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

Eco-Signal Operations Modeling Report

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16. Abstract

This report constitutes the detailed modeling and evaluation results of the Eco-Signal Operations Operational Scenario defined by the AERIS program. The Operational Scenario constitutes four applications that are designed to provide environmental benefits to the users of connected vehicle technology on arterials. The applications use the data available in a connected environment and help reduce fuel consumption and emissions by providing driving feedback, speed advice, granting priority to freight and transit vehicles or by modifying the signal timings on the roadway. This report contains the details of the algorithms developed to model the applications, the details of the analysis as well as the results of each individual application and the applications applied simultaneously.

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Report Summary

Overview of the AERIS Program

As part of its connected vehicle research effort, the U.S. Department of Transportation's (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 the program is to encourage the development of technologies and applications that support a more sustainable relationship between transportation and the environment chiefly through fuel use reductions and resulting emissions reductions. The applications are grouped into Operational Scenarios each encompassing 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 above those of the individual applications. 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.

AERIS applications are designed to work in a connected vehicle environment or a setting where vehicles and infrastructure communicate among themselves and with each other to transmit information that can be used for various purposes. The communication of data is facilitated by Dedicated Short Range Communication (DSRC) systems or other communication means communication (e.g., cellular communications). The range of the DSRC systems is 300 meters, while the cellular systems provide wide-area communications. On-board equipment (OBE) in the vehicles is configured to transmit information such as speed, location, fuel consumption, and ambient weather information 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 phasing and timing (SPaT) information, as well as other dynamic system attributes. Such an exchange of information opens up tremendous 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. Connected vehicle applications are being designed and tested to achieve safety, mobility, and environmental benefits from a connected vehicle system.

Research is underway to explore the possibilities of deriving environmental benefits from the wealth of real-time data that will become available with the use of connected vehicle 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 connected vehicle applications that may provide environmental benefits.

Prior to 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, which resulted in developing five Operational Scenarios for possible study. The second task of this project was an initial benefit-cost analysis (BCA), which used a detailed model that assessed the monetary benefits and costs for each application and bundle of applications as identified in the aforementioned report. 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 data availability. As part of this task, a field experiment was conducted at Turner Fairbank Highway Research Center (TFHRC) to evaluate the benefits of the Eco-Approach at Signalized Intersections application. Based on the results of the selection process, the Eco-Signal Operations, Eco-Lanes, and Low Emissions Zones Operational Scenarios were shortlisted as the concepts most suitable 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-Signal Operations Operational Scenario, with results derived from the modeling in the current task.

Eco-Signal Operations Applications

The Eco-Signal Operations Operational Scenario uses connected vehicle technologies and applications, as well as signal operational communications technologies, to reduce fuel consumption, greenhouse gas (GHG) and criteria air pollutant emissions on signalized arterial roadways. The applications within the scenario are designed to reduce idling, stop-and-go behavior, and inefficient accelerations and decelerations and to improve traffic flow at signalized intersections. The Operational Scenario contains five applications, which were modeled separately and then combined for the last step of the analysis. The applications of the scenario were initially defined as:

Eco-Approach and Departure at Signalized Intersections: This application uses wireless data communications sent from roadside equipment (RSE) units to connected vehicles to encourage “green” approaches to signalized intersections. The application, located in a vehicle, collects signal phase and timing (SPaT) and Geographic Information Description (GID) messages using V2I communications and data from nearby vehicles using V2V communications. Upon receiving these messages, the application would perform calculations to determine the vehicle’s optimal speed to pass the next traffic signal on a green light or to decelerate to a stop in the most eco-friendly manner. This information is then sent to longitudinal vehicle control capabilities in the vehicle to support partial automation. The application also considers a vehicle’s acceleration as it departs from a signalized intersection and engine start-stop technologies.

Eco-Traffic Signal Timing: This application is similar to current traffic signal systems; however the application’s objective is to optimize the performance of traffic signals for the environment. The application collects data from vehicles, such as vehicle location, speed, and emissions data using connected vehicle technologies. It then processes these data to develop signal timing strategies focused on reducing fuel consumption and overall emissions at the intersection, along a corridor, or for a region. The application evaluates traffic and environmental parameters at each intersection in real-time and adapts so the traffic network is optimized using available green time to serve the actual traffic demands while minimizing the environmental impact.

Eco-Traffic Signal Priority (Freight and Transit): This application allows either transit or freight vehicles approaching a signalized intersection to request signal priority. These applications consider the vehicle’s location, speed, vehicle type (e.g., alternative fuel vehicles), and associated emissions to determine whether priority should be granted. Information collected from vehicles approaching the intersection, such as a transit vehicle’s adherence to its schedule, the number of passengers on the transit vehicle, or weight of a truck may also be considered in granting priority. If priority is granted, the traffic signal would hold the green on the approach until the transit or freight vehicle clears the intersection. This application does not consider signal pre-emption, which is reserved for emergency response vehicles.

Connected Eco-Driving: This application provides customized real-time driving advice to drivers so that they can adjust their driving behavior to save fuel and reduce emissions. Eco-driving advice includes recommended driving speeds, optimal acceleration, and optimal deceleration profiles based on prevailing traffic conditions, interactions with nearby vehicles, and upcoming road grades. The application also provides feedback to drivers on their driving behavior to encourage drivers to drive in a more environmentally efficient manner. Finally, the application may also include vehicle-assisted strategies where the vehicle automatically implements the eco-driving strategy (e.g., changes gears, switches power sources, or reduces its speed in an eco-friendly manner).

Wireless Inductive/Resonance Charging: Wireless inductive/resonance charging 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 static charging capable of transferring electric power to a vehicle parked in a garage or on the street and vehicles stopped at a traffic signal or a stop sign. It also supports charging vehicles moving at highway speeds. This application was not modeled as part of the Eco-Signal Operations modeling effort. Data pertaining to the efficiency of wireless charging of vehicles, the number of vehicles equipped with the feature, and the number of vehicles that can be charged at an intersection at a given time were not available for modeling this application. In the future, assumptions regarding these can be made as and when guidance is available.

Modeling Approach and Performance Measures

For the Eco-Signal Operations Operational Scenario, the anticipated impacts of the applications were driver and vehicle behavioral changes, such as smoother driving patterns and reduced stopping at signalized intersections. These specific impacts are best captured using traffic microscopic simulation tools, where individual vehicles are modeled at high temporal and spatial resolution. A traffic microsimulation tool simulates vehicles and their interactions in a very 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-Signal Operations Operational Scenario, Paramics was used as the microsimulation tool to simulate and analyze the impacts from each of the applications.

Since the anticipated impacts of the Eco-Signal Operations applications were 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 corridor-type microsimulation network. As shown in Exhibit 1, the corridor used in this modeling study is a 27-intersection, 6.5-mile segment of El Camino Real in northern California, between Churchill Avenue in Palo Alto and Grant Road in Mountain View. El Camino Real is a major north-south signalized arterial roadway connecting San Francisco and San Jose and is parallel to the US-101 freeway. For the majority of the corridor, there are three lanes in each direction. An existing Paramics model of the El Camino Real was used that was readily available to the AERIS modeling team and calibrated for use from 2005 validation data.

In addition to automobile traffic, the validated Paramics model of El Camino Real had both transit and freight vehicles modeled in the simulation, which allowed for testing of the freight and transit scenarios. The corridor contained a relatively low baseline freight percentage of 1.2 percent of the total traffic demand, covering light, medium, and heavy-duty freight vehicles. The Paramics model had two fixed-route transit routes along the mainline corridor of El Camino Real, one in each the eastbound and westbound travel directions, with bus stops located at most of the cross-street intersections. There were both near and far-side bus stops along the corridor, with constant bus headways of about 10 minutes.

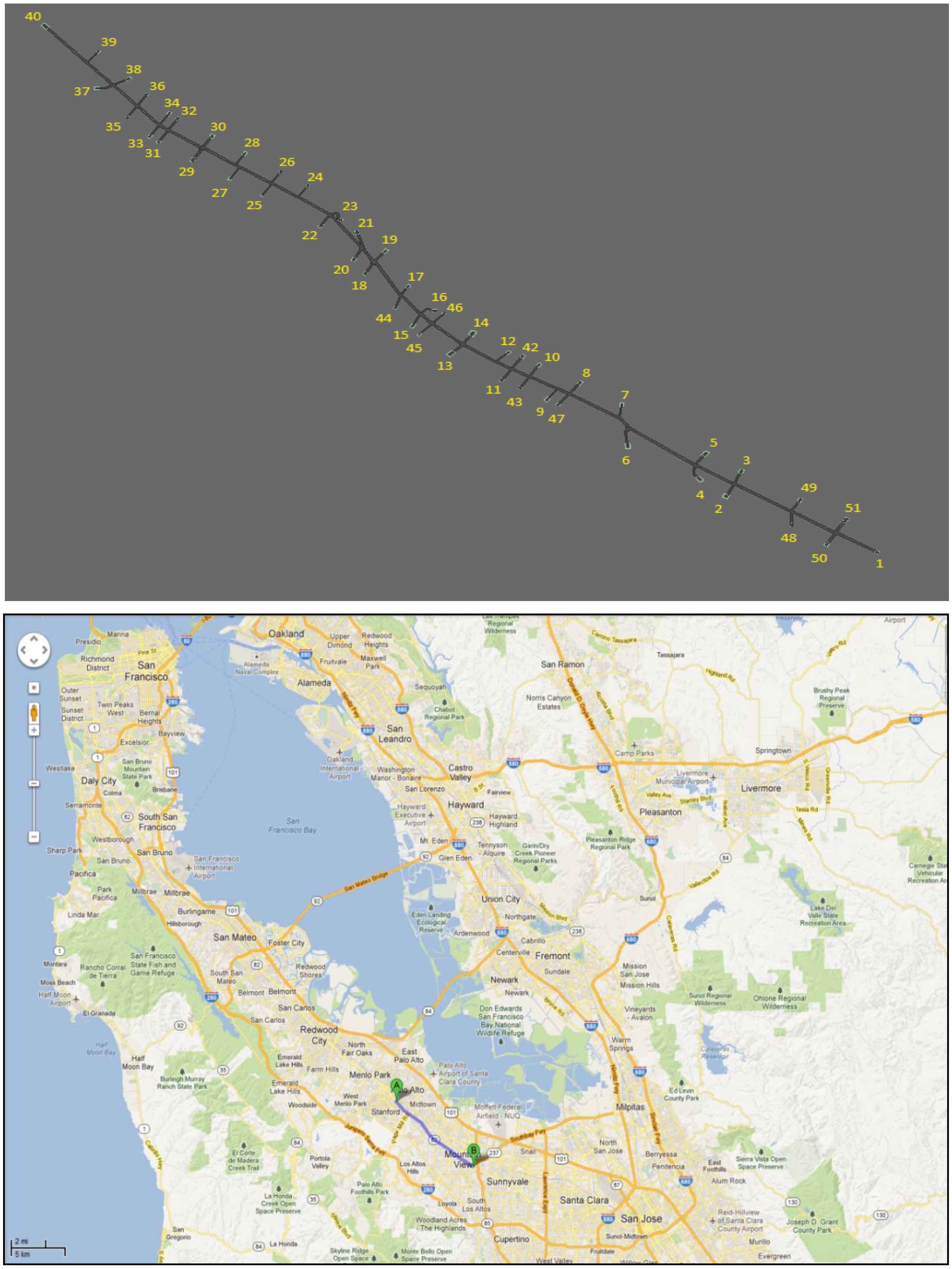


Exhibit 1: 27-Intersection Segment of El Camino Real.

Each application from the Operational Scenario was modeled separately and then modeled in combination with the other applications. The motivation for modeling them separately was to characterize the applications thoroughly before cataloging their interactions with the other applications in the Operational Scenario. The steps involved in the process were as follows:

1. Assess anticipated behavioral changes of the application
2. Identify the scales for modeling the application
3. Develop an algorithm to model the application
4. Evaluate the application using designated performance measures under several analysis scenarios
5. Draw conclusions based on the modeling results

With the use of a microsimulation tool and emissions estimation tool, the MOtor Vehicle Emissions Simulator (MOVES) (developed by the Environmental Protection Agency [EPA]), individual vehicle movements could be modeled and modified as necessary, which allowed fuel consumption and emissions of vehicles to be accurately estimated. The estimation takes into consideration the driving behavior, such as braking and acceleration, and the vehicle type. Individual and combined algorithms for each AERIS connected vehicle application, as well as the MOVES real-time environmental simulator, were developed and implemented using the application programming interface (API) add-on that is included within the “Programmer” program of the Paramics suite of applications. These APIs allowed the team to build custom-built connected vehicle applications and let them interact with the Paramics microsimulation tool.

Before the start of the modeling, it was important to establish the performance measures by which the applications would be analyzed. Performance measures were broadly classified into environmental and mobility measures. Using the APIs developed for the microsimulation tool, as well as the built-in features of the model itself, many environmental and mobility measures were extracted during the modeling process. While generating environmental measures was the primary scope of the analysis, mobility-related measures, such as travel delay, were also considered to determine the potential mobility impacts of the Eco-Signal Operations applications.

Environmental measures considered in the analysis included—

1. Fuel consumption; and
2. Emissions
    a. Carbon dioxide (CO_2)
    b. Particulate matter: PM-10
    c. Particulate matter: PM-2.5
    d. Nitrogen oxides (NOx)
    e. Volatile organic compounds
    f. Hydrocarbons (HC)
    g. Carbon monoxide (CO)

Mobility measures considered in the analysis included—

1. Mainline corridor travel time
2. Delay

To properly assess the impacts of the Eco-Signal Operations Operational Scenario applications, it was first necessary to develop a baseline model from which to compare against, with the assumption that the baseline contains no connected vehicle application deployment (i.e., connected vehicle OBE penetration rate is 0). This “baseline” model was developed from the El Camino Real corridor model discussed above, making use of the calibrated vehicle, freight, and transit demands. The baseline environmental statistics collection made use of the MOVES API plug-in, which estimated the resultant emissions and fuel consumption from the microsimulation model. In addition, overall travel time and other mobility statistics were collected from Paramics outputs to help establish the “baseline conditions.”

From this baseline condition, the impacts of each of the Eco-Signal Operations applications could then be measured by comparing the resultant emissions along the El Camino microsimulation model with the individual application algorithms active against the “baseline” statistics that were collected. To understand the impacts of each of the applications in simulation, a variety of scenarios were generated to characterize the detailed behavior of the application under different conditions, such as the varying vehicle demand of the network, the percentage of trucks, different communication ranges and delay, fleet mix, and most importantly the connected vehicle OBE penetration rates. The increasing levels of OBE penetration rates help to show the impact of the applications being introduced over the years as the technology is slowly adopted by the vehicle manufacturers and the infrastructure is introduced and built by the local, regional, state, and federal entities.

Modeling Scenarios

To gain a proper understanding of the resulting impacts of the individual, as well as combined, impacts of the Eco-Signal Operations application impacts, it was important to test different scenarios that varied different simulation parameters. While certain applications had special needs, such as testing the effects of baseline signal coordination on the effects of signal optimization, there were several parameters that were used for the majority of the applications, as well as the combined modeling effort. Using these parameters allowed for a depth of understanding of the impact of the applications in a variety of situations. The general parameters were divided into two major groups:

Generic Traffic Simulation Parameters: These parameters helped capture the impact of applications in various traffic conditions.

1. **Traffic Demand:** Traffic demand was represented by volume-to-capacity (V/C) ratio computed for each roadway. General values used for the analysis were 0.38 (under-saturated/half demand), 0.77 (baseline demand), and 1.00 (saturation/congested conditions).
2. **Percentage of Freight Vehicles:** Freight vehicles have a significant impact on the emissions profile of the corridor, as well as affecting capacity on a roadway due to size. Varying the amount of these vehicles in the system helped to understand the application’s impact at different scales of implementation. Typical values include: 1.2 percent (baseline), 5 percent, 10 percent, 15 percent, 20 percent, and 25 percent of the total traffic demand composition.
3. **Frequency of Transit Vehicles:** Transit vehicles also have a larger impact on the total emissions than the average passenger vehicle and occupy a significant amount of capacity on the roadway. The baseline frequency of about 6 buses/hour (10 minute headway) was small, so examining higher frequencies help to gain an understanding of the impact of applications in a more urban, heavier transit area. Additional values of 25, 50, and 100 buses per hour were used.

Connected Vehicle Parameters: These parameters represented the changes in prevalence of connected vehicle technology. For the modeling, it was assumed that all signalized intersections were equipped with RSE technology (i.e., 100 percent penetration rate).

1. **OBE Penetration Rate:** The percentage of vehicles on the roadway equipped with connected vehicle technology. Varying the OBE penetration rate helped to gauge the impact of the applications during the years that the vehicle fleet is slowly being introduced to connected vehicle technology. Values used for analysis were 20 percent, 35 percent, 50 percent, 65 percent, 80 percent, and 100 percent.
2. **Communication Distance:** The maximum range of communication between connected vehicles and the connected infrastructure. Modeling communication distance helped to analyze whether DSRC technology's maximum range of 300 meters was sufficient or if other wireless communication technologies would be feasible. The Values used for modeling communication distance were 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 750, and 1,000 meters.
3. **Communication Delay:** The delay in transmission of information from vehicles to the infrastructure or in acquisition of information to vehicles from the infrastructure. Communication delay was considered to help analyze whether higher latency, more flexible systems could be implemented. Values used for modeling were 0.5, 1.0, 2.5, 5.0, and 10.0 seconds.

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

Eco-Approach and Departure at Signalized Intersections Application

In modeling the Eco-Approach and Departure at Signalized Intersections application, an API plug-in was developed to implement the algorithm responsible for calculating eco-speed trajectories for vehicles. The algorithm developed considered real-time signal phase and timing (SPaT) data along the El Camino Real corridor to support environmentally friendly speed recommendations for individual vehicles. The algorithm and functions of the API performed the following functions in the microsimulation environment:

1. Collection of vehicles' characteristics (e.g., vehicle type) and second-by-second speed data
2. Collection of SPaT messages
3. Estimation of vehicles' energy consumption and pollutant emissions based on the MOVES model
4. Generation of vehicles' advisory speeds

The algorithm became active when the vehicle was within the maximum communication range of the connected RSE (300 meters) unit positioned at a signalized intersection. Vehicles communicate with the RSE unit once per second to determine the best approach to the intersection on a vehicle-by-vehicle basis. Depending on the conditions of each different vehicle's approach to the intersection, the application considered four possible speed trajectories to be suggested to the vehicle:

1. The light will change from green to red before the vehicle arrives, suggesting a slightly higher speed.
2. The light is currently red but will soon be green, suggesting a slightly slow trajectory so the vehicle will arrive on the next green and does not need to stop.
3. The light is currently red and will remain red long enough that the vehicle must come to a stop, suggesting a slow trajectory so the vehicle will slow to a stop with a more environmentally friendly trajectory.

4. The light will be green when the vehicle arrives at its current speed, indicating the vehicle need not change its trajectory.

A conceptual image of the Eco-Approach and Departure at Signalized Intersections application is shown in Exhibit 2. Connected vehicle messages are exchanged between the vehicle and the RSE unit in real time to determine the eco-friendly trajectory for each vehicle and implement it as it approaches the intersection.

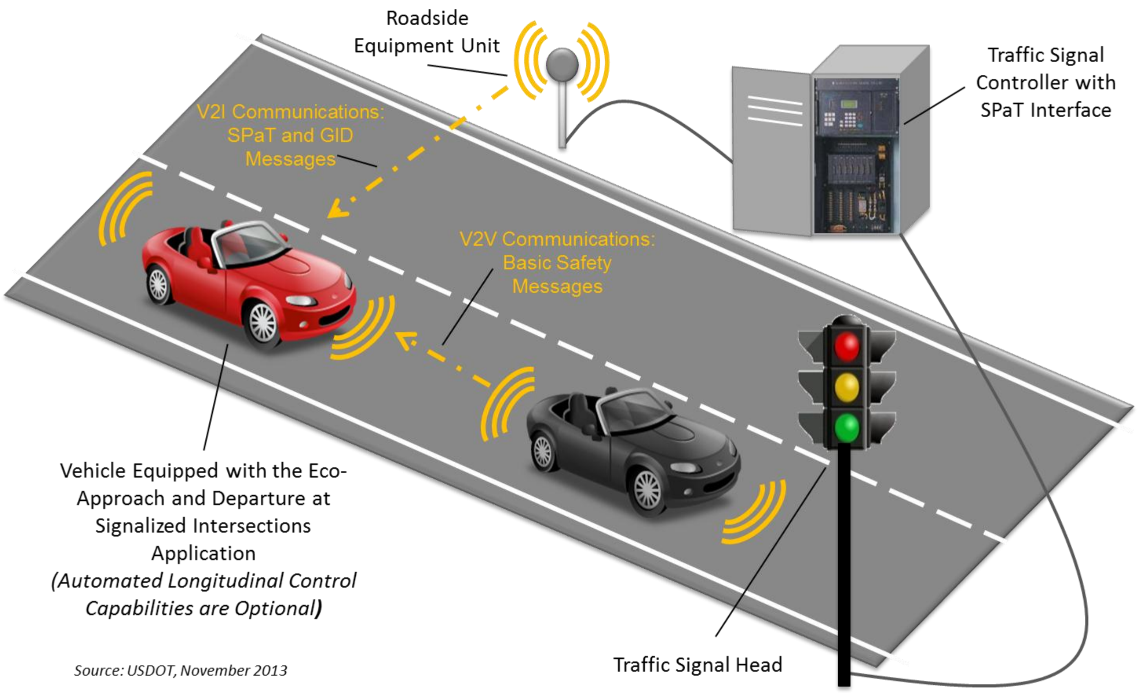


Exhibit 2: Eco-Approach and Departure at Signalized Intersections Illustrated.

In addition to the eco-approach component of the application, departure advice was also considered to provide additional environmental benefits. Preliminary analysis also indicated significant improvements with partial automated longitudinal control capabilities; however automated strategies were not modeled as part of this effort.

The range of benefits observed from the sensitivity analyses performed is summarized below in Exhibit 3 as fuel consumption savings. Sensitivity analyses focused on the El Camino Real corridor with both a coordinated and uncoordinated timing plan to measure the effects of baseline coordination on the overall environmental benefits for the Eco-Approach and Departure application.

Exhibit 3: Range of Benefits of the Eco-Approach and Departure at Signalized Intersections Application at Various Scenarios in Terms of CO_2 Reduction.

El Camino Corridor		CV OBE Penetration Rate						Mainline V/C Ratio		
		20%	35%	50%	65%	80%	100%	0.38	0.77	1.00
3 Int.	Coordinated	1.2%	-	2.4%	-	2.6%	2.8%	2.8%	2.8%	3.0%
	Uncoordinated	1.0%	-	3.9%	-	4.0%	4.3%	8.1%	4.3%	2.5%
27 Int.	Coordinated	-0.04%	0.04%	0.1%	0.3%	0.4%	0.4%	2.0%	0.4%	-1.1%

It was observed that the Eco-Approach and Departure at Signalized Intersections application offers varying levels of benefits for different operating conditions. Hypothetical tests of the application on a smaller, 3-intersection model of the El Camino Real with well-spaced, urban signalized intersection systems offered higher benefits than the benefits observed for the larger, 27-intersection El Camino Real corridor. These well-spaced distances give the vehicle enough time to recover from the departure from the previous intersection and prepare for the next intersection's approach trajectory. It can also be seen that the application offered higher environmental benefits on an uncoordinated corridor, which shows that it could be applied successfully in settings where no current optimized plan exists. On the 27-intersection corridor with closely spaced, urban intersections, the application had significantly less improvements in emissions and fuel consumption. This is owing to queue spillback on intersections that are spaced closer than the DSRC communication range and the artificial bottlenecks caused by vehicles entering and leaving the approach/departure zones. The spillback and the bottlenecks intensify in saturated traffic situations, as can be seen by the "disbenefit" that is experienced in the analysis scenario with a 1.00 V/C ratio.

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

1. The application is less effective when the corridor becomes congested. As congestion increases, there is less room for individual vehicles to change their speeds when approaching traffic signals.
2. There are disadvantages to the travel times of vehicles along the corridor, since the application slows down the vehicles to match the eco-friendly speed profiles. There is not a significant increase in intersection delay, on the other hand, because the vehicles stop less at the stop line with their new trajectories.
3. Even at low or moderate connected vehicle technology penetration levels, the application still has a positive network-wide effect, which results from unequipped vehicles also gaining environmental benefits from following equipped vehicles. Such findings increase the attractiveness of this application as an early candidate for field testing and deployment.
4. The results show that the application is very sensitive to the communication range between RSE and OBE. By receiving the SPaT information far ahead of the intersection, drivers would have more time to change their vehicle speed and thus reduce unnecessary stops at the signals.
5. The analyses indicate that the Eco-Approach and Departure at Signalized Intersections application can achieve an additional 1 percent to 3 percent in fuel savings and emissions reduction compared with the algorithm that did not consider the departure component.

While there was a lot of useful information obtained from the sensitivity analyses that were conducted, 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:

1. Additional energy/environment benefits may be obtained through a more customized vehicle trajectory planning algorithm, which can optimize a vehicle's trajectory based on traffic conditions and on detailed vehicle dynamics and its interaction with the other vehicles.
2. This application, when combined with automated longitudinal control capabilities, could provide significant energy/environmental benefits. This additional capability could also improve the throughput of the corridor which is beneficial to the environment.
3. Other technologies, such as engine start-stop technology, may be integrated with this application to achieve additional energy savings.
4. Modeling results were designed for fixed-time signals. Under actuated signal control scenarios, it is more difficult to estimate SPaT information, which might result in lower environmental benefits than fixed-time signals.

Eco-Traffic Signal Timing Application

The Eco-Traffic Signal Timing application was based on a standalone program that interfaces with the Paramics microsimulation model. The two programs ran together in a complementary loop to simultaneously develop and test signal timing plans. The optimization of a signalized corridor was a complex problem and involved many decision variables. For the Eco-Traffic Signal Timing application, there was a need to optimize the traffic signals for a certain set of parameters. For each signal in the network, the following parameters were changed to improve the emissions at the signalized intersection approaches:

1. Green time for each phase
2. Total signal cycle length
3. Offset of signals (to maintain coordination on the corridor)

Signal optimization techniques may also consider changes to phase orders and phase deletion. However, these two variables were not considered when modeling the Eco-Traffic Signal Timing application.

As defined by the AERIS Program, the Eco-Traffic Signal Timing application was intended to be real-time, adaptive signal timing optimization application similar to existing adaptive signal control systems, such as the Sydney Coordinated Adaptive Traffic System (SCATS) or the Cycle Offset Optimization Technique (SCOOT). These adaptive signal timing systems change signal timings in real-time as traffic conditions change. Since the development of an on-line adaptive signal control algorithm would be complex requiring significant time and effort to develop, the AERIS research team decided to conduct an off-line optimization to better understand the potential benefits of the application. Within the scope and budget and time of the AERIS project, there was not enough data or research available at the time to create algorithms for real-time predictive timing changes based on the emissions at the approach and what is needed to improve them. Predicting the future changes in emissions in real-time is much more complicated, and less understood than traditional mobility-based optimization methods. The majority of successful research in this topic has been with using “offline” methods, therefore, an “offline” approach was chosen for the AERIS project. This approach aggregates the connected vehicle real-time data and then uses that to do an optimization outside the network, and then returns the timings to be implemented.

When considering optimization for a corridor with multiple signals, the complexity increases because the optimization also must consider how each change affects the nearby intersections and the system as a whole. The combination of the variables used for the optimization creates a significant amount of possible timing scenarios to consider. Therefore, a heuristic solution method known as a genetic algorithm (GA) was used to develop the timing plans. A GA is a method of finding an optimal solution from a large set of possible solutions using Darwin's theory of evolution, or "survival of the fittest approach", in which non-optimal timing plans are discarded in favor of better solutions. This is an iterative process of creating a set of plans, evaluating the proposed plans, and then modifying the plans to eventually reach the "best" plan.

The GA was implemented in an executable program (*.exe) that complemented the Paramics model. The Genetic Algorithm for Signal Timing Optimization (GASTO) program contained a function that called the Paramics microsimulation model to test the signal timings in practice and then use the information to develop the next set of solutions in an automated loop. The MOVES API in Paramics was used to develop an aggregate of the network-wide emissions that was then used by the GASTO program to evaluate and rank different signal timing plans. The components of the Eco-Traffic Signal Timing application were designed to fulfill the following four functions:

1. The GASTO GA developed a set of timing plans to test in Paramics
2. The microsimulation model tested the timing plans on the El Camino Real corridor
3. The MOVES API model plug-in used real-time vehicle information to record environmental measures and create a network aggregate to export to the GA
4. The GA used the results from the microsimulation run to "learn" and improve the next set of timings

A conceptual image of the Eco-Traffic Signal Timing application is shown in Exhibit 4. Connected vehicle messages are sent from the vehicle to the RSE infrastructure in real time at all of the intersections along the corridor to aggregate the resultant emissions at the TMC. This information is then used to update the signal timing to improve the environmental conditions along the corridor.

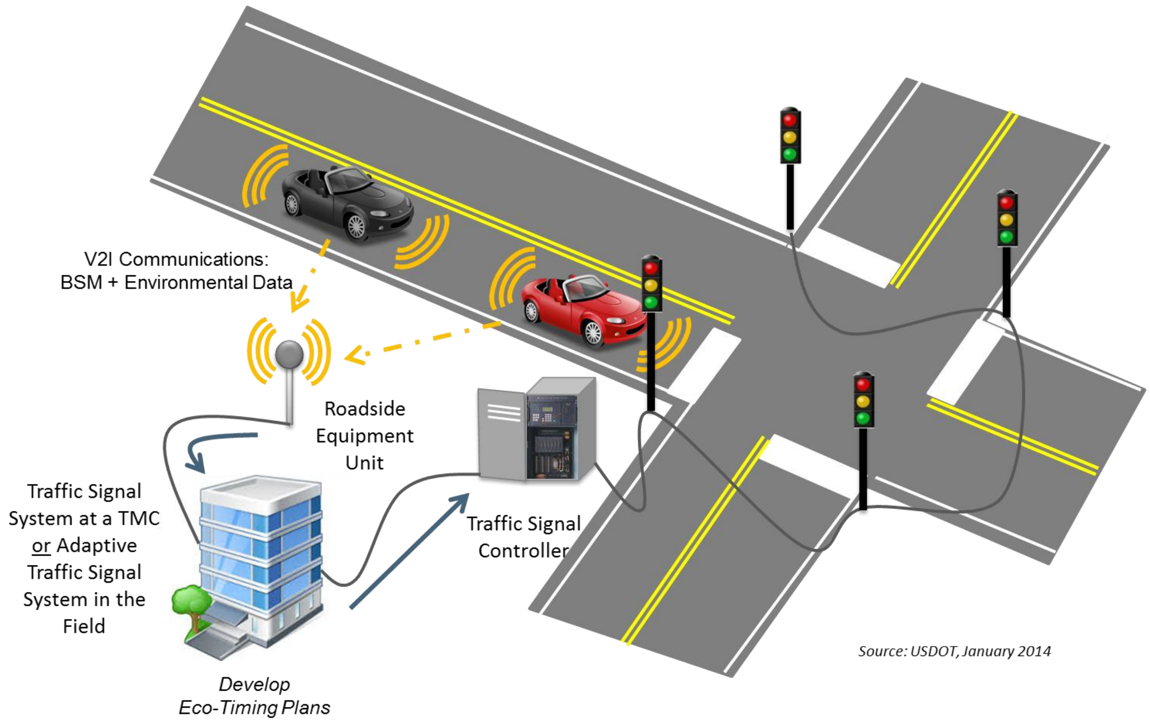


Exhibit 4: Eco-Traffic Signal Timing Application Illustrated

The Eco-Traffic Signal Timing application is one of the cornerstones of the Eco-Signal Operations Operational Scenario, as it is the application that develops the signal timing plan that determines the SPaT information used to compute the advice of the other applications within the same scenario. In developing the GA, it was necessary to develop timing limitations and minimum safe green times to ensure that the safety standards were met for both vehicles and pedestrians in the model. It was found that using the Highway Capacity Manual (HCM) minimum standards produced a safe and realistic timing plans that also showed significant improvement in the environmental and fuel consumption measures that were analyzed.

The possible range of benefits from the sensitivity analyses are summarized below in Exhibit 5 as fuel consumption improvements. The sensitivity analyses were first conducted on the smaller, 3-intersection model of the El Camino Real corridor, and then the full 27-intersection model to realize the range of benefits on different scenarios and locations. The Eco-Traffic Signal Timing application was tested on the corridor with already well-coordinated signal timings to fully realize the potential of the application to optimize beyond traditional methods.

Exhibit 5: Range of Benefits of the Eco-Traffic Signal Timing Application at Various Scenarios in Terms of Fuel Consumption/CO^2 Reduction.

El Camino Corridor		CV OBE Penetration Rate						Mainline V/C Ratio		
		20%	35%	50%	65%	80%	100%	0.38	0.77	1.00
3 Int.	Coordinated	0.2%	2.1%	3.3%	3.4%	3.9%	4.5%	4.3%	4.5%	1.7%
27 Int.	Coordinated	0.8%	1.8%	4.4%	4.5%	5.1%	5.3%	-	5.3%	-

The sensitivity analyses show that similar benefits were realized on the two corridors, despite the difference in size and complexity of the corridor signals. While benefits are not realized at very low levels of connected vehicle penetration (< 20%), it can be seen that the application provides benefits at all other penetration rates. In addition, the optimization provides benefits at all levels of vehicle demand, although the benefits decrease as the system reaches saturation. This is expected, as the system has little opportunity to push more vehicles through the intersections as the capacity is consumed.

Throughout this report and the modeling analyses, it is stated that the model was calibrated and that the environmental improvements gained are “on top of” those from mobility-based optimization. To prove this statement, the El Camino Real timing plans were put into an off-the-shelf optimization program for several different optimization tests. The off-the shelf optimization program was not able to find a better plan, ultimately showing that the corridor was already sufficiently calibrated-coordinated, and that the Eco-Traffic Signal Timing application algorithm was able to provide additional environmental savings over the traditional methods.

The resulting signal timing plans that were produced by the GASTO program optimization were relatively similar for all of the sensitivity analyses but much different than those of the corridor for the baseline signal plan. The timing plans for the El Camino Real in the baseline model were quite long (130 seconds), with a large amount of the time reserved for the major approaches along the corridor. The GASTO program’s solutions had uniformly much lower cycle lengths (60–70 seconds), which were around the minimum possible value while still maintaining HCM minimum timings.

General outcomes and conclusions were formed on the performance of the application in various situations. The major conclusions of the application are—

1. Overall, there is a 4 percent to 5 percent improvement in fuel consumption and environmental measures over the baseline scenario at full connected vehicle penetration, with a 1 percent to 4 percent improvement at partial connected vehicle penetration in a fully coordinated network. This shows that the application will be beneficial, even at lower levels of penetration.
2. The application yields benefits in both congested and non-congested traffic conditions, which means that the application is viable for both peak and off-peak travel conditions.
3. GA optimization was conducted for both mobility and environmental objectives. It was observed that the environmental objective resulted in a 5 percent improvement in emissions while the mobility objective resulted in a 2 percent improvement in emissions, even though there are obvious correlations in the two objectives.

While there was a lot of useful information obtained from the sensitivity analyses conducted, 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:

1. More sensitivity analyses should be undertaken on a “grid”-type network, which would have higher side-street volumes, to better understand the effects of coordination of signals with an environmentally based signal optimization.
2. A future version of the GASTO program could look at localized emissions at the intersections, rather than an aggregate at network level, in an attempt to create an improved optimization procedure.
3. Future research could focus on phase order and phase deletion, as well as looking at the optimization of actuated timing plans.
4. The resultant timing plans and changes from the baseline signal plan could be used as a template in the design of a “real-time” method of optimization, as the GASTO program helped to expand the knowledge of environmentally based optimization.

Eco-Traffic Signal Priority Application

The Eco-Traffic Signal Priority application determines when to grant traffic signal priority for transit vehicles or freight vehicles. The application was initially modeled for each vehicle type (i.e., transit and freight vehicle types) to gauge the impact on each vehicle type before applying it to all the vehicles in the model. The model was designed to simulate connected vehicle technology by detecting and monitoring a vehicle’s position and characteristics in real-time and using this information to detect and process priority requests from those vehicles. The algorithm that considered signal priority requests and SPaT message information processing API functions were almost identical for the two vehicle types and work with the following steps:

1. Detect and receive priority requests from eligible vehicles.
2. Determine trajectory information, vehicle information, and surrounding queue/congestion information in real time.
3. Process the priority request based on information gathered in the custom module.
4. Grant priority and update signal timings, or deny priority request.
5. Return the signal phase lengths to baseline timing after the vehicle passes the intersection.

The major difference between the algorithms for the different vehicle types was the module that processes the priority request based on real-time vehicle information. For the Eco-Freight Signal Priority application, the vehicle is assigned a “priority level,” depending on vehicle parameters such as size, weight, and emissions class, as well as whether or not it is approaching the intersection as part of a natural platoon. These vehicle parameters were used to categorize vehicles in order to compute priority levels. Priority levels determine when a vehicle can be granted priority, and for how long.

For the Eco-Transit Signal Priority application, transit vehicles are monitored in real-time to determine whether they are on schedule or lagging behind schedule. For this application, it was assumed that environmental benefits were obtained not only from the bus itself, but by people switching from personal car to public transit. While this phase of modeling was not intended to capture mode shift, it is envisioned that the first implementation will promote a mode shift by creating an on-time service which is more reliable. The objective of this application was to determine if transit vehicles were behind schedule due to congestion and then attempt to reduce overall emissions by ensuring that the transit vehicles were as close to schedule as possible.

For both of these applications, specialized sensitivity analyses were performed for different levels of freight and transit frequency in the model, since this factor would have a much higher importance for these applications than for the other three applications. An additional parameter of importance for sensitivity testing was the length of the possible granted priority. The longer the signal priority, the greater the chance that a vehicle would be on a trajectory that would result in a green extension. However, these longer priorities could ultimately detrimentally impact the flows through opposing approaches and phases at that intersection.

A conceptual image of the Eco-Traffic Signal Priority application is shown in Exhibit 6 as one possible implementation along a transportation corridor. Connected vehicle messages are exchanged between the vehicle and the RSE infrastructure in real time to determine if a signal priority should be granted for the freight or transit vehicle as it approaches the intersection.

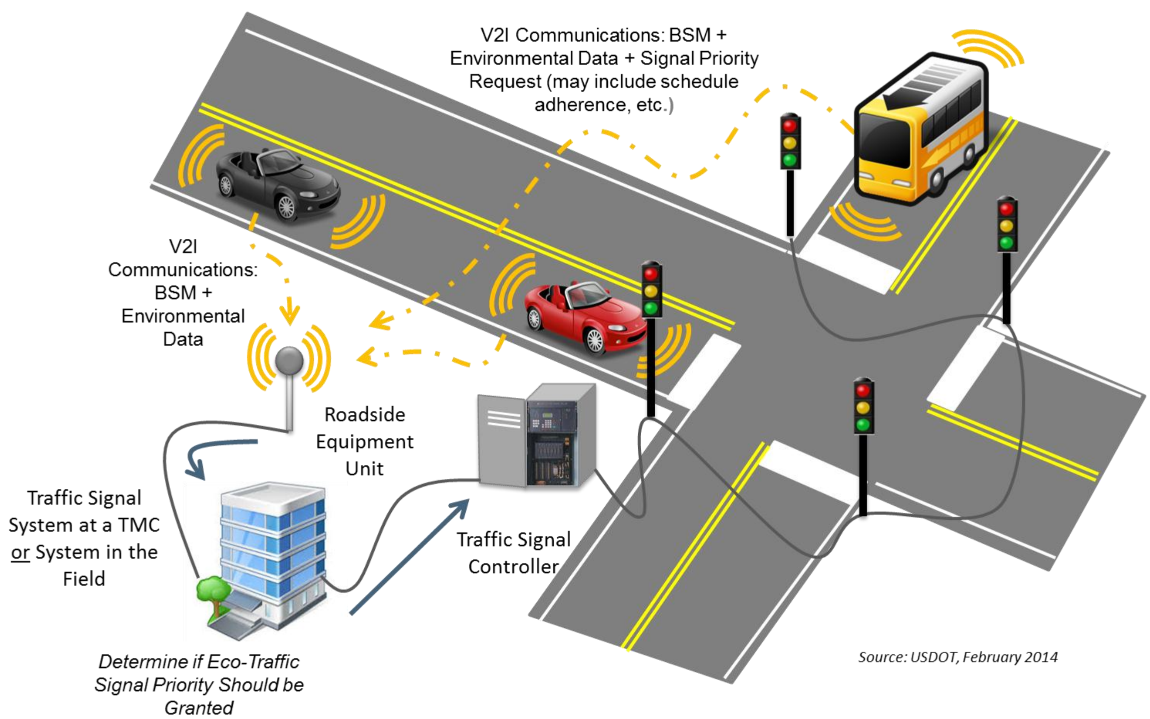


Exhibit 6: Eco-Traffic Signal Priority Application Illustrated.

The expected range of benefits from the sensitivity analyses is summarized in Exhibit 7 as fuel consumption savings. This exhibit details the Eco-Traffic Signal Priority application's effect on different levels of congestion and due to different levels of technology penetration. The results for passenger, freight and transit vehicles are shown separately, as it is expected that non-connected vehicles and passenger vehicles that share the additional green time during the signal priority also experience fuel savings.

Exhibit 7: Range of Benefits of the Eco-Traffic Signal Priority Application at Various Scenarios in Terms of Fuel Consumption/CO^2 Reduction.

		El Camino Corridor	CV OBE Penetration Rate						Mainline V/C Ratio		
			20%	35%	50%	65%	80%	100%	0.38	0.77	1.00
Eco-Freight Signal Priority	27 Int.	Freight	1.5%	2.1%	2.3%	2.3%	2.6%	2.8%	3.8%	2.8%	4.7%
		Passenger	1.0%	1.7%	2.0%	2.1%	2.2%	1.9%	3.6%	1.9%	3.0%
Eco-Transit Signal Priority	27 Int.	Transit	-	-	-	-	-	1.5%	0.2%	1.5%	1.0%
		All	-	-	-	-	-	-0.5%	-1.0%	-0.5%	-0.6%

The results of the analysis show that the application is able to achieve moderate fuel savings for both freight and passenger vehicles with the granting of freight signal priority, which increases with increasing penetration rate. The additional green time of the granted priorities increased the effective capacity of the corridor mainline, which gave additional benefits to the passenger and non-connected freight vehicles along the corridor. The granting of transit signal priorities only brought minor improvements in fuel consumption, as there are a very low number of transit vehicles along the El Camino Real. However, in a high-transit city, like New York City, this application could potentially show larger improvements to fuel consumption.

