs required to enable the use of the CV applications considered in this study are expected to be sunk costs that will be incurred whether or not these applications are implemented. It is important to emphasize that this BCA measures only the incremental cost of implementing these environmentally optimized applications and does not analyze the costs associated with equipment assumed to be in place in the future (e.g., CV RSE).

Figure 71 provides the baseline cost elements that were not accounted for in the BCA, for reasons described earlier. It also shows the cost elements for each of three major categories: infrastructure, in-vehicle, and operation and maintenance costs that are attributed to the AERIS applications. It should be noted that not all of the applications will require each of the cost elements.

Category	Cost Element
Baseline	Roadside Equipment (RSE) units On-Board Equipment (OBE) units Telecom Backhaul The Connected Vehicle Core System Traffic Signal Systems On-Board Display Vehicle Longitudinal Control Powertrain Control
Infrastructure	Closed Circuit Television Cameras Road Signs Environmental Sensors Ramp Meters
In-Vehicle	On-Board Equipment, (marginal costs to integrate application)
Operation and Maintenance	System Integration & Back Office Online Presence Application Development Education & Outreach Telecom Backhaul, (marginal costs to process environmental data) Non-DSRC communication (i.e. cellular)

These costs are not included in BCA; as it is assumed that connected vehicle infrastructure exist

These costs are attributed to AERIS applications; Only *incremental* costs to install and operate AERIS applications above and beyond those costs in the baseline

Figure 71: Cost Elements

National Extrapolation. Estimating unit benefits and costs for each application and developing the baseline provided the basic information for extrapolating the analysis to the nation. However, it is recognized that transportation and infrastructure characteristics (e.g., number of traffic signals) vary widely between cities (e.g., urban versus rural) within the United States. To account for this variability, a model and tool was developed for this analysis. The tool has transportation-specific projections for a set of six “representative areas.” It takes into account the differences in urban versus rural areas, large versus small cities, and very densely populated cities versus cities with larger footprints. Figure 72 illustrates the key differentiators of the six representative areas.

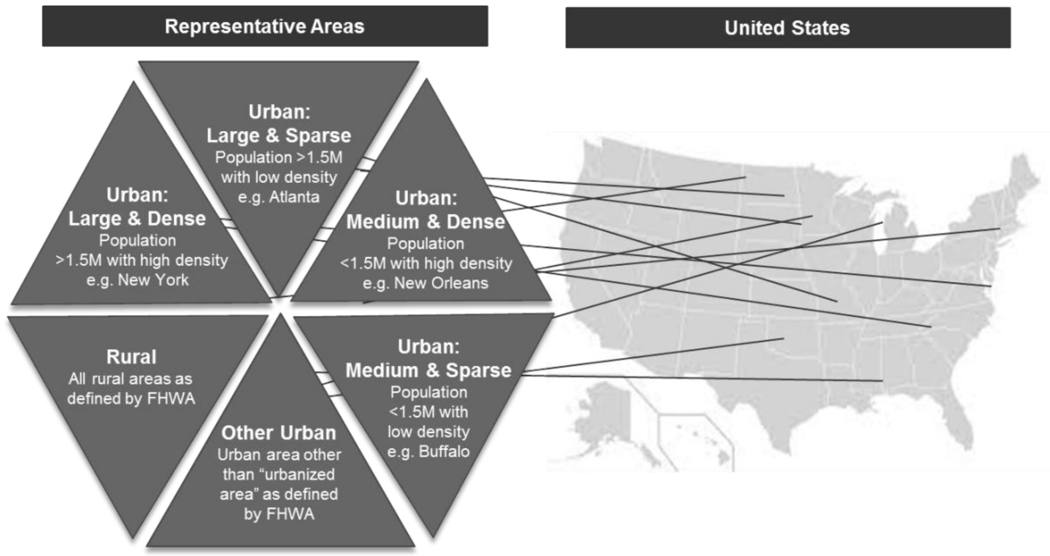


Figure 72: Extrapolation Approach

The representative area transportation statistics, along with unit costs and benefits and the baseline, are all employed in a model developed for the purpose of this BCA. Figure 72 is a representation of the model. The unit values for each application are inputs, and the deployment rate for the application, CV infrastructure, and compliance rates determines how often the application can potentially be used. Finally, the baseline scenario assumptions determine the underlying changes in transportation over time (e.g., VMT). This information works together to produce the annual net benefit results; Figure 73 shows the overall model functionality.