With all of the analyses that were performed, general outcomes and conclusions were formed on the performance of the applications in various situations. While both the Eco-Freight and Eco-Transit Signal Priority applications were built on the same framework, the resultant conclusions were different between the applications. Other major conclusions, in addition to those above, regarding the Eco-Freight Signal Priority application are—

1. Passenger vehicles and unequipped freight vehicles in the network saw an improvement in emissions and fuel consumption because they also benefited from the additional mainline green time given to freight vehicles.
2. When granting priority, the farther the decision to change the green time is made from the signal, the less environmental/fuel improvement is realized, because it is harder to predict queuing and traffic patterns in advance.
3. Emissions and fuel consumption for freight vehicles improved as the maximum green extension or red truncation threshold is increased, but the emissions for the non-freight vehicles on the side streets increase at longer extension times.
4. Using the priority-based granting criteria, the number of priorities granted is about 18 percent to 19 percent of the total priorities requested by freight vehicles approaching the intersection.

For the Eco-Transit Signal Priority application, the major conclusions from the application sensitivity modeling are the following:

1. The application did not provide a significant improvement in the level of emissions and delay for the other vehicles on the network, because the amount of transit vehicles in the network was low, meaning there are less green extensions in the model.
2. Using the schedule adherence aspect of the application yielded a smaller improvement in the resultant emissions, because priorities would be denied more often, but improved the overall transit performance.

3. As the bus frequency increased in the network, there were no additional savings found for emissions or fuel consumption when compared to the baseline, which means the application would have similar impacts in different levels of transit demand.
4. Travel time improvements observed in many of the scenarios were on the order of 1 percent to 3 percent with decreasing communication distance, resulting in larger improvements.

While there was a lot of useful information obtained from the Eco-Freight and Eco-Transit Signal Priority applications, 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 applications:

1. Since the applications have the potential to impact side streets detrimentally, more sensitivity analyses should be undertaken on a “grid”-type network area to better understand the effects on side-street traffic.
2. A real-time predictive emissions module could be developed to provide the algorithm with a more accurate picture of the impact of granting or not granting priority to vehicles based on the traffic waiting at each approach of the intersection.
3. About 17 percent of priorities granted to freight vehicles are missed due to unforeseen queuing or shockwave scenarios. Future improvements to the algorithm could include better arrival time and trajectory planning prediction at intersection approaches.
4. Future investigations of the transit application should consider passenger throughput and overall shift from car to transit, which would have a direct and large impact on emissions savings, as criteria for assessing a priority request.

Connected Eco-Driving Application

The Connected Eco-Driving application provides customized real-time eco-driving advice to drivers, based on prevailing traffic conditions and local interactions with nearby vehicles on different types of roadway. The eco-driving advice may include—

1. Recommended driving speeds (including acceleration/deceleration)
2. Feedback to drivers (online or offline) on their driving behavior
3. Vehicle-assisted strategies (e.g., adjust speed according to traffic and signals, change gear, switch power source [hybrid vehicles]).
4. Advice can be applied on an individual vehicle basis or to traffic as a whole.

The Connected Eco-Driving application consisted of several components to work in unison to provide ultimate improvements in acceleration and deceleration advice. For the purposes of the AERIS modeling effort, the Connected Eco-Driving application consisted of the general eco-driving advice that was provided to the vehicles for this application, which is one simple way to reduce fuel consumption and resultant pollutants.

The eco-driving principles were provided to drivers on their driving behavior to encourage them to drive in a more environmentally efficient manner. Within the model, a heuristic, iterative procedure was implemented to calibrate the eco-friendly acceleration/deceleration profiles for Paramics inputs. Exhibit 8 presents examples of default acceleration profiles and eco-acceleration profiles used in Paramics for passenger cars. As can be seen from the exhibit, the accelerations under eco-scenarios (light gray) are milder than the default values (dark gray) across different speeds. Similar procedures have been applied to other vehicle types and the deceleration-speed profiles as well.

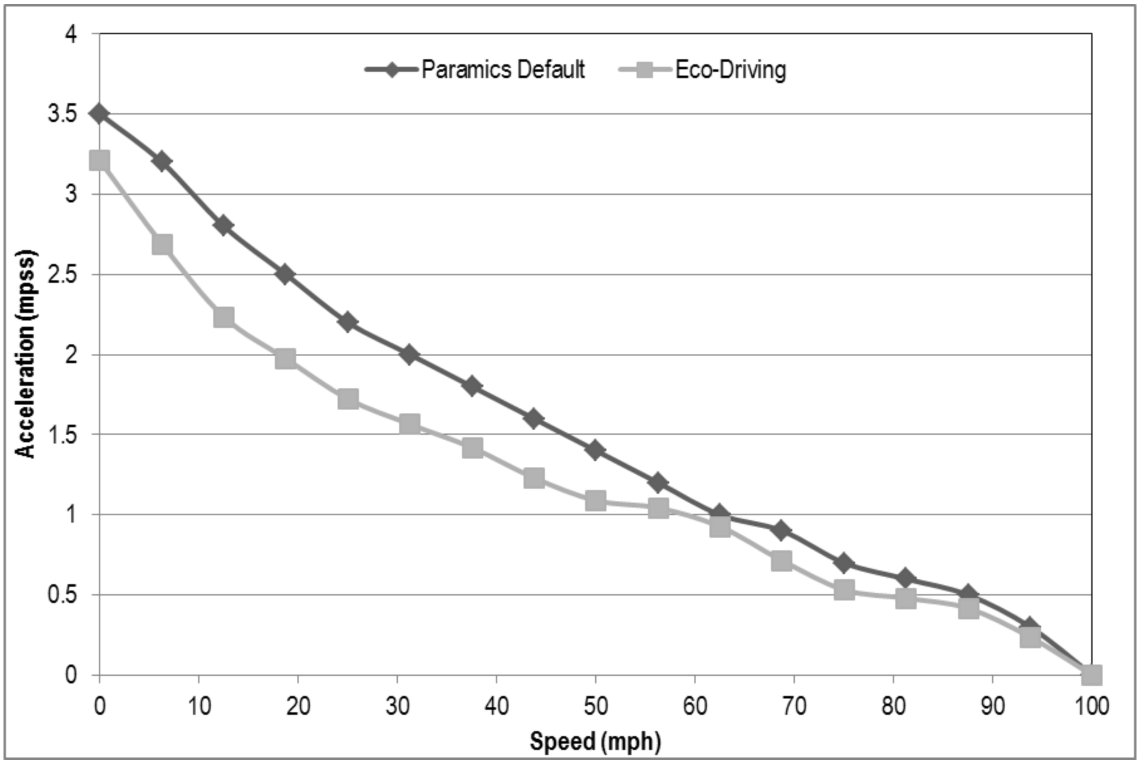


Exhibit 8: Example Acceleration/Deceleration Profiles in Paramics for Passenger Cars: Default vs. Eco-Driving.

To model the impacts resulting from use of the general eco-driving principles, the research team modified the acceleration/deceleration profiles in Paramics based on a real-world eco-driving field study conducted in Riverside, California. In this study, global positioning system (GPS) and fuel consumption data were collected from vehicles with and without the eco-driving feedback application which aims at reducing the acceleration/deceleration rates of vehicle operations. The study covered both freeways and arterials under a variety of traffic congestion levels. The data were used to evaluate the impacts of eco-driving feedback on driving behaviors and the corresponding fuel consumption.

A conceptual image of the Connected Eco-Driving application is shown in Exhibit 9 as one possible implementation along a transportation corridor. Connected vehicle messages are exchanged between the vehicle and the RSE infrastructure in real time to determine the eco-friendly acceleration and deceleration for each vehicle and implement it as it travels along the corridor.

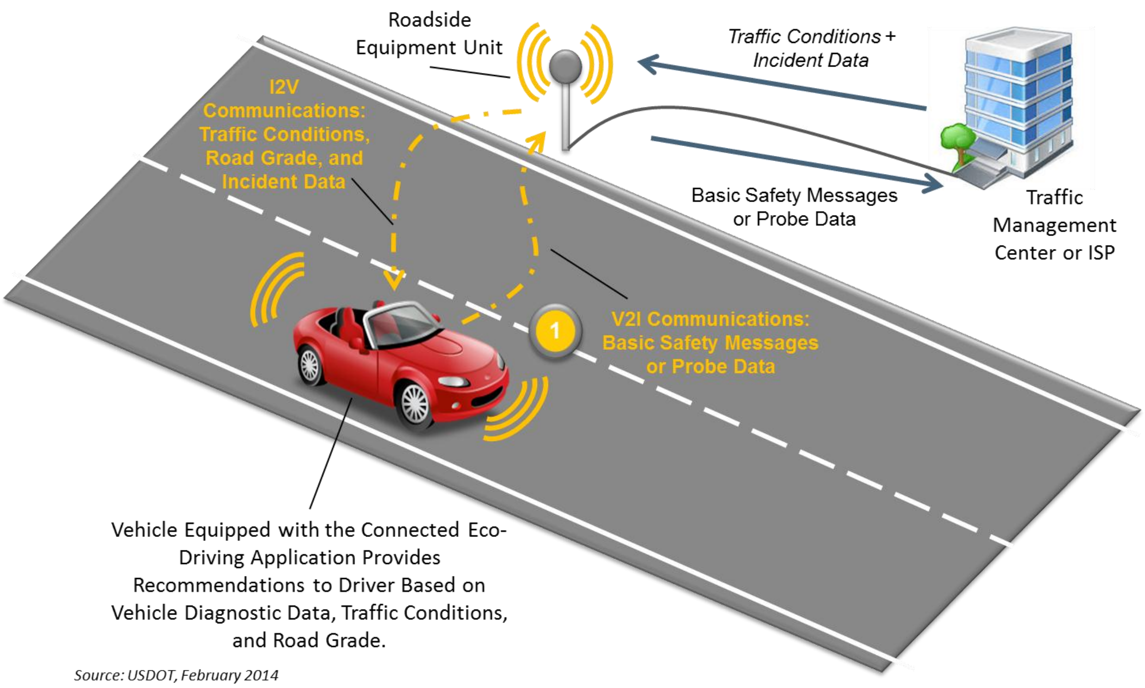


Exhibit 9: Connected Eco-Driving Application Illustrated

The expected range of benefits from the sensitivity analyses are summarized in Exhibit 10 for fuel consumption, CO_2 and carbon monoxide (CO) savings. The carbon monoxide savings are shown for this application, because the smoothing of trajectories before and after the intersection in terms of acceleration and deceleration is expected to have a larger impact on this measure, rather than the fuel savings along the corridor.

Exhibit 10: Range of Possible Emissions and Fuel Savings Benefits of Connected Eco Driving Application at Various Scenarios

El Camino Corridor		CV OBE Penetration Rate						Mainline V/C Ratio		
		20%	35%	50%	65%	80%	100%	0.38	0.77	1.00
27 Int.	Fuel/CO2	-0.4%	-	0.12%	-	0.18%	0.36%	3.5%	0.4%	-1.4%
	Carbon Monoxide	4.7%	-	10.8%	-	15.4%	18.4%	26.8%	18.4%	21.2%

The results of the analyses show only minimal fuel savings along the El Camino Real corridor for the Connected Eco-Driving application at baseline levels of vehicle demand. However, there are potentially much higher benefits when the demand is very low along the corridor. In addition, like the Eco-Approach and Departure at Signalized Intersections application, vehicle advice is not effective in saturated conditions often causing a “disbenefit”. On the other hand, the results show that the application provides significant reductions in carbon monoxide at all demand levels. This is due to improved acceleration and deceleration trajectories.

General outcomes and conclusions were formed on the performance of the application in various situations. Other major conclusions, in addition to those above, of the Connected Eco-Driving application are:

1. The General Eco-Driving Principles component is quite robust to the demand variations, and the changes in energy consumption and vehicle hours traveled (VHT) are within 3 percent.
2. The sensitivity analyses on penetration rate showed that there is minimal variation in MOEs for the General Eco-Driving Principles module when applying the 27-intersection El Camino Real corridor (known as ECR-27) (baseline traffic demand).
3. For most of the results for the analyzed model, the improvements of energy and CO_2 emissions are much smaller than improvements for other criteria emissions. A possible explanation would be that the emissions factors of these criteria pollutants are much more sensitive to the changes in vehicles’ trajectories due to the implementation of these modules.

While there were many impactful conclusions from the Connected Eco-Driving application, 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:

1. The willingness/ability of drivers to actively follow the eco-speed, acceleration, and deceleration advice given to them from connected vehicle technologies will greatly affect the results in relation to future implementation of the applications. Future modeling efforts could and should have a focus on the user compliance rate.
2. The eco-friendly acceleration and deceleration values were determined through research and hard-coded into the connected vehicles at the beginning of the simulation runs. Future research and improvements in eco-algorithms could yield a method of providing this advice dynamically to conform to changing traffic conditions.
3. Again, additional application testing should be done for the combined modeling on a network system that is less a main corridor and has roughly equal traffic approaching from different directions.

Combined Modeling of the Eco-Signal Operations Applications

Following the individual modeling of the five applications within the Eco-Signal Operations Operational Scenario, the applications were then combined to function simultaneously within the same modeling environment. To properly understand the impacts of the applications in this Operational Scenario, it was important to model the interactions of the applications and estimate the overall benefits to ensure that the applications under the Operational Scenario are compatible and do not significantly negate the each other's benefits.

To combine the applications in the modeling environment to test the impacts of the combined Operational Scenario, some additional technical improvements were carried out on the individual algorithms and APIs used for the Paramics program. This included combination of some similar applications into a single interface, while making minor improvements to help understand the interactions and reduce technical conflicts of the technology. This process, however, did not involve any major functionality of any of the application algorithms, and they all perform in the same manner as discussed above in the individual modeling sections. The overall design of the combined application APIs and their connection with the Paramics microsimulation model are shown in Exhibit 11.

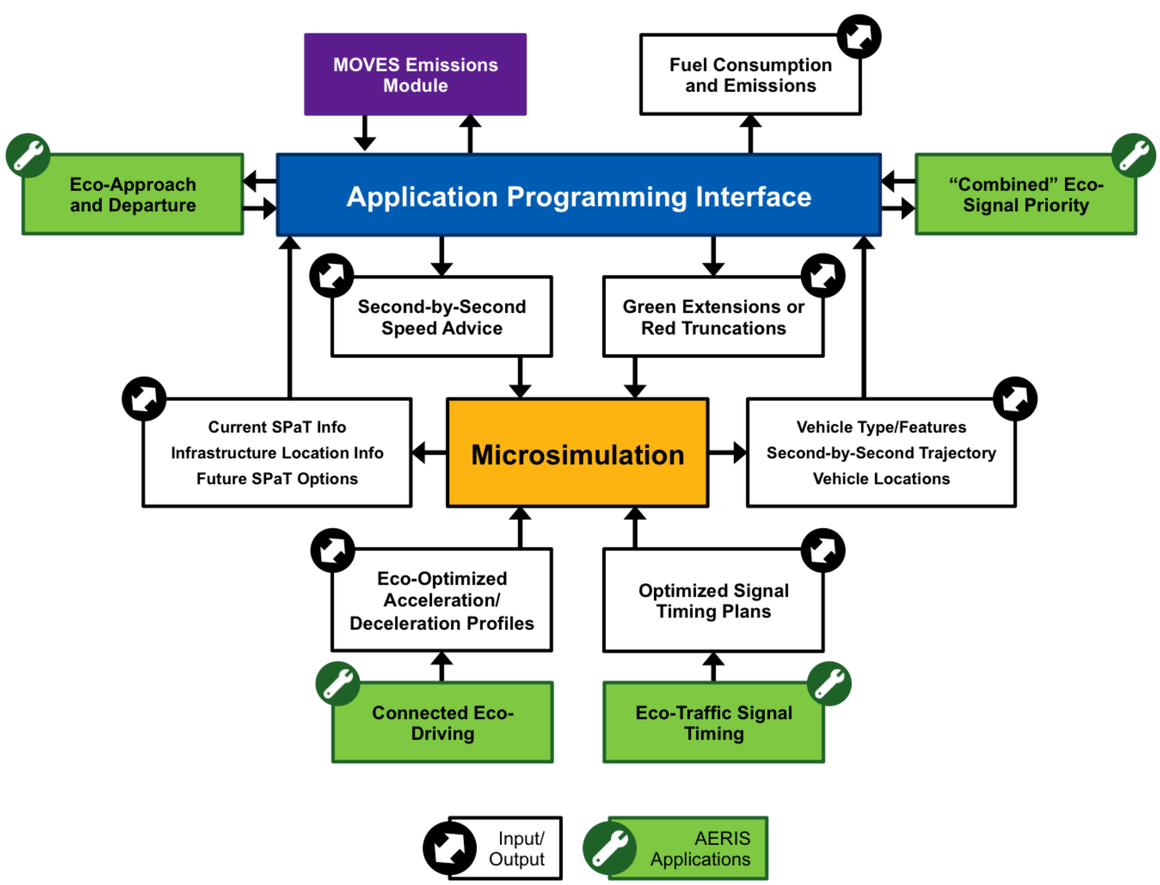


Exhibit 11: Interactions among the Models and APIs.

This figure shows the interactions among the models and the Application programming interface (API). The microsimulation generates current SPaT, infrastructure location, and future SPaT information and options along with vehicle type, vehicle trajectories, and vehicle locations. This information is passed to the API. The API passes this information to the eco-approach/departure module, the combined eco-signal priority module, and moves. These modules generate fuel consumption and emission estimates, and second by second speed advice and green extensions or red truncation information to be passed back to the microsimulation model. The connected eco driving module and the eco traffic signal timing module general eco optimized acceleration/deceleration profiles and optimized signal timing plans and pass it back to the microsimulation model.

The expected range of benefits from the sensitivity analyses are summarized in Exhibit 10 as fuel consumption savings. This helps to explain the overall impact of the combined applications of the Eco-Signal Operations Concept for all the vehicles in the El Camino Real corridor model.

Exhibit 12: Range of Fuel Savings Benefits of the Combined Applications of the Eco-Signal Operations Scenario.

El Camino Corridor		CV OBE Penetration Rate						Mainline V/C Ratio		
		20%	35%	50%	65%	80%	100%	0.38	0.77	1.00
27 Int.	**Coordinated**	**3.3%**	**4.8%**	**6.3%**	**8.4%**	**8.6%**	**10.2%**	**11.2%**	**10.2%**	**1.9%**

The results of the combined analysis of the applications show significant improvements in fuel consumption can be obtained. While the benefits obtained were not “additive” of all of the individual applications, the results showed that no single application was significantly affected or hindered by any other application. It was also observed that the Operational Scenario does not have a significant affect at saturated conditions. As the capacity is filled and the congestion builds, there is little that can be done from a signal standpoint to improve throughput and environmental measures.

The combined modeling was subjected to similar sensitivity parameters as the individual modeling of applications. Many of the results of the combined modeling of applications had similar patterns to the individual modeling, such as increasing penetration rate being consistent with increasing environmental improvements. Other major conclusions specific to the combined modeling are as follows:

1. The combined applications worked well together, and although the environmental benefits of the combination of the five applications did not exactly equate to the sum of the results of the individual modeling, none of the applications were seen to conflict with or nullify the results of any of the other applications within the Operational Scenario.
2. Passenger, freight, and transit vehicles experienced significant environmental benefits at all levels of connected vehicle OBE penetration rate.
3. Passenger and freight vehicles in the network that were not connected received significant incidental benefits from the combined Eco-Signal Operations applications, such as improved signal timings, extended green lights from granted priorities, and speed advice of the vehicles in front of them.
4. The overall percentage impact of the combined applications was similar for both the current 2005 and the future 2030 fleet mixes for all pollutant types, indicating that the applications

would be beneficial even in future conditions where the fleet mix consists of a higher number of vehicles with low emissions which is expected to possibly nullify environmental gains.

In addition to the major conclusions of the combined modeling of applications, additional questions and opportunities to learn more through future research were discovered. Should combined modeling of these applications be researched further in future work, the following are opportunities to better understand the applications:

1. It is hypothesized that the performance of the Eco-Approach and Departure at Signalized Intersections and Eco-Traffic Signal Timing applications in combination could be greatly improved if the traffic signal timing optimization process includes the eco-friendly speed advice to vehicles during the runs. Since the Eco-Approach and Departure at Signalized Intersections application changes the trajectories of the vehicles, it is possible that the signal timings would be better able to adapt.
2. More research could yield fixes and improvements to the combined applications that will help mitigate the disadvantages experienced by freight vehicles in lower levels of connected vehicle OBE implementation. This will make early implementation of applications more attractive to freight operators.

Explanation of Benefits

Individual modeling and the combined modeling of applications show significant improvement in fuel consumption and resultant emissions that were analyzed during the modeling process. While these percentages show improvement, the savings may not be easy to understand for the average user or entity planning to deploy the technology. To further break down the benefits of the applications, Exhibit 13 shows each of the applications and how the percentage improvement in fuel consumption translates to financial savings for the typical user. For each of the vehicle types, a “typical user” is defined to 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 potentially 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 among most of the country.

Exhibit 13: Monetary Savings Snapshot for the Improvement in Fuel Consumption for Each of the Eco-Signal Operations Applications, for a Typical User.

Application	Vehicle Type	Max Fuel Consumption Improvement	Potential Benefits to Users	
			Savings per Mile	Savings per Year per Vehicle
Eco-Traffic Signal Timing	All	4.5%	$0.008	$65
Eco-Freight Signal Priority	Freight	3.5%	$0.019	$570
Eco-Transit Signal Priority	Transit	2.0%	$0.015	$670
Eco-Approach and Departure	All	12.0%	$0.024	$210
Connected Eco-Driving	All	3.0%	$0.006	$52
Combined Applications	Passenger	9.6%	$0.018	$145
	Freight	9.8%	$0.053	$1,590
	Transit	3.1%	$0.023	$1,040

The assumptions used for the calculation of benefits in Exhibit 13 are as follows:

- The average traffic composition is 98% light duty vehicles (LDV) including passenger cars and Sport Utility Vehicles (SUV); and 2% trucks.

- The miles per gallon (MPG) for a passenger car is 24.0, SUV is 17.0, truck is 7.3, and transit vehicle is 4.0.
- The average arterial miles traveled (VMT) by a LDV is 8,250, truck is 30,000, and transit vehicle is 44,600.
- The average price of fuel per gallon for an LDV is $3.67, truck is $3.95 (diesel) and transit vehicle is $3.00 (CNG+diesel).

As seen in Exhibit 13, the range of benefits for fuel consumption savings is large and the impact is much different depending on the vehicle type and how many vehicles are owned and operated by a fleet operator of business. The combined modeling of the applications shows that maximum benefits are received by freight vehicles along the El Camino Real corridor, which is encouraging because freight vehicles have the highest impact on emissions and health issues in local urban communities near urban arterials.

Conclusions

The results that were obtained from the variety of sensitivity analyses of the Eco-Signal Operations applications allows researcher to draw several 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-Signal Operations Operational Scenario showed greater benefits with higher levels of connected vehicle technology as the technology provides the applications with more information, which help them, perform better, with any detrimental side effects to non-connected vehicles falling off quickly in higher levels of implementation. In most cases, even at lower penetration rates, the other surrounding vehicles derived a benefit from the connected vehicles. For example, in the case of Eco-Traffic Signal Priority, non-connected vehicles on the mainline benefited from the priority granted. In the case of the Connected Eco-Driving and Eco-Approach and Departure at Signalized Intersections applications, non-connected vehicles could follow the ones that were following eco-driving principles and benefit from them. With all of the benefits at the lower levels of connected vehicle penetration, it shows that the Eco-Signal Operations Operational Scenario will be useful for implementation even in the early stages of connected vehicle OBE and RSE technology being available to the public.

The major finding of the combined modeling showed that while the improvements of the combined modeling of applications did not exactly equate to the additive improvements of all the individual modeling, there are no conflicting elements that nullify the effects of any of the applications. When combined, the applications of the Eco-Signal Operations Operational Scenario result in fuel consumption improvements of about 10 percent using the 27-intersection El Camino Real corridor model. There are also emissions improvements of other resultant pollutants of 15 percent to 25 percent. The combined modeling also shows that different applications improve different emissions in different ways, and this is owing to the goal of each application, whether to improve the vehicle trajectory or to reduce queuing time at the intersection approach. The other sensitivity analyses of the combined modeling show similar results to those of the individual modeling, such as the increasing benefits with increasing penetration rate and the reduction in improvements in higher levels of congestion when the corridor reaches full saturation.

The information provided in this report is intended as the first step in a line of research to improve the environment using connected vehicle technology. Overall, it was found that many impacts or interesting findings of several of the applications, especially the Eco-Signal Timing and Eco-Signal Priority applications, are highly dependent on the shape and configuration of the roadway on which they are implemented. The fact that the El Camino Real is a corridor, with the majority of the traffic on the mainline with only minor side-street traffic, could have an impact on the operations of the applications. Because of this, there should be more research on different types and configurations of roadways to better represent the road network in the United States. In addition, many of the application algorithm pieces had assumptions such as “offline” or hard-coded values, rather than more “online” or real-time processes such as would be more realistic with the future implementation of connected vehicle technologies. The results of the sensitivity analyses have given a better understanding of the unknowns from the beginning of the project, so these insights, in combination with future research, could yield significantly more improvements and more dynamic, environmental connected vehicle technologies.

Finally, the details of the individual algorithms were implemented using the tools, and more details are described in individual sections of this report. Extensive sensitivity analyses were carried out to study the impacts of the applications in a variety of situations that could potentially be encountered from location to location when the applications are implemented in the future. Each section of the report details all of the conclusions and future modeling opportunities found for the individual modeling, as well as the combined modeling of applications.

Chapter 1. Introduction

This report is focused on modeling the Applications for the Environment: Real-time Information Synthesis (AERIS) Program's Eco-Signal Operations Scenario, with a detailed focus on the development of the scenario framework, algorithm development, and application needs for the operational scenario, as well as the modeling and results gained from detailed simulation analysis. The Eco-Signal Operations Operational Scenario uses connected vehicle technologies and applications, as well as signal operational communications technologies, to reduce fuel consumption, greenhouse gas (GHG) and criteria air pollutant emissions on signalized arterial roadways. The applications within the scenario are designed to reduce idling, stop-and-go behavior, and inefficient accelerations and decelerations and to improve traffic flow at signalized intersections.

The Eco-Signal Operations Scenario is a package of five individual arterial- and traffic signal-based applications that were designed to work both individually, as well as in combination, in order to meet the AERIS program's objectives of reducing environmental impacts in transportation systems. The individual applications of the Eco-Signal Operations 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 U.S. Department of Transportation's (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 the program is to use connected vehicle technology to reduce the environmental impact of road transportation. A connected vehicle 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 connected vehicle setting.

The AERIS applications are designed to create significant benefits in terms of reductions in emissions (e.g., greenhouse gas [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:

- Identify connected vehicle 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 (i.e., system users, system operators, policy decision makers, etc.).
- Identify vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-grid (V2G) data exchanges via wireless technologies of various types.
- Model and analyze connected vehicle applications to estimate the potential environmental impact reduction benefits.
- Develop a prototype for one of the applications to test its efficacy and usefulness.

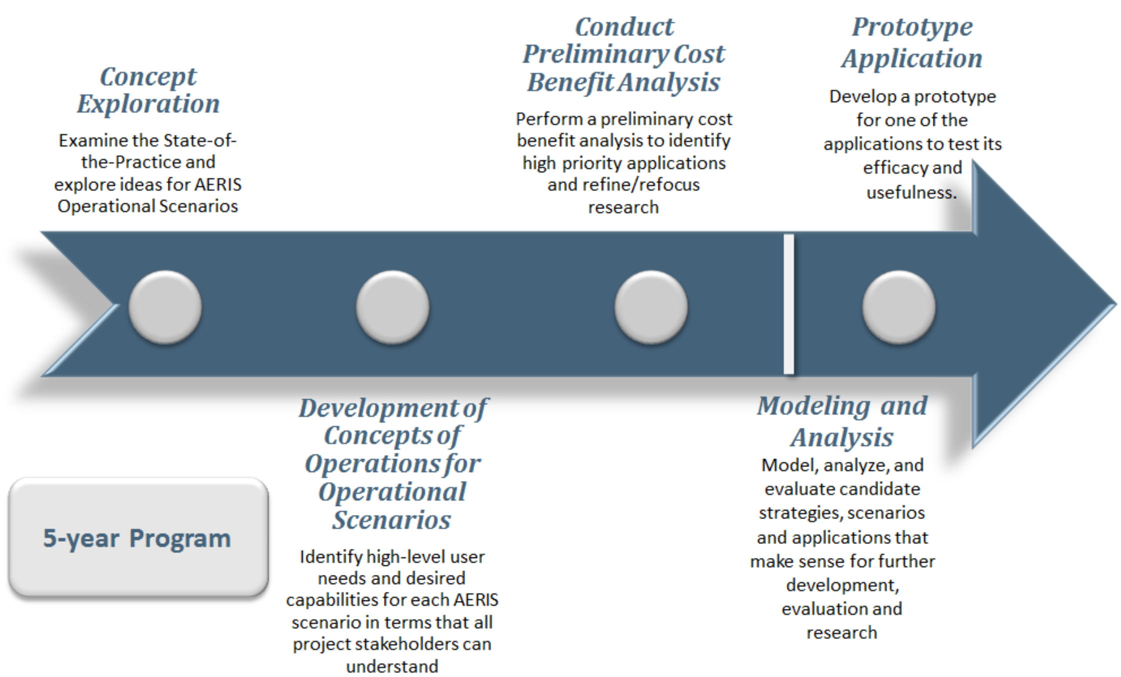


Figure 1: The AERIS approach (Source: USDOT, AERIS Factsheet, http://www.its.dot.gov/factsheets/pdf/AERIS_factsheet.pdf, Accessed on 9/11/14)

The AERIS Program is a five year program consisting of a phased research approach (Figure 1).

- 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 (i) environmental applications, (ii) assessment of technologies to collect environmental data, (iii) environmental models, (iv) behavioral and activity-based models, and (v) evaluation of environmental ITS deployments. Additionally, six Broad Agency Announcement (BAA) projects were conducted.
- Development of Concepts of Operations for Operational Scenarios – The next phase focused on the identification of environmental applications and the development of Concept of Operations 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 Benefit Cost Analysis – Once the ConOps were developed, a preliminary benefit cost analysis was performed to identify high priority applications and refine/refocus the research.

- Modeling and Analysis – The high priority applications from the benefit cost analysis 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 connected vehicle 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 Applications for the Environment: Real-Time Information Synthesis (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 above those of the individual applications.

Each Operational Scenario is comprised of applications, regulatory/policy tools, educational tools and performance measures. Applications are technological solutions (e.g., software, hardware, interfaces) designed to ingest, process, and disseminate data in order 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 if a vehicle should be granted priority at a signalized intersection, and then communicate this priority request to a traffic signal controller.

Applications are complemented with regulatory/policy and educational tools to further support the Operational Scenario.

Identification and Evaluation of Transformative Environmental Applications and Strategies Project

Prior to 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 benefit-cost analysis (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.

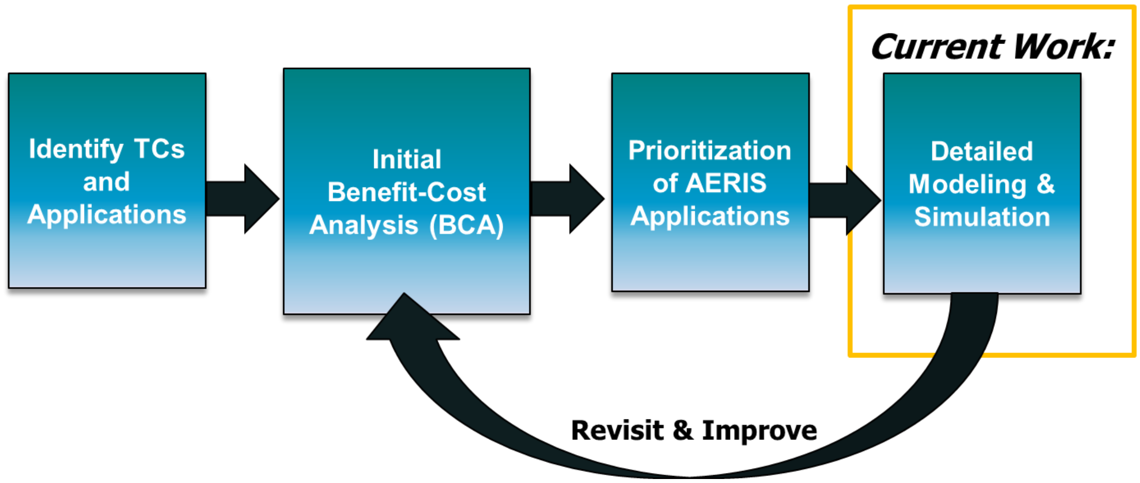


Figure 2: The Role of Modeling and Simulation.

Summary of Previous Tasks

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

1. **Eco-Signal Operations:** This Operational Scenario uses connected vehicle 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.
3. **Eco-Lanes:** This Operational Scenario includes dedicated lanes optimized for the environment, referred to as Eco-Lanes. Eco-Lanes are similar to high-occupancy vehicle and high-occupancy toll lanes; however, these lanes are optimized for the environment using connected vehicle data and can be responsive to real-time traffic and environmental conditions.
4. **Low Emissions Zones:** The AERIS program seeks to expand on the concept of low emissions zones by investigating the potential of connected vehicle 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.
5. **Eco-Traveler Information:** This Operational Scenario enables development of new, advanced traveler information applications through integrated, multisource, 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.

6. **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 at a national scale. A BCA model was developed to assess the benefits and costs of each application at 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., Federal Transit Administration [FTA]) and connected vehicle 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 to 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.

Key questions pertaining to modeling that were considered include the following:

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 is 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 chapters:

- **Chapter 1** provides the background and overview for AERIS modeling activities.
- **Chapter 2** presents an overview of the five AERIS applications tested as part of this effort.
- **Chapter 3** presents the common modeling elements for all the AERIS application 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.
- **Chapter 4–Chapter 7** describe how each of the five AERIS 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:

a. 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.
b. Algorithm: This section describes the algorithm used to implement the AERIS application.
c. 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.
d. Scenarios: This section describes the scenarios modeled.
e. 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.
f. Findings and Opportunities for Future Research: This section details qualitative findings and suggests topics for future research.

- **Chapter 8** describes how a scenario was created to model the five AERIS applications together in a single simulation model to understand the synergies between applications and potential tradeoffs. It presents the efforts to combine the algorithms, 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.

- **Chapter 9** presents observations and conclusions from the entire modeling effort.

- **Appendix A** provides a list of acronyms used in the report.

- **Appendix B** presents the technical details of the development of the MOtor Vehicle Emissions Simulator (MOVES) plug-in that is used for the estimation of emissions and fuel consumption.

- **Appendix C** contains all the signal timing plans and origination-destination (OD) matrices used in the various scenarios tested in this effort.

- **Appendix D** describes a supplementary application called Eco-Speed Harmonization. The application was tested with the other Eco-Signal Operations applications and was found to yield significant benefits.

- **Appendix E** describes the BCA results that were estimated using the BCA model developed as part of an earlier task in the AERIS project.

Chapter 2. Eco-Signal Operations Applications

This chapter describes how the Eco-Signal Operations Operational Scenario uses signal operations technologies to decrease fuel consumption and GHG and criteria air pollutant emissions by reducing idling, the number of stops, and unnecessary accelerations and decelerations, as well as improving traffic flow at signalized intersections. The Eco-Signal Operations Operational Scenario uses connected vehicle technologies to reduce fuel consumption and GHG and criteria air pollutant emissions on arterials.

Figure 4 illustrates the Eco-Signal Operations Operational Scenario as envisioned by the AERIS program.

Operational Scenario Description

- The Eco-Signal Operations Operational Scenario uses connected vehicle technologies to decrease fuel consumption and emissions by reducing idling, the number of stops, unnecessary accelerations and decelerations, and improving traffic flow at signalized intersections.
- The Operational Scenario features the following applications: (1) Eco-Approach and Departure at Signalized Intersections, (2) Eco-Traffic Signal Timing, (3) Eco-Traffic Signal Priority, (4) Wireless Inductive/Resonance Charging, and (5) Connected Eco-Driving.

Potential Benefits

- The Eco-Approach and Departure at Signalized Intersections application provides up to 13% fuel reduction benefits for a coordinated corridor above the baseline:
  - 8% of the benefit is attributable to signal coordination
  - 5% attributable to the application
- Eco-Traffic Signal Timing provides up to 5% improvement in fuel consumption and environmental measures at full connected vehicle penetration.
- Eco-Signal Priority applications provide 2-4% fuel reduction benefits, resulting in approximately $650,000 savings per year for a transit or delivery truck fleet of 1,000 vehicles.
- Combined modeling of the Eco-Signal Operations applications resulted in a 9.6% reduction in fuel consumption and CO_2 over the baseline.

Operational Scenario Visualization

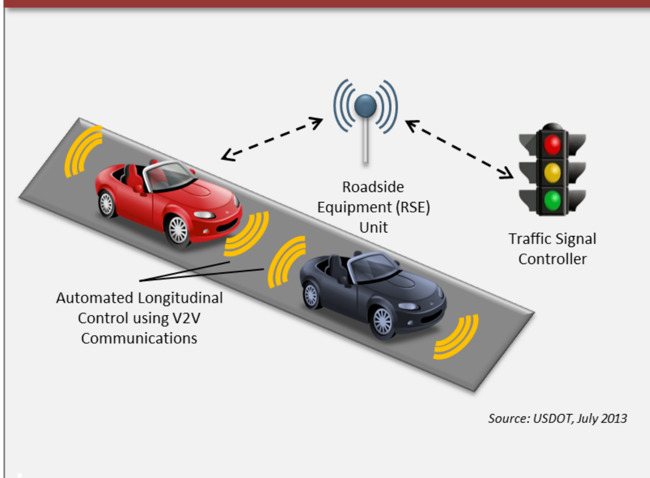


Figure 4: Eco-Signal Operations Operational Scenario (Source: USDOT ITS-JPO, www.its.dot.gov/aeris/pdf/AERIS_Operational_Scenarios011014.pdf, accessed April 13, 2014).

The descriptions of the applications are provided below as described by the AERIS program.

Eco-Approach and Departure at Signalized Intersections

This application uses wireless data communications sent from roadside equipment (RSE) unit to connected vehicles to encourage “green” approaches to signalized intersections. The application, located in a vehicle, collects Signal Phasing and Timing (SPaT) and geographic information description messages using vehicle-to-infrastructure (V2I) communications and data from nearby vehicles using vehicle-to-vehicle (V2V) communications. Upon receiving these messages, the application would perform calculations to determine the vehicle’s optimal speed to pass the next traffic signal on a green light or to decelerate to a stop in the most eco-friendly manner. This information is then sent to longitudinal vehicle control capabilities in the vehicle to support partial automation. The application also considers a vehicle’s acceleration as it departs from a signalized intersection and engine start-stop technologies.

Eco-Traffic Signal Timing

This application is similar to current traffic signal systems; however, the application’s objective is to optimize the performance of traffic signals for the environment. The application collects data from vehicles, such as vehicle location, speed, and emissions data, using connected vehicle technologies. It then processes these data to develop signal timing strategies focused on reducing fuel consumption and overall emissions at the intersection, along a corridor, or for a region. The application evaluates traffic and environmental parameters at each intersection in real time and adapts so the traffic network is optimized using available green time to serve the actual traffic demands while minimizing the environmental impact.

Eco-Traffic Signal Priority

This application is actually two, one for transit vehicles and one for freight vehicles, allowing them to request signal priority when approaching a signalized intersection. These applications consider the vehicle’s location, speed, vehicle type (e.g., alternative fuel vehicles), and associated emissions to determine whether priority should be granted. Information collected from vehicles approaching the intersection, such as a transit vehicle’s adherence to its schedule, the number of passengers on the transit vehicle, or weight of a truck, may also be considered in granting priority. If priority is granted, the traffic signal would hold the green light on the approach until the transit or freight vehicle clears the intersection. This application does not consider signal pre-emption, which is reserved for emergency response vehicles.

Connected Eco-Driving

This application provides customized real-time driving advice to drivers so that they can adjust their driving behavior to save fuel and reduce emissions. Eco-driving advice includes recommended driving speeds and optimal acceleration and deceleration profiles based on prevailing traffic conditions, interactions with nearby vehicles, and upcoming road grades. The application also provides feedback to drivers on their driving behavior to encourage drivers to drive in a more environmentally efficient manner. Finally, the application may include vehicle-assisted strategies whereby the vehicle automatically implements the eco-driving strategy (e.g., changes gears, switches power source, or reduces its speed in an eco-friendly manner).

Wireless Inductive/Resonance Charging

Wireless inductive/resonance charging 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 moving at highway speeds. Roadside charging infrastructure supports static charging capable of transferring electric power to a vehicle parked in a garage or on the street and vehicles stopped at a traffic signal or stop sign.

This application was not modeled as part of the Eco-Signal Operations modeling effort. Data pertaining to the efficiency of wireless charging of vehicles, the number of vehicles equipped with the feature, and the number of vehicles that can be charged at an intersection at a given time were not available for modeling this application. In the future, assumptions regarding these can be made as and when guidance is available.

Applications Modeled

The Eco-Signal Operations applications were modeled using different modeling techniques to evaluate their benefits. There were several assumptions that were made to model the applications on a transportation network. The applications are listed in the respective modeling section of each application. Due to limitations with the existing models or other technical constraints, the applications modeled may not match the definitions of the applications in this section. The goal of this modeling exercise was not to model the applications extensively and in great detail, it was to understand if the applications yielded benefits and test their interactions with other applications in the same Operational Scenario.

The Wireless Inductive/Resonance charging application was not modeled as part of this project. There is very little data available to model the application. The existing modeling tools do not have the required features to model the application as well.

Chapter 3. Common Modeling Elements

Model Region Description

For the modeling of Eco-Signal Operations applications, an arterial network was primarily used. In this section, we describe the networks or subsets of networks that were used for testing the Eco-Signal Operations applications. An arterial corridor was used to model the applications because the anticipated impacts of the applications were mostly driving behavior impacts and not travel demand impacts such as destination choice or route choice. Table 1 presents an assessment of how much each application influences the 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						Modeling Scale	Comments
	Destination Choice	Mode Choice	Time-of-Day Choice	Route Choice	Lane Choice	Driving Behavior		
Eco-Approach and Departure at Signalized Intersections					◔	●	Corridor Simulation	Changes in driving behavior are expected. Corridor simulation is sufficient to capture effects of application.
Eco-Traffic Signal Timing				◔	◑	●	Corridor Simulation	Route choice impact is likely to be minimal. Primary changes are likely to be seen in driving behavior and speed profiles.
Eco-Traffic Signal Priority		◔	◔	◔	◑	●	Regional/ Corridor Simulation	Mode choice may be affected if transit becomes more reliable and efficient, but impact is likely to be minimal. Even though regional simulation is beneficial, corridor-level simulation is sufficient to capture effects of application.
Connected Eco-Driving				◔	◑	●	Corridor Simulation	Route changes may or may not be seen depending on whether travel time is improved by application. Corridor simulation is sufficient to capture effects of application.

Legend:

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

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

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

Hypothetical Network (Referred to as HPN)

A generic hypothetical corridor with three fixed-time signalized intersections was used for some of the analyses. The lengths of the links between neighboring intersections were set to 600 meters. The speed limit was set at 50 mph. The effective green time for the pass-through phase was 30 seconds, with the total cycle length set to 60 seconds. Both cross-traffic and turning traffic were included in the simulations. Two lanes were assigned for the through traffic and one lane for left-turn-only traffic, on both mainline and cross-street. Right-turn was also permitted. It was a multi-lane network with cross-traffic and turning traffic. Figure 5 shows the intersection layout and the traffic flows.

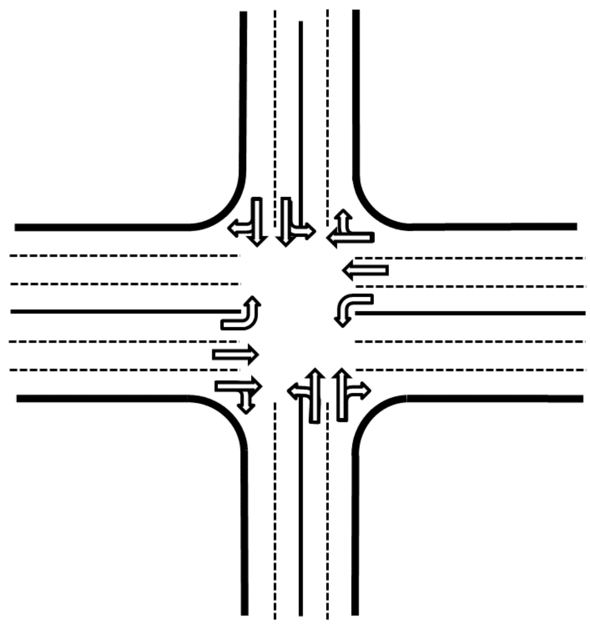


Figure 5: Intersection Layout and Traffic Flows.

El Camino Real 27-Intersection Network (Referred to as ECR-27)

As shown in Figure 6, the corridor used in this modeling study is a 27-intersection, 6.5-mile segment of the El Camino Real in northern California between Churchill Avenue in Palo Alto and Grant Road in Mountain View. The El Camino Real is a major north-south arterial connecting San Francisco and San Jose and is parallel to the US-101 freeway. For the majority of the corridor, there are three lanes along each direction. The intersection spacing varies from 650 feet to 1600 feet, and the speed limit is 40 mph.

Vehicle demands and their OD patterns were calibrated to a typical weekday in summer 2005. It is to be noted that the mainline volumes are significantly higher than the ones for the intersecting streets. The traffic signals along the segment are both actuated and coordinated. Signal settings in the model were based on the parameter values exported from the actual traffic signal system in July 2005.

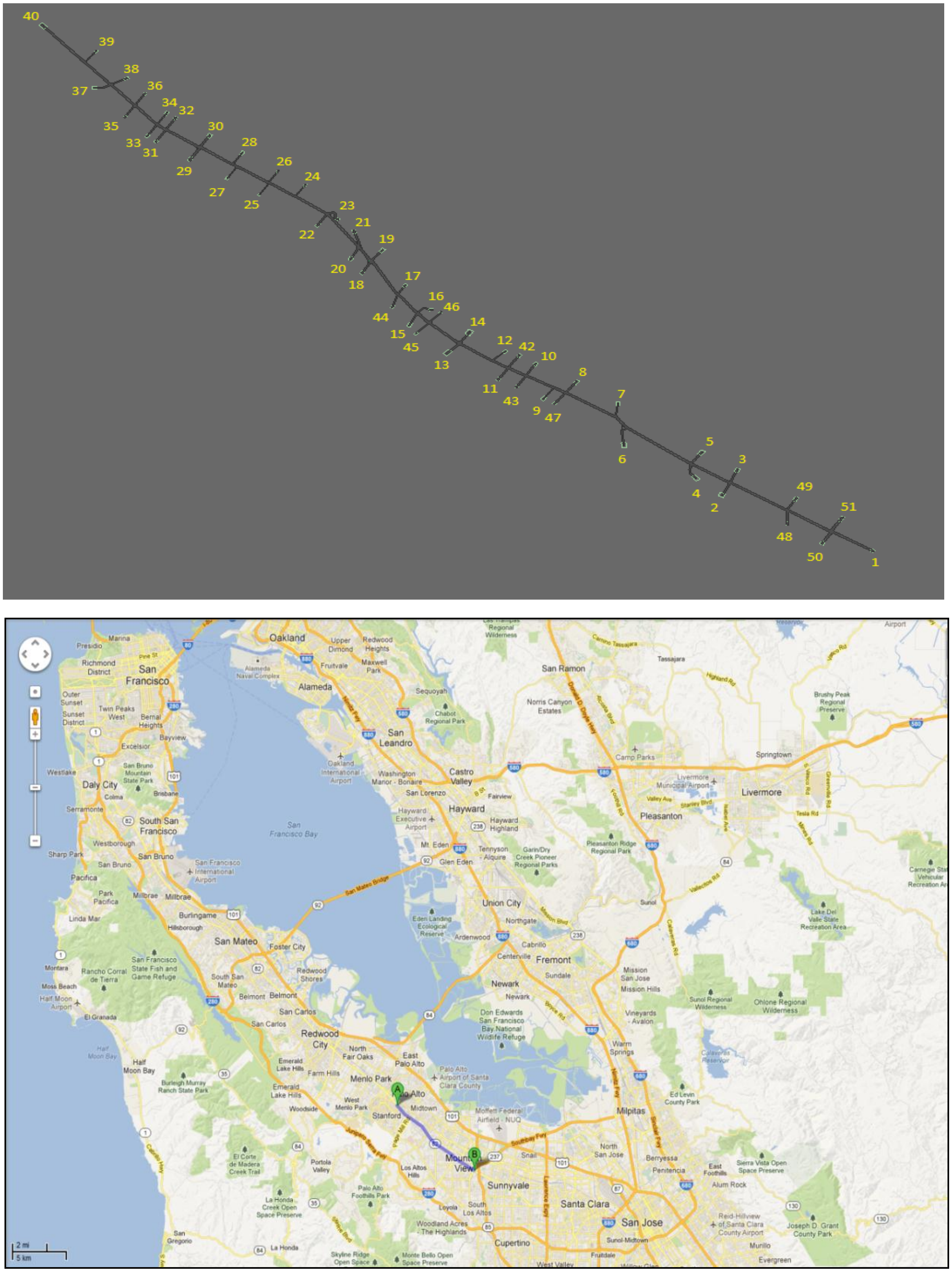


Figure 6: 27-Intersection Segment of El Camino Real.

The subsequent evaluation of the applications' potential environmental benefits was conducted based on this assumption. The baseline timings for the El Camino Real network can be seen in Appendix C for all of the intersections in the network.

The baseline El Camino Real network is primarily a passenger vehicle corridor, with only a small percentage of heavy vehicles. The calibrated fleet mix of the El Camino Real Paramics network can be seen in Table 2.

Table 2: Fleet Mix in the El Camino Real Network.

Vehicle Type	Percent of Total Vehicles
Cars	98.80%
Heavy Vehicles	1.20%

It was determined that a smaller network of intersections would be needed for the analysis to help with detailed sensitivity analyses, so in addition to the full 27-intersection El Camino Real network, a 3-intersection subset of this model was developed for use in Paramics. This segment was developed to represent the same intersections from the larger 27-intersection model with the same calibrated demands and timings. To keep the OD pattern intact for the 3-intersection segment, traffic demand from 50 zones was aggregated into 7 zones. This smaller network is described in further detail in section *El Camino Real 3-Intersection Network* on page 15.

Modification for the Eco-Transit Signal Priority Application

Fixed-route transit vehicles are coded into the Paramics model to represent the buses in use along the El Camino Real. The bus route has transit vehicles traveling the length of the El Camino Real in both the westbound and eastbound directions, with headways of about 5 minutes between them. Associated transit stops are also coded into the Paramics network at cross-streets to facilitate realistic transit vehicle performance. Further sensitivity tests are also conducted with respect to increasing the bus frequencies with smaller headways, while keeping their routings and the passenger and freight volumes constant.

The Paramics simulation was coded such that all of the signals were under fixed-time control as the default signal phase and timing implemented in July 2005. The subsequent evaluation of this application's potential environmental benefits was conducted based on this assumption. Owing to their coordination, the common cycle length for all intersections is 130 seconds. However, the prioritization affects the phase lengths during priority and returns to normal phase length after two signal cycles. The priority algorithm carries out red termination only if the next phase provides priority to the movement required, and extends the green phase if extra green is needed for the priority movement. The Eco-Transit Signal Priority algorithm contains feedback and offset setting procedures within the current cycle and next cycle after the Eco-Transit Signal Priority is granted so neither cycle length or multi-intersection coordination is changed. In detail, feedback and offset are set to one or more phases by decreasing phase length so that total cycle length keeps steady. In addition, the bus cannot request priority if it has been granted priority by the signal ahead. However, if the bus has been denied priority it can request priority at the time that the vehicle is estimated to reach the next signal.

Modification for the Eco-Freight Signal Priority Application

The heavy freight vehicles in the network are represented as a percentage of the total OD pair demand in the microsimulation network, meaning that there are potentially freight vehicles on all of the approaches and possible routings throughout the network. Since this is a corridor model with the majority of traffic on the El Camino Real mainline approaches, the vast majority of freight vehicles will be on the mainline approaches to each of the intersections. This is a common reality in freight volumes on arterial roadways, carrying goods along major traffic routes, with priorities serving only these movements.

In the early planning stages of the Eco-Freight Signal Priority application, the modeling was intended to be carried out in a microsimulation model of a freight hub, or freight-heavy area. However, it was decided to model the application on the El Camino Real to fit with the other AERIS applications being modeled for this project. The freight volumes along the El Camino Real corridor are quite low, however, as shown in Table 2. It was decided to increase the freight volumes in the network for analyses, in order to use this model but not miss out on examining the effects of the application in a freight corridor. To this end, many of the sensitivity analyses were conducted with a freight volume of 10 percent, while others were tested with the freight vehicle volumes from baseline conditions.

Model Calibration

This El Camino Real model network was developed in Paramics by the California Partners for Advanced Transportation TecHnology (PATH), which developed it in previous research on evaluating the effectiveness of ITS technologies, as documented in the Yin, et al., report (2007). According to the report, the model was calibrated against field data of roadway geometry, traffic OD matrix, vehicle mix, and traffic signal timings for the year 2005. No other information regarding model calibration is available.

El Camino Real 3-Intersection Network (Referred to as ECR-3)

One of the networks used in this modeling study is a 3-intersection segment of the El Camino Real in northern California which is a small subset of the 27 intersection network mentioned above. El Camino Real is a major north-south arterial connecting San Francisco and San Jose and is parallel to the US-101 freeway. In this entire segment (Figure 7), there are three lanes along each direction. The intersection spacing varies from 200 meters to 500 meters, and the speed limit is 40 mph.

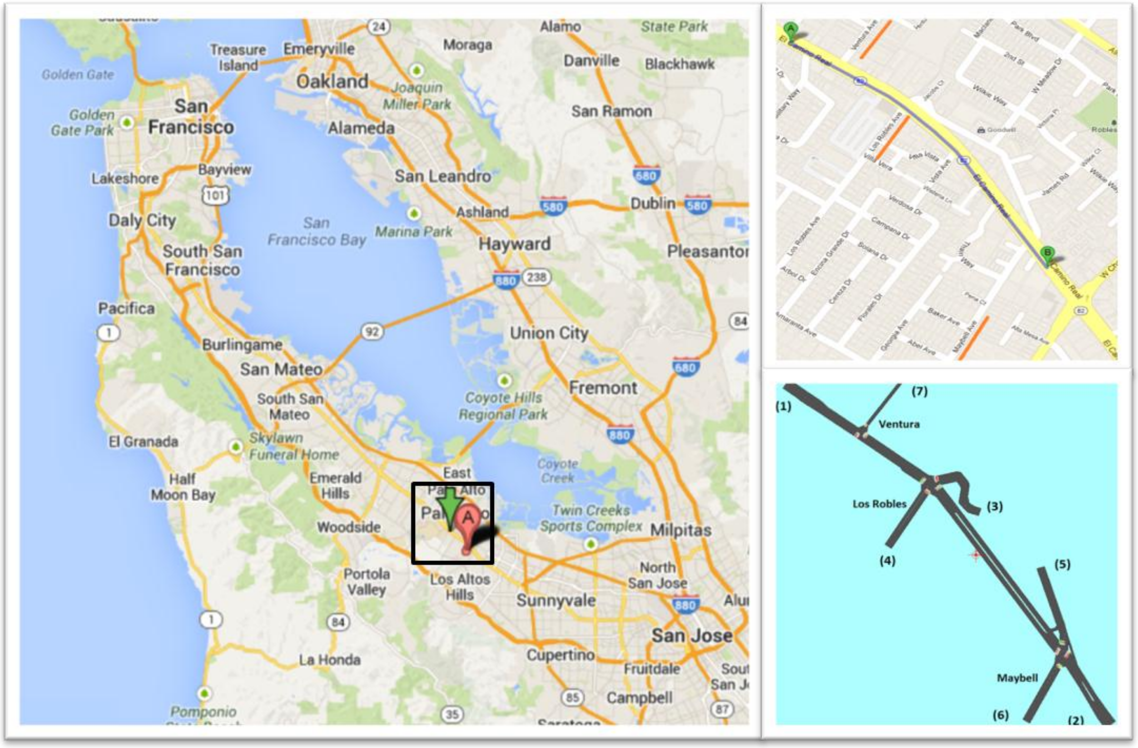


Figure 7: 3-Intersection Segment of El Camino Real.

This 3-intersection segment of the El Camino Real corridor was coded in Paramics, a traffic microsimulation tool. Vehicle demands and their OD patterns were calibrated for a typical weekday morning between 7:15 a.m. and 9:30 a.m. in summer 2005, using the data available (see the tables in Appendix C, where row numbers are origin zone numbers and column numbers are destination zone numbers). It is to be noted that the original network has 27 intersections. To keep the OD pattern intact for the truncated 3-intersection segment, traffic demand from 50 zones was aggregated into 7 zones, as shown in Figure 7 (zone numbers are shown in parentheses). In addition, two vehicle types have been defined in this network: light-duty vehicles and buses (see Table 3).

Table 3: Fleet Mix in the El Camino Real Network.

Vehicle Type	Penetration
Car	98.8%
Bus	1.2%

Traffic signals along this segment—used as the baseline—were already actuated and coordinated to some extent. However, after reviewing the time-space diagram for the corridor, the analysis team determined that the coordination of the timing plans between intersections could be improved to allow for a larger green wave along northbound and southbound El Camino Real. It is to be noted that the mainline volumes are significantly higher than the ones for the intersecting streets.

While the baseline included actuated and coordinated signal timing plans, for this analysis, the Paramics simulation was coded such that all three of the traffic signals were under fixed-time control as the default signal phase and timing. The fixed-time plans created by the California Department of Transportation were implemented in the field in July 2005. The subsequent evaluation of this application's potential environmental benefits was conducted based on this assumption. Appendix C lists the green splits of all three signals along the main corridor. Owing to their coordination, the common cycle length of these three intersections (Ventura Avenue, Los Robles Avenue, and Maybell Avenue) is 130 seconds.

Model Calibration

This El Camino Real model network was developed in Paramics by PATH, which developed it in previous research on evaluating the effectiveness of ITS technologies, as documented in the Yin, et al., report (2007). According to the report, the model was calibrated against field data of roadway geometry, traffic OD matrix, vehicle mix, and traffic signal timings for the year 2005. No other information regarding model calibration is available.

Modeling Approach

This section describes the overall modeling approach to analyze the environmental impacts of the Eco-Signal Operations Operational Scenario. The individual applications are considered 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-Signal Operations applications were identified in the "Eco-Signal Operations Analysis Plan," dated September 2013. In addition, the functions of the application that are not considered for modeling were also identified for each application. For this Operational Scenario, the applications are all developed for fixed-time signals and unactuated signals.

The modeling framework adopted to model Eco-Signal Operations applications is presented in Figure 8. The modeling tools used are: microsimulation tool and emissions tool. The identified network (i.e., links, nodes, and their characteristics) and traffic control devices, such as signals, are coded in the microsimulation tool. In addition, travel demand, OD patterns, and vehicle fleet mix are required inputs to the microsimulation. The OD trip tables will be used to create volume inputs for the microsimulation. The vehicle fleet mix will be derived from vehicle registration databases or obtained directly from available field data. Lastly, as the traffic microsimulation tool models detailed driving behavior model parameters, such as driver reaction time, mean target headway will be calibrated for the corridor and subsequently used.

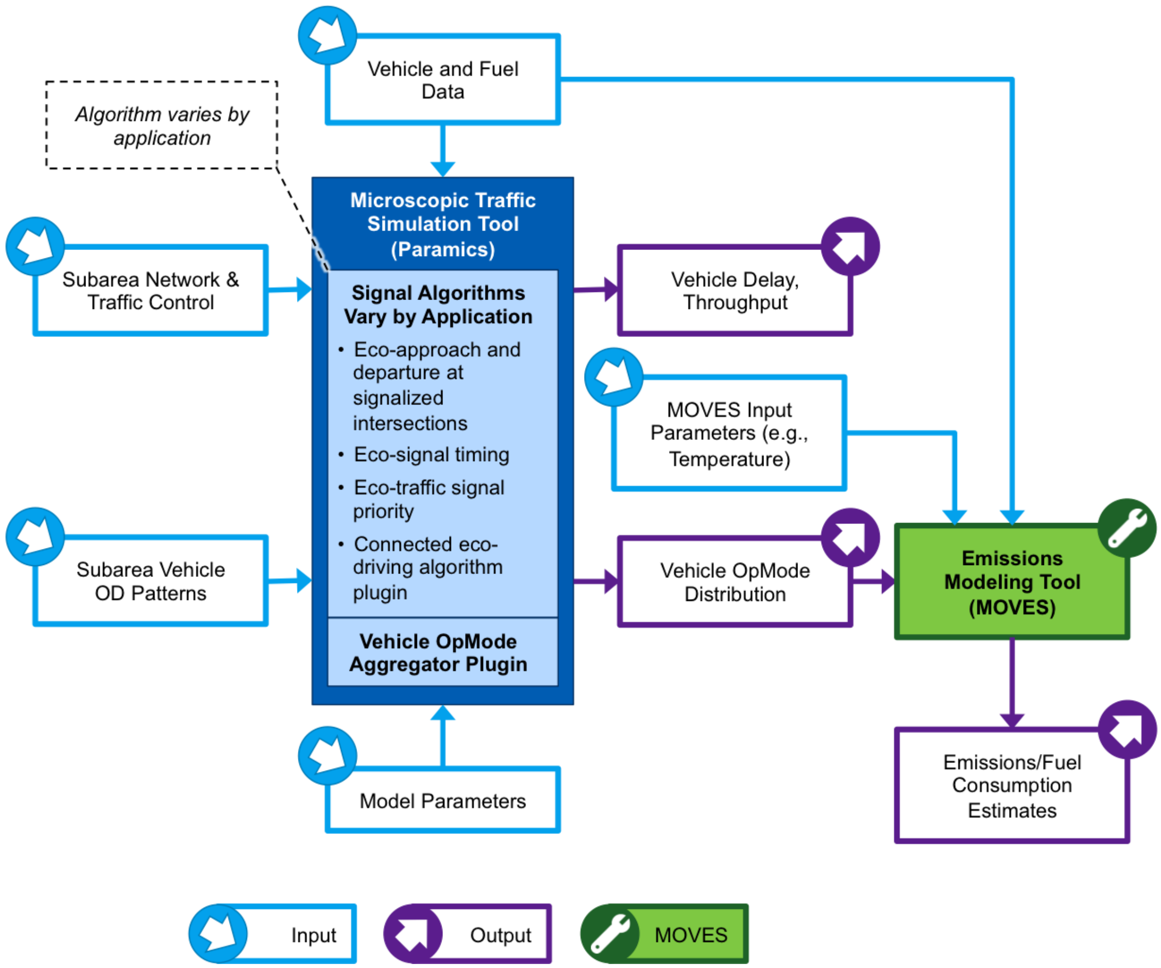


Figure 8: Modeling Framework for Eco-Signal Operations Applications.

Quadstone Paramics traffic microsimulation software was used to model the Eco-Signal Operations applications. Paramics supports the development and implementation of plug-ins 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.

With the use of its built-in application program interface (API), Paramics supports the implementation of plug-ins that can be developed to enable users to interface with its core simulation engine to perform specific tasks. Two plug-ins are needed for Eco-Signal Operations 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. In order for Paramics to quickly and efficiently build a useful input file for the emissions model, the vehicle OpMode aggregator plug-in serves as a direct virtual interface between the traffic microsimulation tool and the emissions modeling tool.

There are a number of tools that estimate emissions at various scales that range from macro to micro. Microscale vehicle emission models that are commonly used in the United States include:

1. University of California at Riverside's CMEM
2. Virginia Tech's VT-Micro model
3. MOVES

MOVES is the latest vehicle emission-modeling tool of the Environmental Protection Agency (EPA); it can estimate macro-, meso-, and micro-scale vehicle emissions. MOVES also has several features, such as the ability to estimate particulate and air toxic emissions, for alternative fuel vehicles. MOVES was selected for analysis because it is necessary to model emissions for future-year vehicles.

There are three general approaches that 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. Then, MOVES will 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. Then, MOVES 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. Then, MOVES 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 one as 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. The vehicle OpMode aggregator Paramics plug-in does the following:

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

This procedure is illustrated in Figure 9.

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 will then be applied to the vehicle OpMode distributions to estimate emissions for the scenario simulated. This process is used to estimate emissions for both the baseline scenario and the scenario where the Eco-Signal Operations applications are implemented. Then, the emission results from both scenarios are compared to determine benefits of the applications.

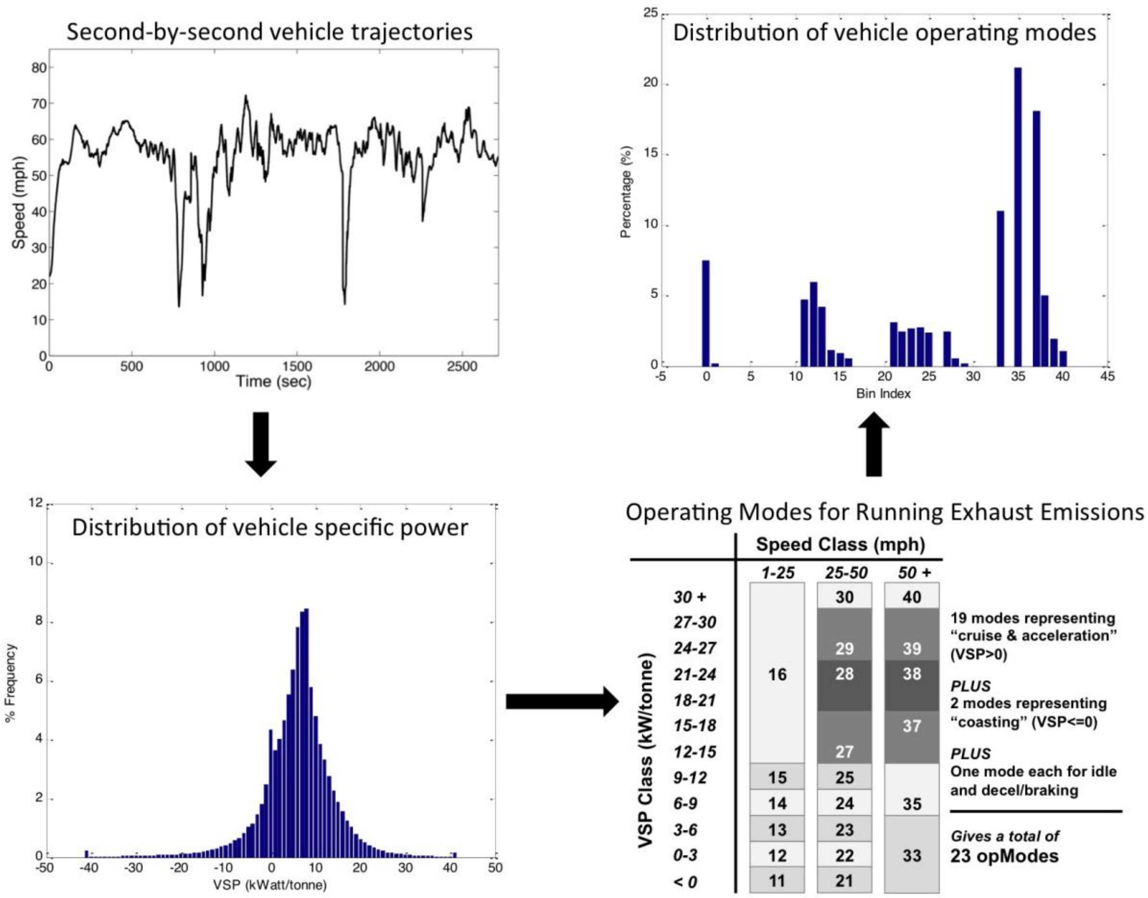


Figure 9: Procedure for Creating Vehicle OpMode Distribution.

Simulation Runs

Prior to modeling each application, the calibration was completed. Owing to the stochastic nature of the microsimulation, multiple runs were made using different seed numbers. The seed number is the starting number for the random number generator used by Paramics. To initialize a simulation run, a random number is generated from a uniform random distribution to determine the time between vehicle releases. The required number of runs is determined by—

$$N = (t_{\alpha/2} \cdot \frac{\delta}{\mu\varepsilon})^2$$

Where μ and δ are the mean and standard deviation of the estimated emissions based on the already conducted runs; ε is the allowable error specified as a fraction of the mean μ; and $t_{\alpha/2}$ is the critical value of the t distribution at the significance level α. This calculation is performed for both CO_2 emissions and energy consumption. The higher calculated N of these two is the required number of runs. If the number of conducted runs is larger than the required number of runs, the simulation for that scenario is finished. Otherwise, one more run is made and the required number of runs is updated accordingly. In our simulation, the significance level was set to 0.05. The allowable error was set at 2 percent.

Sensitivity Testing

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

Generic Traffic Simulation Parameters: These parameters are the traffic demand levels and percentage of freight vehicles or frequency of transit vehicles. They help capture the impact of applications in various traffic conditions normally seen on a corridor.

- **Traffic Demand:** Traffic demand is represented by volume-to-capacity (V/C) ratio computed for each roadway. A V/C ratio greater than 1.00 represents an oversaturated or heavily congested condition on the roadway. The impact of traffic demand on the performance of applications is very important for analysis.
- **Percentage of Freight Vehicles or Frequency of Transit Vehicles:** Freight percentage in the vehicle mix affects the performance of some applications. Heavy vehicles have higher emissions and fuel consumption. The benefits obtained for these vehicles using the Eco-Signal Operations applications were assessed. Not all applications are analyzed using these parameters. The applications that were tested with varying freight percentages in the vehicle mix are the Eco-Freight Signal Priority and Eco-Traffic Signal Timing applications. The frequency of transit vehicles parameter was varied only for the analysis of the Eco-Transit Signal Priority application. It was important to evaluate the benefit of the application under heavy transit demand.

Connected Vehicle Parameters: These include the following:

- **On-Board Equipment (OBE) Penetration Rate:** The OBE penetration rate is the percentage of vehicles on the roadway that are equipped with connected vehicle technology. All applications were modeled with varying OBE penetration rates. These scenarios help capture the impact of data transmitted from the connected vehicles.
- **Communication Distance:** Communication distance is the range of communication between connected vehicles and the infrastructure. These scenarios were designed to estimate the optimum communication range for each application.
- **Communication Delay:** Communication delay is the delay in transmission of information from vehicles to the infrastructure or from the infrastructure to vehicles.

Application-Related Parameters: These parameters are those specific to each application. For the Eco-Transit Signal Priority application, scenarios with and without schedule adherence were modeled. For the Eco-Approach and Departure at Signalized Intersections application, coordinated and uncoordinated signal timing scenarios were used.

- **Maximum Extension Time:** For the Eco-Traffic Signal Priority applications, the maximum extension time is the maximum duration for which a green signal can be held or a red signal can be truncated to grant priority to a transit or freight vehicle.
- **Schedule Adherence:** Schedule adherence is a criterion considered for granting priority to transit vehicles. Scenarios with and without consideration for this criterion were modeled.

Using the above listed parameters, scenarios appropriate for each application were created for the sensitivity analyses. The scenarios modeled for each of the applications is listed in the “Scenarios” section of chapters 4-8.

Performance Measures

The performance measures used for evaluation of the Eco-Signal Operations applications are presented below. Performance measures can be broadly classified into environmental and mobility measures. While generating environmental measures is the primary scope of analysis, mobility-related measures, such as delay, are used to determine the potential mobility impacts of the Eco-Signal Operations applications.

Environmental measures considered in the analysis include:

1. Fuel consumption
2. Emissions
    - Carbon dioxide (CO_2)
    - Particulate matter: PM-10
    - Particulate matter: PM-2.5
    - Oxides of nitrogen (NOx)
    - Volatile organic compounds
    - Hydrocarbons (HC)
    - Carbon monoxide (CO)

Mobility measures considered in the analysis include—

1. Mainline corridor travel time
2. Delay

Microsimulation outputs are used to compute most of the performance measures using the MOVES plug-in. It is to be noted that the secondary measures are only used to examine whether the performance has been affected adversely. All the applications are evaluated based on benefits achieved in terms of the primary measures only.

Chapter 4. Eco-Approach and Departure at Signalized Intersections Application

Application Description

The description of the application is provided in Chapter 2 under section *Eco-Approach and Departure at Signalized Intersections* on page 9. The application is graphically illustrated in Figure 10.

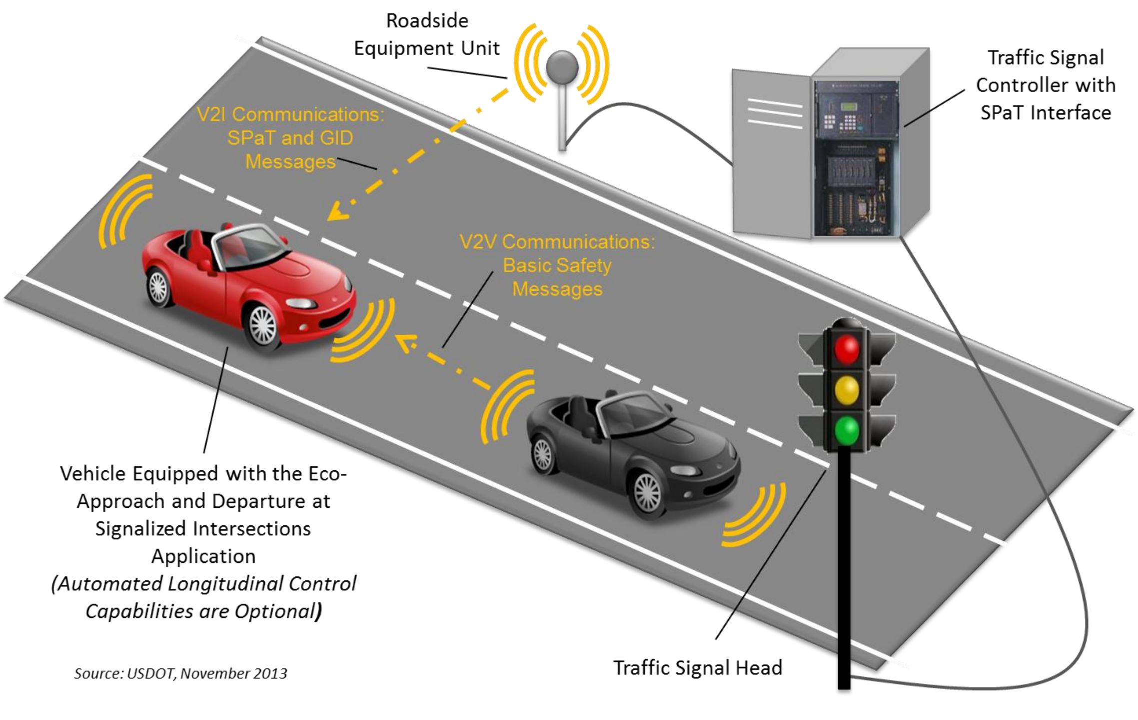


Figure 10: Eco-Approach and Departure at Signalized Intersections Illustrated

Hypotheses

Providing speed advice to drivers who are within a communication range of signals (300 meters) as their vehicle is approaching and departing signalized intersections will reduce emissions and lower fuel consumption during congested traffic conditions by 3 percent to 4 percent under partial connected vehicle penetration and 6 percent to 8 percent under full connected vehicle penetration. The percentage of fuel savings during off-peak hours is expected to be higher as drivers have more ability to adjust their vehicle's speed.

Algorithm

The overall block diagram of the arterial velocity planning algorithm is shown in Figure 11.

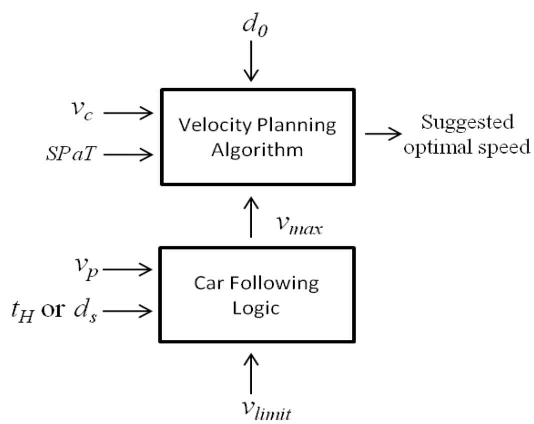


Figure 11: Block Diagram of the Arterial Velocity Planning Algorithm.

The control logic for the velocity planner requires several input parameters:

- v_{limit}: local speed limit
- d_s: safe headway distance
- t_H: safe headway time
- v_p: velocity of preceding vehicle
- v_{max}: maximum speed based on vehicle following logic and local speed limit
- v_c: current vehicle velocity, obtained from OBD
- d_0: distance from vehicle to the intersection, obtained from OBE
- t_{signal}: possible green time window for vehicle to pass the intersection
- t_{r1}: time until signal changes to red, from SPaT messages
- t_{g1}: time until signal changes to green, from SPaT messages
- t_{r2}: time until signal changes to red the second time, from SPaT messages
- v_{target}: target velocity window for vehicle to pass the next intersection in green phase
- v_l, v_h: target minimum and maximum speed of v_{target}.

The control logic for the optimal velocity tries to minimize the vehicle's fuel consumption by minimizing the total tractive power demand and the idling time while ensuring that the optimal velocity is less than or equal to v_{limit}. To avoid idling, the vehicle should reach the intersection during the green phase of the signal. Depending on the current phase of the signal, the travel time to the intersection is given as:

$$t \in \begin{cases} [0, t_{r1}) \cup [t_{g1}, t_{r2}) \; if\ signal = green \\ [t_{g1}, t_{r1}) \; if\ signal = red \end{cases}$$

Figure 12 then represents the target velocity selection logic. The acceleration and deceleration trajectory planning is as follows.

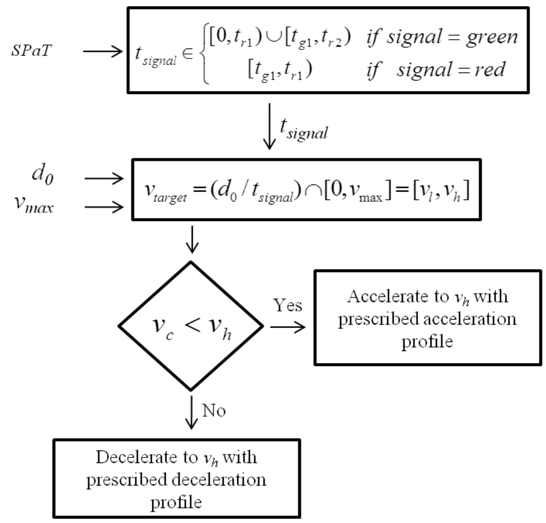


Figure 12: Control Logic for Optimal Velocity Determination.

To stay within the targeted range of velocity, or to achieve a velocity so the vehicle can reach the intersection at a specific time, the vehicle needs the ability to accelerate or decelerate at specific times. There are an infinite number of ways to accelerate or decelerate from one speed to another. Several suggested trajectory planning algorithms include constant acceleration/deceleration rates, linear-acceleration/deceleration rates, and constant power rates. The algorithm in this study is designed to choose an acceleration/deceleration profile that minimizes fuel consumption/emissions and is still comfortable to the passengers (i.e., has low jerk).

To ensure a smooth trajectory, a family of velocity profiles is chosen with a trigonometric increase in velocity given by:

$$v = \begin{cases} v_h - v_d\, cos(mt) \;\; t \in [0, \frac{\pi}{2m}) \\ v_h - v_d \frac{m}{n} cos\, n\left(t - \frac{\pi}{2m} + \frac{\pi}{2n}\right) \;\; t \in \left[\frac{\pi}{2m}, (\frac{\pi}{2n} + \frac{\pi}{2m})\right) \;\; v \\ v_h + v_d \frac{m}{n} \;\; t \in \left[\left(\frac{\pi}{2n} + \frac{\pi}{2m}\right), \frac{d_0}{v_h}\right] \end{cases}$$

$$= \begin{cases} v_h - v_d\, cos(st) \;\; for\ t = 0 \text{ to} \frac{\pi}{2s} \\ v_h - v_d * \frac{s}{a} * cos\, a\left(t - \frac{\pi}{2s} + \frac{\pi}{2a}\right) \text{ for } t = \frac{\pi}{2s} \text{ to}(\frac{\pi}{2a} + \frac{\pi}{2s}) \\ v_h + v_d * \frac{s}{a} \;\; for\ t = (\frac{\pi}{2a} + \frac{\pi}{2s}) to \frac{d}{v_h} \end{cases}$$

where d_0 is the target distance, v_h is the upper bound of the target speed, and v_d is defined such that $v_d = v_h - v_c$.

The three regions in the equations above are divided by π/2s and (π/2a+π/2s), which are t_1 and t_2 in Figure 13 and Figure 14, respectively. The parameters m and n in the above equations define the family of velocity profiles. Different pairs of (m, n) correspond to different velocity profiles. Parameter m controls the rate of change of acceleration/deceleration in region A and parameter n controls the rate of change of acceleration/deceleration in region B of Figure 13 and Figure 14. Given a value of m, the choice of n will depend on the requirement that the vehicle has to reach the next intersection at a specific time.

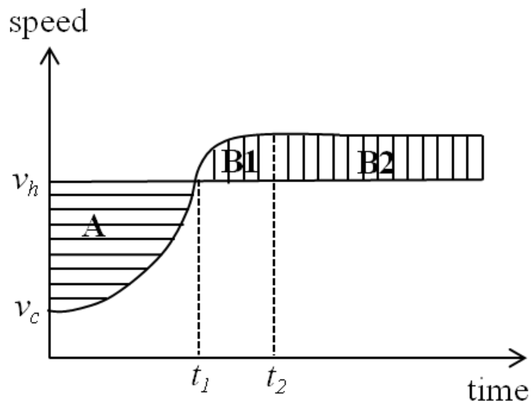


Figure 13: Acceleration Profile for Reaching a Specific Location at a Specific Time.

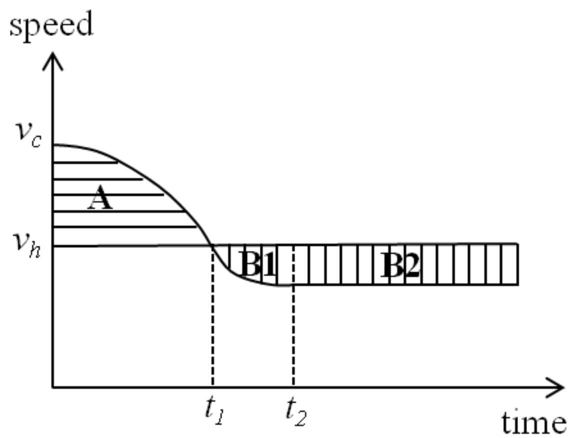


Figure 14: Deceleration Profile for Reaching a Specific Location at a Specific Time.

It is assumed that if the vehicle travels at this constant target speed v_h, it will reach the next intersection within green phase in the shortest time. Since the vehicle's initial speed may not be exactly equal to v_h, in order to reach the next intersection in the same shortest time, the area (which equates to the traveled distance in a velocity-time diagram) of A has to be equal to the area of B1 and B2 in Figure 14. With this constraint, the following equations are derived:

$$\int_{0}^{\frac{\pi}{2m}} (v_h - v_d \cos(mt))dt - \int_{0}^{\frac{\pi}{2m}} v_h dt$$

$$+ \int_{\frac{\pi}{2m}}^{\frac{\pi}{2m}+\frac{\pi}{2n}} \left(v_h - v_d m \frac{\cos n\left(t - \frac{\pi}{2m} + \frac{\pi}{2n}\right)}{n} \right) dt = \int_{\frac{\pi}{2m}}^{\frac{d}{v_h}} v_h dt - \int_{\frac{\pi}{2m}+\frac{\pi}{2n}}^{\frac{d}{v_h}} \left(v_h + v_d \frac{m}{n} \right) dt$$

Solving the above equation gives the following equation relating m and n:

$$n^2 - m\left(Tm - \frac{\pi}{2}\right)n - m^2\left(1 - \frac{\pi}{2}\right) = 0$$

The above equation is quadratic in n, for a value of m. The above equation has real roots only if $m \geq 3.08/T$ or $0 \leq m \leq 0.06/T$. For a value of m, n can take the positive value:

$$n = \frac{1}{2}\left(m\left(Tm - \frac{\pi}{2}\right) + \sqrt{m^2\left(\frac{\pi}{2} - Tm\right)^2 - 4m^2\left(\frac{\pi}{2} - 1\right)}\right)$$

where $T = \frac{d}{v_h}$ (i.e., the time required to reach the target distance).

The larger the value of m, the sharper the acceleration will be. The limit of m will be dictated by the power of the vehicle, safety, and the ride comfort (i.e., constrained jerk). When combined with the total integrated tractive power of the trajectory, it can be seen that to minimize fuel consumption for the total acceleration maneuver, we should choose m as large as possible. This runs counter to the standard eco-driving advice that says that we should always accelerate slowly. When given a time and distance constraint, the best trajectory will accelerate quickly, reach a target velocity, and then remain at a constant velocity for a long period of time until the position is reached.