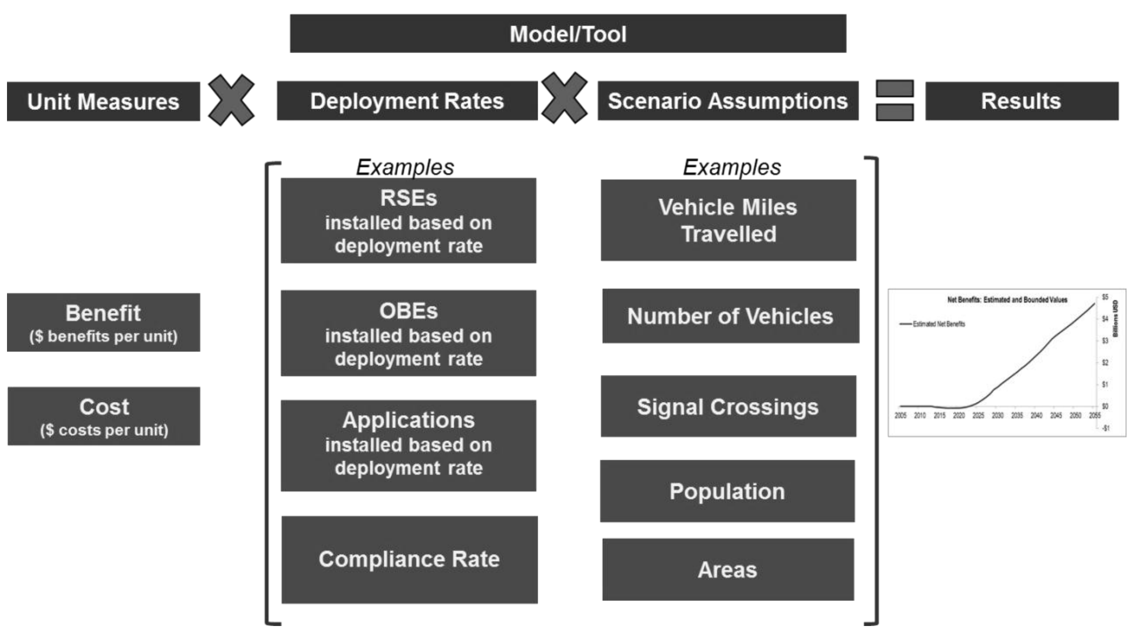


Figure 73: Extrapolation Tool

Using the modeling results, the initial AERIS BCA was updated to estimate the benefits of the Eco-Lanes applications. The goal of the analysis was to estimate benefits for a study period between years 2019 and 2055. Year 2019 is when the CV technology deployment is assumed to begin, and Year 2055 is when full penetration of the CV technology is expected. The approach for this analysis is largely based on the initial BCA carried out before the modeling of the application. The methodology and results of the initial BCA are documented in a companion report titled *AERIS Applications for the Environment: Real-Time Information Synthesis Identification and Evaluation of Transformative Environmental Applications and Strategies Project, Initial Benefit-Cost Analysis, September 2012*.

The benefit calculation procedure is documented in the remainder of this section. The benefit-cost model developed for the purpose of assessing the benefits and costs of implementing the AERIS applications allows us to enter a representative value of benefit for an application based on AERIS application modeling results or related research efforts. The input benefit is adjusted for the period of analysis, which also considers the CV technology deployment rates and adoption rates along with numerous other factors. In this analysis, the Eco-Lanes applications' modeling results are used as input to the BCA model. The BCA model considers the variation in traffic demands throughout the day and throughout the year as well as the traffic growth between different years during the period of analysis. A single representative value of benefit is input into the BCA model to estimate the benefits over the period of analysis.

Unit Benefit Estimation

The unit benefits are calculated in terms of fuel saved per mile of travel on a freeway where Eco-Lanes applications are deployed. VMT in the study network was obtained from the simulation model. The total estimated fuel consumption is obtained from the MOVES plugin that runs in conjunction with the microsimulation model as described in the rest of the report. The normalized fuel savings per mile of freeway travel are used in the BCA model to obtain the benefits over the future years.

As an input to the BCA, results from the microsimulation for a scenario with 3600 vph and 100 percent penetration rate on the GHFN was used for the ESH application. For the Eco-CACC application, results from the microsimulation model for 25,000 vehicle volume over a duration of 1 hour on the SR-91 E network with 40-meter triggering distance and 5-meter spacing with a dedicated eco-lane was used. The overall savings for the network was used. Refer to Chapters 4 and 5 for further details regarding the microsimulation results. These values are adjusted based on the deployment rates and compliance rates over the future years, while accounting for future fleet mixes, growth in population, and several other macroeconomic factors.