The maximum jerk can be calculated by:

$$jerk_{max} = -v_d mn$$

By taking into consideration the ride comfort, a driver can tolerate up to a maximum acceleration of $2.5m/s^2$ with a gradually increasing jerk profile. Therefore we choose a constraint on the maximum m value given by

$$|jerk_{max}| = v_d mn \leq 10 \text{ and } |a_{max}| \leq 2.5m/s^2$$

Modeling Approach

The traffic microsimulation software Paramics was used to model the movement of individual vehicles and their interactions in detail. To be consistent with the modeling efforts on other AERIS applications, the latest version of Paramics (V. 6.9.3) was used. It is important to note that there is significant difference in the results that were obtained when an older version of Paramics (V. 6.7.2) was used. This difference is due to improvements to the vehicle interactions— or vehicle-following logic— implemented in this latest version. Therefore, the research team conducted additional sensitivity analysis to quantitatively identify the difference owing to the shift of Paramics version as well as the switch from the Comprehensive Modal Emission Model (CMEM) to the EPA's MOVES model. Detailed results have been documented in Appendix B.

As part of the evaluation, detailed speed profiles of every vehicle were examined to estimate emissions and energy consumption. As part of the programming environment, Paramics supports the development of plug-ins using its API that enables users to interface with its core simulation engine to perform specific tasks. The interaction between different models and API used in this application is shown in Figure 15. Several plug-ins have been developed for the Eco-Approach and Departure at Signalized Intersections application to fulfill the following functions:

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

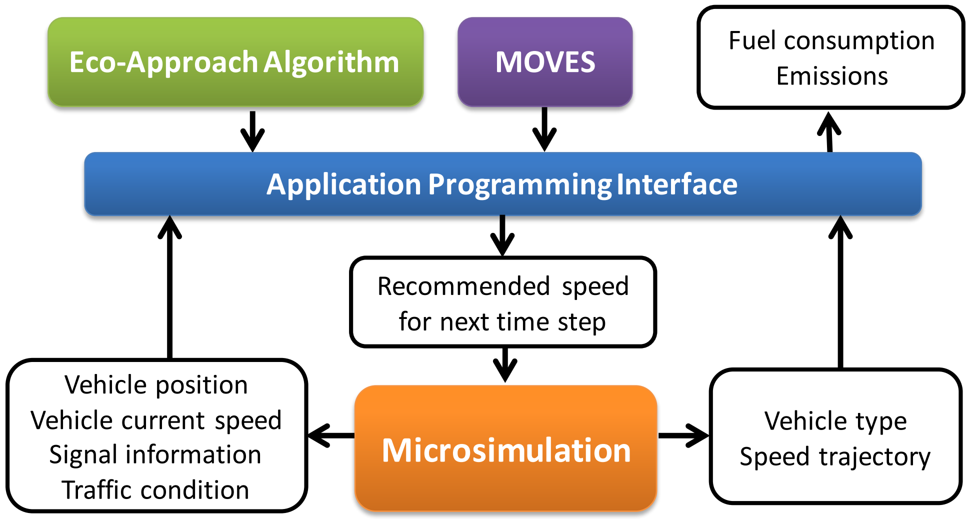


Figure 15: Diagram of Interactions between the Models and API.

For each simulation run, the vehicle velocity profile for a baseline case (i.e., for vehicles that do not have the Eco-Approach and Departure at Signalized Intersections algorithm) was created for comparison purposes. For this baseline comparison, it was assumed that under the typical driving behavior along a signalized corridor, the drivers attempt to cruise at or around the speed limit until they are visually aware of the traffic signal ahead. If the signal is green, the drivers simply maintain the cruise speed while crossing the intersection. If the signal is red, the drivers slow down, stop, and then wait until the light turns green. Once the signal turns green, the drivers accelerate back to the speed limit on the link. This driving behavior is applied at every intersection in the baseline case.

For comparison purposes, the energy and emissions for the baseline case (i.e., for vehicles that do not have the Eco-Approach and Departure at Signalized Intersection application) are also calculated for the same type of vehicle. The analysis team applied the algorithm to a single vehicle on a hypothetical 11-signal intersection corridor. For the corridor, the link lengths between consecutive signalized intersections are set to be 500m, and the speed limit is set to 40 mph. All the signals are fixed-time, two-phased signals. The cycle length is 50 seconds, and the green time of the mainline phase is 20 seconds. There is no coordination among the signals. Refer to Xia, et al. (2011), for more details on simulation setup. Table 4 compares the energy and emissions results between two individual vehicles (one baseline vehicle without the application and another equipped with the application). The results for both vehicles are given in terms of the average value and the standard deviation. According to Table 4, the equipped vehicle consumed 12.48 percent less fuel and produced 13.22 percent less CO_2 emission. Furthermore, the difference in average travel time per mile (TTPM) is relatively small, 0.73 percent faster for the equipped vehicle than for the unequipped vehicle.

Table 4: Average Vehicle Energy, Emissions, and TTPM Comparisons.

	Baseline		Eco-Approach		
	Avg.	S.D.	Avg.	S.D.	Improvement
Fuel (g/mi)	167.87	1.97	146.91	2.56	12.48%
CO_2 (g/mi)	439.60	3.57	381.49	3.72	13.22%
TTPM (sec/mi)	122.08	1.43	121.18	1.23	0.73%

Scenarios

The application was modeled in two phases: Eco-Approach only and both Eco-Approach and Departure at Signalized Intersections. An exhaustive set of scenarios were modeled for each application phase. The remainder of this section details the scenarios modeled. The modeling results that follow in the next section are organized in the same fashion.

The network used for modeling the scenarios was predominantly the El Camino Real 3-Intersection Network (Referred to as ECR-3). Only a part of the analysis was carried out on the Hypothetical Network (Referred to as HPN). A list of scenarios modeled is presented below.

Eco-Approach at Signalized Intersections Evaluation Scenarios

- **Coordination of ECR-3 Network:** The analysis of the ECR-3 network revealed that the network used for modeling was not fully coordinated. An attempt was made to coordinate the signal timings.
- **Eco-Approach on Coordinated ECR-3 Network—Demand:** The Eco-Approach at Signalized Intersections application was modeled on the coordinated ECR-3 network. The demand was varied using V/C ratios 0.38, 0.77, and 1.0.
- **Eco-Approach on Uncoordinated ECR-3 Network—Demand:** The Eco-Approach at Signalized Intersections application was modeled on the uncoordinated ECR-3 network. The demand was varied using V/C ratios 0.38, 0.77, and 1.0.
- **Eco-Approach on Coordinated ECR-3 Network—Connected Vehicle Penetration Rate:** The Eco-Approach at Signalized Intersections application was modeled on the coordinated ECR-3 network. The demand was varied using V/C ratios 0.38, 0.77, and 1.0. The connected vehicle penetration rate was varied using 0 percent, 20 percent, 50 percent, 80 percent, and 100 percent values.
- **Eco-Approach on Uncoordinated ECR-3 Network—Connected Vehicle Penetration Rate:** The Eco-Approach at Signalized Intersections application was modeled on the uncoordinated ECR-3 network. The demand was varied using V/C ratios 0.38, 0.77, and 1.0. The connected vehicle penetration rate was varied using 0 percent, 20 percent, 50 percent, 80 percent, and 100 percent values.
- **Eco-Approach and Departure on the ECR-27 Network —**The baseline and application models for the 27-intersection model were used from the baseline conditions, such as baseline transit and freight (1.2%) demands, as well as a baseline mainline V/C ratio of 0.77. The Eco-Approach and Departure application was modeled for increasing connected vehicle OBE penetration rates along the 27-intersection El Camino Real corridor.
- **Eco-Approach on Coordinated ECR-3 Network—Vehicle Model Year:** The Eco-Approach at Signalized Intersections application was modeled on the coordinated ECR-3 network. The demand used was the baseline V/C rate of 0.77. Model years 2005 and 2020 were compared.

The connected vehicle penetration rate was varied using 0 percent, 20 percent, 50 percent, 80 percent, and 100 percent values.

- **Sensitivity Analyses on HPN—Communication Range, and Communication Delay:** A sensitivity analysis of communication distance and communication delay was carried out using the HPN. The demand used was the baseline V/C rate of 0.77. Communication distances of 1, 200, 300, 400, 500, and 600 meters were used. Communication delays of 0, 0.5, 2, and 5 seconds were used.

Modeling Results for Eco-Approach and Departure at Signalized Intersections Evaluation Scenarios

- **Eco-Approach and Departure on Coordinated ECR-3 Network—Demand and Connected Vehicle Penetration Rate:** The Eco-Approach and Departure at Signalized Intersections application was modeled on the coordinated ECR-3 network. The demand was varied using V/C ratios 0.38, 0.77, and 1.0. The connected vehicle penetration rate was varied using 0 percent, 20 percent, 50 percent, 80 percent, and 100 percent values.
- **Eco-Approach and Departure on Uncoordinated ECR-3 Network—Demand and Connected Vehicle Penetration Rate:** The Eco-Approach and Departure at Signalized Intersections application was modeled on the uncoordinated ECR-3 network. The demand was varied using V/C ratios 0.38, 0.77, and 1.0. The connected vehicle penetration rate was varied using 0 percent, 20 percent, 50 percent, 80 percent, and 100 percent values.

Modeling Results for Eco-Approach at Signalized Intersections Application

Coordination of ECR-3 Network

To assess the benefits of the Eco-Approach at Signalized Intersections application, baseline models were developed with the assumption that there is no application deployment (i.e., OBE penetration rate is 0 percent). The environmental impacts were estimated by the aforementioned plug-ins. Then, a variety of scenarios were generated by varying vehicle demand and OBE penetration rates.

Signal coordination is designed to enable most vehicles in the mainline flow to pass through intersections along the corridor within the green phase. Vehicles are expected to experience less interruption from coordinated signals, thus having less unnecessary acceleration and stop-and-go behaviors. To get further insights into the benefits from the Eco-Approach and Departure at Signalized Intersections application, it is necessary to investigate the amount of energy savings and emission reductions that can be achieved on top of signal coordination.

As discussed above, the traffic signals (with default settings) along the segment are not well coordinated. This can be verified by the time-distance diagrams shown in Figure 16 and Figure 17.

It is to be noted that the yellow time is not displayed in these diagrams for simplicity. As shown in the diagrams, the green bandwidth on neither the southbound direction nor the northbound direction is optimized.

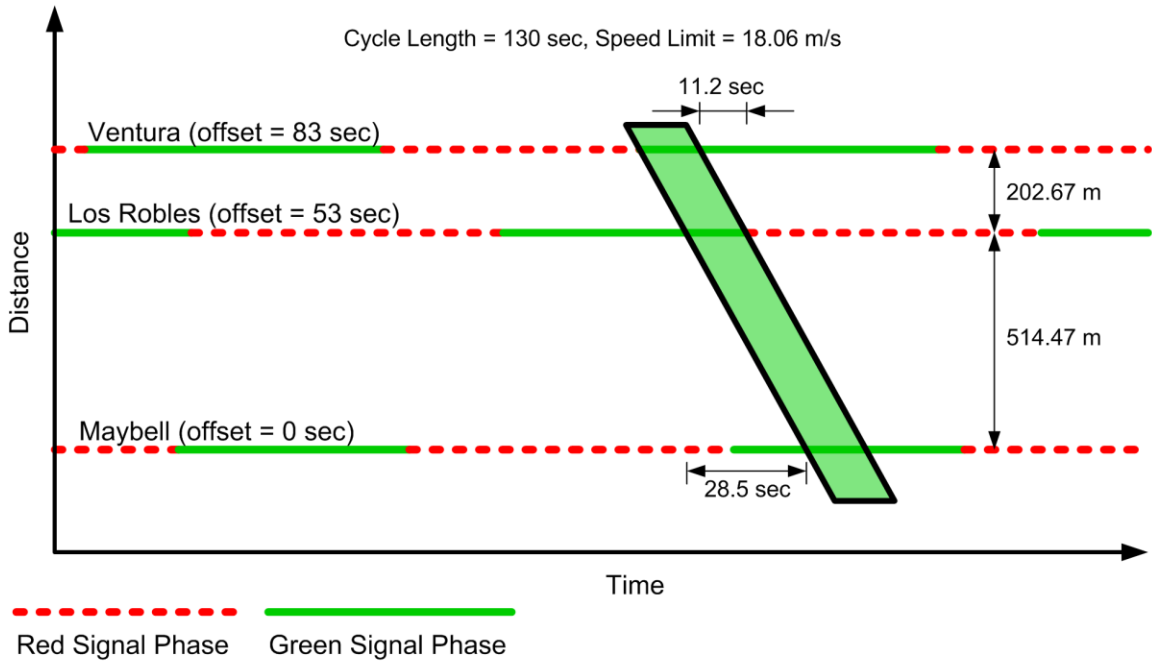


Figure 16: Green Band of Original Signal on Southbound Direction.

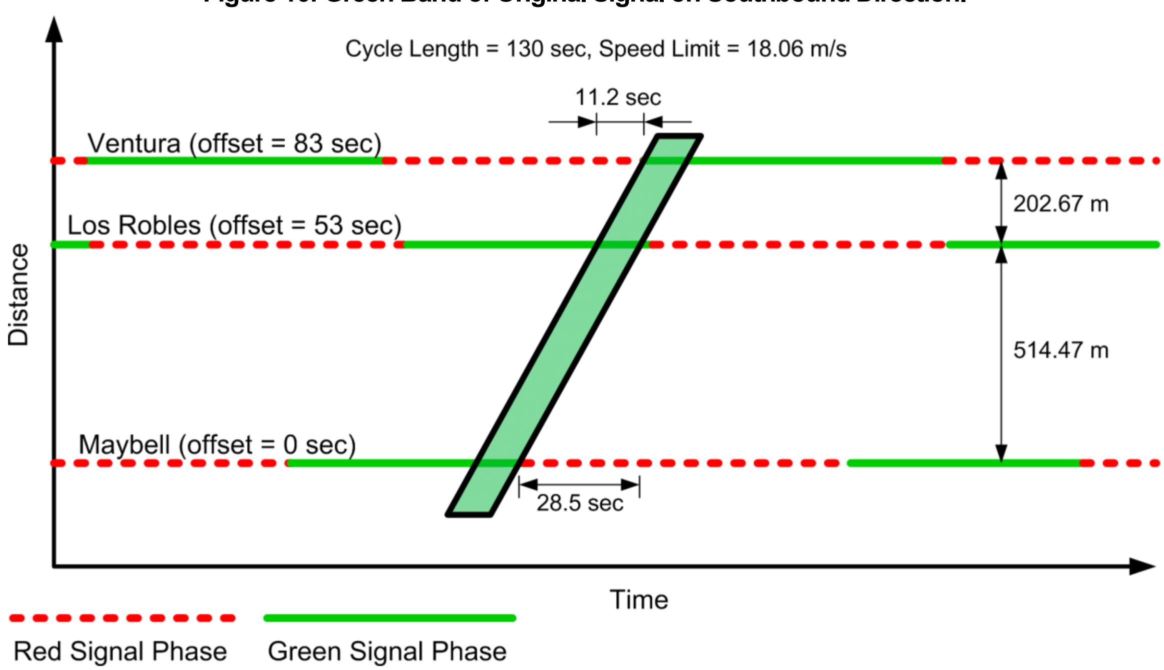


Figure 17: Green Band of Original Signal on Northbound Direction.

As illustrated in these two figures, better coordinated signal plans can be obtained with just minor changes on the offsets but keeping the cycle length, phase sequence, and green split intact. It should be pointed out that additional improvements to coordination may be achieved by using traffic signal timing optimization tools, such as Synchro. In the following analyses, the (coordinated) signal settings rather than the original ones are applied to the model, as shown in Figure 18 and Figure 19.

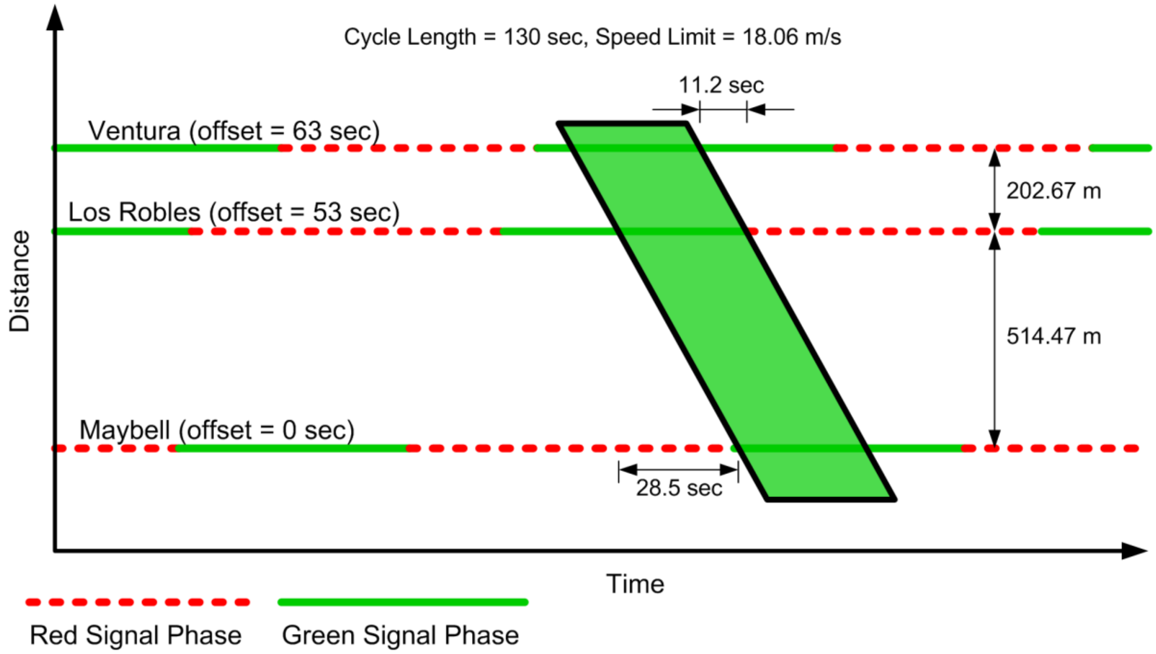


Figure 18: Green Band of Coordinated Signal on Southbound Direction.

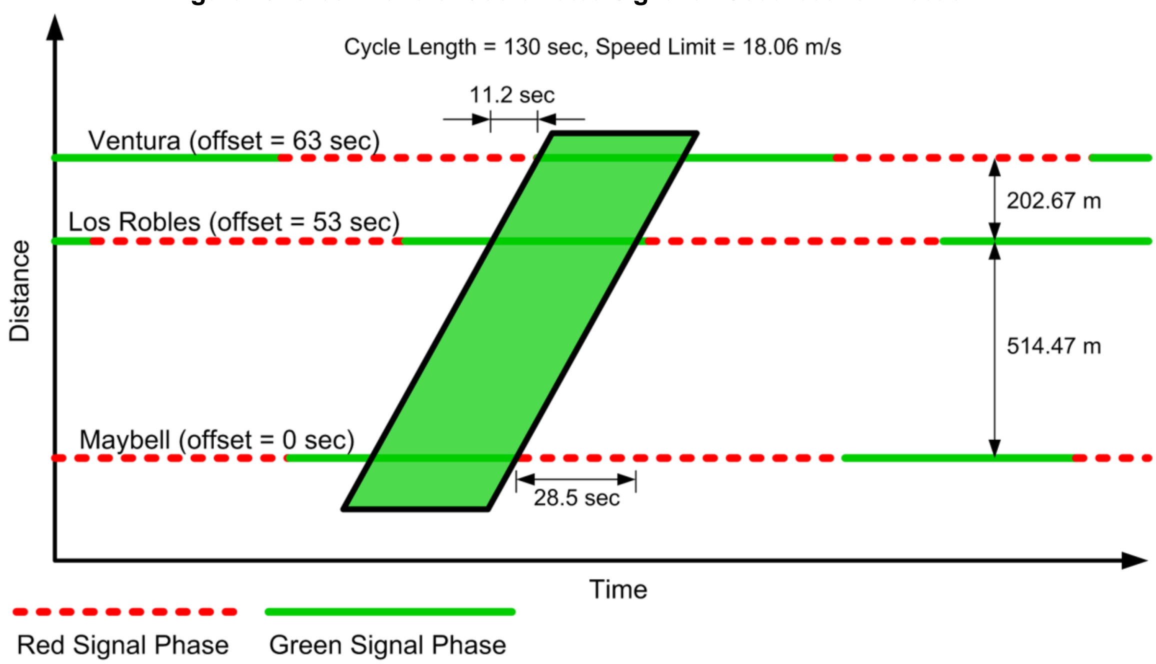


Figure 19: Green Band of Coordinated Signal on Northbound Direction.

Eco-Approach on Coordinated ECR-3 Network—Demand

The performance of the Eco-Approach at Signalized Intersections application under the coordinated signal plan is illustrated in Figure 20 and Table 5. The results show small energy savings and emissions reduction (2 percent to 3 percent) at different V/C ratios. These results take into account the mainline flow as well as the cross-street traffic.

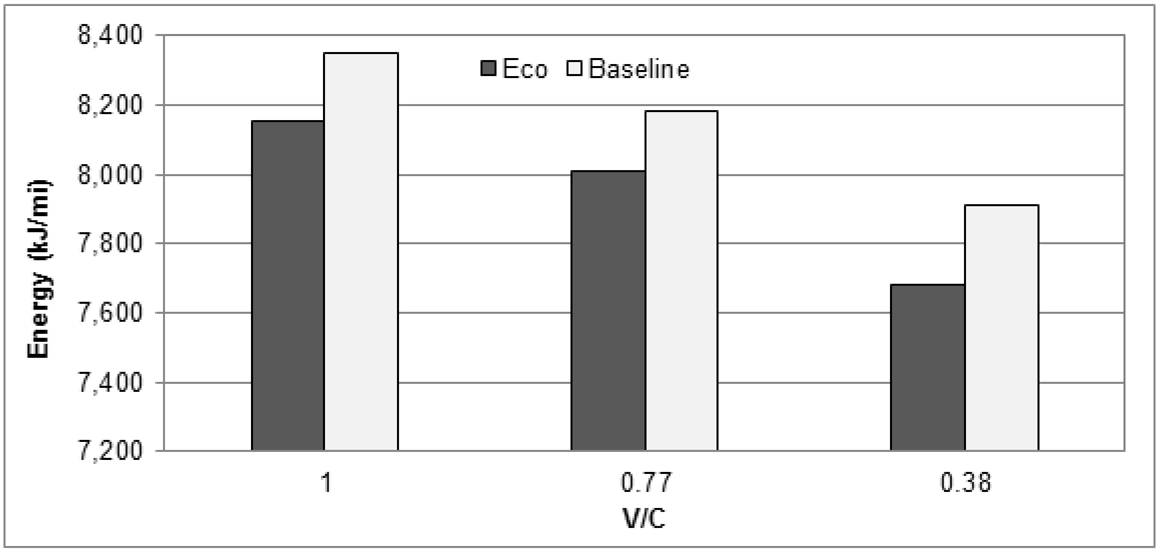


Figure 20: Energy Consumption on a Coordinated Network.

Table 5: Performance of the Eco-Approach at Signalized Intersections Application on a Coordinated Network.

	V/C	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	Average Travel Time per Vehicle
Baseline	1.00	8,347.75	601.02	13.00	0.41	1.83	0.13	98.94
	0.77	8,183.43	589.55	12.98	0.41	1.85	0.13	94.20
	0.38	7,910.53	569.18	13.07	0.40	1.69	0.13	90.48
Eco	1.00	8,152.64	587.50	12.02	0.39	1.78	0.12	97.63
	0.77	8,010.20	577.27	11.96	0.39	1.75	0.12	95.76
	0.38	7,682.70	552.70	11.87	0.38	1.63	0.11	90.25
Saving %	1.00	2.34	2.25	7.54	4.89	2.56	6.11	1.32
	0.77	2.12	2.08	7.84	4.68	5.40	8.98	-1.65
	0.38	2.88	2.89	9.20	5.48	3.81	9.27	0.25

To obtain further insight into the impacts of signal coordination, another set of simulation runs was conducted by filtering out the effects of cross-street traffic and non-platoon-like arrival pattern at the first intersection in each direction. Figure 21 and Table 6 provide the performance measures of the Eco-Approach at Signalized Intersections application in a purely coordinated corridor. It turns out that there is also a small amount (2 percent to 3 percent) of energy savings and emissions reduction owing to the deployment of this application on top of signal coordination.

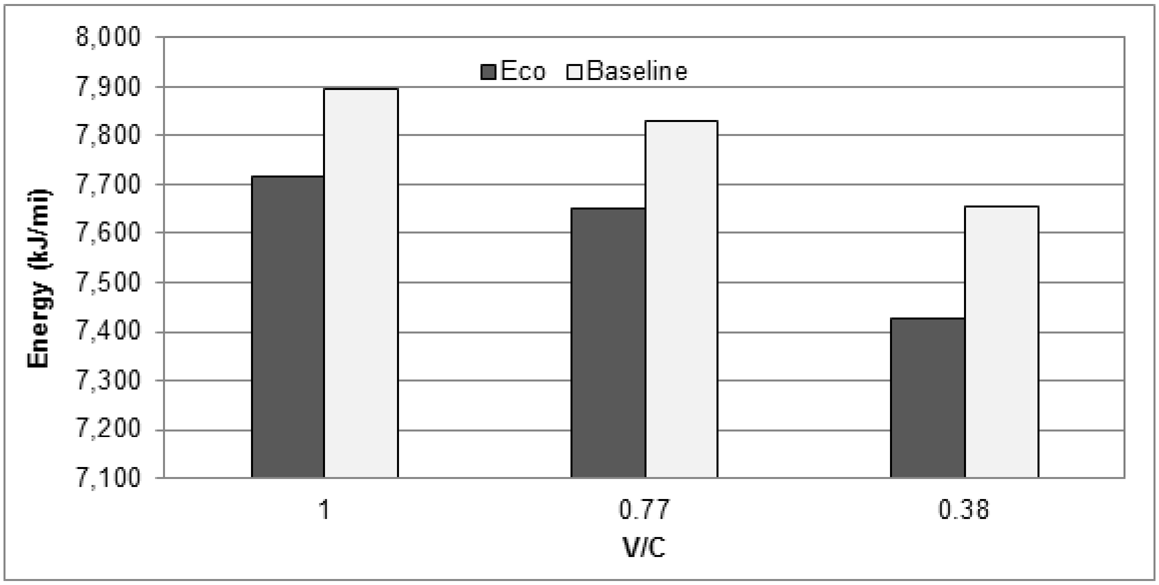


Figure 21: Energy Consumption on a Purely Coordinated Corridor.

Table 6: Performance of Eco-Approach at Signalized Intersections Application on a Purely Coordinated Corridor.

	V/C	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	Average Travel Time per Vehicle
Baseline	1.00	7,893.50	568.75	12.20	0.39	1.74	0.12	100.05
	0.77	7,828.40	563.97	12.34	0.39	1.71	0.12	99.02
	0.38	7,655.82	550.84	12.68	0.39	1.68	0.12	93.25
Eco	1.00	7,716.38	556.18	11.45	0.37	1.60	0.11	100.07
	0.77	7,652.40	551.39	11.46	0.37	1.66	0.11	97.80
	0.38	7,425.95	534.22	11.59	0.36	1.59	0.11	92.69
Saving %	1.00	2.24	2.21	6.15	4.16	8.20	11.29	-0.02
	0.77	2.25	2.23	7.15	4.68	3.22	7.51	1.23
	0.38	3.00	3.02	8.60	5.94	5.55	9.24	0.60

Eco-Approach on Uncoordinated ECR-3 Network—Demand

Figure 22 shows energy consumption results on an uncoordinated network including cross-traffic with different V/C ratios, followed by Table 7 with detailed results of both fuel efficiency and mobility. According to the results, the Eco-Approach at Signalized Intersections application provides greater improvement on an uncoordinated network than on a coordinated network.

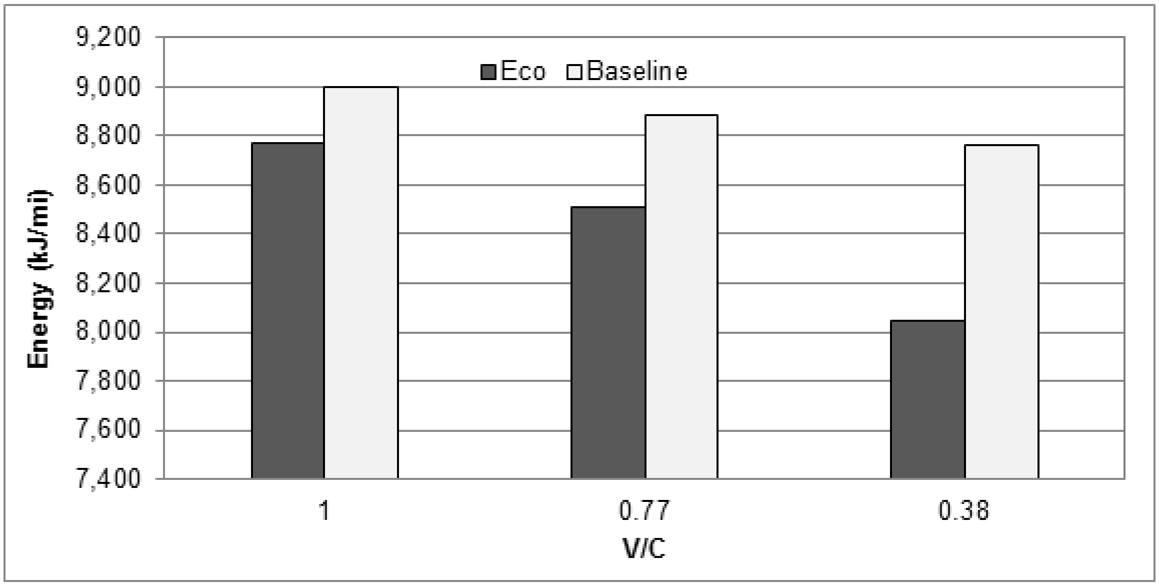


Figure 22: Energy Consumption on an Uncoordinated Network.

Table 7: Performance of Eco-Approach at Signalized Intersections Application on an Uncoordinated Network.

	V/C	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	Average Travel Time per Vehicle
Baseline	1.00	8,997.08	647.70	13.55	0.45	1.87	0.13	125.12
	0.77	8,887.79	640.62	13.69	0.45	1.91	0.13	118.31
	0.38	8,760.11	630.78	13.91	0.44	2.03	0.15	108.16
Eco-Approach	1.00	8,772.78	632.06	11.86	0.42	1.78	0.11	126.89
	0.77	8,509.31	613.72	11.68	0.41	1.74	0.11	118.75
	0.38	8,046.89	579.04	11.69	0.39	1.64	0.11	107.68
Saving %	1.00	2.49	2.41	12.47	6.17	4.92	13.74	-1.42
	0.77	4.26	4.20	14.72	8.38	9.11	17.20	-0.36
	0.38	8.14	8.20	15.96	10.95	19.20	25.69	0.44

Eco-Approach on Coordinated ECR-3 Network—Connected Vehicle Penetration Rate

Table 8 presents the results of energy consumption and CO_2 emissions with varying traffic demands and penetration rates of connected vehicle technology in a coordinated network, considering both the mainline flow and cross-street traffic. According to the results, more energy savings and CO_2 emissions reduction can be achieved by higher penetration of connected vehicles. In general, the less congested traffic (V/C = 0.38) shows higher energy savings and emissions reduction than the more congested scenarios.

Table 8: Energy Consumption and Emissions With V/C Ranging From 0.38 to 1.00 and Penetration Rate Ranging From 0% to 100% for a Coordinated Network.

V/C = 1.00							
Connected Vehicle Penetration (%)	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	Average Travel Time per Vehicle
0	8,347.75	601.02	13.00	0.41	1.83	0.13	98.94
20	8,253.32	594.42	12.73	0.41	1.74	0.12	99.44
50	8,154.57	587.42	12.35	0.40	1.71	0.12	98.17
80	8,142.05	586.48	12.07	0.39	1.76	0.12	97.99
100	8,097.19	583.57	12.00	0.39	1.73	0.12	97.14
Saving %							
20	1.13	1.10	2.07	1.61	4.77	5.00	-0.50
50	2.31	2.26	4.94	3.51	6.47	8.31	0.78
80	2.46	2.42	7.13	4.65	3.88	7.34	0.96
100	3.00	2.90	7.67	5.49	5.39	8.11	1.82

V/C = 0.77							
Connected Vehicle Penetration (%)	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	Average Travel Time per Vehicle
0	8,183.43	589.55	12.98	0.41	1.85	0.13	94.20
20	8,082.57	582.31	12.73	0.40	1.72	0.12	95.26
50	7,989.64	575.65	12.37	0.39	1.68	0.12	94.01
80	7,967.83	574.13	12.19	0.39	1.66	0.12	94.60
100	7,952.54	573.12	11.88	0.38	1.69	0.12	95.72
Saving %							
20	1.23	1.23	1.93	1.51	7.01	7.38	-1.12
50	2.37	2.36	4.70	3.58	9.11	10.35	0.20
80	2.63	2.62	6.07	4.24	9.94	11.68	-0.43
100	2.82	2.79	8.47	5.41	8.31	11.81	-1.61

V/C = 0.38							
Connected Vehicle Penetration (%)	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	Average Travel Time per Vehicle
0	7,910.53	569.18	13.07	0.40	1.69	0.13	90.48
20	7,872.10	566.38	12.87	0.39	1.65	0.12	91.62
50	7,807.90	561.81	12.42	0.39	1.65	0.12	92.06
80	7,775.91	559.44	12.14	0.38	1.65	0.12	91.71
100	7,682.70	552.70	11.87	0.38	1.63	0.11	90.25
Saving %							
20	0.49	0.49	1.56	0.76	2.35	3.07	-1.27

V/C = 0.38							
Connected Vehicle Penetration (%)	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	Average Travel Time per Vehicle
50	1.30	1.30	4.98	3.01	2.43	5.00	-1.75
80	1.70	1.71	7.14	3.81	2.39	6.84	-1.36
100	2.88	2.89	9.20	5.48	3.81	9.27	0.25

Figure 23 shows the energy savings results with different penetration rates of connected vehicles and different V/C ratios. As can be observed from the figure, the higher the penetration rate of this technology, the more system-wide benefits in terms of energy savings can be obtained. In addition, even for low or moderate penetration rate (e.g., 50 percent), indirect network benefits can still be achieved owing to the behavior adaptation of unequipped vehicles to the equipped ones. For example, a vehicle that is not equipped with the application may follow a vehicle equipped with the application and travel in a more eco-friendly manner (i.e., less unnecessary stop-and-go).

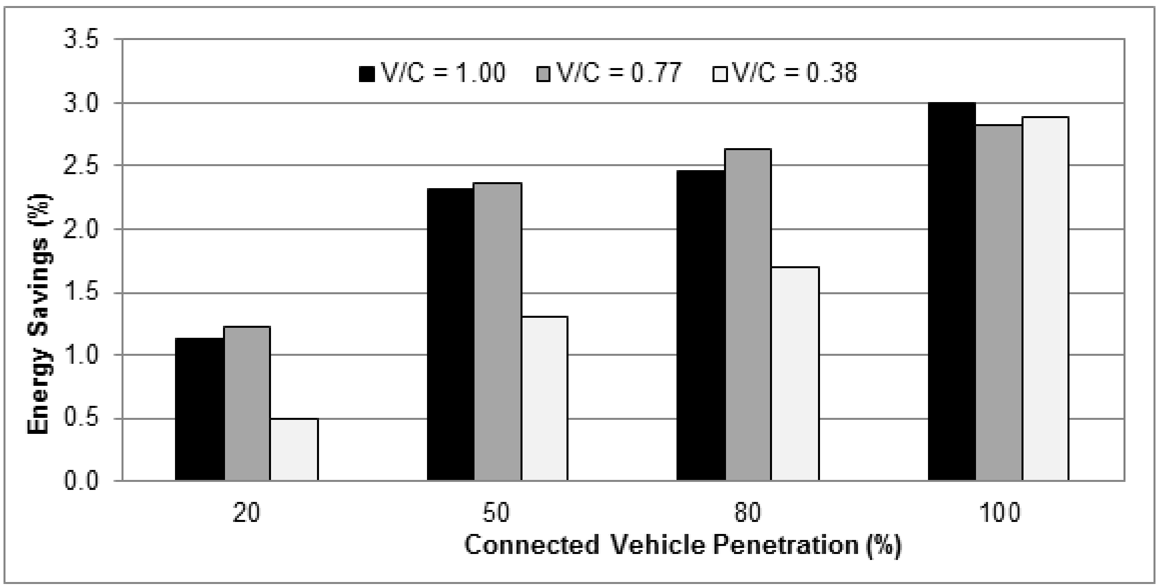


Figure 23: Energy Savings vs. Penetration Rate at Morning Peak Hours for a Coordinated Network.

Eco-Approach on Uncoordinated ECR-3 Network—Connected Vehicle Penetration Rate

To further highlight the effects of signal coordination, another set of signal parameters was developed to create uncoordinated scenarios. As shown in Figure 24 and Figure 25, the green bandwidths are zero on both southbound and northbound directions under the uncoordinated signal plan.

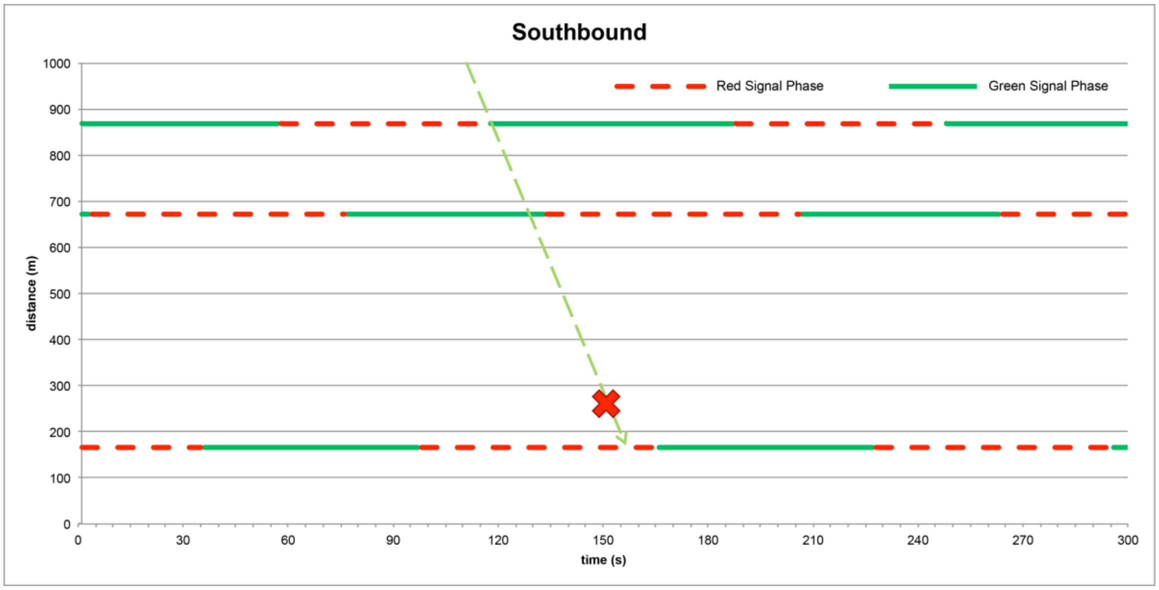


Figure 24: Green Band of Uncoordinated Signals in Southbound Direction.

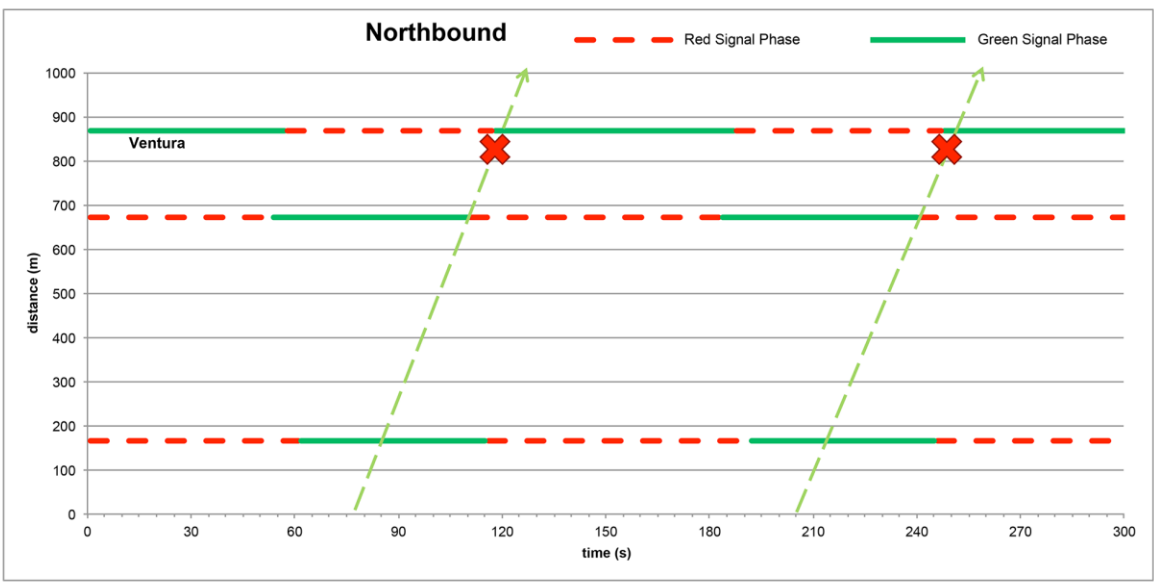


Figure 25: Green Band of Uncoordinated Signals in Northbound Direction.

Table 9 and Figure 26 show energy consumption and CO_2 emissions with varying traffic demands and penetration rates of connected vehicle technology in an uncoordinated network, considering both the mainline flow and cross-street traffic.

Table 9: Energy Consumption and Emissions With V/C Ranging From 0.38 to 1.00 and Penetration Rate Ranging From 0% to 100% for an Uncoordinated Network.