BCA

The unit benefit estimates obtained are plugged into the BCA model to acquire detailed benefit estimates for the whole of the United States between 2019 and 2055 (refer to *AERIS Applications for the Environment: Real-Time Information Synthesis Identification and Evaluation of Transformative Environmental Applications and Strategies Project, Initial Benefit-Cost Analysis, September 2012* for details). The CV deployment is assumed to begin at 2019; Figure C-5 shows the application deployment rates.

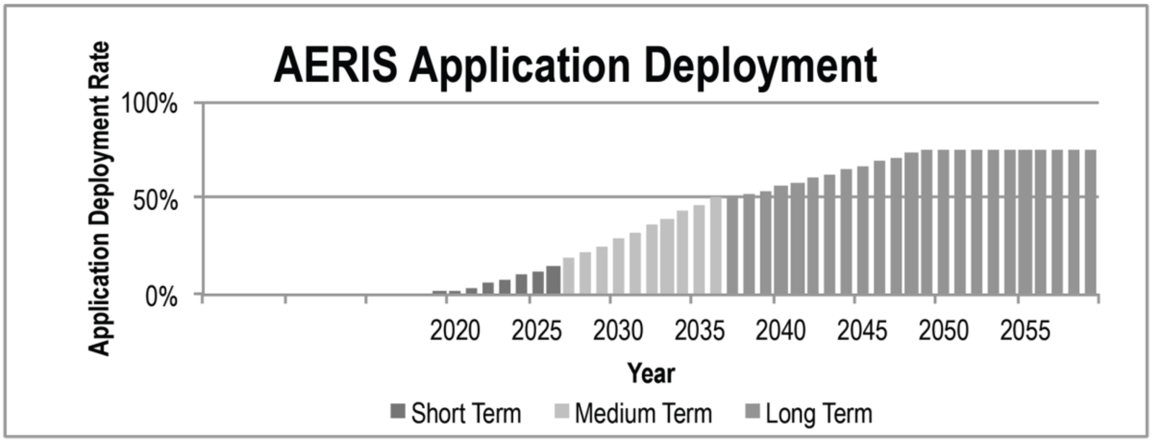
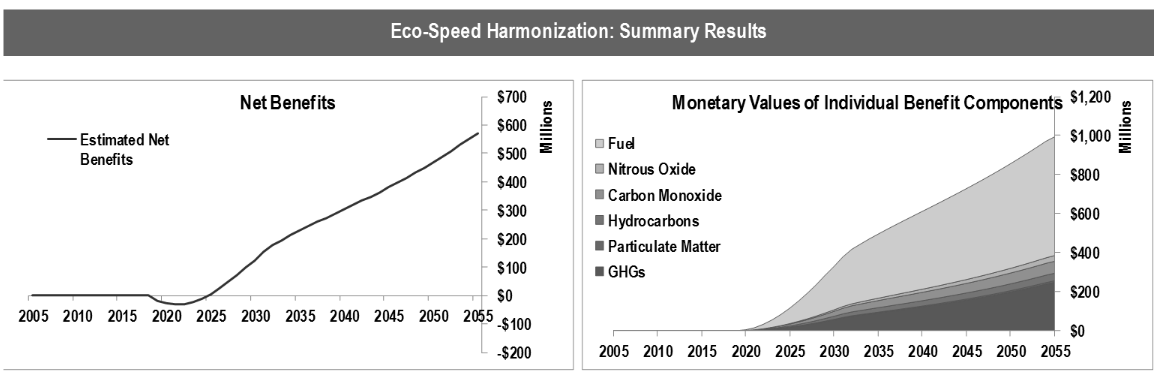


Figure 74: Application Deployment Rates for the Duration of Analysis

Results of the analysis are presented in the following paragraphs. For accurate comparison, results of the scenarios with baseline demand with 100 percent OBE penetration rate on the SR-91 E network were used for each application. Figure 70 presents the modeling results that were input into the model to generate the following BCA graphs.

Figure 75 presents the net benefits of the ESH application. The benefits outweigh the costs of deploying the applications by a large margin. It can also be seen that the benefits increase in the future years, when the OBE penetration rates and application deployment rates are higher.