V/C = 1.00							
Connected Vehicle Penetration (%)	**Energy (kJ/mi)**	**CO_2 (g/mi)**	**CO (g/mi)**	**HC (g/mi)**	**NOx (g/mi)**	**PM (g/mi)**	**Average Travel Time per Vehicle**
0	8,997.08	647.70	13.55	0.45	1.87	0.13	125.12
20	8,844.93	636.75	12.90	0.44	1.77	0.12	124.16
50	8,832.84	636.02	12.34	0.43	1.77	0.11	125.74
80	8,797.50	633.75	11.96	0.43	1.80	0.11	126.26
100	8,772.78	632.06	11.86	0.42	1.78	0.11	126.89
Saving %							
20	1.69	1.69	4.77	2.73	5.45	8.83	0.76
50	1.83	1.80	8.93	4.35	5.21	11.88	-0.50
80	2.22	2.15	11.70	5.73	3.93	12.20	-0.92
100	2.49	2.41	12.47	6.17	4.92	13.74	-1.42

V/C = 0.77							
Connected Vehicle Penetration (%)	**Energy (kJ/mi)**	**CO_2 (g/mi)**	**CO (g/mi)**	**HC (g/mi)**	**NOx (g/mi)**	**PM (g/mi)**	**Average Travel Time per Vehicle**
0	8,887.79	640.62	13.69	0.45	1.91	0.13	118.31
20	8,798.62	634.29	12.95	0.44	2.00	0.14	115.29
50	8,541.45	615.85	12.18	0.42	1.78	0.12	115.38
80	8,535.41	615.49	11.91	0.41	1.79	0.12	116.56
100	8,509.31	613.72	11.68	0.41	1.74	0.11	118.75
Saving %							
20	1.00	0.99	5.44	3.06	-4.39	-1.36	2.56
50	3.90	3.87	11.03	7.20	6.79	12.05	2.48
80	3.96	3.92	13.00	7.92	6.37	12.95	1.48
100	4.26	4.20	14.72	8.38	9.11	17.20	-0.36

V/C = 0.38							
Connected Vehicle Penetration (%)	**Energy (kJ/mi)**	**CO_2 (g/mi)**	**CO (g/mi)**	**HC (g/mi)**	**NOx (g/mi)**	**PM (g/mi)**	**Average Travel Time per Vehicle**
0	8,760.11	630.78	13.91	0.44	2.03	0.15	108.16
20	8,319.29	598.83	13.23	0.42	1.67	0.12	108.27
50	8,241.15	593.10	12.43	0.41	1.70	0.12	108.70
80	8,123.89	584.53	11.92	0.40	1.62	0.11	109.56
100	8,046.89	579.04	11.69	0.39	1.64	0.11	107.68
Saving %							
20	5.03	5.07	4.83	4.51	17.57	18.26	-0.10
50	5.92	5.97	10.63	7.78	16.23	19.69	-0.50
80	7.26	7.33	14.28	9.86	20.15	25.60	-1.30
100	8.14	8.20	15.96	10.95	19.20	25.69	0.44

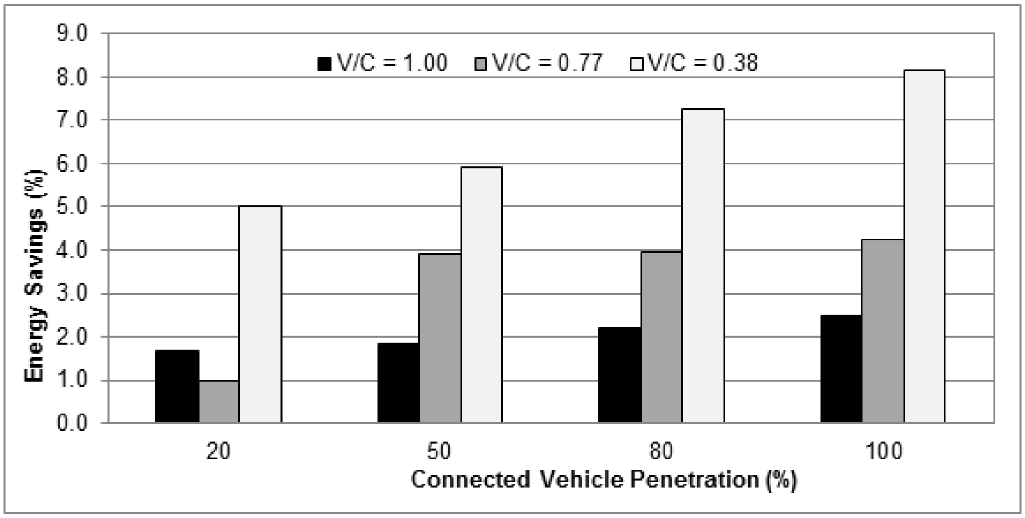


Figure 26: Energy Savings vs. Penetration Rate at Morning Peak Hours for an Uncoordinated Network.

Eco-Approach and Departure on the ECR-27 Network

In addition to the sensitivity analyses on the 3-intersection Paramics model of the El Camino Real corridor, an Eco-Approach and Departure application impact analysis was conducted on the full 27-intersection, coordinated El Camino Real corridor. The baseline and application models for the 27-intersection model were used from the baseline conditions, such as baseline transit and freight (1.2%) demands, as well as a baseline mainline V/C ratio of 0.77. The Eco-Approach and Departure application was modeled for increasing connected vehicle OBE penetration rates along the 27-intersection El Camino Real corridor. Figure 27 below shows the percent improvement in fuel consumption for each vehicle type as a result of the application.

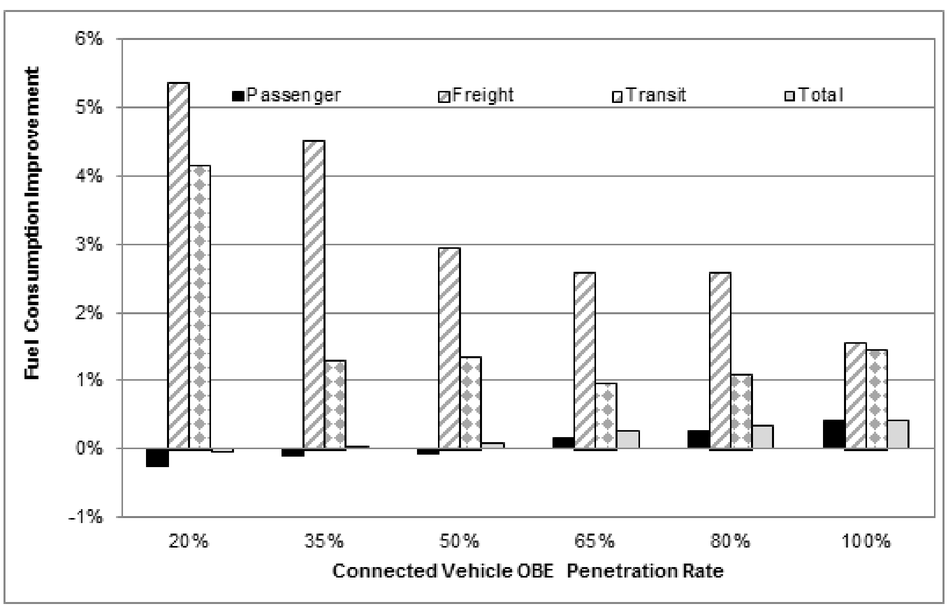


Figure 27: Fuel Consumption Savings vs. OBE Penetration Rate by Vehicle Type

In the figure above, it can be seen that the overall impact of the application to all vehicles in the 27-intersection model is quite small, with the maximum overall improvement in fuel consumption of only about 0.4%. This is a significant difference than what was seen in the smaller 3-intersection model, as well as the hypothetical tests in a model with well-spaced intersections and less traffic. These results show that in corridors with tightly-spaced, urban intersections, the application does not provide significant environmental reduction. In addition, significant improvements in fuel consumption for freight and transit vehicles are observed along the corridor. These vehicles produce more emissions and have sensitive driving profiles, so the application provides significant benefits to these vehicles, especially in lower levels of connected vehicle penetration. As the overall number of connected vehicles increases over time, the network of vehicles becomes homogenous, and the improvement to the freight and transit vehicles decreases. 98% of the vehicles on the El Camino Real are personal passenger, so the total emission improvement overall is not significant, even with the large improvements to the freight and transit vehicles.

In addition to the emissions and fuel savings on the El Camino Real, the analysis also looked at the change in the overall network VHT as a result of the Eco-Approach and Departure application. This VHT represents the total vehicle hours traveled by vehicles along the mainline El Camino Real. The results of this analysis are shown below in Figure 28 for all vehicles with increasing connected vehicle OBE penetration rate.

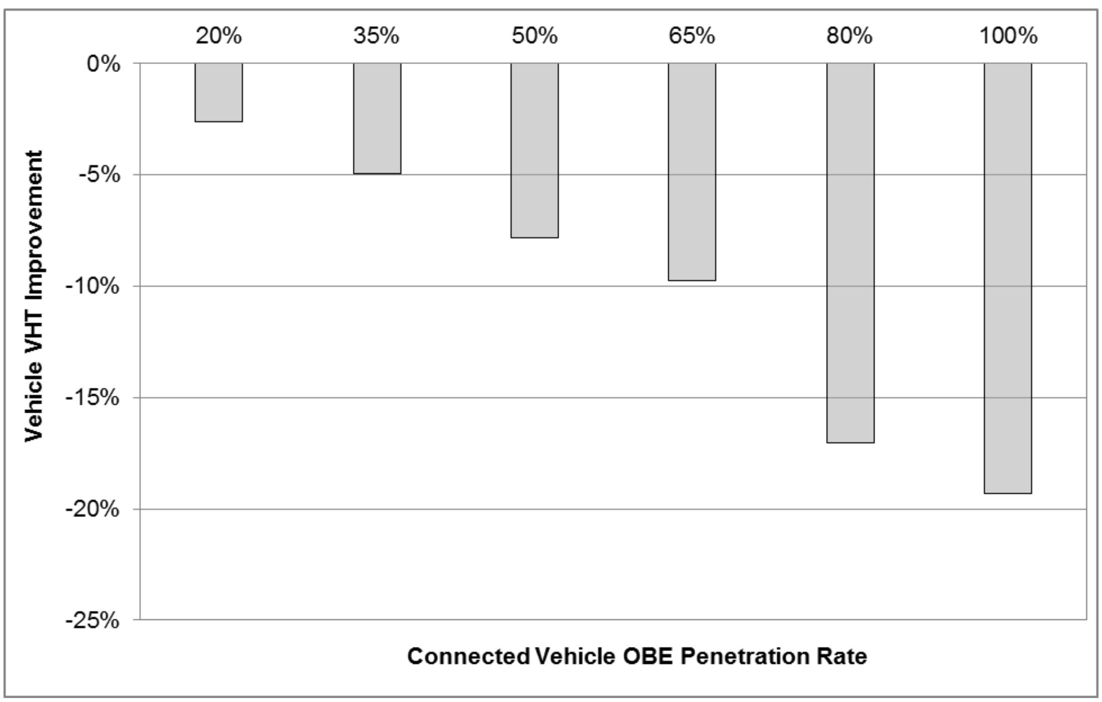


Figure 28: Vehicle VHT Savings vs. OBE Penetration Rate by Vehicle Type

As can be seen in the figure above, the Eco-Approach and Departure application results in an overall "disbenefit" to the VHT of the El Camino Real while working to provide benefits to the environmental measures of effectiveness. As the penetration rate of connected vehicle OBE technology increases, resulting in more vehicles receiving speed advice, the mobility "disbenefit" increases. Through further study, it was found that this is due to a number of reasons, but mostly due to the closely-spaced, urban intersections along the El Camino Real corridor. There are a number of reasons that this corridor could result in a mobility "disbenefit", namely:

- There is less space between the upstream and downstream signals along the arterial for the application to improve the system performance when the traffic demand increases. This lack of space means that the change in speed has little impact on the overall environmental savings, but causes a noticeable reduction in mobility.
- The implementation of the Eco-Approach and Departure application may cause "moving bottlenecks" under high traffic volumes due to the smoothed deceleration/acceleration by the leading/preceding vehicles. These bottlenecks are created in regions where vehicles move from one area of speed advice to another, and where the downstream recommended speed is less than upstream speed.
- These "moving bottlenecks" may result in queue spill-backs (or application-induced oversaturated traffic condition) in the region where the storage space (intersection spacing) is not enough. When the bottleneck occurs immediately after the upstream signal it meters the traffic from moving through the intersection. While this results in environmental improvements, there is a significant negative impact to mobility.

In addition to the figures above, Table 10 below provides detailed emissions, fuel consumption, and VHT information for the Eco-Approach and Departure application with increasing connected vehicle OBE penetration rate for the 27-intersection El Camino Real corridor.

Table 10: Fuel Consumption, Emissions, and VHT for Increasing OBE Connected Vehicle Penetration Rate

Connected Vehicle Penetration (%)	Fuel (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	VHT (total hours)
0	10,277	739.45	16.49	0.554	2.05	0.108	1,308
20	10,273	739.14	16.03	0.554	1.99	0.102	1,342
35	10,273	739.17	16.13	0.554	2.03	0.105	1,373
50	10,268	738.78	16.01	0.554	2.01	0.103	1,411
65	10,249	737.46	15.90	0.553	2.00	0.102	1,436
80	10,243	737.78	15.96	0.553	2.00	0.102	1,531
100	10,233	736.31	15.67	0.553	1.98	0.101	1,561
			Saving %				
20	0.04	0.04	2.81	-0.07	2,31	4,87	-2.6
35	0.04	0.04	2.19	0.02	0.94	2.85	-5.0
50	0.09	0.09	2.91	-0.10	1.88	4.31	-7.9
65	0.27	0.27	3.63	0.12	2.13	4.83	-9.8
80	0.33	0.23	3.25	0.05	2.26	4.88	-17.1
100	0.42	0.43	4.97	0.08	3.06	6.49	-19.3

The analysis of the Eco-Approach and Departure at Signalized Intersections for the 27-intersection corridor of the El Camino Real also looked at the impact of different demand levels, expressed as the V/C ratio of the mainline corridor traffic. This analysis used the same baseline model, traffic demand, and freight and transit demand levels as the previous analysis. The three demand levels considered for this analysis were the baseline (0.77 V/C), undersaturated conditions (0.38 V/C), and the saturated conditions (1.00 V/C). The resulting improvements to fuel consumption from the application can be seen below in Figure 29 for all vehicles in the network, for each of the three demand levels.

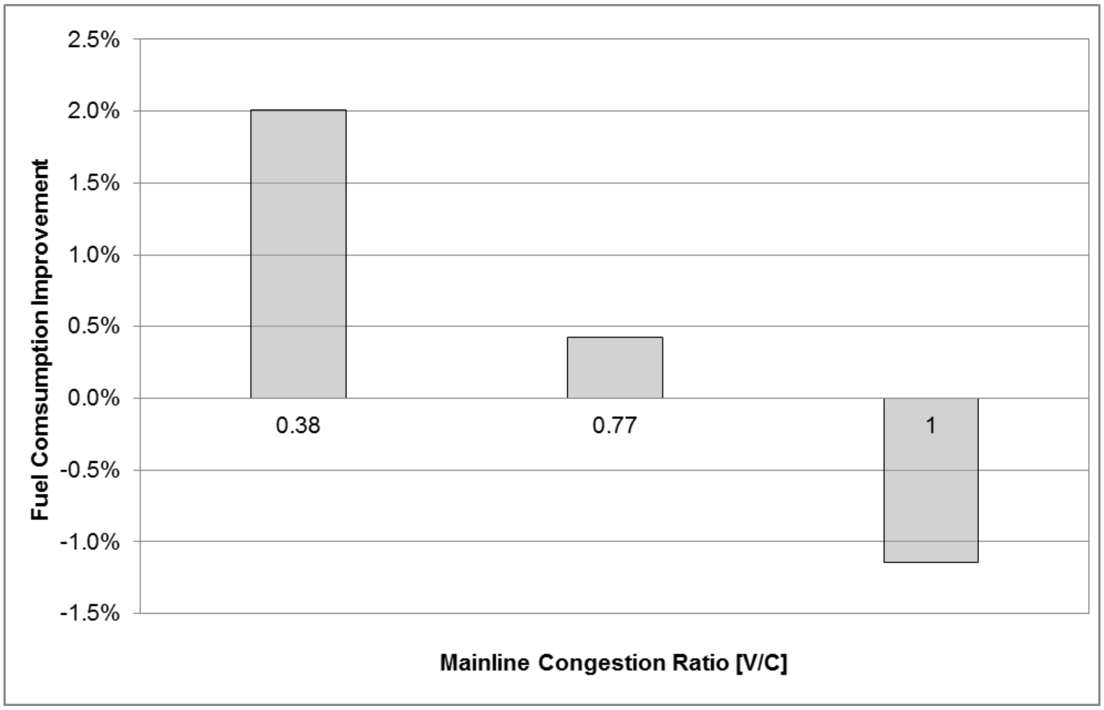


Figure 29: Fuel Consumption Savings vs. Vehicle Demand (Mainline V/C Ratio)

As seen the figure above, there is a significant difference in the resulting environmental improvement from the application for different levels of demand and congestion along the corridor. As seen in previous figures, there is only a slight improvement in fuel consumption with the application at the baseline demand, but there is a noticeable improvement of around 2% in undersaturated conditions. The low traffic and additional space on the roadway allow the application to provide better speed advice and successfully follow it along the corridor, even with the closely-spaced intersections. Conversely, in saturated flow conditions, the application cannot provide accurate speed advice or that advice cannot be properly followed, resulting in an overall “disbenefit” to the system. This shows that the application works better in lower traffic conditions, where vehicle trajectories can be easily modified without extraneous vehicles causing queuing and stopping conditions.

In addition to the emissions and fuel savings on the El Camino Real corridor, the analysis also looked at the change in the overall network VHT as a result of the Eco-Approach and Departure application for the different demand levels. The overall improvement of the application for all vehicles is shown below in Figure 30 at the three demand levels.

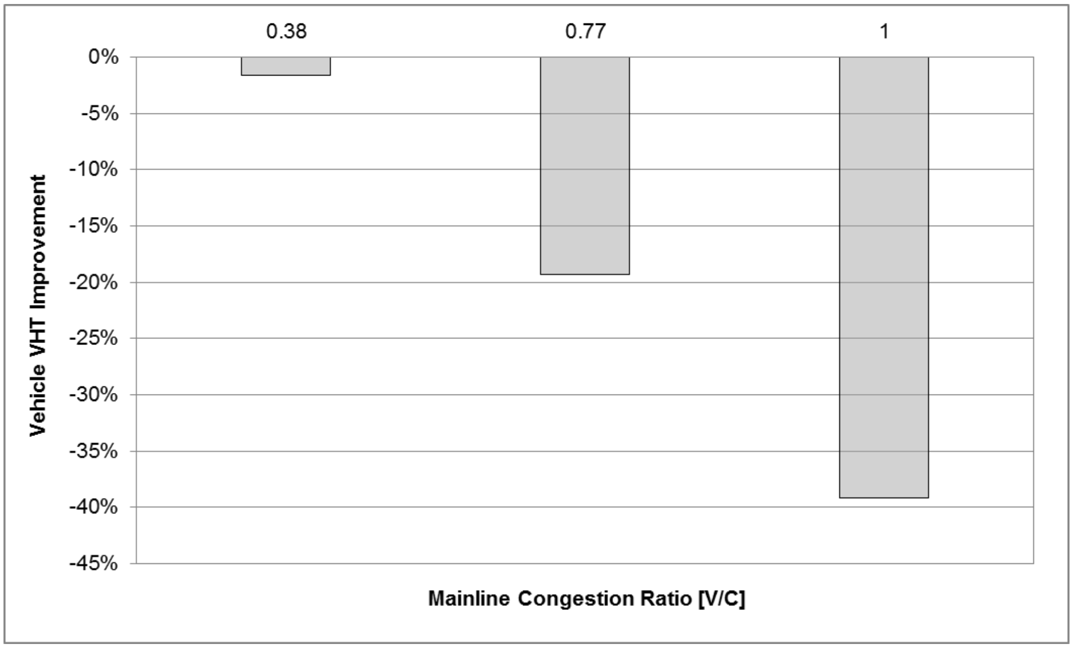


Figure 30: Vehicle VHT Savings vs. Vehicle Demand (Mainline V/C Ratio)

As explained earlier in this section, there is a noticeable “disbenefit” in mobility (VHT) due to the features of the corridor in relation to the application. This can also be seen at different demand levels at different levels of impact in the analysis. In undersaturated conditions along the El Camino Real corridor, the application offers significant improvements to environmental measures, with minimal impacts on mobility, since there are fewer vehicles on the roadway. At the baseline demand level, there is a significant disbenefit in mobility, with some improvements in fuel consumption. However, along a corridor like the El Camino Real, the application cannot accurately provide speed advice in the saturated conditions due to limited trajectory improvement space. This inability manifests itself as detrimental impacts to both the fuel consumption, as well as the mobility measures at full saturation.

Table 11 below provides detailed emissions, fuel consumption, and VHT information for the Eco-Approach and Departure application for different mainline V/C ratio demands for the 27-intersection El Camino Real corridor.

Table 11: Fuel Consumption, Emissions, and VHT for Different Mainline Vehicle Demands

	V/C	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	VHT (total hours)
Baseline	1.00	10,706	770.20	16.49	0.568	2.01	0.102	2,399
	0.77	10,277	739.45	16.50	0.553	2.04	0.108	1,308
	0.38	10,140	730.04	16.77	0.539	2.30	0.126	588
Eco	1.00	10,829	786.19	15.93	0.605	1.98	0.097	3,340
	0.77	10,233	736.31	15.67	0.553	1.98	0.101	1,561
	0.38	9,936	715.35	15.69	0.528	2.23	0.118	597
Saving %	1.00	-1.15	-2.08	3.40	-3.15	1.69	5.23	-39.2
	0.77	0.42	0.43	4.97	0.08	3.06	6.49	-19.3
	0.38	2.01	2.01	6.45	2.09	3.11	6.26	-1.6

Comparison of Coordinated and Uncoordinated Network Results

As discussed previously, vehicles traveling on a signal-coordinated corridor have less unnecessary acceleration and stop-and-go behavior. Figure 31 and Table 12 show that in this uncoordinated 3-intersection segment, the vehicles consume 17 percent to 19 percent more energy than with the coordinated signal plan when there is no application deployment. More stops and longer travel time are also observed in the uncoordinated network. It should be pointed out that the results take into account both the mainline flow and cross-street traffic.

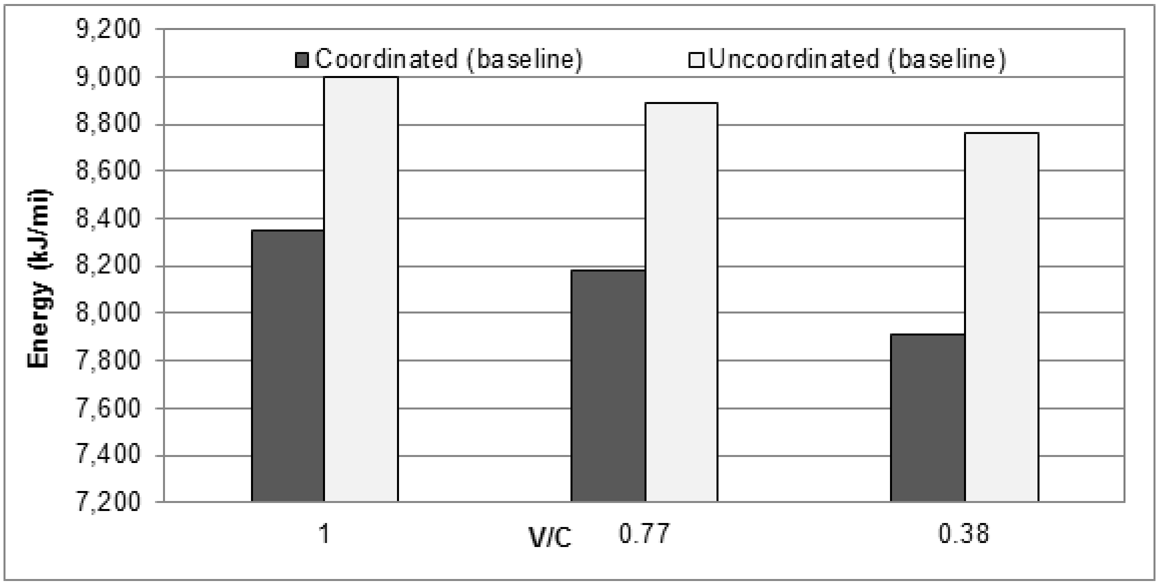


Figure 31: Comparison of Energy Consumption on Coordinated and Uncoordinated Networks Without Eco-Approach at Signalized Intersections Application.

Table 12: Baseline Comparison of Energy Consumption and Emissions on Coordinated and Uncoordinated Networks Without Eco-Approach at Signalized Intersections Application.

V/C	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	Average Travel Time per Vehicle
			Coordinated (baseline)				
1.00	8,347.75	601.02	12.99	0.41	1.82	0.12	98.94
0.77	8,183.43	589.55	12.98	0.41	1.85	0.13	94.20
0.38	7,910.53	569.18	13.07	0.40	1.69	0.13	90.48
			Uncoordinated (baseline)				
1.00	8,997.08	647.70	13.55	0.45	1.87	0.13	125.12
0.77	8,887.79	640.62	13.69	0.45	1.91	0.13	118.31
0.38	8,760.11	630.78	13.91	0.44	2.03	0.15	108.16
			Improvement (%)				
1.00	7.22	7.21	4.07	8.88	2.23	0.46	20.92
0.77	7.93	7.97	5.22	9.56	3.41	1.02	20.38
0.38	9.70	9.77	6.01	10.04	16.56	14.27	16.35

Eco-Approach on Coordinated ECR-3 Network—Vehicle Model Year

To estimate the impacts of the Eco-Approach at Signalized Intersections application on the future fleet mix, another plug-in was created based on the MOVES 2010b model, which projects fuel type and engine technology for Year 2020 (see Appendix B for more details on the plug-in development). As shown in Figure 32, if the V/C ratio of the coordinated El Camino Real network is 0.77, then the energy consumption and CO_2 emissions will be reduced by up to 4.3 percent in 2020 as a result of application deployment. In the meantime, CO, HC, and NOx emissions will decrease by up to 9.9 percent, 11.1 percent, and 20.0 percent, respectively, depending on different connected vehicle penetration rates. There is no significant improvement on PM emission and travel time.

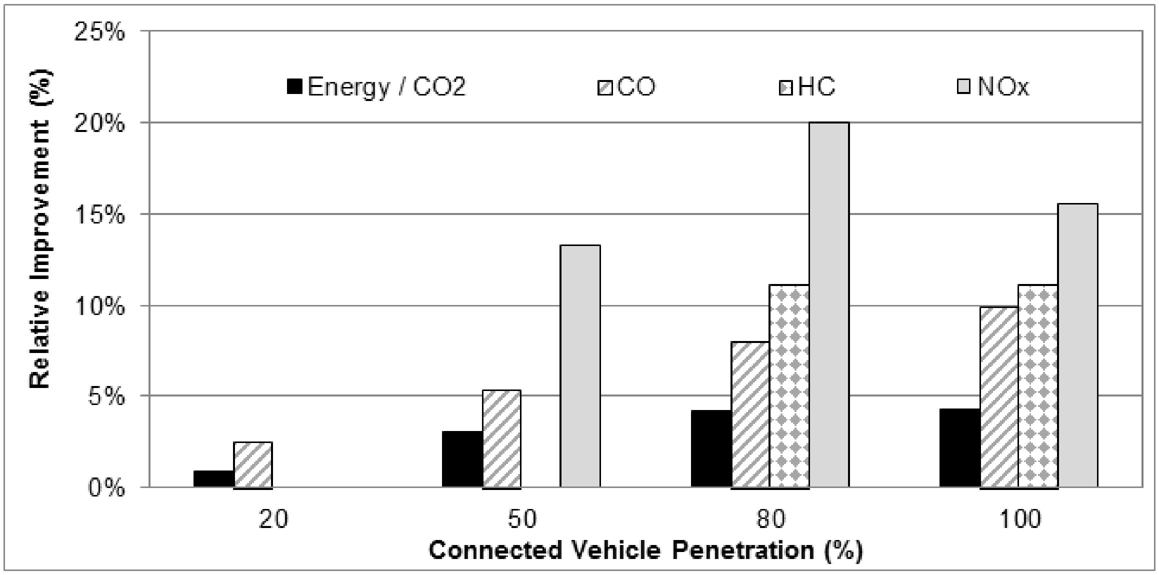


Figure 32: Estimated Benefits in Energy and Emissions Owing to the Eco-Approach at Signalized Intersections Application in Year 2020 Under Different Penetration Rates (V/C = 0.77, Coordinated Network).

When compared to Year 2005, it turns out that the energy consumption and CO_2 emission will be reduced by 9.7 percent to 11.4 percent (varying with penetration rate) in year 2020 for the coordinated El Camino Real network, although the travel time difference is trivial (see Table 13). In addition, emissions of other pollutants, such as HC, NOx, and PM, will be decreased by as much as 75 percent. This may be a result of more widespread deployment of alternative fuel types and advanced engine technology by 2020.

As can also be observed from Table 13, the MOVES model predicts higher benefits (in percent) for the Year 2020 fleet than the Year 2005 fleet if the technology is deployed. Further investigation reveals that the OpMode distributions in scenarios with deployment of the Eco-Approach at Signalized Intersection application will shift to the right-hand side—that is, higher frequency in the higher OpMode bins but less in the “decelerate” (Bin 0) and “idle” (Bin 1) OpMode bins, as compared to those in baseline scenarios. Although the emission factors of Year 2020 are consistently lower than those of Year 2005 under different OpMode bins, these values drop much more drastically in the higher OpMode bins, which results in higher relative benefits in Year 2020.

Table 13: Energy and Emissions Comparisons Between MOVES 2005 and MOVES 2020 (V/C = 0.77, Coordinated Network).

	Connected Vehicle Penetration (%)	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	Average Travel Time per Vehicle
MOVES Year 2005	0	8,183.43	589.55	12.98	0.41	1.85	0.13	94.20
	20	8,082.57	582.31	12.73	0.40	1.72	0.12	95.26
	50	7,989.64	575.65	12.37	0.39	1.68	0.12	94.01
	80	7,967.83	574.13	12.19	0.39	1.66	0.12	94.60
	100	7,952.54	573.12	11.88	0.38	1.69	0.12	95.72
MOVES Year 2020	0	7,391.35	530.57	6.78	0.09	0.45	0.04	95.31
	20	7,328.91	526.08	6.61	0.09	0.45	0.04	94.45
	50	7,164.92	514.36	6.42	0.09	0.39	0.04	94.55
	80	7,079.74	508.22	6.24	0.08	0.36	0.04	94.81
	100	7,076.92	508.06	6.11	0.08	0.38	0.04	95.72

Sensitivity Analyses on HPN—Communication Range and Communication Delay

Sensitivity analyses on communication range and communication delay were conducted on the *Hypothetical Network (Referred to as HPN)*.

Communication Range

Since the link lengths in this network are identically 600 meters long, the connected vehicles start receiving SPaT messages at 600 meters from the next intersection. Results in Figure 33 and Table 14 show how energy savings achieved by the Eco-Approach at Signalized Intersections application can be affected by communication range. It is found that energy savings drastically go down as communication range decreases. A potential hypothesis would be that as the communication distance gets shorter, there is less room remaining for vehicles to plan their trajectories.

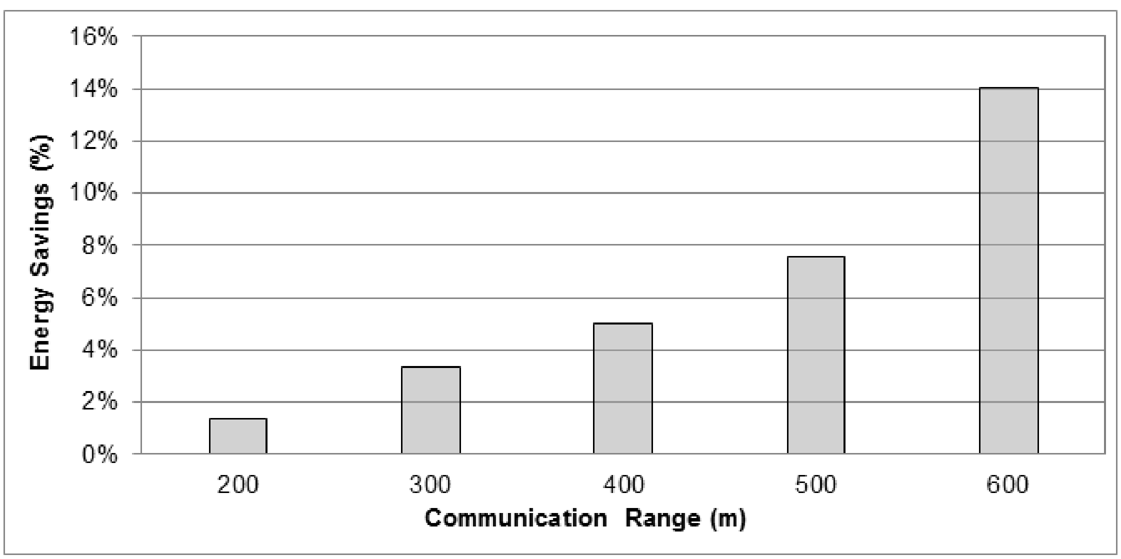


Figure 33: Energy Savings With Different Communication Ranges.

Table 14: Energy Savings With Different Communication Ranges.

Communication Range (m)	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	Average Travel Time per Vehicle
0	7,111.386	510.8926	11.29671	0.332242	1.24896	0.077727	117.2542
200	7,015.719	504.0861	11.08579	0.32982	1.215221	0.0764	119.4448
300	6,873.504	494.117	10.46333	0.31925	1.150927	0.070073	121.0781
400	6,756.343	485.8191	10.33578	0.31621	1.12311	0.069146	120.9452
500	6,573.096	472.7962	9.932904	0.308152	1.077173	0.066514	121.1494
600	6,114.309	440.0973	8.424865	0.278476	0.954197	0.053223	122.4164
Energy Saving %							
200	1.345272	1.33228	1.867084	0.728987	2.701368	1.707257	-1.86823
300	3.345091	3.283587	7.377159	3.910403	7.849171	9.847286	-3.26116
400	4.992605	4.907775	8.506214	4.825398	10.07638	11.03992	-3.14786
500	7.569418	7.456821	12.07256	7.250739	13.7544	14.42613	-3.32198
600	14.02086	13.85717	25.42193	16.18278	23.60068	31.52572	-4.40252

Communication Delay

In the real world, owing to a variety of software and hardware issues, communication delay is inevitable. The effect of communication delay was also simulated in Paramics. In a zero-delay situation, vehicles would get recommended speeds based on current information (e.g., the vehicle's current speed, distance to intersection, and SPaT message); while in a Δt-second-delay situation, vehicles would get recommended speeds based on old information, which is Δt second earlier. Based on extensive modeling, it has been found that the Eco-Approach at Signalized Intersections application was not largely affected by the communication delay, as shown in Figure 34 and Table 15. Even when the communication signal is delayed for 10 seconds, energy savings decrease by only approximately 15 percent. When delay is under 2 seconds, there is no noticeable decrease in energy savings.

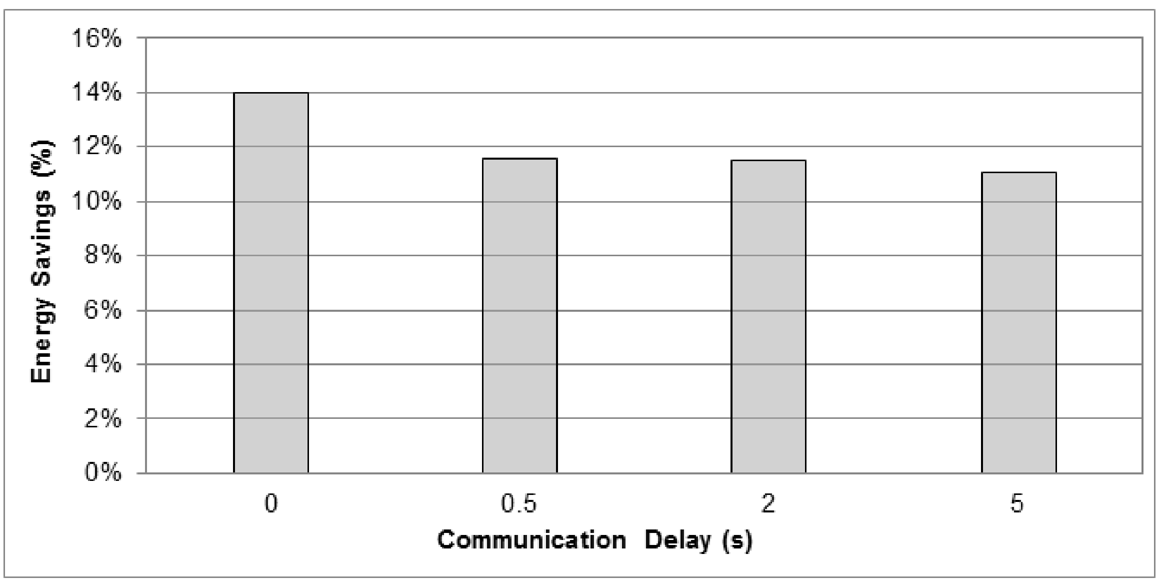


Figure 34: Energy Savings With Different Communication Delays.

Table 15: Energy Savings With Different Communication Delays.

Communication Delay (s)	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	Average Travel Time per Vehicle
Baseline	7,111.386	510.8926	11.29671	0.332242	1.24896	0.077727	117.2542
0	6,114.309	440.0973	8.424865	0.278476	0.954197	0.053223	122.4164
0.5	6,286.531	452.3648	8.543696	0.281889	1.000559	0.053157	117.2288
2	6,294.867	452.9274	8.556977	0.281947	1.005437	0.053277	116.3854
5	6,323.199	454.9448	8.674797	0.284279	1.014502	0.054387	116.226
Energy Saving %							
0	14.02086	13.85717	25.42193	16.18278	23.60068	31.52572	-4.40252
0.5	11.59908	11.45599	24.37002	15.15552	19.88863	31.61064	0.021717
2	11.48186	11.34586	24.25246	15.13806	19.49806	31.45625	0.741021
5	11.08346	10.95099	23.2095	14.43616	18.77226	30.02818	0.876966

Therefore, it can be concluded that this application is very sensitive to communication range but not very much affected by communication delay. In this regard, the 4G/LTE network may be the ideal candidate for implementing this application.

Modeling Results for Eco-Approach and Departure at Signalized Intersections Evaluation Scenarios

To get a better understanding of performance of the Eco-Approach and Departure at Signalized Intersections application, the research team used the same 3-intersection El Camino Real corridor and conducted side-by-side comparison with the Eco-Approach at Signalized Intersections algorithm. Similar to the preceding discussion, scenarios with both coordinated and uncoordinated signal settings have been modeled, and the results are presented in the following sections.

Eco-Approach and Departure on Coordinated ECR-3 Network—Demand and Connected Vehicle Penetration Rate

Results from the coordinated network are summarized in Figure 35, Figure 36, and Table 16. As can be seen, applying the Eco-Approach and Departure algorithm on top of the Eco-Approach one can achieve an additional 1 percent to 3 percent in fuel and emissions benefits for a coordinated signal setting in the 3-intersection El Camino Real network. In addition, generally, travel time per vehicle is compromised by less than 10 percent, thanks to the modification on departure trajectory design. The travel time is minimized in terms of the sinusoidal acceleration trajectory. Compared with the default acceleration trajectory (say, maximum acceleration), the travel time is still longer.

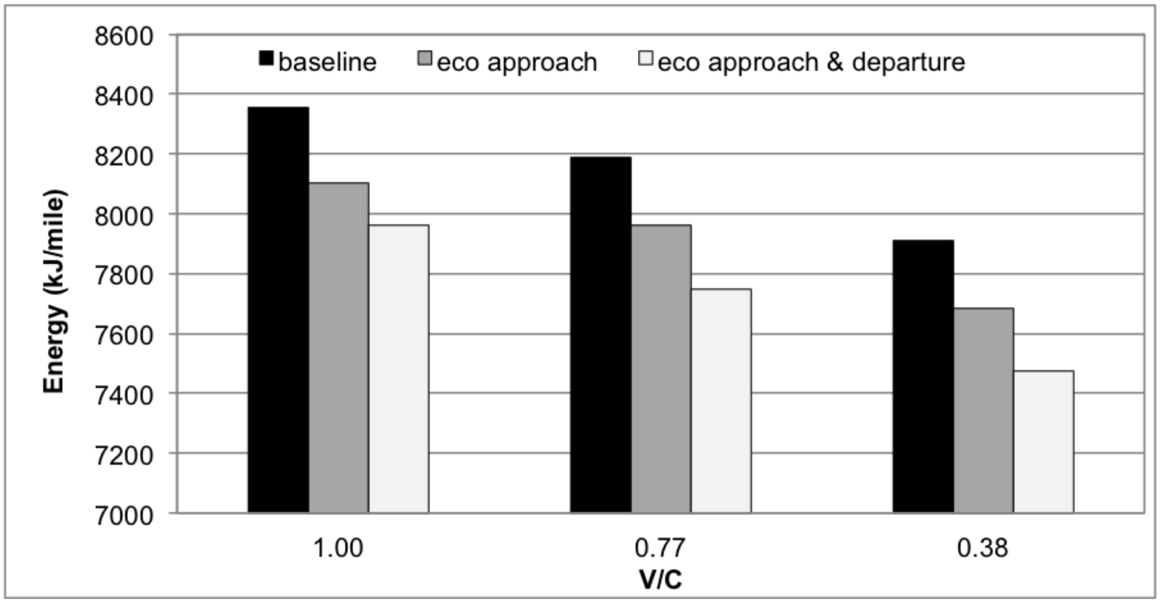


Figure 35: Comparison of Energy Consumption Over Different V/C Ratios (100% Penetration Rate, Coordinated Network): Baseline vs. Eco-Approach and Eco-Approach and Departure Applications.

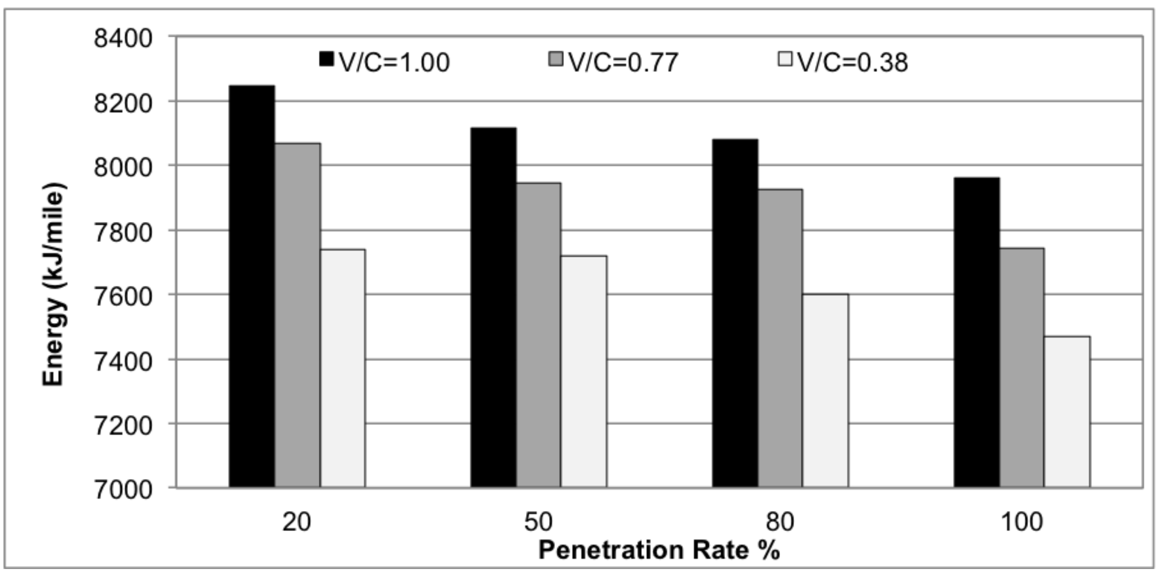


Figure 36: Comparison of Energy Savings Owing to Eco-Approach and Departure Application Over Different V/C Ratios and Penetration Rates (Coordinated Network).

Table 16: Comparison of Measures of Effectiveness (MOE) With V/C Ratio Ranging From 0.38 to 1.00 and Penetration Rate From 0% to 100% for a Coordinated Network: Eco-Approach (eco_app) vs. Eco-Approach and Departure (eco_app&dep) Applications (TT = total time).

Scenario	V/C	Penetr %	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	TT/ veh
Baseline	1.00	0	8,347.75	601.02	13.00	0.41	1.83	0.13	98.94
eco_app	1.00	20	8,253.32	594.42	12.73	0.41	1.74	0.12	99.44
	1.00	50	8,154.57	587.42	12.35	0.40	1.71	0.12	98.17
	1.00	80	8,142.05	586.48	12.07	0.39	1.76	0.12	97.99
	1.00	100	8,097.19	583.57	12.00	0.39	1.73	0.12	97.14
					Saving %				
	1.00	20	1.13	1.10	2.07	1.61	4.77	5.00	-0.50
	1.00	50	2.31	2.26	4.94	3.51	6.47	8.31	0.78
	1.00	80	2.46	2.42	7.13	4.65	3.88	7.34	0.96
	1.00	100	3.00	2.90	7.67	5.49	5.39	8.11	1.82

Scenario	V/C	Penetr %	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	TT/ veh
baseline	1.00	0	8,347.75	601.02	13.00	0.41	1.83	0.13	98.94
eco_app& dep	1.00	20	8,245.16	594.50	11.99	0.40	1.71	0.11	96.26
	1.00	50	8,118.88	585.32	12.22	0.40	1.73	0.12	98.28
	1.00	80	8,078.11	582.33	12.58	0.40	1.66	0.12	105.34
	1.00	100	7,957.46	574.17	11.33	0.38	1.55	0.10	105.67
					Saving %				
	1.00	20	1.23	1.08	7.78	3.51	6.53	10.86	2.70
	1.00	50	2.74	2.61	5.97	4.18	5.20	7.32	0.67
	1.00	80	3.23	3.11	3.17	3.82	8.96	8.37	-6.47
	1.00	100	4.68	4.47	12.80	7.16	15.45	20.84	-6.80

Scenario	V/C	Penetr%	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	TT/ veh
Baseline	0.77	0	8,183.43	589.55	12.98	0.41	1.85	0.13	94.20
eco_app	0.77	20	8,082.57	582.31	12.73	0.40	1.72	0.12	95.26
	0.77	50	7,989.64	575.65	12.37	0.39	1.68	0.12	94.01
	0.77	80	7,967.83	574.13	12.19	0.39	1.66	0.12	94.60
	0.77	100	7,952.54	573.12	11.88	0.38	1.69	0.12	95.72
					Saving %				
	0.77	20	1.23	1.23	1.93	1.51	7.01	7.38	-1.12
	0.77	50	2.37	2.36	4.70	3.58	9.11	10.35	0.20
	0.77	80	2.63	2.62	6.07	4.24	9.94	11.68	-0.43
	0.77	100	2.82	2.79	8.47	5.41	8.31	11.81	-1.61

Scenario	V/C	Penetr %	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	TT/ veh
Baseline	0.77	0	8,183.43	589.55	12.98	0.41	1.85	0.13	94.20
eco_app& dep	0.77	20	8,071.69	581.59	12.78	0.40	1.73	0.12	94.88
	0.77	50	7,945.01	572.46	12.26	0.39	1.62	0.11	96.65
	0.77	80	7,922.35	571.18	11.51	0.38	1.56	0.10	96.86
	0.77	100	7,742.33	557.89	11.83	0.38	1.41	0.10	103.58
					Saving %				
	0.77	20	1.37	1.35	1.53	1.80	6.19	5.95	-0.72
	0.77	50	2.91	2.90	5.52	4.37	12.36	13.75	-2.60
	0.77	80	3.19	3.12	11.32	5.68	15.62	20.82	-2.83
	0.77	100	5.39	5.37	8.87	7.10	23.48	25.70	-9.95

Scenario	V/C	Penetr %	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	TT/ veh
Baseline	0.38	0	7,910.53	569.18	13.07	0.40	1.69	0.13	90.48
eco_app	0.38	20	7,872.10	566.38	12.87	0.39	1.65	0.12	91.62
	0.38	50	7,807.90	561.81	12.42	0.39	1.65	0.12	92.06
	0.38	80	7,775.91	559.44	12.14	0.38	1.65	0.12	91.71
	0.38	100	7,682.70	552.70	11.87	0.38	1.63	0.11	90.25
	Saving %								
	0.38	20	0.49	0.49	1.56	0.76	2.35	3.07	-1.27
	0.38	50	1.30	1.30	4.98	3.01	2.43	5.00	-1.75
	0.38	80	1.70	1.71	7.14	3.81	2.39	6.84	-1.36
	0.38	100	2.88	2.89	9.20	5.48	3.81	9.27	0.25

Scenario	V/C	Penetr %	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	TT/ veh
Baseline	0.38	0	7,910.53	569.18	13.07	0.40	1.69	0.13	90.48
eco_app& dep	0.38	20	7,738.77	556.81	11.45	0.37	1.69	0.11	88.92
	0.38	50	7,721.25	555.47	10.99	0.37	1.58	0.10	92.16
	0.38	80	7,587.76	545.87	11.68	0.37	1.59	0.11	96.56
	0.38	100	7,473.06	537.58	10.46	0.36	1.48	0.09	97.59
	Saving %								
	0.38	20	2.17	2.17	12.43	5.92	-0.23	11.16	1.72
	0.38	50	2.39	2.41	15.88	7.47	6.45	18.86	-1.86
	0.38	80	4.08	4.10	10.62	6.54	5.79	13.93	-6.73
	0.38	100	5.53	5.55	19.97	10.36	12.49	25.57	-7.87

Eco-Approach and Departure on Uncoordinated ECR-3 Network—Demand and Connected Vehicle Penetration Rate

Similar to the coordinated network, an additional 1 percent to 3 percent improvement in fuel and emissions can be witness by applying the Eco-Approach and Departure at Signalized Intersections module to the uncoordinated 3-intersection El Camino Real corridor, compared to the results from the Eco-Approach at Signalized Intersections algorithm. In addition, the average travel time generally increases by less than 8 percent. Figure 37, Figure 38, and Table 17 summarize all these results. The Eco-Approach and Departure module has more benefits in energy savings but not necessarily in travel time savings than the Eco-Approach algorithm, owing to the less aggressive acceleration profile used when departing.

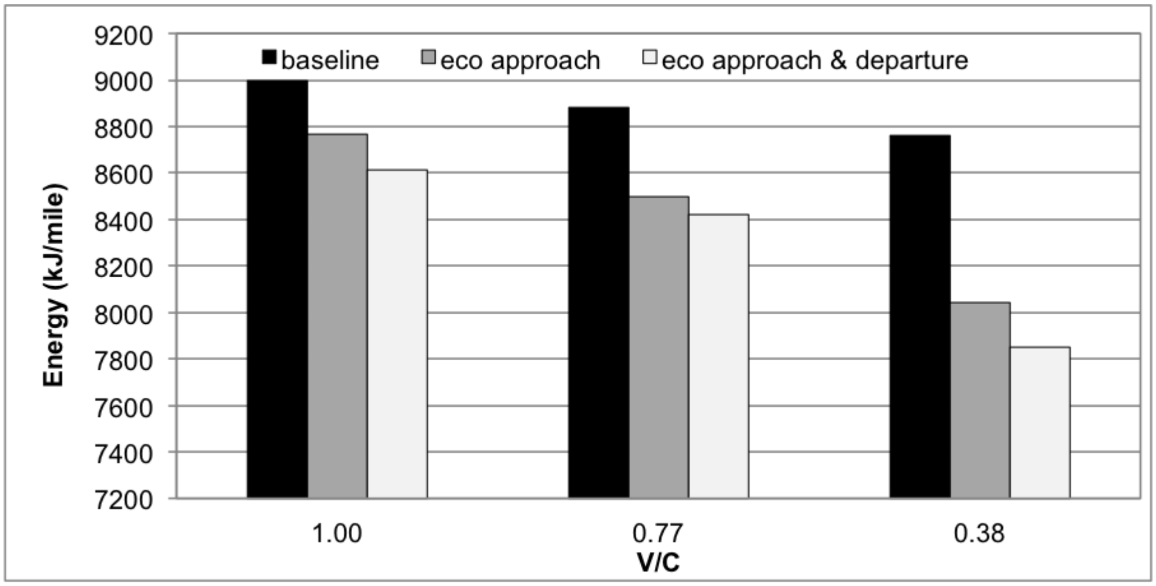


Figure 37: Comparison of Energy Consumption Over Different V/C Ratios (100% Penetration Rate, Uncoordinated Network): Baseline vs. Eco-Approach and Eco-Approach and Departure Applications.

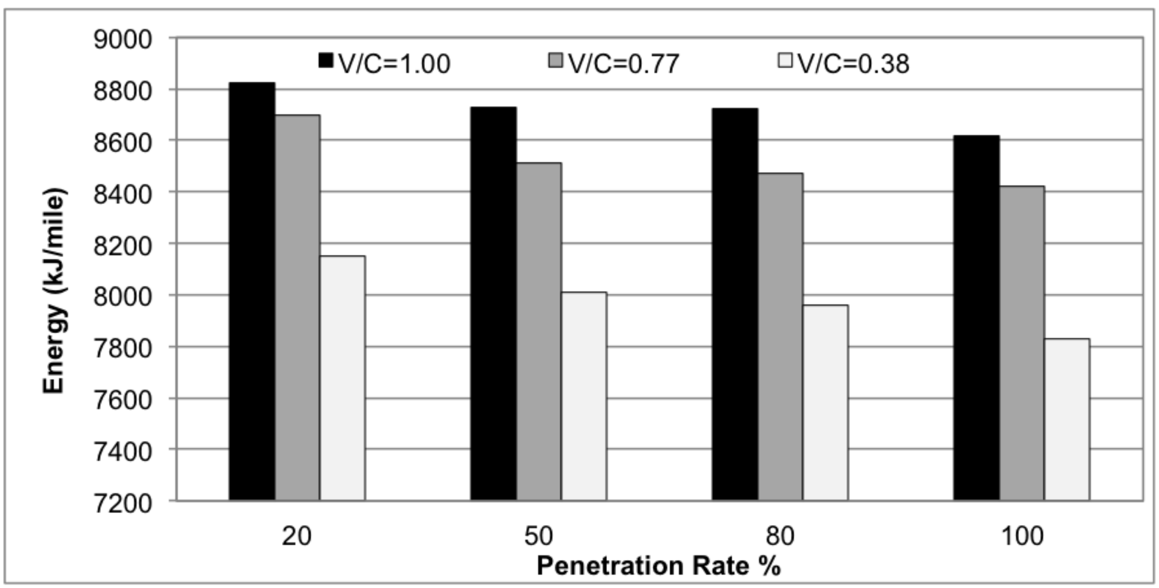


Figure 38: Comparison of Energy Savings Owing to Eco-Approach and Departure Application Over Different V/C Ratios and Penetration Rates (Uncoordinated Network).

Table 17: Comparison of MOEs With V/C Ratio Ranging From 0.38 to 1.00 and Penetration Rate From 0% to 100% for an Uncoordinated Network: Eco-Approach (eco_app) vs. Eco-Approach and Departure (eco_app&dep) Applications (TT = total time).

Scenario	V/C	Penetr %	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	TT/ veh
Baseline	1.00	0	8,997.08	647.70	13.55	0.45	1.87	0.13	125.12
eco_app	1.00	20	8,844.93	636.75	12.90	0.44	1.77	0.12	124.16
	1.00	50	8,832.84	636.02	12.34	0.43	1.77	0.11	125.74
	1.00	80	8,797.50	633.75	11.96	0.43	1.80	0.11	126.26
	1.00	100	8,772.78	632.06	11.86	0.42	1.78	0.11	126.89
					Saving %				
	1.00	20	1.69	1.69	4.80	2.22	5.35	7.69	0.77
	1.00	50	1.83	1.80	8.93	4.44	5.35	15.38	-0.50
	1.00	80	2.22	2.15	11.73	4.44	3.74	15.38	-0.91
	1.00	100	2.49	2.41	12.47	6.67	4.81	15.38	-1.41

Scenario	V/C	Penetr %	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	TT/ veh
Baseline	1.00	0	8,997.08	647.70	13.55	0.45	1.87	0.13	125.12
eco_app&dep	1.00	20	8,829.94	636.06	12.59	0.43	2.03	0.13	124.06
	1.00	50	8,736.43	629.70	11.53	0.42	1.84	0.11	126.47
	1.00	80	8,728.17	628.79	12.03	0.43	1.83	0.12	129.66
	1.00	100	8,621.25	621.46	11.69	0.42	1.82	0.11	133.60
					Saving %				
	1.00	20	1.86	1.80	7.07	3.44	-8.59	-2.94	0.85
	1.00	50	2.90	2.78	14.88	5.90	1.41	13.67	-1.08
	1.00	80	2.99	2.92	11.23	5.53	1.92	9.35	-3.63
	1.00	100	4.18	4.05	13.69	7.19	2.56	11.70	-6.78

Scenario	V/C	Penetr %	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	TT/veh
Baseline	0.77	0	8,887.79	640.62	13.69	0.45	1.91	0.13	118.31
eco_app	0.77	20	8,798.62	634.29	12.95	0.44	2.00	0.14	115.29
	0.77	50	8,541.45	615.85	12.18	0.42	1.78	0.12	115.38
	0.77	80	8,535.41	615.49	11.91	0.41	1.79	0.12	116.56
	0.77	100	8,509.31	613.72	11.68	0.41	1.74	0.11	118.75
					Saving %				
	0.77	20	1.00	0.99	5.41	2.22	-4.71	-7.69	2.55
	0.77	50	3.90	3.87	11.03	6.67	6.81	7.69	2.48
	0.77	80	3.96	3.92	13.00	8.89	6.28	7.69	1.48
	0.77	100	4.26	4.20	14.68	8.89	8.90	15.38	-0.37

Scenario	V/C	Penetr %	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	TT/veh
Baseline	0.77	0	8,887.79	640.62	13.69	0.45	1.91	0.13	118.31
eco_app&dep	0.77	20	8,702.35	627.37	12.82	0.43	1.83	0.12	114.91
	0.77	50	8,509.90	613.77	11.70	0.42	1.77	0.11	115.18
	0.77	80	8,472.60	611.09	11.59	0.41	1.52	0.09	119.47
	0.77	100	8,425.44	607.35	12.19	0.42	1.55	0.10	121.76
					Saving %				
	0.77	20	2.09	2.07	6.38	3.63	3.97	8.24	2.87
	0.77	50	4.25	4.19	14.54	7.65	7.10	15.77	2.64
	0.77	80	4.67	4.61	15.30	8.09	20.53	29.64	-0.98
	0.77	100	5.20	5.19	10.94	7.53	19.07	24.37	-2.92

Scenario	V/C	Penetr %	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	TT/ veh
Baseline	0.38	0	8,760.11	630.78	13.91	0.44	2.03	0.15	108.16
eco_app	0.38	20	8,319.29	598.83	13.23	0.42	1.67	0.12	108.27
	0.38	50	8,241.15	593.10	12.43	0.41	1.70	0.12	108.70
	0.38	80	8,123.89	584.53	11.92	0.40	1.62	0.11	109.56
	0.38	100	8,046.89	579.04	11.69	0.39	1.64	0.11	107.68
	Saving %								
	0.38	20	5.03	5.07	4.89	4.55	17.73	20.00	-0.10
	0.38	50	5.92	5.97	10.64	6.82	16.26	20.00	-0.50
	0.38	80	7.26	7.33	14.31	9.09	20.20	26.67	-1.29
	0.38	100	8.14	8.20	15.96	11.36	19.21	26.67	0.44

Scenario	V/C	Penetr %	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)	TT/ veh
Baseline	0.38	0	8,760.11	630.78	13.91	0.44	2.03	0.15	108.16
eco_app&dep	0.38	20	8,160.36	587.67	12.46	0.40	2.02	0.14	105.39
	0.38	50	8,014.54	577.02	10.84	0.38	1.98	0.13	107.64
	0.38	80	7,979.99	574.55	11.70	0.39	1.83	0.13	108.74
	0.38	100	7,846.91	564.88	11.06	0.38	1.80	0.12	109.78
	Saving %								
	0.38	20	6.85	6.83	10.42	8.12	0.71	4.11	2.56
	0.38	50	8.51	8.52	22.05	13.17	2.30	13.80	0.48
	0.38	80	8.91	8.92	15.91	11.19	10.07	16.38	-0.54
	0.38	100	10.42	10.45	20.50	14.05	11.39	19.68	-1.50

Findings and Opportunities for Future Research

Prior to modeling, the hypothesis that was generated based on literature review stated: Providing speed advice to drivers who are within a communication range of signals (300 meters) as their vehicle is approaching and departing signalized intersections will reduce emissions and lower fuel consumption during congested traffic conditions by 3 percent to 4 percent under partial connected vehicle penetration and 6 percent to 8 percent under full connected vehicle penetration.

The modeling results shown in this chapter are consistent with those reported in previous studies. It is found that the Eco-Approach and Departure at Signalized Intersections application results in 2 percent to 8 percent energy savings, without significantly increasing travel time. Such benefit comes from the eco-friendly approach (i.e., less aggressive maneuvering owing to having prior knowledge of the signal phase change) of equipped vehicles without causing extra delay at traffic signals. The energy savings benefit of the application depends on a variety of factors, including congestion level, penetration rate, communication conditions, and signal coordination. More specifically—

1. The application is less effective when the corridor becomes congested. As congestion increases, there is less room for individual vehicles to change their speeds when approaching traffic signals.
2. The higher the penetration rate of this technology, the more energy savings and emission reductions can be achieved. An interesting finding is that even at low or moderate connected vehicle technology penetration levels, the application still has a positive indirect network-wide effect, which results from the fact that unequipped vehicles also gain energy and

environmental benefits from following equipped vehicles. Such findings increase the attractiveness of this application as an early candidate for field testing and deployment.

3. The results from the hypothetical model show that the Eco-Approach and Departure at Signalized Intersections application is very sensitive to communication range between RSE and OBE. By receiving the SPaT information far ahead of the intersection, drivers would have more time to change their vehicles' speeds and thus reduce unnecessary stops at the signals. On the other hand, the results reveal that the application is less sensitive to communication delay.
4. For a signalized corridor, signal coordination has significant impacts on fuel efficiency (at different congestion levels) by itself and also on the amount of benefits from the application. The modeling results indicate that the application provides greater benefits for a corridor on which traffic signals are less coordinated. This is because traffic flow with better progression (owing to better signal coordination) is less likely to experience frequent stops and significant delays in the first place.
5. The analyses on the 3-intersection El Camino Real corridor indicate that the Eco-Approach and Departure module can achieve an additional 1 percent to 3 percent in fuel savings and emissions reduction under either coordinated or uncoordinated signal settings, compared with the Eco-Approach algorithm. Average travel time is compromised by less than 8 percent, owing to the longer acceleration time (less aggressive acceleration) resulting from the trajectory smoothing in the modified algorithm.

Based on the above findings from the modeling effort, the research team has the following recommendations and remarks:

1. Additional energy and environment benefits may be obtained through a more customized vehicle trajectory planning algorithm, which does not depend on the simplified mathematical model (e.g., trigonometric function as currently used) but on detailed vehicle dynamics (e.g., engine/motor map, tire friction). By taking into account additional inputs, such as traffic conditions, roadway grade, and weather, real-time optimization of the vehicle's recommended speed can be performed to achieve better performance, based on short-term prediction of propulsion power.
2. The Eco-Approach and Departure at Signalized Intersections application, when combined with cooperative adaptive cruise control (CACC), could provide significant energy and environmental benefits. CACC and longitudinal control capabilities (1) allow the vehicle to better follow the recommended speed profile than a human can; (2) can shorten the delay owed to drivers' reaction time; and (3) have potential to better cooperate with other vehicles and/or infrastructure in a complex environment than a human can and (4) improve throughput of the corridor.
3. Other technologies, such as engine start-stop technology, can also be integrated with the Eco-Approach and Departure at Signalized Intersections application to achieve additional energy savings. However, potential unintended environmental impacts (e.g., emission spikes from engine starts) should also be investigated.
4. Sensitivity analyses on communication range and communication delay in the hypothetical model indicate that this application could be well enabled by just cellular communication rather than Dedicated Short Range Communication (DSRC) (which is necessary for time-critical applications, such as those that are safety-related). With cellular communication, SPaT information could be available at a longer distance away from the traffic signal, allowing the

application to plan a vehicle trajectory not just for one intersection at a time but for an entire corridor ("green band").

Modeling results were designed for fixed-time signals. Under actuated signal control scenarios, it is much more difficult to estimate SPaT information (e.g., the remaining time of the current phase), which might result in lower environmental benefits than expected. In a separate project, we are investigating the effectiveness of this application under actuated signal control.

Chapter 5. Eco-Traffic Signal Timing Application

Application Description

The description of the application is provided in Chapter 2 under the section "Eco-Traffic Signal Timing" on page 9. The application is graphically illustrated in Figure 39.

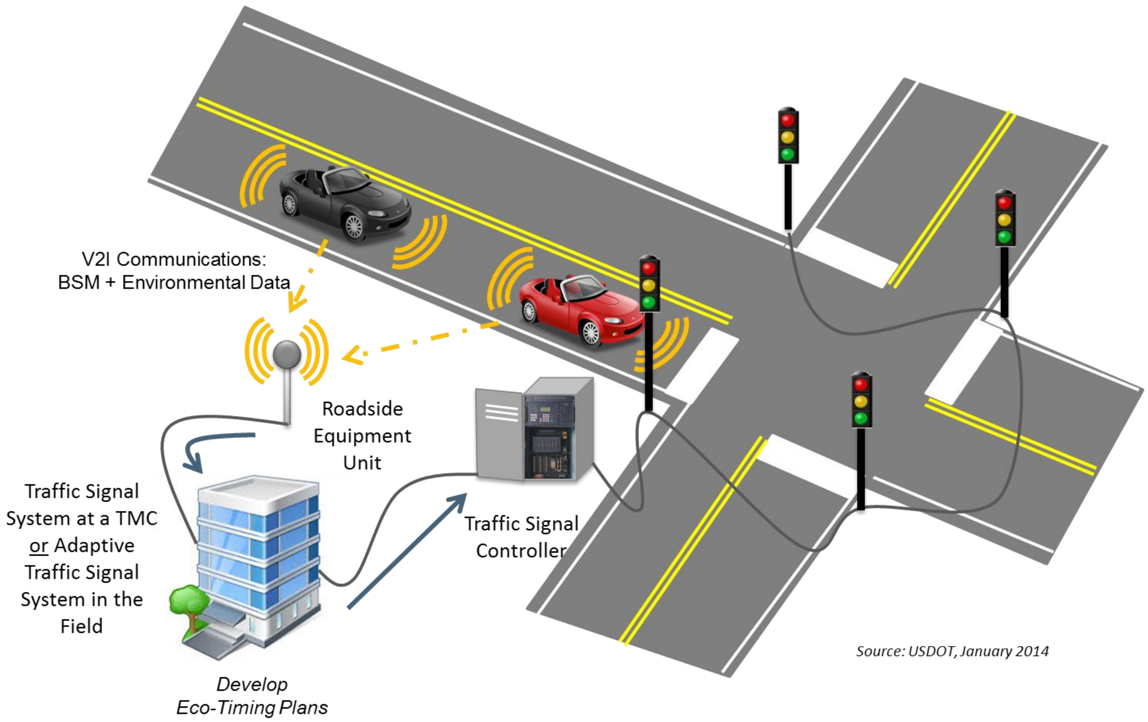


Figure 39: Eco-Traffic Signal Timing Application Illustrated.

Hypotheses

If the Eco-Traffic Signal Timing application is used to dynamically adjust signal phase and timing plans based on the speed of vehicles approaching an intersection and vehicle emissions characteristics, then there will be emissions reductions and lowered fuel consumption during congested traffic conditions in the range of 2 percent to 3 percent under partial connected vehicle penetration and 4 percent to 6 percent under full connected vehicle penetration. The percentage fuel savings during off-peak hours are expected to be higher as the intersection would have more capacity left for optimization.

Algorithm

Signal timing optimization is a process that has been used and improved on for years in the transportation planning field. It involves the modification of the signal timing plan for one or more intersections in a system to improve one or more desired measures of effectiveness. The traditional methods of optimization are focused on mobility and throughput measures, such as travel time and delay, but the Eco-Traffic Signal Timing AERIS application is focused on signal timing optimization that improves environmental measures, such as fuel consumption and vehicle emissions. Additional tools, such as microsimulation traffic models, have been developed to allow traffic planners to test signal plans in a simulated environment to gauge their effectiveness at low cost and effort.

The Eco-Traffic Signal Timing application is based on a standalone program that interfaces with Paramics. The two programs run together in a complementary loop to simultaneously develop and test signal timing plans. The optimization of a set of signal timing plans for a network corridor is a complex problem that involves many decision variables. For each signal in the network, there is the potential to change each phase's green time, the signal's cycle length and offset, as well as the phasing order. When considering a system with multiple signals, the problem's complexity increases because the optimization also must consider how each of the changes affects the nearby intersections and the system as a whole. For this analysis, phasing order was the only signal timing variable that was not considered for optimization. The combination of the used variables for the optimization creates a significant amount of possible timing scenarios to consider. Therefore, a heuristic solution method, known as a *genetic algorithm,* is used to develop the timing plans. The GA was implemented in an executable program (*.exe) that complements the Paramics model and has been named the Genetic Algorithm for Signal Timing Optimization (GASTO). The workings of GASTO are explained in the following section. The overall structure of the Eco-Traffic Signal Timing algorithm can be seen in Figure 40.

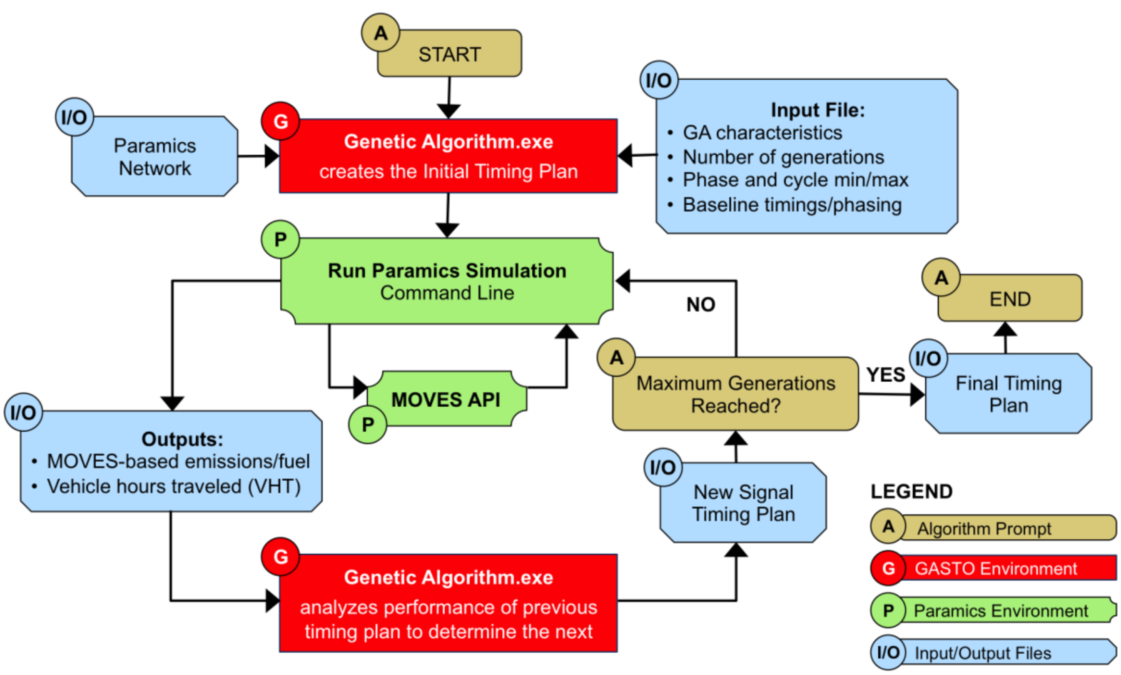


Figure 40: General Structure of the Eco-Traffic Signal Timing Application Implemented Using a GA.

Using the Paramics network as a baseline for signal timing and phasing as well as the basis for traffic and geometry with which to test signal timing, along with the GA user inputs shown in Figure 40 (explained in more detail in the “Modeling Approach” section), the GASTO program creates an initial set of timing plans to begin the optimization process. The GASTO program not only contains a GA component but also has an interface with the microsimulation software, Paramics, which allows the program to call and run the simulation autonomously to test the signal timing plans. Running the program autonomously in a loop provides many benefits to the process, including—

- Greatly increasing the speed of the runs, which in turn helps complete the GASTO runs significantly faster
- Needing no input from the operator during the process.

The environmental results of the Paramics simulation are developed using MOVES, which runs in real time in parallel with the simulation to monitor emissions and create output files containing relevant measures of effectiveness for the user. The GASTO program uses the output file of the Paramics run, either in terms of environmental benefits or average travel time, to help evaluate and improve the fitness of timing plans. During each “loop,” the GA creates a new set of signal timing plans, which are inserted into the Paramics network, and then tested one by one when the simulation is run again by the GASTO program. This process continues until a user-defined stopping point is reached (maximum number of generations), and the final result is a “final” signal timing plan representing the “best” timing solution for the network.

GA for Signal Timing Optimization

A GA is an optimization technique that seeks to minimize an objective function (such as total delay) and uses methods inspired by natural evolution to search for new solutions. In the context of the AERIS application for Eco-Traffic Signal Timing, the objective function of the GA is to minimize the environmental impact in terms of emissions, and the solution is a new set of signal timings to accomplish this. GAs provide a flexible, rigorous, scalable framework to solve challenging optimization problems. It is important to note that although a GA is a method that continually finds “better” solutions, like all optimization techniques based on natural processes intended to solve challenging, large-scale problems, there is no way to guarantee that any particular solution is the “best.”

The GA begins with a randomly generated initial population of individuals that represent potential solutions. In the context of this application, an “individual” represents one possible signal timing plan, and a population is a set of many signal timing plans. The population evolves according to a “natural selection” process, where the best individuals are identified and combined using a crossover technique to form new individuals that enter the population. Each individual timing plan is tested using the Paramics and MOVES integrated traffic simulation to obtain the total system travel time and total emissions that result from that signal timing plan. The GA then uses methodological techniques that are explained in more detail in the next section to find new solutions.

Table 18 contains a summary of terminology related to a GA and an explanation of its specific meaning in this modeling application.

Table 18: Fleet GA Terminology and the AERIS Context.

Term	Explanation in GA Context	Representation in the GASTO Application
GA variable	The quantities that the GA changes to find better solutions, which the GA represents as binary numbers	Each part of the signal timing plan for each intersection, including cycle length, offset, and green time
Chromosome	Possible solution consisting of a set of GA variables	A complete signal timing plan, including cycle length, offset, and green time for all intersections, written in binary representation
Generation	An iteration of the algorithm	A complete cycle of performing each GA procedure a single time, including a Paramics simulation for all chromosomes, crossover, and mutation
Population	The set of chromosomes at any given generation	The set of all signal timing plans that the GA is currently testing
Fitness	The measure of how "good" a chromosome is in terms of minimizing the objective function	Either the total system travel time or the total emissions associated with a specific signal timing plan
Crossover	A GA procedure to find new solutions based on the evolutionary equivalent of "breeding"	Using a binary representation
Culling percentage	How much of the population to replace during each crossover procedure	50 percent was generally used
Mutation	A GA procedure that also finds new solutions, based on the evolutionary equivalent	Modification of signal timing plans in the population to find new solutions
Mutation rate	The probability that each bit of the binary chromosome representation can mutate	Mutation rate = 0.05
Mutation frequency	How often (by generation) to perform mutation	Chromosomes were mutated every generation
Parent (chromosome)	A set of chromosomes	
Child (chromosome)	A set of chromosomes	

With the additional knowledge of these terms and features of the GASTO program, the general structure of the application algorithm can be expanded to show the internal workings of the GA with respect to the process as a whole. A more detailed structure of the GASTO program can be seen in Figure 41.

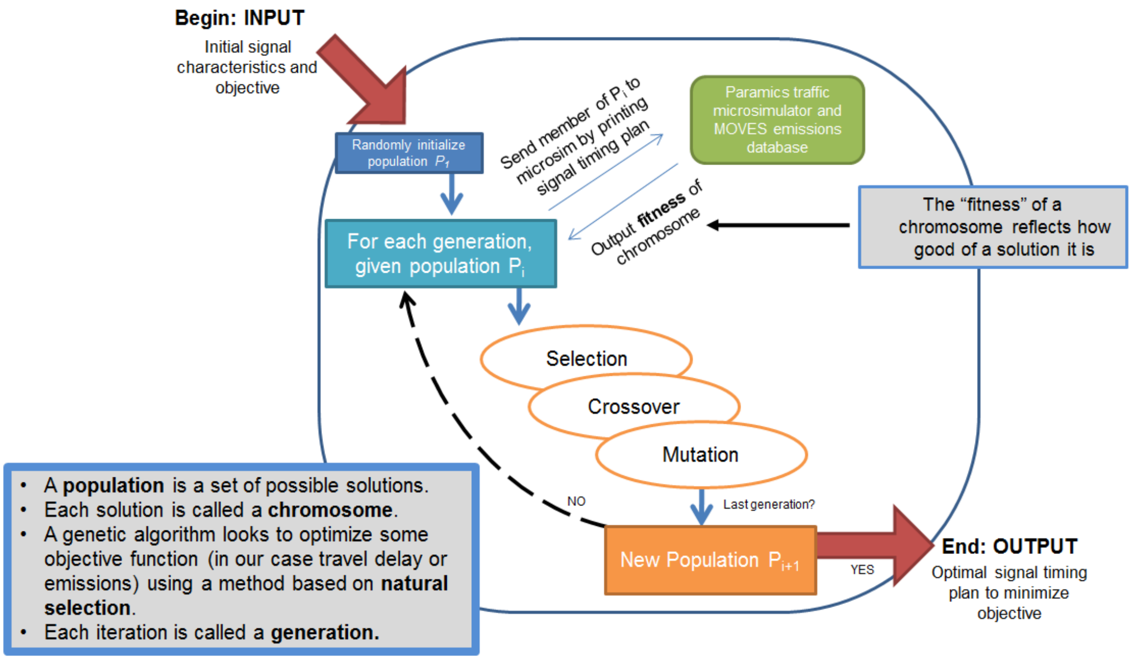


Figure 41: Detailed Structure of the GASTO Program.

For the remainder of this section, the GASTO program is introduced in more detail. The main GASTO application process consists of three main procedures that take place during each generation: fitness evaluation, crossover, and mutation. This process can be seen in more detail in Figure 42.

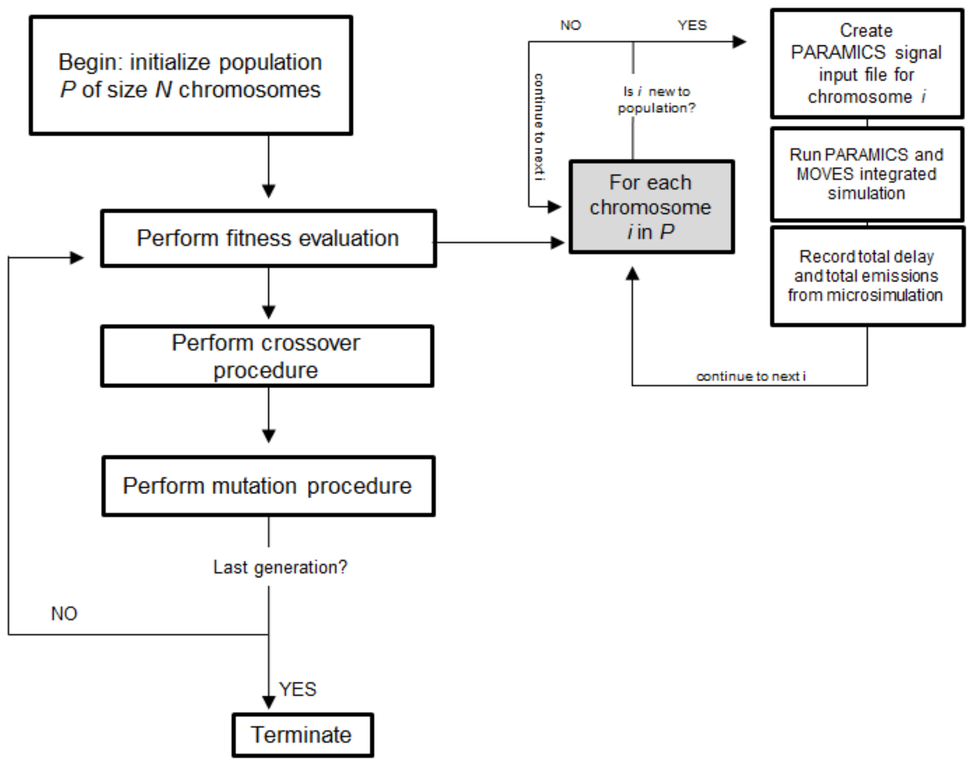


Figure 42: Outline of GASTO.

The fitness evaluation procedure provides a means to judge how "good" each chromosome is in terms of minimizing the specified objective of either environmental or mobility measures. The GA uses this fitness score to provide a search direction. As a chromosome represents a possible signal timing plan, its fitness is obtained by running the Paramics microsimulation, resulting in values for total delay and total emissions. The information for this chromosome is represented in the signal input file, created by GASTO for Paramics, which contains the timing plan variables such as green times, cycle lengths, offsets, and phasing plans (defined in more detail in the following paragraphs).

The crossover procedure and the mutation procedure are the methods used by the GA to find new, better solutions. The crossover procedure begins by eliminating a percentage of the population as specified by the input culling percentage. The "weakest" members of the population, here represented by chromosomes with the highest total delay or total emissions value (depending on the objective), are deleted. To generate new chromosomes, two chromosomes from the remaining population are randomly selected to be "parents." Two "child" chromosomes are created by taking half of the binary representation of each parent to form a new number for each of the GA variables. This procedure requires the culling percentage as an input from the user. Figure 43 illustrates this process, where C_1 and C_2 are parent chromosomes and C' represents the child chromosomes. Note that the number depicted for cycle length does not include a minimum cycle length time (i.e., actual C_2 cycle length equals $5 + 30$).

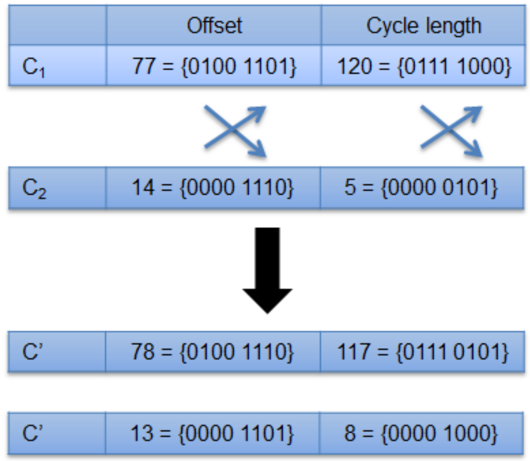


Figure 43: Overview of the Crossover Procedure.

Similar to the principles of natural biology, the mutation process maintains diversity in a population. For the mutation procedure, the user inputs two parameters: the mutation frequency and the mutation rate. During generations that include mutation, each bit of the binary representation of each variable has the specified probability of flipping from a '1' to a '0' or from a '0' to a '1'. Table 19 illustrates a possible mutation process for chromosome C_1. The figure shows that the mutation process caused the sixth bit (decimal number 32) of the offset to flip from a '0' to a '1.' This changed the offset decimal number from a 77 to a 109. In Figure 43, the mutation process did not change the value for the cycle length.

Table 19: Possible Mutation Process for a Chromosome c1.

Chromosome		Offset	Cycle Length
Before mutation:	C_1	77 = {01**0**0 1101}	120 = {0111 1000}
After mutation:	C'	109 = {01**1**0 1101}	120 = {0111 1000}

If a chromosome is mutated, a new copy of that chromosome is created with the random mutations and added to the population. This is further illustrated in Table 19, when chromosome C_1 is mutated and becomes a new chromosome, denoted C'. After the mutation shown in Table 19, both chromosomes C_1 and C' will be present in the population at the beginning of the next generation. The new chromosome's fitness will then be evaluated in the next generation. However, because an additional chromosome was added during the previous generation, the number of chromosomes "culled" will be the culling percentage plus the number of chromosomes mutated. The GA terminates when it has run for the user-specified number of generations.

GASTO is tailored to solve for the signal timing plan for the network corridor. For this modeling effort, the GA uses a binary representation for all variables. The GA is able to optimize four decision variables for each intersection:

1. **Cycle Length:** Total sum of green time, yellow time, and all-red time for all phases of an intersection
2. **Cycle Offset:** The amount of time the beginning of a phase is delayed in relation to a master intersection, to allow better coordination between signals
3. **Green Split:** The total green time assigned to a phase
4. **Phasing Plan:** The order and arrangements of movements within all the phases of a signal plan.

To use the phasing plan optimization feature of the GA, all of the possible phasing plan orders and configurations must be provided by the user in advance for the program to choose from. This requires some preplanning, and would be specific to each corridor or system for which the GA was used to optimize the signal timing plans. For this analysis, this feature was not used because it would have added another level of complexity and computation time to find a reasonable solution to the optimization problem.

Each GA chromosome contains a complete possible signal timing plan, including each of the four specifications for each intersection.

The user inputs for GASTO include the following:

1. Paramics microsimulation network
2. Objective to be minimized
3. Size of the population
4. Number of generations
5. Culling percentage
6. Mutation frequency and rate
7. Minimum cycle length, maximum cycle length, and minimum and maximum green time.

GASTO then performs the specified number of generations using the method outlined in Figure 44 and outputs the best signal timing plan it has found that minimizes the selected objective.

Modeling Approach

This section details how the model was created to test the Eco-Traffic Signal Timing application's hypotheses and how performance measures were generated from the model.

Paramics was used to model the movement of individual vehicles and their interactions in detail. To be consistent with the modeling efforts on other AERIS applications, the latest version of Paramics (V. 6.9.3) was used.