Signposts (Moderate)	2025	2055	Total*
Costs (Billion USD)	$0.11	$0.43	$1.53
Benefits (Billion USD)	$0.12	$0.99	$2.6
Net Benefits (Billion USD)	$0.01	$0.57	$1.1
Benefit-Cost Ratio	1:1	2:1	2:1
GHG Emissions Reduction (Million Tons)	0.2	1.3	26
GHG Emissions Reduction (% of baseline)	0.0%	0.1%	0.0%

*$ Value Totals are the Net Present Value in 2012 Assuming a 7% Discount Rate

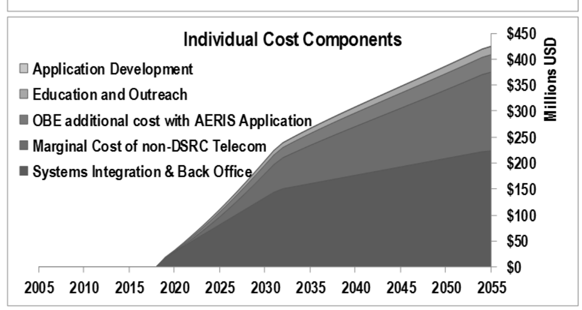
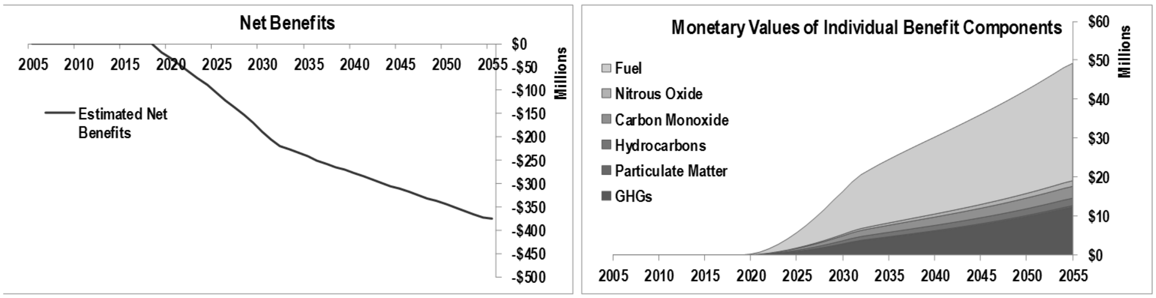


Figure 75: Net Benefits, Total Costs, and Total Benefits of the ESH application

Figure 76 presents the net benefits, costs, and total benefits of the Eco-CACC application. The Eco-CACC application provides very little benefit as compared with the costs incurred. From the microsimulation results, it could be seen that the vehicles using the dedicated eco-lanes had higher benefits as compared with the other lanes. The overall benefits for the network are relatively low.

Eco-Adaptive Cruise Control: Summary Results



Signposts (Moderate)	2025	2055	Total*
Costs (Billion USD)	$0.11	$0.43	$1.53
Benefits (Billion USD)	$0.01	$0.05	$0.1
Net Benefits (Billion USD)	-$0.10	-$0.38	-$1.4
Benefit-Cost Ratio	NA	NA	NA
GHG Emissions Reduction (Million Tons)	0.0	0.1	1
GHG Emissions Reduction (% of baseline)	0.0%	0.0%	0.0%

*$ Value Totals are the Net Present Value in 2012 Assuming a 7% Discount Rate

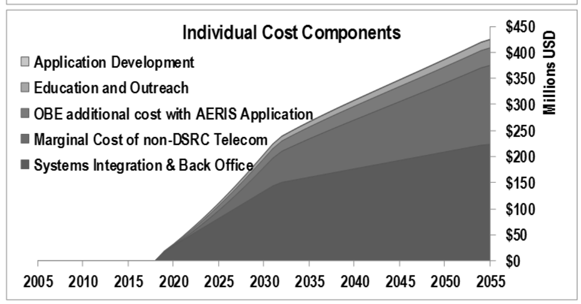


Figure 76: Comparison of Total Benefits of Each Application, Along With the Benefits of All the Applications Combined

All the results are presented in Net Present Value assuming a 7 percent discount rate. It is clear that deploying the ESH application yields high benefits even in the early stages of deployment. The Eco-CACC application provides benefits for individual users but the overall benefits on the network are fairly low as compared with the costs incurred in deploying the application. It is to be noted that the costs incurred are estimated separately for each application. If the infrastructure for deploying Eco-CACC is already in place as part of other deployments, there are benefits that can be expected from the Eco-CACC application as well.

U.S. Department of Transportation
ITS Joint Program Office-HOIT
1200 New Jersey Avenue, SE
Washington, DC 20590

Toll-Free "Help Line" 866-367-7487

www.its.dot.gov

[FHWA Document Number]

U.S. Department of Transportation