As part of the evaluation, detailed speed profiles of every vehicle were examined to estimate emissions and fuel consumption. As part of the programming environment, Paramics supported the development of plugins using its API, which enabled users to interface with its core simulation engine to perform specific tasks. The interaction between different models and API used in this application is shown in Figure 44. An API was developed that used the above-mentioned vehicle profiles to simulate the function of the MOVES emissions model in the Paramics environment. The components of the Eco-Traffic Signal Timing application were designed to fulfill the following four functions:

1. The GASTO GA develops a set of timing plans to test in Paramics.
2. The microsimulation model tests the timing plans on the El Camino Real corridor.
3. The MOVES API model plug-in uses real-time vehicle information to record environmental measures to export to the GA.
4. The GA uses the results from the microsimulation run to "learn" and improve the next set of timings.

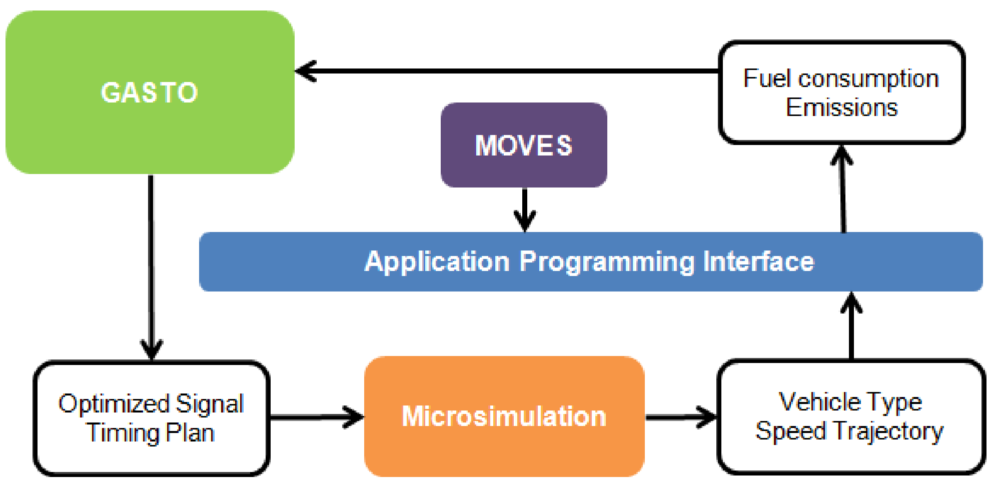


Figure 44: Diagram of Interactions Among the Model Components and the API.

For the Eco-Traffic Signal Timing application, the GASTO program was used for the optimization of the following for each intersection in the El Camino Real corridor:

1. Cycle offset
2. Green split
3. Cycle length.

As mentioned, the option for the GA to optimize a signal phasing plan from a set of possible phase patterns (provided at the beginning by the user) is not considered in this analysis, to simplify the set of possible solutions that the GA would have to search to find the best set of timing plans.

Parameters related to a GA are highly case specific. Therefore, extensive sensitivity testing was conducted to determine the best configuration for the user-defined GASTO input parameters, described earlier in the section “GA for Signal Timing Optimization.” The characteristics that were selected are shown in Table 20 and were held constant throughout the analysis and through all sensitivity tests with both the 3- and 27-intersection models.

Table 20: GA Selection Method Criteria for the Eco-Traffic Signal Timing Application.

Feature	Setting
Generations	60
Population	50
Culling Percentage	50%
Mutation Rate	5%
Mutation Frequency	Once per generation
Minimum Phase Length	6 sec
Maximum Phase Length	127 sec
Minimum Cycle Length	30 sec
Maximum Cycle Length	270 sec
Emission Type Targeted	CO_2
Delay Type Targeted	Network Travel Time

Empirical evidence demonstrates that a high mutation rate and high culling percentage enable GASTO to more efficiently explore the solution space. Qualitative reasoning from the analogy of natural evolution supports this observation. A higher culling percentage means that more individuals (i.e., possible solutions) enter the population. This aids the GA in efficiently searching for better solutions. However, a high culling percentage also means a smaller pool of “parents” to choose from. Over time (i.e., many generations) this causes a population to become uniform (i.e., identical parents create identical children). However, a high mutation rate ensures that diversity in the population is maintained.

The minimum phase length of 6 seconds, the minimum cycle length of 30 seconds, and the maximum cycle length of 270 seconds were selected to be representative of real traffic characteristics. The maximum phase length of 127 was selected because this was the largest number that could be represented by seven bits (0111|1111 = 127). Limiting the memory used in the GA binary variable representation was identified as an efficient method of constraining the cycle length (although this method was not suitable for other GASTO variables).

Sensitivity analyses also showed that higher populations with a fewer number of generations were more computationally efficient than the opposite. **To minimize emissions in the GA objective function, carbon dioxide (CO_2) was found to be a good indicator of fuel/energy savings for vehicles, so it was used as the optimization target for the objective function in the GA.** This was confirmed by the results, because a reduction in both CO_2 and fuel consumption occurred in all analyses.

GA Random Seed

Although GAs have been used to optimize signal timing plans based on mobility measure reduction, the introduction of the GASTO program as a way to perform offline signal timing optimization to reduce fuel usage and environmental impacts was a relatively new endeavor. Because this was a new endeavor, the implementation and design of the program were challenging and a learning process for all members of the team. One of the most debated challenges of GASTO's operation was how to best understand and handle the random effects of modeling when used with the GA. In the case of microsimulation modeling, this was handled by the random number generator, which was seeded by a random seed, either chosen by the operator or seeded automatically by the program, at the beginning of the run. The statistical importance of varying the random seed in modeling is well known and well documented in the field with regard to traditional modeling. From the beginning of the analysis, it was unknown exactly what effect this would have on the operation of the GA with regard to finding possible solutions, so it required quite a bit of analysis.

For the GASTO program run process, there were two random seeds. The first seed was associated only with the GA and was used to generate the initial population of chromosomes, and the second was the seed of the Paramics microsimulation run that analyzed each of chromosomes for fitness. Initial runs of the GASTO program used a default seed value in Paramics that would initialize the same for each chromosome. Using a default seed value was initially believed to be the best and most accurate way to run the GA. Resulting analyses of the answers of the GASTO process found strange biases and associated artifacts that indicated to the team that the best answer could not be found using only one seed. Two methods were proposed to deal with the effect of bias on the microsimulation system:

1. The first procedure involved using multiple random seeds to be run for each chromosome and then averaging their results to determine the fitness score for use in the GASTO program. The set of random seeds would remain the same between generations to limit any dangers that may occur from randomness. The problem with this procedure was that the computation time was too long for the problem that needed to be solved. GASTO already required between 1 and 4 days to solve the optimization problem, and the introduction of "x" seed runs would multiply this by "x" times.
2. The second procedure involved running GASTO once for each chromosome and allowing Paramics to select a random seed at the beginning of each run. There was no control in this procedure for the replication of similar seeds from generation to generation. It was originally considered to be "dangerous" to let the program choose at random, without regard to uniformity, but it was later decided that this method more closely represented reality, where no two days are exactly the same. Statistical runs comparing the results of different seeds showed no large variance in results from seed to seed.

In addition, it was determined that using random seeds would eliminate particular signal timing plans that were only "good" solutions because of some unrepeatable randomness. If a signal timing plan was "good" for a number of random seeds, it would remain highly ranked during all generations of the GA, giving it a higher probability of being selected to help find even better solutions. Therefore, solutions from this method would be more robust.

With regard to the scope and time interests of this project, it was decided that the second method would be used to run the sensitivity analyses for the Eco-Traffic Signal Timing application. To test this assumption, a simple sensitivity analysis was run to compare the "Default Seed" method with the

"Random Seed" method. The results of this analysis are presented in Figure 45, which represents the convergence curve of the GASTO process over the generational selection process.

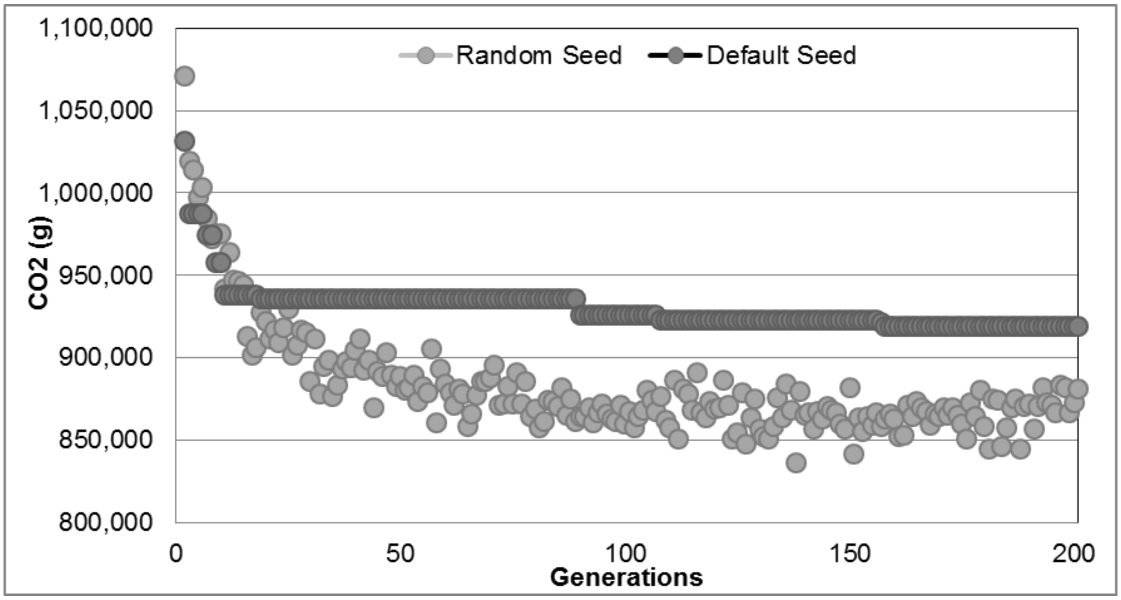


Figure 45: Convergence Curve for GASTO Run for Both the "Default Seed" and "Random Seed" Optimization Methods.

As can be seen in Figure 45, both methods start to find better solutions quickly, gaining a 5 percent to 8 percent improvement within 20 generations. After that point, however, it seems that the Default Seed method starts to acquire a bias and gets "stuck." It is unable to find a better solution for many generations, and then it finds one that is only slightly better. The Random Seed method, on the other hand, continues to improve for some time afterward. The distribution of results has a bit of "noise" that can be seen in the curve because random seeds provide slightly better or worse answers for the same timing patterns. This method shows that through the introduction of a differing random seed and small changes in traffic patterns in the microsimulation tool, GASTO was able to more efficiently explore the solution space, resulting in better solutions.

Minimum Phasing and Timing Limitations

Another aspect of the GASTO model that was discovered through testing was the need to implement minimum phase times to keep the resulting timing plans "realistic." Because the GA is not inherently a tool that was designed for transportation planning but rather a mathematic tool that has been harnessed to help solve the problem, GASTO does not have any natural restraints or understanding of the typical rules of signal planning. Initial tests of GASTO for the 3-intersection El Camino Real network showed very low cycle lengths, with phase lengths as low as 1 or even 0 seconds. The model was showing that these low timings were not only possible in the model, but that they were actually producing better results. The problem with these timings is that they are not realistic, because the model may not always perfectly replicate real-world conditions of drivers, such as start-up lost time and driver hesitation, despite being accurately calibrated. Through testing and discussion within the team, it was decided that the minimum phase length for all phases would be 6 seconds. Unfortunately, the GASTO program did not have the ability to assign different minimum values for different types of approach (e.g., left turns versus mainline through) but could only provide a global minimum for the system.

To test the results of the program, a sensitivity analysis was conducted that compared the original, unrestrained model with the new model with a 6-second minimum phase restriction. Each model was run with 100 percent connected vehicle penetration, with baseline characteristics and demand. As shown in Figure 46, the resulting fuel savings/environmental improvements and delay improvements are slightly less for the model with a minimum phase restriction. This shows that GASTO can produce timing plans that have better results if it is allowed to defy what we consider in the traditional planning community as "acceptable."

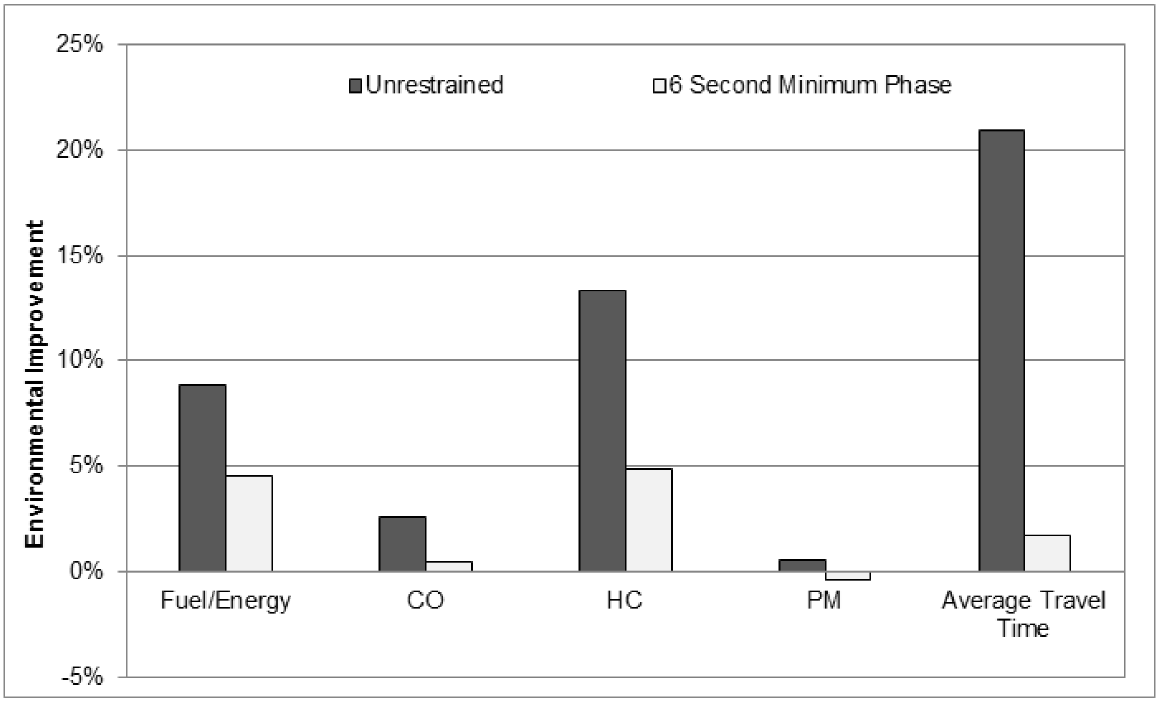


Figure 46: Environmental Improvement for Unrestrained Versus Minimum Phase Length GASTO Model against the Baseline.

However, there are still significant improvements in both the environmental and mobility benefits with the restriction in place. Therefore, this minimum phase restriction was used for all modeling done in the Eco-Traffic Signal Timing application.

Since the optimization of traffic signal timings would eventually be introduced into a real-world corridor system, it is also necessary to consider other minimum phase requirements, such as Highway Capacity Manual (HCM) minimum pedestrian green times for phases to allow for safe crossing of the El Camino Real mainline. Since the GASTO program is at heart a mathematical program, its optimization procedures do not allow for detailed understanding of HCM procedures or requirements. As a consequence, some of the resulting timings violate the minimum safe crossing times for pedestrians and needed to be adjusted for use in the El Camino Real corridor to have a realistic simulation value and measure of effectiveness.

Scenarios

An exhaustive set of scenarios was modeled for each application. This section details the scenarios modeled. The modeling results that follow in the next section are organized in the same fashion.

The network used for modeling the scenarios was the El-Camino Real 27-intersection network (referred to as ECR-27).

A list of scenarios modeled is presented below.

- **Eco-Traffic Signal Timing on ECR-3—Connected Vehicle OBE Penetration Rate:** Eco-Traffic Signal Timing on ECR-3—connected vehicle OBE Penetration Rate: The application is implemented on the ECR-3 with a demand of V/C = 0.77 and 10 percent trucks on the network. Penetration rates of 0 percent, 20 percent, 35 percent, 50 percent, 65 percent, 80 percent, and 100 percent are used.
- **Eco-Traffic Signal Timing on ECR-3—Demand Level: Eco-Traffic Signal Timing on ECR-3—Demand Level:** The application is implemented on the ECR-3 with demand levels of V/C = 0.38, 0.77, and 1.0.
- **Eco-Traffic Signal Timing on ECR-3—Emissions vs. Delay Optimization: Eco-Traffic Signal Timing on ECR-3—Emissions vs. Delay Optimization:** The application is implemented on the ECR-3 by optimizing the signal timings to minimize delay and by optimizing the signal timings to minimize emissions. The scenarios are implemented with demand levels of V/C = 0.38, 0.77, and 1.0.
- **Eco-Traffic Signal Timing on ECR-3—Percentage of Trucks: Eco-Traffic Signal Timing on ECR-3—Percentage of Trucks:** The application is implemented on the ECR-3 with demand level of V/C = 0.77, and the connected vehicle penetration rate is assumed to be 100 percent implementation of vehicles' OBEs. The truck percentages tested are 1 percent, 5 percent, 10 percent, 15 percent, 20 percent, and 25 percent.
- **Eco-Traffic Signal Timing on ECR-27—Connected Vehicle OBE Penetration Rate:** Eco-Traffic Signal Timing on ECR-27—connected vehicle OBE Penetration Rate: The application is implemented on the ECR-27 with a demand of V/C = 0.83 and 10 percent trucks on the network. Penetration rates of 0 percent, 20 percent, 35 percent, 50 percent, 65 percent, 80 percent, and 100 percent are used.
- **Eco-Traffic Signal Timing on ECR-3 and ECR-27 Compared With Traditional Optimization:** These scenarios were modeled to assess the ability of the Eco-Traffic Signal Timing algorithm to carry out optimization for minimum delay and a traditional delay optimization method. The application is implemented on ECR-3 and ECR-27 networks for their respective baseline demand levels of V/C = 0.77 and 0.83 and 100 percent penetration rate.

Modeling Results

To assess the benefits of the Eco-Traffic Signal Timing application, baseline models were developed with the assumption that there was no application deployment (i.e., connected vehicle penetration rate is 0). The environmental impacts were estimated by the MOVES API plug-in. Emissions and travel time statistics were collected from each of the baseline simulation runs to establish the baseline conditions. The application benefits were then measured by comparing the performance of the networks with the Eco-Traffic Signal Timing application active. Then, a variety of sensitivity scenarios were generated to characterize the detailed behavior of the application under different conditions. The three primary sensitivity parameters that were examined were as follows:

- Penetration rate of the connected vehicle technology, specifically the penetration of the OBE
- Congestion ratio (V/C ratio)
- Percentage of trucks.

For purposes of the Eco-Traffic Signal Timing application, it was assumed that all of the intersections along the El Camino Real in the microsimulation models are equipped with connected vehicle RSE technology. These RSEs would function to detect and record the real-time emissions from vehicles in the network, to pass the information to the GASTO GA that optimizes the signal timing plans based on this information.

The Eco-Traffic Signal Timing application was designed to work for both the small 3-intersection model and the larger 27-intersection model of the El Camino Real Paramics model. The majority of the tests discussed in this section, however, are presented using the smaller model with 3 intersections, as a proof of concept for the GA for optimizing signal timings based on environmental parameters. The 27-intersection model is extremely computationally intensive, with runs taking about a week for each scenario, and further research is recommended to test the GASTO program on larger networks with more coordination issues. Unless otherwise mentioned, the results presented in this section are for the 3-intersection version of the El Camino Real Paramics model.

Eco-Traffic Signal Timing on ECR-3—Connected Vehicle OBE Penetration Rate

Because connected vehicles will likely be introduced on a “rolling” implementation over time, it is important to analyze the impacts of the Eco-Traffic Signal Timing application at varying levels of OBE penetration rates. This rolling implementation will enable an understanding of whether the application will provide environmental benefits to motorists and to the system as connected vehicles are introduced over time or only after they have been fully adopted in the future. The way that connected vehicle penetration influences the system is somewhat different for the Eco-Traffic Signal Timing application than for the other applications in the Eco-Signal Operations Operational Scenario. To test the varied connected vehicle penetration rates for this application in simulation, only those vehicles that are “connected” were able to transmit their environmental information to the GASTO GA to make decisions on signal timing plans. This means that the decisions were made based only on the information that was available from connected vehicles, but was applied to the entire system. If the information was insignificant or lacking, the resulting signal timing plan that was generated as output from the GASTO program may not be an accurate reflection of system characteristics.

For this analysis, a baseline V/C ratio of 0.77 and percentage trucks of 10 percent was used in the model runs. The environmental and mobility results for increasing levels of connected vehicle OBE penetration rates are presented in Figure 47. The results in Table 21 represent all of the vehicles in the entire system, not just those that are equipped with OBEs. As Figure 47 shows, increasing energy savings and greater reductions in CO_2 emissions can be achieved as connected vehicle penetration increases. Figure 47 also shows that extremely low implementation rates (i.e., 20 percent and lower) may not provide an improvement in the system and could even provide a disadvantage because the amount of information the timings are using to make a decision is very low.

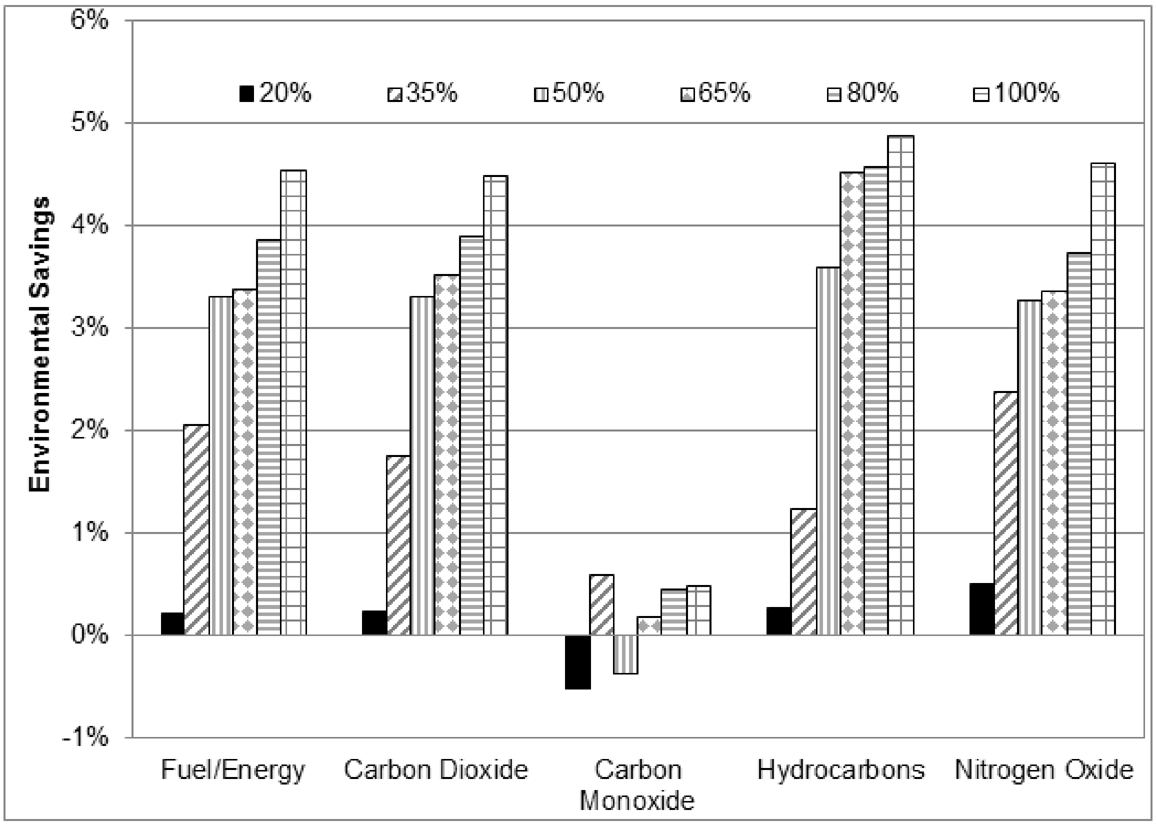


Figure 47: Environmental Savings for Each Connected Vehicle Penetration Rate Against Baseline (No Penetration).

The connected vehicle penetration rates listed in the analysis represent the percentage of vehicles that the system is getting information from, although not necessarily only from vehicle OBEs. The results show that at very low levels of connected vehicle penetration, conventional ITS technologies currently in use should be employed in addition to connected vehicle technology to improve the result; however, the data that can be collected with this technology is limited in comparison to connected vehicles. To this end, the application also could use only conventional ITS technologies, such as roadside sensors, to estimate the roadside emissions and provide them to the GA for signal timing optimization, instead of getting the information directly from the vehicles.

Although the traditional planning methods for corridor management are based on the belief that higher cycle lengths are more appropriate for maintaining corridor integrity, the tests on the small section (3-

intersection model) show that a smaller cycle length provides substantial savings for the system in terms of mobility measures, while also providing significant environmental and fuel savings for all system users. The environmentally optimized signal timing plan for the 3-intersection El Camino Real is shown in Appendix C in Table 87, where it can be seen that there are significant reductions in the green times in all of the intersections, especially at Los Robles and Maybell, in comparison to the baseline signal timing plan (Appendix C, Table 84). Many of the approaches are at the minimum allowed green time of 6 seconds (see the Modeling Approach section), which illustrates that short green times and the resulting short cycle lengths help reduce the emissions and delay in the system better than long cycle lengths.

As can be observed from Figure 47, different measures of effectiveness have different magnitudes of improvement, but the overall trend explained above holds true. Fuel/energy savings and CO_2 savings are nearly identical when analyzed by the MOVES emissions module in Paramics. It also can be seen that optimizing the system for fuel/CO_2 improvement does not provide significant improvements in some pollutants, such as CO, which may indicate that they are not as sensitive to the optimization procedure. As explained above, there is little to no improvement in the 20 percent and below connected vehicle penetration, while immediate benefits can be seen at 35 percent and above. Near-maximum benefits are already being experienced by 65 percent penetration, while the benefits are still minor as the OBE penetration rate reaches 100 percent.

To help assess the relative magnitude of increasing levels of connected vehicle OBE penetration, relative to the baseline, Table 21 presents additional results for the different environmental measures in more detail.

Table 21: Environmental and Mobility Results With Connected Vehicle Rate From Baseline

Connected Vehicle Penetration (%)	Energy (kJ)	CO_2 (g)	CO (g)	HC (g)	NOx (g)	PM (g)
0	11,118,954.7	791,106.8	8,418.8	165.1	790.5	12.3
20	11,093,949.6	789,301.8	8,461.9	164.7	786.5	12.4
35	10,890,867.4	777,259.3	8,369.7	163.1	771.8	12.4
50	10,752,896.4	765,047.3	8,450.8	159.2	764.8	12.3
65	10,743,916.5	763,344.2	8,404.0	157.7	764.0	12.4
80	10,690,762.0	760,349.3	8,381.9	157.6	761.1	12.3
100	10,615,758.0	755,639.3	8,377.5	157.1	754.1	12.3
% Saving compared to Baseline						
20	-0.2%	-0.2%	0.5%	-0.3%	-0.5%	0.7%
35	-2.1%	-1.8%	-0.6%	-1.2%	-2.4%	0.9%
50	-3.3%	-3.3%	0.4%	-3.6%	-3.3%	0.0%
65	-3.4%	-3.5%	-0.2%	-4.5%	-3.3%	0.8%
80	-3.9%	-3.9%	-0.4%	-4.6%	-3.7%	0.2%
100	-4.5%	-4.5%	-0.5%	-4.9%	-4.6%	0.4%

In addition to the environmental benefits to the system from the use of the environmental-based Eco-Traffic Signal Timing application, a small improvement to the overall vehicle travel time can be seen along the El Camino Real corridor. It could be expected from signal timing plan optimization that there would be corresponding improvements in mobility, such as reductions in travel time and approach delay at the intersection. It was hypothesized that the improvements to shorter trips could be having a significant influence on the overall improvement for the trips along the corridor, which could throw off the overall travel time of the El Camino Real corridor. Therefore, the travel time analyzed for this sensitivity analysis is shown only for the mainline trips passing from one side of the network to the other. The travel time was collected for each increasing level of connected vehicle OBE penetration rate, and can be seen in Figure 48.

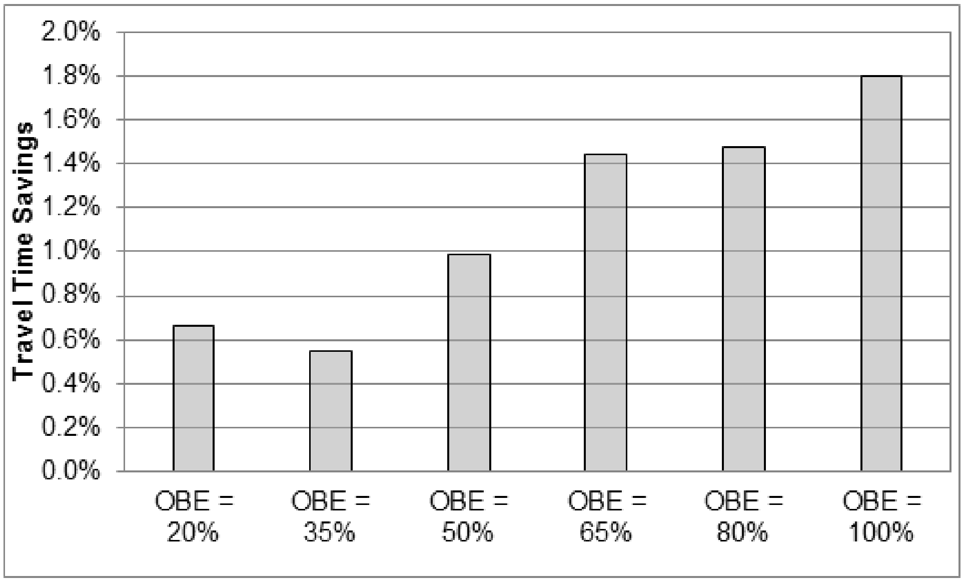


Figure 48: Average Travel Time Savings for Each Connected Vehicle Penetration Rate Against Baseline (No Penetration).

As shown in the figure, increasing improvements in average vehicle travel for the corridor can be achieved with increasing levels of connected vehicle OBE penetration rate. The patterns of increase are similar to the environmental improvements gained by the optimization, showing that there is some correlation in the optimization procedure between the two methods. While small, there are improvements in travel time even at the lowest levels of OBE penetration rate, meaning that there is no disadvantage in mobility from increased improvements in environmental measures gained from the optimization approach. This is important when considering implementation of the optimization methods in a real-world corridor or network, as adoption and compliance would be more likely if there is no loss in mobility.

Eco-Traffic Signal Timing on ECR-3—Demand Level

To better understand the impact of signal timing optimization on environmental effects under various operational conditions, it is important to look at the effects of signal timings in different levels of traffic conditions. The baseline demand for the El Camino Real Paramics network is operating at a V/C ratio of roughly 0.77 at the major controlling intersection approaches of the mainline. It should be noted that not all approaches to the intersections are operating at a V/C ratio of 0.77, because this is a mainline corridor with significantly less volume on the side-street approaches. To supplement the analysis of the application, the baseline and Eco-Traffic Signal Timing application models were run for two additional scenarios: a low-demand scenario (V/C = 0.38) and a saturated network scenario (V/C = 1.00). Because not all of the approaches are the same V/C ratio, the approach to increasing or decreasing the demand was undertaken by simply raising the demand on all approaches by an equal percentage, to bring the controlling approaches to the desired V/C ratio. The proportion of approach volume on the side streets was not increased in relation to the mainline at each of the intersections along the corridor. The resulting optimized signal timing plans are shown in Appendix C in Table 86, Table 87, and Table 88 for the 0.38, 0.77, and 1.00 V/C ratios, respectively. The results of the analysis can be seen in Figure 49, which shows the environmental and travel time savings achieved by the application versus the baseline condition at each of the demand levels for all network vehicles.

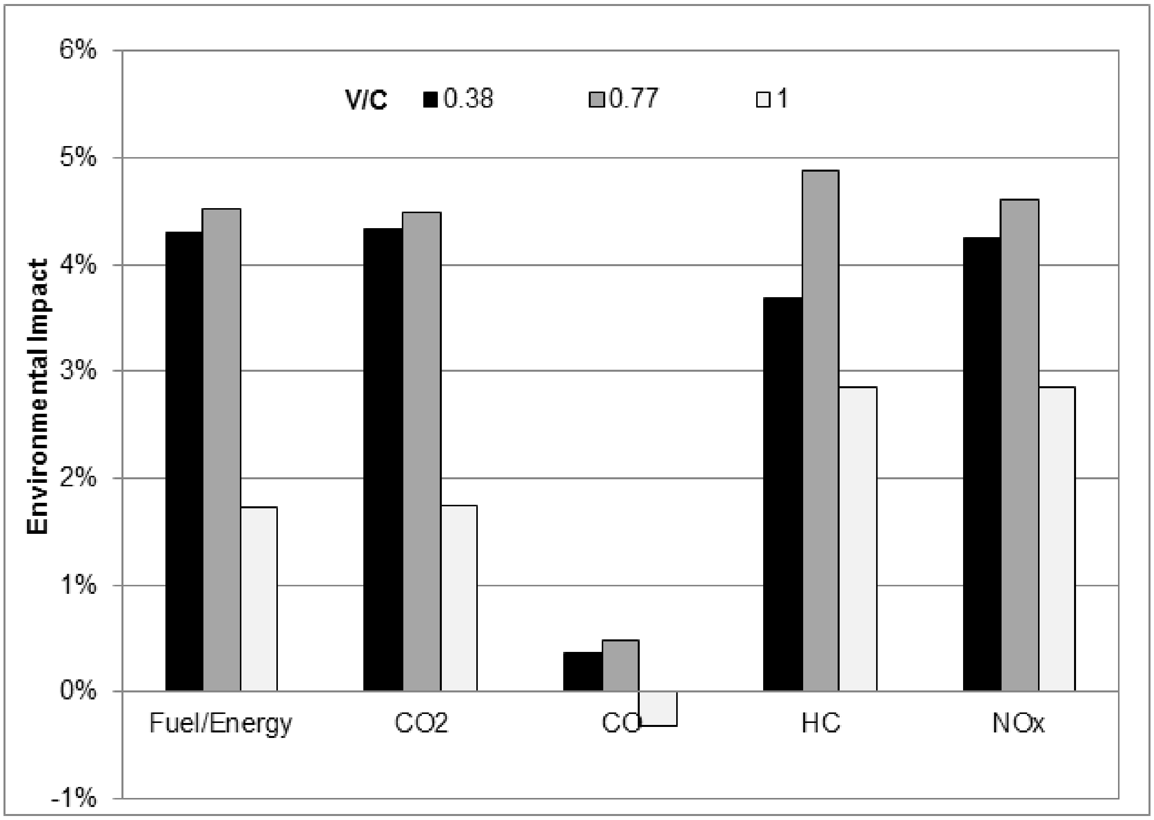


Figure 49: Environmental and Mobility Savings Against the Baseline for Varying Levels of Demand.

As seen in the figure, there are very similar patterns in the results for environmental savings for the baseline (0.77) and under-saturated (0.38) demand ratios, though at different magnitudes. Both of these demand conditions show that significant savings can be achieved at both of these congestion ratios, though there are slightly better savings in the baseline conditions. This is due to the fact that the under-saturated condition would have very little congestion or queuing, so there would be slightly less ability to improve over the baseline condition. The congested condition (1.00), however, shows significantly less improvements in environmental performance than the other two conditions in terms of all emissions. This is due to the approaches on the mainline of the El Camino Real corridor being at saturation, which would not allow for much more improvement in throughput for vehicles in the model. This can be seen across the emissions with about 50 percent of the improvements of the other two conditions. However, the results show that the Eco-Traffic Signal Timing application will be able to provide environmental benefits in all congestion levels, meaning that the application can be used in a variety of locations, and for both peak and off-peak periods.

Figure 49 also shows that some of the environmental pollutants have quite a different pattern of results for different demand scenarios. CO, again, has a significantly smaller magnitude because it has shown a much lower sensitivity to optimization than other environmental measures. However, it can still be seen that as the demand increases, the effectiveness of the Eco-Traffic Signal Timing application decreases in terms of resultant measures.

To help assess the relative magnitude of the different demand scenarios relative to the baseline, Table 22 provides additional details for the emissions and mobility results.

Table 22: Detailed Comparison of Varying V/C Demand Ratios vs. Baseline for All Network Vehicles.

V/C	Energy (kJ)	CO_2 (g)	CO (g)	HC (g)	NOx (g)	PM (g)
Baseline						
1.00	14,922,814	1,061,779.0	11,027.8	221.2	1,052.2	16.19
0.77	11,118,955	791,106.8	8,418.8	165.1	790.5	12.3
0.38	5,218,258	371,263.5	4,040.2	73.0	345.9	6.06
Eco-Signal Optimization						
1.00	14,664,445	1,043,277.4	11,062.5	214.9	1022.1	16.2
0.77	10,615,758	755,639.3	8,377.5	157.1	754.1	12.3
0.38	4,994,049	355,162.0	4025.6	72.3	331.3	6.1
% Saving Compared to Baseline						
1.00	-1.7%	-1.7%	0.3%	-2.8%	-2.9%	0.2%
0.77	-4.5%	-4.5%	-0.5%	-4.9%	-4.6%	0.4%
0.38	-4.3%	-4.3%	-0.4%	-1.0%	-4.3%	0.8%

Eco-Traffic Signal Timing on ECR-3—Emissions vs. Delay Optimization

The GASTO program was created from an earlier version of the program, which, like so many previous programs before it, was designed to optimize based on mobility impacts. For purposes of testing, this mobility optimization feature was left in to use as a sensitivity analysis measure to test the differences of environmental versus mobility optimization in a targeted corridor. This sensitivity analysis is important to show what, if any, are the differences that can be seen when a corridor is optimized with an environmental, rather than mobility, focus. The analysis tested the 3-intersection El Camino Real at three demand V/C ratios (0.38, 0.77, and 1.00) for each optimization type, for both environmental and mobility output measures. The resulting optimized signal timing plans obtained from the GA for the sensitivity analyses are shown in Appendix C in Table 88, Table 89, and Table 90 for the 0.38, 0.77, and 1.00 V/C ratios, respectively. The connected vehicle penetration rate was assumed to be 100 percent, with 10 percent heavy vehicles. The results of the analysis of environmental benefits are presented in Figure 50.

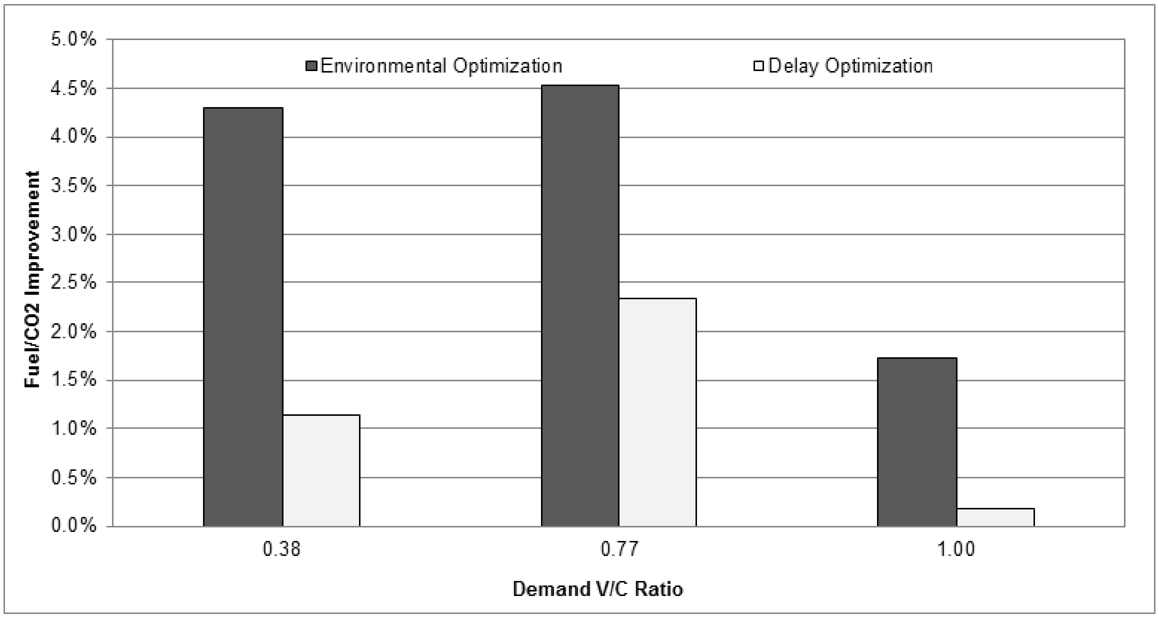


Figure 50: Energy Savings for Environmental vs. Delay Optimization Method for the Three Demand Ratios.

As can be seen in the figure, the environmental optimization was able to achieve significantly more environmental improvement than the delay optimization in all three levels of congestion for the El Camino Real modeled corridor. Similar environmental improvements were obtained in both the under-saturated and baseline congestion levels when optimizing with an environmental objective. When optimizing for the delay objective, the baseline demand condition is able to obtain the largest amount of emissions reductions, though still only half as much as that obtained by the environmental optimization. In the under-saturated conditions for the delay optimization, the improvements gained are reduced owing to the fact that there is less congestion and queuing in the model, so there is less delay to optimize. Since there is not much need to improve the delay, the resultant environmental gains are also much smaller. The significant difference in optimization methods in under-saturated conditions shows that there can be a big difference in resultant environmental improvements in certain situations. In the saturated conditions (1.00 V/C), there is statistically no improvement in fuel consumption when optimizing for delay, since there is little improvement to be gained with the major approaches already at capacity.

In addition to the environmental measures of the two techniques, the analysis also looked at the average travel time. This is also important to understand the difference between the mobility and environmental optimization methods. It can help support the patterns of results explained above. The results of the mobility benefits gained from the two optimization techniques are presented in Figure 51.

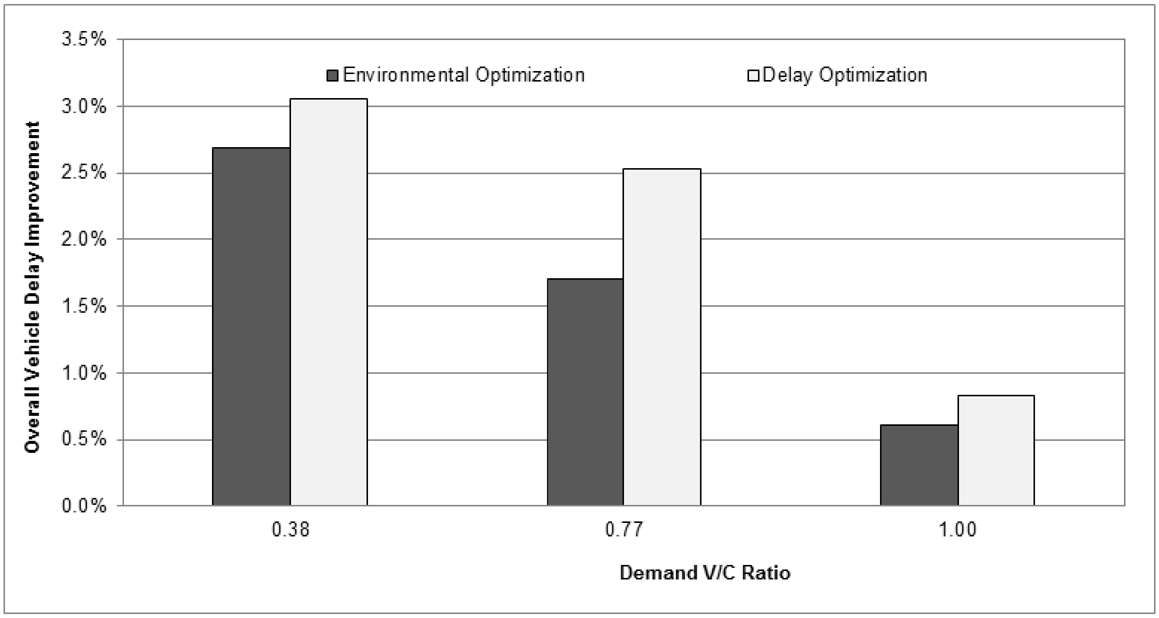


Figure 51: Delay Savings for Environmental vs. Delay Optimization Method for the Three Demand Ratios.

As can be seen in this figure, the resulting mobility benefits were higher for the delay optimization method for all three of the demand ratios that were tested. This was the expected result when looking at the optimization of delay in the system. As shown in the environmental results in the figure, the most average vehicle travel time improvements were obtained in the baseline congestion level (0.77 V/C), which resulted in the greatest environmental improvements obtained by the delay optimization method. Figure 51 also shows that there were only small improvements in average vehicle travel time between the delay and environmental optimization methods; however, there were significantly larger fuel and emissions improvements in the environmental optimization. This once again shows that the environmental optimization can provide much better results when used in certain situations. Once again, there were very little, if any, statistically significant travel time improvements in either of the optimization methods at high levels of congestion and saturation (1.00 V/C).

Eco-Traffic Signal Timing on ECR-3—Percentage of Trucks

There are many different aspects to consider when determining how to optimize a system for environmental benefits. As explained previously, there is a noticeable correlation between improvements in mobility and environment, but there are slight differences in the profiles of emissions output in contrast to rather uniform, known results from mobility measures such as delay. Trucks in the corridor produce significantly more emissions per unit than passenger cars, so while the total delay per vehicle may be changing, there could be a different pattern in the environmental results. The El Camino Real model has a baseline truck percentage of only 1.2 percent, which is relatively low, so a sensitivity analysis was conducted of increasing levels of truck percentage in the model from the baseline up to 25 percent. Truck percentages of 25 percent or higher are rare and would be extreme in all but the heaviest freight areas, but the analysis was necessary to test the theoretical limits and features of the GA. For this analysis, the connected vehicle penetration rate is assumed to be 100 percent implementation of vehicles' OBEs, and the vehicle demand is the baseline vehicular traffic of roughly 0.77 V/C ratio for the major approaches. Figure 52 presents the fuel consumption and environmental improvement results with an increasing percentage of trucks, for all network vehicles, considering both the mainline flow and cross-street traffic.

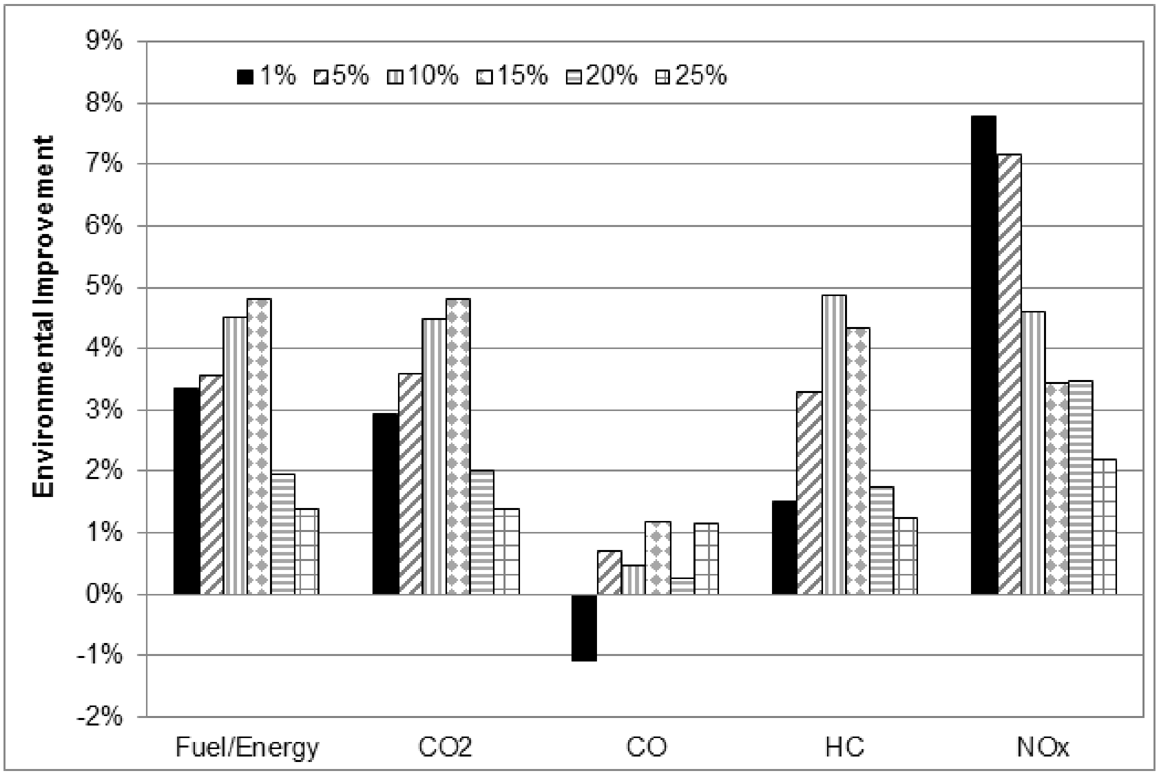


Figure 52: Environmental Savings for All Vehicles for Varying Percent of Trucks vs. the Baseline.

As shown in the figure, it can be seen that there are noticeable improvements in fuel consumption and CO_2 even at the lowest percentage of freight trucks in the system. As the percentage of trucks in the system increases, there are increasing environmental improvements, up to 15 percent of trucks. Since there are more high-emission vehicles along the corridor, the GASTO program has more options to improve the optimization of signals along the corridor. This allows for more fuel consumption improvements up to a point. When freight vehicles in the network continue to rise to 20 percent or more in the network, the physical space taken up by so many freight vehicles causes capacity restraints. These capacity restraints, in turn, restrict the optimization from gaining environmental improvements that are as significant. It is likely that this trend would continue as the freight vehicles in the network increase, up to the point that there could eventually be disadvantages in these situations.

When compared to the environmental pollutants caused by the level of trucks in the system, slightly different patterns can be seen for other environmental pollutants. As shown above, some pollutants are less sensitive to the optimization of fuel/CO_2 in the system. One example is CO, which receives significantly less improvement, or even a disadvantage in some instances. Nitrates, on the other hand, receive a large improvement at low levels of trucks. As the amount of trucks increase, however, there is a noticeable decrease in environmental benefit.

To assess the relative magnitude of the different demand scenarios relative to the baseline, Table 23 presents additional details on the emissions and mobility results.

Table 23: Energy/Emissions at 1% to 25% Truck Saturation, Eco-Traffic Signal Timing vs. Baseline.

Percent Trucks (%)	Energy	CO_2	CO	HC	NOx	PM
Baseline						
1.2	8,153,694	580,116	5,561.7	48.9	179.7	10.3
5	9,833,561	699,645	7,172.3	109.9	499.8	11.2
10	11,118,955	791,107	8,418.8	165.1	790.5	12.3
15	12,536,756	891,989	9,820.1	224.7	1,102.5	13.2
20	14,009,378	996,774	11,275.9	286.5	1,427.5	14.2
25	15,494,042	1,102,391	12,744.3	348.6	1,754.3	15.1
Eco-Traffic Signal Timing						
1.2	7,880,612	563,084	5,621.5	48.2	165.8	10.3
5	9,483,209	674,494	7,119.9	106.3	464.0	11.2
10	10,615,758	755,639	8,377.5	157.1	754.1	12.3
15	11,933,333	849,039	9,703.7	215.0	1,064.3	13.3
20	13,731,585	976,543	11,243.6	281.5	1,377.7	14.1
25	15,276,252	1,086,894	12,596.8	344.2	1,715.5	14.9
Savings (%)						
1.2	-3.3%	-2.9%	1.1%	-1.5%	-7.8%	0.0%
5	-3.6%	-3.6%	-0.7%	-3.3%	-7.2%	0.6%
10	-4.5%	-4.5%	-0.5%	-4.9%	-4.6%	0.4%
15	-4.8%	-4.8%	-1.2%	-4.3%	-3.5%	0.3%
20	-2.0%	-2.0%	-0.3%	-1.8%	-3.5%	-0.3%
25	-1.4%	-1.4%	-1.2%	-1.2%	-2.2%	-1.2%

Eco-Traffic Signal Timing on ECR-27—Connected Vehicle OBE Penetration Rate

As explained in the introduction to the Modeling Results section, the majority of the modeling results for the Eco-Traffic Signal Timing application were completed in the 3-intersection El Camino Real model owing to the computational problems of running multiple scenarios with the full model. Each scenario took between 4 days and a week, depending on the complexity and the demand. However, it was necessary to test the GASTO application on the 27-intersection Paramics model for at least one test in order to measure the impact of the application on a “realistic” corridor model. The vehicle demand used in the analysis was the baseline demand, with an average V/C ratio of 0.83 at the major approaches. The environmental results of this analysis are shown for all vehicles in the network in Figure 53.

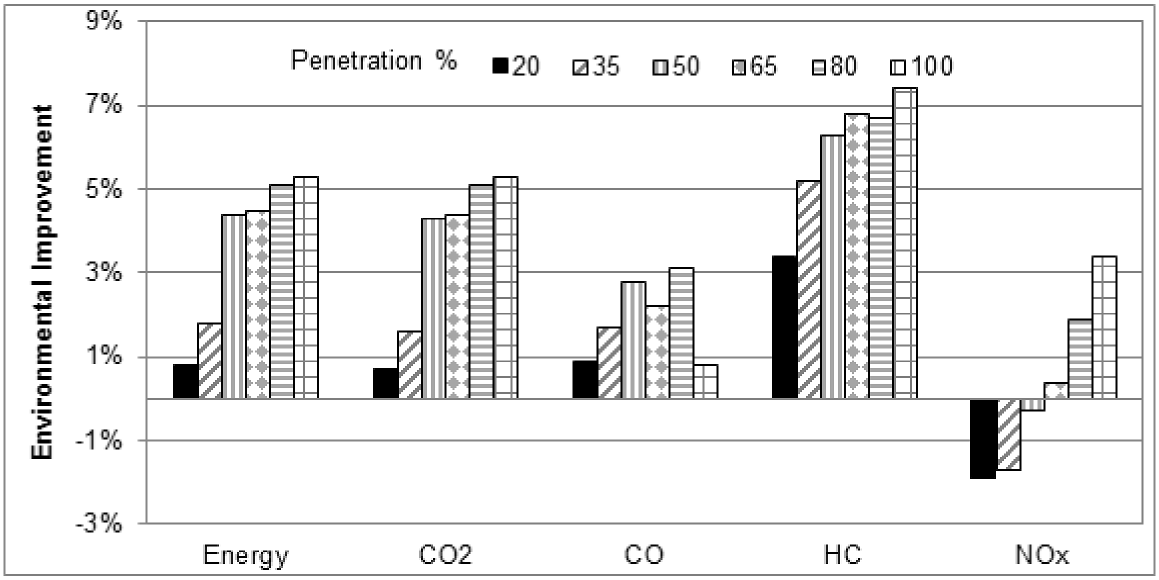


Figure 53: Environmental Savings for All Vehicles for Increasing Levels of Connected Vehicle OBE Rate for the 27-Intersection El Camino Real Corridor.

As shown in the figure, the same increasing environmental improvements for fuel and CO_2 can be seen with increasing levels of connected vehicle OBE penetration rate on the 27-intersection El Camino real corridor as was seen for the 3-intersection El Camino Real model in previous sensitivity tests. The maximum fuel consumption improvements attained are slightly higher, however, at around 5.3 percent for fuel and CO_2 improvements. The main difference between the test network and the full 27-intersection El Camino Real model is in the CO and nitrogen oxide pollutants. In the test network, CO showed no significant change as a result of sensitivity of the pollutant to the optimization process. This is probably owing to the small size of the network and the fact that it has fewer intersections and vehicles than the full 27-intersection model. When there are more vehicles traveling for longer distances, the optimization is better able to create a signal timing plan that yields more improvements among other pollutant types as well. However, Figure 53 also shows that in the optimization for the lower levels of OBE penetration rate, nitrogen oxide experiences a disadvantage with the signal timing plan. This turns into an improvement, on the other hand, as a larger percentage of vehicles in the network are “equipped.

More detailed results for the environmental improvements from the sensitivity analysis can be seen in Table 24.

Table 24: Detailed Comparison of Environmental Measures for the Full 27-Intersection El Camino Real Network vs. the Baseline for Increasing Levels of OBE Penetration.

Connected Vehicle Penetration (%)	Energy (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)
0	10,859.7	785.04	11.342	0.531	3.915	0.202
20	10,773.8	779.57	11.246	0.513	3.990	0.223
35	10,666.9	772.25	11.146	0.504	3.981	0.253
50	10,384.1	751.55	11.024	0.498	3.925	0.242
65	10,371.3	750.50	11.096	0.495	3.901	0.224
80	10,301.6	744.97	10.991	0.496	3.840	0.204
100	10,280.9	743.27	11.250	0.492	3.781	0.198
% Saving Compared to Baseline						
20	-0.8%	-0.7%	-0.9%	-3.4%	1.9%	10.4%
35	-1.8%	-1.6%	-1.7%	-5.2%	1.7%	25.2%
50	-4.4%	-4.3%	-2.8%	-6.3%	0.3%	19.8%
65	-4.5%	-4.4%	-2.2%	-6.8%	-0.4%	11.1%
80	-5.1%	-5.1%	-3.1%	-6.7%	-1.9%	1.0%
100	-5.3%	-5.3%	-0.8%	-7.4%	-3.4%	-1.9%

The resulting optimized signal plans for the 27-intersection El Camino Real model are shown in Table 92 of Appendix C and can be compared to the baseline timings in Table 91.

Table 92 shows that the green times and resulting signal timings are again significantly lower than the baseline timings. The improvements in emissions and travel time show that these short cycle lengths are much more beneficial to the El Camino Real corridor than the baseline times. In many cases, the cycle lengths and green times are similar to those in the 3-intersection analysis, first referenced in the Eco-Traffic Signal Timing on ECR-3—connected vehicle OBE Penetration Rate section. There are many intersections with longer green times, especially those with larger side-street or left-turn volumes, which are there to prevent queuing and congestion. The offsets of these intersections help to prevent clashing from the different cycle lengths. Again, many of the intersection green times are at the minimum of 6 seconds (see Modeling Approach section) for a number of different types of movements and phases.

Like the analyses conducted on the 3-intersection model, a significant improvement in travel time can be seen again with the 27-intersection El Camino Real network when looking at all of the trips in the network and their resultant travel times. The network is much larger and more complex than the 3-intersection model, so a trip length analysis was conducted for the larger network to better understand the trips and separate out the results to eliminate this bias. The trip length distributions of vehicles in the 27-intersection El Camino Real model are shown in Table 25.

Table 25: Distribution of Trip Lengths for the 27-Intersection El Camino Real Network.

Trip Length	Number of Trips	Percent of Total
< 0.5 mile	10,142	46.4%
0.5 to 1 mile	3,863	17.7%
1 to 2 miles	4,057	18.6%
2 to 3 miles	1,664	7.6%
3 to 4 miles	1,039	4.8%
4 to 5 miles	498	2.3%
> 5 miles	310	1.4%
Mainline Pass-Through	276	1.3%

As shown in the table, the majority of the trips in the 27-intersection El Camino Real network are short trips of half a mile or less, with only a small fraction of trips traveling the length of the El Camino Real network from one end to another. Using the same trip lengths, the trip times were analyzed for the baseline and optimized signal timing plan scenarios for each of the trip lengths. The results of this analysis are shown in Table 26.

Table 26: Improvements in Trip Time for the 27-Intersection El Camino Real Network by Trip Length.

Trip Length	Baseline (mm:ss)	Optimized (mm:ss)	Difference (s)	Difference (%)
< 0.5 mile	0:01:47	0:01:15	-32.4	-30.2%
0.5 to 1 mile	0:03:10	0:02:24	-45.7	-24.0%
1 to 2 miles	0:05:06	0:04:11	-54.2	-17.7%
2 to 3 miles	0:08:06	0:06:43	-82.7	-17.0%
3 to 4 miles	0:11:09	0:09:19	-109.7	-16.4%
4 to 5 miles	0:13:28	0:11:43	-105.8	-13.1%
> 5 miles	0:16:40	0:14:24	-135.3	-13.5%
Mainline Pass-Through	0:18:22	0:16:40	-101.5	-9.2%

The results show a significant difference in the travel time improvement based on the length of the trip. The very short trips in the network would serve to skew the travel time for vehicles on the mainline, and therefore they should be removed. Only the trips from the whole mainline were used in computing the travel time savings. Using this method, the travel time savings could be computed for each level of connected vehicle OBE penetration rate. The travel time improvements for this analysis are shown in Figure 54.

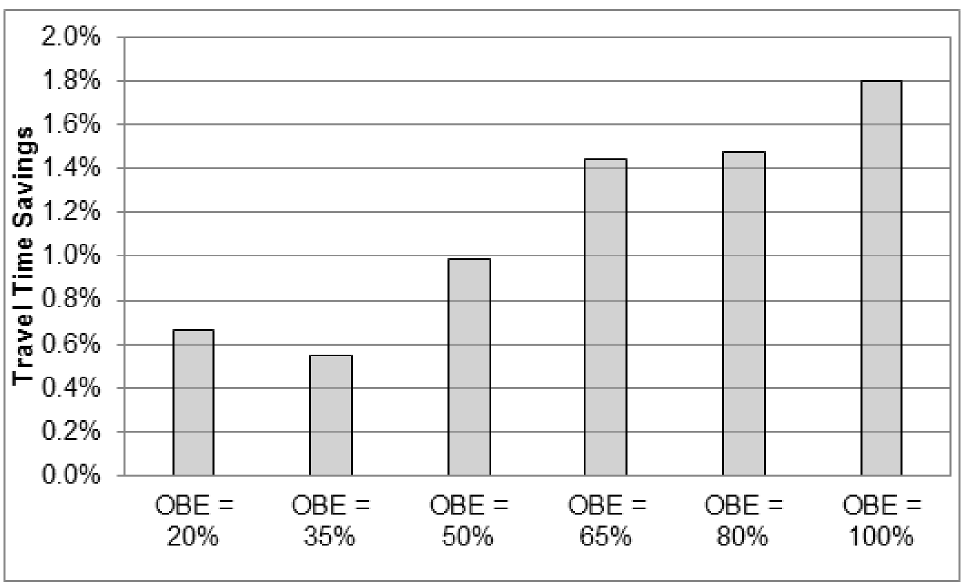


Figure 54: Environmental Savings for All Vehicles for Increasing Levels of Connected vehicle OBE Rate for the 27-Intersection El Camino Real Corridor.

As shown in the figure, the same pattern arises: As connected vehicle OBE penetration rate increases, the travel time savings increases in parallel. Once again, it can be seen that there is a correlation between mobility and environmental improvements when optimizing the signal timings using an environmental method. The length of the network, as stated in the Model Region Description section of Chapter 3, is about 6.5 miles with a baseline trip time of about 17.5 minutes. These trips have the lowest improvement in travel time, about 9.2 percent, which translates to about 1 minute and 40 seconds per vehicle.

Eco-Traffic Signal Timing on ECR-3 and ECR-27 Compared With Traditional Optimization

During signal timing optimization investigations, it was discussed that the baseline signal timings from the El Camino Real Paramics model may not be the optimum signal timing for the corridor, and that this may have contributed to the significant improvements in environmental and mobility measures with the Eco-Traffic Signal Timing application. It was decided that the Synchro program would be used to run a mobility-based optimization on the existing signal timings to compare with the results obtained by the GA. The El Camino Real model was built in Synchro, with data from the existing baseline Paramics model, and the signal timings were optimized using two methods:

Optimizing only the green times, leaving the cycle length, phasing, and offset the same as in the the baseline (optimized timings shown in

1. Table 93 in Appendix C)

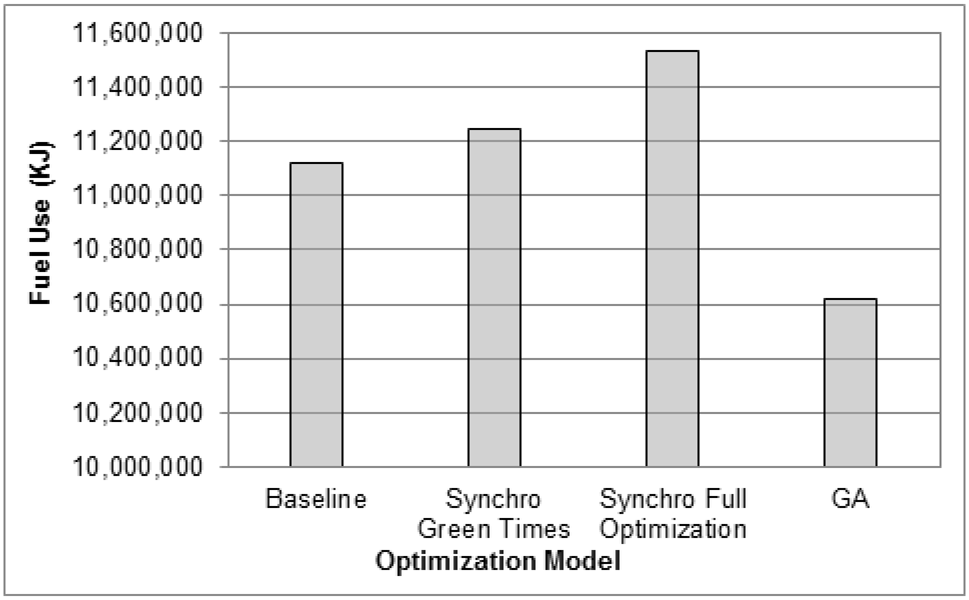
2. Full optimization of the system, with new cycle lengths, lead/lag phasing order, and offset, as well as green times (optimized timings shown in Table 94 in Appendix C)

The results of the Synchro model were obtained using the HCM results module built into the program to assess the quality of the timings. The results, shown in Table 27, show that Synchro yields a significant improvement in delay at the intersection level for both optimization methods, with the full optimization providing a significantly better result.

Table 27: HCM Delay Results From the Two Different Optimization Methods vs. the Baseline.

Cross Street	Baseline (s)	Green Time Opt (s)	Full Opt (s)
Churchill	13.3	11.9	9.1
Park Serra	23.4	26.3	14.9
Stanford	38.2	44.5	9.0
Cambridge	30.5	27.9	10.1
California	8.4	11.2	17.9
Pagemill	44.6	54.4	17.5
Matadero	33.0	22.3	29.7
Curtner	10.1	12.0	1.2
Los Robles	51.8	44.1	21.6
Maybell	16.2	9.7	18.7
Arastradero	31.9	29.9	20.1
Dinah	34.9	20.5	21.7
Los Altos	30.2	26.6	8.4
Del Medio	22.7	25.5	12.9
San Antonio	37.5	38.4	19.2
Showers	20.6	21.2	9.3
Jordan	25.1	18.0	17.0
Ortega	31.0	20.6	8.8
Distel	16.8	14.4	11.5
Rengstroff	34.3	28.1	21.6
Escuela	86.8	39.1	22.9
El Monte	31.5	35.2	15.8
Miramonte	29.3	39.0	22.7
Castro	34.9	33.5	23.2
Calderon	29.6	21.3	9.1
Grant	34.2	44.5	18.0
Portage	20.3	16.3	8.8
Hansen	21.2	9.9	15.2
Difference From the Baseline			
Total (s)		-96.0	-300.4

After the timings were obtained from the Synchro optimization, they were input back into the Paramics model and run in the same way all other results were obtained for the baseline and application modeling. The modeling was completed for both the 3-intersection and 27-intersection models of the El Camino Real, with results shown in Figure 55 and Figure 56, respectively.



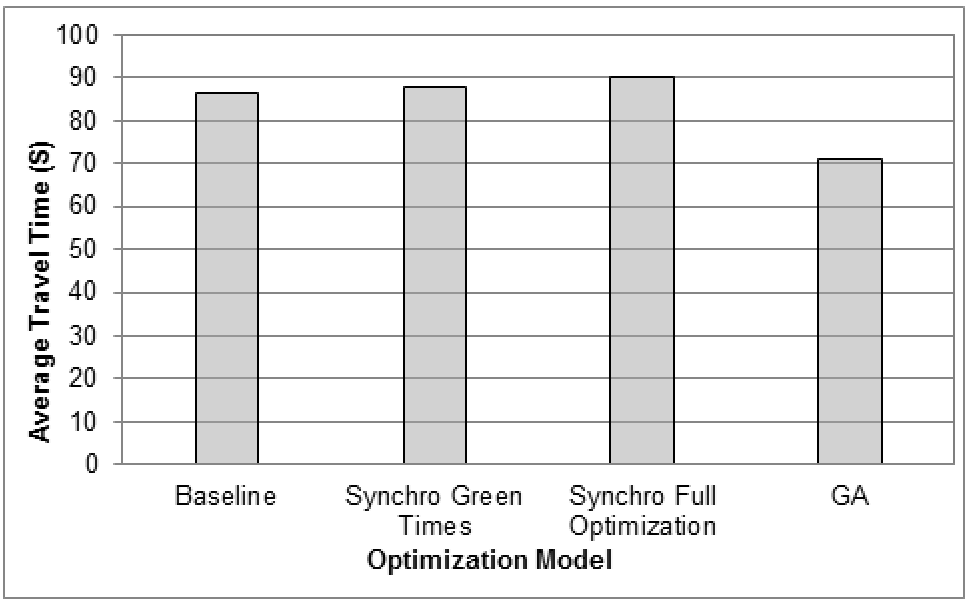


Figure 55: Energy and Delay Results for Synchro Optimizations and GA Optimizations vs. the Baseline for the 3-Intersection Model.

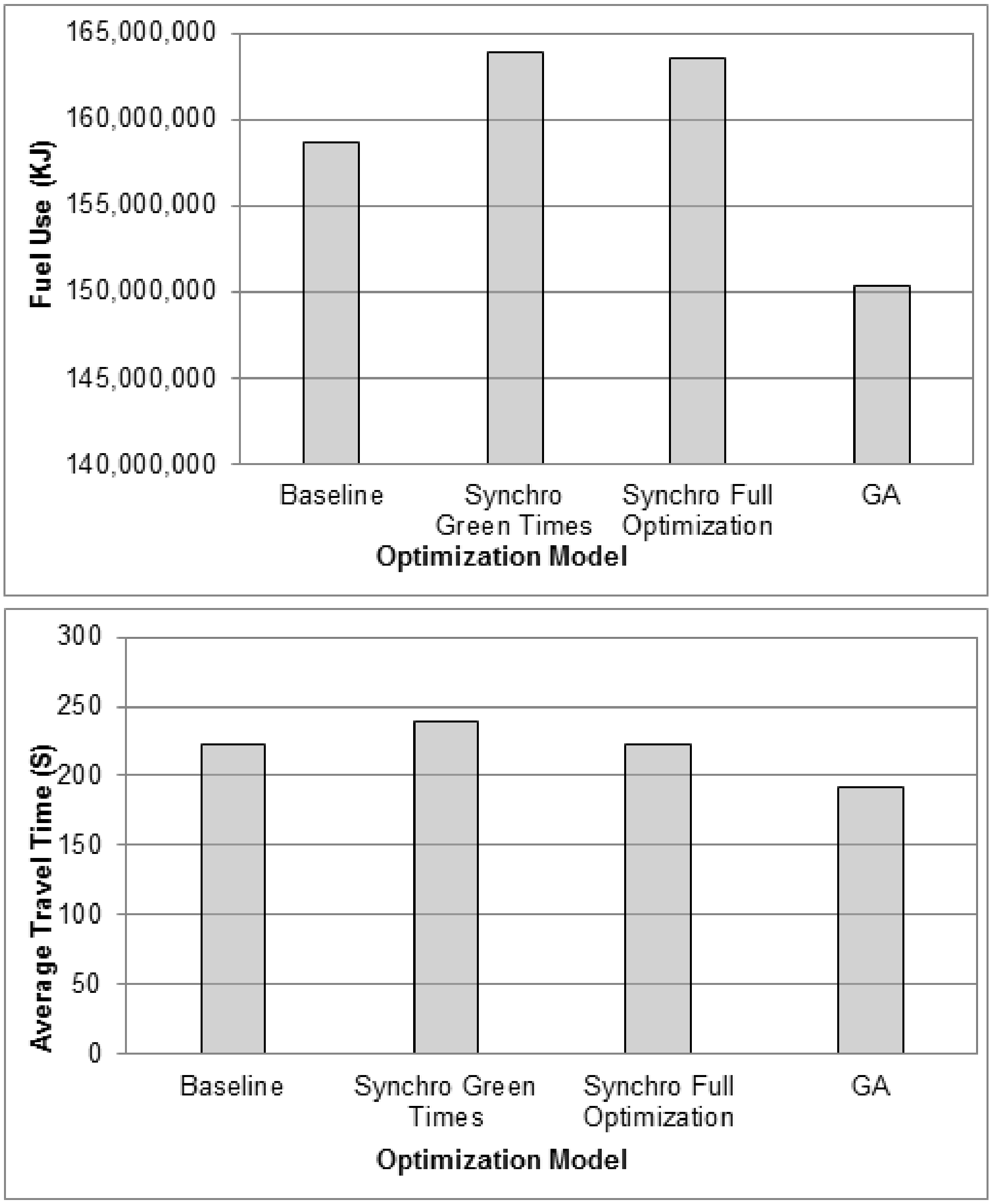


Figure 56: Energy and Delay Results for Synchro Optimizations and GA Optimizations vs. the Baseline for the 27-Intersection Model.

These figures show that for both the 3-intersection and 27-intersection El Camino Real models, both of the Synchro optimization methods are either similar or slightly worse than the baseline model. Despite the fact that the Synchro model shows that there should be a significant decrease in delay in the model, the Paramics model shows that the HCM timings are not as good as the baseline optimized corridor timings that currently exist in the real system. This could have two possible causes: The first is that the timings that exist in the corridor model are the "best" possible from a traditional mobility optimization method that would be currently employed in transportation planning. The second is the inherent inability of macro-type optimizations of the system, such as Synchro and HCM, to capture the relationship between the signals in the corridor with regard to offsets and coordination. In either case, the GA employed by the Eco-Traffic Signal Timing application produces a better timing plan for the El Camino Real corridor.

More detailed emissions and mobility results for the Synchro analysis can be seen in Table 28.

Table 28: Detailed Comparison of Different Optimization Methods vs. the Baseline for the 3-Intersection and 27-Intersection El Camino Real Paramics Models.

3-Intersection Model						
V/C	**Energy (kJ)**	**CO_2 (g)**	**CO (g)**	**HC (g)**	**NOx (g)**	**PM (g)**
Baseline	11,118,955	791,106.8	8,418.8	165.14	790.5	12.3
GT Opt	11,246,122	800,141.3	8,571.4	163.91	776.1	12.7
Full Opt	11,529,891	820,331.1	8,754.5	171.42	805.3	12.8
GA Opt	10,615,758	755,639	8,377.5	157.1	754.1	12.3
Difference						
GT Opt	1.1%	1.1%	1.8%	-0.7%	-1.8%	3.2%
Full Opt	3.7%	3.7%	4.0%	3.8%	1.9%	4.3%
GA Opt	-4.5%	-4.5%	-0.5%	-4.9%	-4.6%	0.4%

27-Intersection Model						
V/C	**Energy (kJ)**	**CO_2 (g)**	**CO (g)**	**HC (g)**	**NOx (g)**	**PM (g)**
Baseline	158,711,577	11,265,610	109,803.7	2,562.9	12,334.1	151.40
GT Opt	163,858,093	11,622,911	110,256.8	2,632.6	12,550.4	152.42
Full Opt	163,538,342	11,608,376	112,440.6	2,683.2	12,692.7	154.33
GA Opt	150,299,863	10,668,533	108,925.3	2,373.2	11,914.7	148.52
Difference						
GT Opt	3.2%	3.2%	0.4%	2.7%	1.8%	0.7%
Full Opt	3.0%	3.0%	2.4%	4.7%	2.9%	1.9%
GA Opt	-5.3%	-5.3%	-0.8%	-7.4%	-3.4%	-1.9%

One other interesting fact that was learned during the Synchro sensitivity analysis was related to the cycle lengths in the optimization (see Table 92 and Table 94 in Appendix C). For the full optimization method where the values were unrestrained, the Synchro optimization favored network cycle lengths that were very short, around 60–70 seconds for most intersections in the El Camino Real network. In addition, many of the green times are at the absolute minimum possible length to produce better mobility results. The same trend is visible in the GA optimization method, which prefers lower cycle and phase lengths. Traditional transportation planning would typically prefer longer cycle lengths for corridors such as the El Camino Real, but both the GA and the Synchro optimization methods show that shorter cycle lengths perform either similarly or much better.

Findings and Opportunities for Future Research

Prior to modeling, the hypothesis that was generated based on literature review stated that if the Eco-Traffic Signal Timing application is used to dynamically adjust signal phase and timing plans based on the speed of vehicles approaching an intersection and vehicle emissions characteristics, there will be emissions reductions and lowered fuel consumption during congested traffic conditions in the range of 2 percent to 3 percent under partial connected vehicle penetration and 4 percent to 6 under full connected vehicle penetration. The results of sensitivity analysis show that for a small corridor with fewer intersections, fuel consumption and emissions reductions of around 1 percent to 4 percent can be obtained for partial vehicle penetration, and 4 percent to 5.5 percent for full connected vehicle penetration when compared to baseline models. For all modeling, the Eco-Traffic Signal Timing application obtained mobility benefits of 1 percent to 9 percent in the corridor, depending on network size and level of connected vehicle penetration. The energy savings benefit of the application depends on a variety of factors, including congestion level, penetration rate of OBE as well as RSE, and communication conditions. More specifically—

1. Very low connected vehicle penetration rates (i.e., 20 percent or less) have a limited benefit on the system for optimizing signal timings. This is assuming that no other ITS technologies or data are being used in conjunction. The energy/fuel benefits increase as the connected vehicle OBE penetration rate increases. The improvement is evident and significant as soon as 35 percent connected vehicle implementation is reached, which indicates that this application would be a good candidate for early adoption.
2. Optimization of signal timings using fuel/CO_2 environmental benefits as the target of the fitness function has a significant net benefit on all mobility measures (namely, average travel time) in the system as well. This indicates that there is a correlation between improvements in emissions and improvements in travel time.
3. Signal timing optimization for a target emission, such as CO_2, may not have a corresponding improvement in another emission. While testing has shown that fuel, CO_2, and average travel time in the model all follow similar trends, there are pollutants such as CO and particulate matter that are not particularly sensitive to optimization.
4. The percentage of trucks in the system has a moderate effect on the ability of the GASTO program to optimize environmental measures over baseline conditions. At very low truck percentages (i.e., baseline of 1.2 percent), the stream of vehicles is much too homogeneous to gain large improvements in emissions. The results for a percentage of trucks of about 5 percent to 20 percent show similar relative emissions improvements, while results start to get worse at levels higher than 20 percent, as the congestion of truck traffic clogs the system.
5. Optimization of signal timings for different levels of demand V/C ratios results in similar relative improvements in fuel/energy and average travel time as compared to the baseline model. Other pollutants, however, show fewer improvements as the demand increases. In all the demand cases, though, there is notable improvement over the baseline conditions in terms of all environmental measures.
6. When the GASTO program is run with either fuel/energy or delay as the target for the objective function, the resulting emissions are similar for the baseline and higher demand scenario. The resulting average travel time is slightly higher for the delay optimization method. Only in the lowest demand category did the delay model underperform in both categories.
7. The GASTO program for the Eco-Traffic Signal Timing application outperformed a Synchro optimization in terms of both system-wide travel time and all environmental measures. This analysis also showed that the baseline Paramics models for the El Camino Real network were already well timed.
8. Running the GASTO program with randomly generated Paramics model seeds at each run provides a much more robust analysis of the corridor, and results in a timing plan that is better and more representative of the conditions, than a similar run with a “default” seed value.
9. Optimization runs show that in order to improve environmental and mobility measures in the El Camino Real network, much lower cycle lengths outperform the baseline cycle lengths. This is in contrast to the traditional idea that longer cycle lengths are needed for corridors, but the lower cycle lengths were also found in the Synchro analysis. See Appendix C for baseline and optimized signal timing plans used in this analysis.
10. The GASTO program needs a minimum green phase threshold to prevent it from creating “unrealistic” timing plans with phases as low as 1 second. The restricted timing plans did not

perform as well as the unrestricted timings but still showed significant improvements in both environmental and mobility measures.

11. Optimization using the GASTO application for larger models may not provide the best signal timing plan for every intersection in large models, resulting in reduced environmental improvements. This is because the optimization process uses only one global number as the optimization target. This process can be mitigated by using supplementary processes, such as additional smaller GA runs, on the intersections that are not properly optimized in the main run.

Based on the above findings from the modeling effort, the research team has the following recommendations and remarks:

1. The GASTO program showed great improvements in the 3-intersection model, as well as in initial tests involving the 27-intersection model. More sensitivity analyses should be undertaken on the larger model to better understand the effects of coordination of signals with environmental-based signal optimization.
2. For larger models, split optimizations for separate “clusters” of signals in the corridor model could be tested to prove the hypothesis that a better solution can be thus obtained than from using one optimization for the whole corridor.
3. An improved future version of the GASTO program could look at localized emissions at intersections, rather than at the global value, in an attempt to create even more improved optimization of signal timing plans.
4. A future iteration of the GASTO program was intended to have the ability to test alternative phasing plans and phasing orders and to eliminate phases. Additional research into this could yield better solutions, as well as open up additional avenues for future research.
5. In the sensitivity analyses above, it was mentioned that another method for analyzing the random patterns of the modeling could be developed by running a simulation with multiple seeds per chromosome and then averaging the results. The budget and scope could not handle the intense computational times, but additional research could yield a more computationally efficient way to test this method. It would help to better understand the capabilities of the GA to create more eco-friendly timing plans.
6. The GASTO program is an “offline” optimization method, which means that it is designed to optimize the timings based on known values to create representative timing plans after the fact, not in real time. More research should be devoted to developing an “online” signal timing optimization program to change the timings in real time for the AERIS program. This was not looked at by the team, owing to the lack of research done in the field, but a theoretical “proof-of-concept” model could be developed to test in reality for future projects.
7. This application is designed for fixed-time signals. The timing plan that is designed by the GASTO program is meant to cover the whole analysis period and was not designed to produce an actuated timing plan, unless it was only the base plan, which could be altered within the simulation period. This would seriously complicate the calculation process of the GA. A possible “online” method would better suit an actuated-type environment.
8. Additional application testing should be done on a network system that is less a main corridor and has roughly equal traffic approaching from different directions. This will test the ability of the application to balance network conditions, unlike with the El Camino Real, which has the vast majority of the emissions and traffic on the mainline.

Additional analysis could be done to show the potential benefits that a jurisdiction might achieve when implementing the application along a corridor that is not well optimized. The results could them be used to show the range of benefits that a jurisdiction might be able to achieve.

Chapter 6. Eco-Traffic Signal Priority Application

Application Description

The description of the application is provided in the section "Eco-Traffic Signal Priority" on page 9. The application has two components: Eco-Transit Signal Priority and Eco-Freight Signal Priority. The components are graphically illustrated in Figure 57 and Figure 58, respectively.

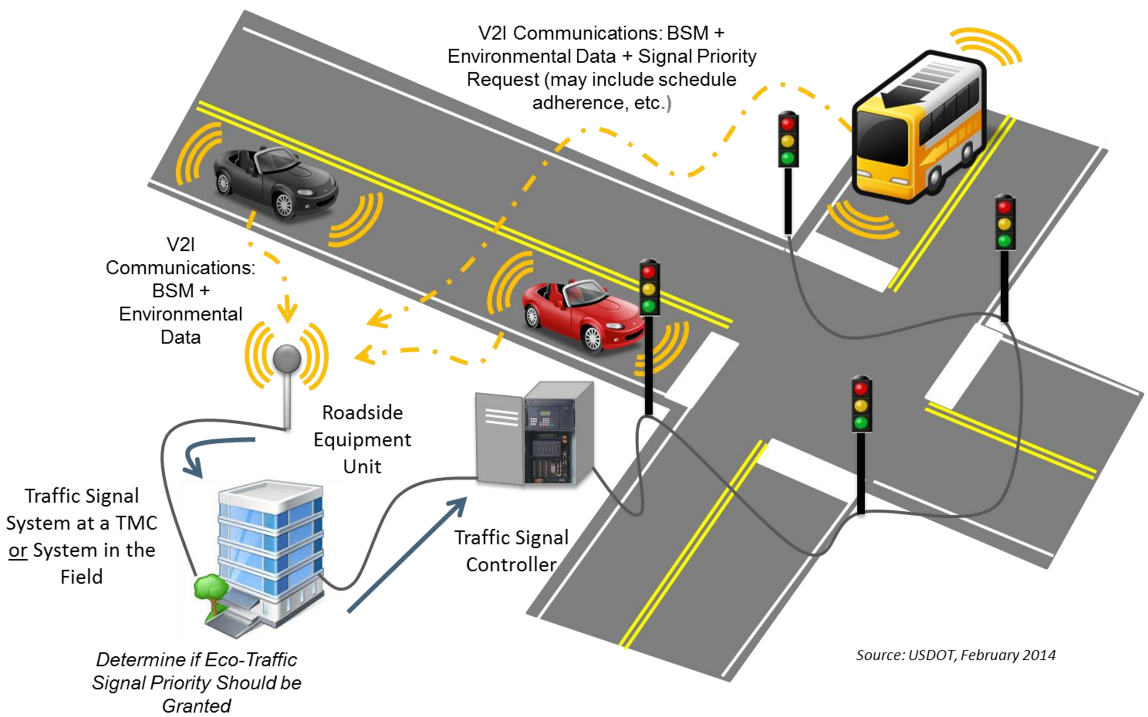


Figure 57: Eco-Transit Signal Priority Application Illustrated

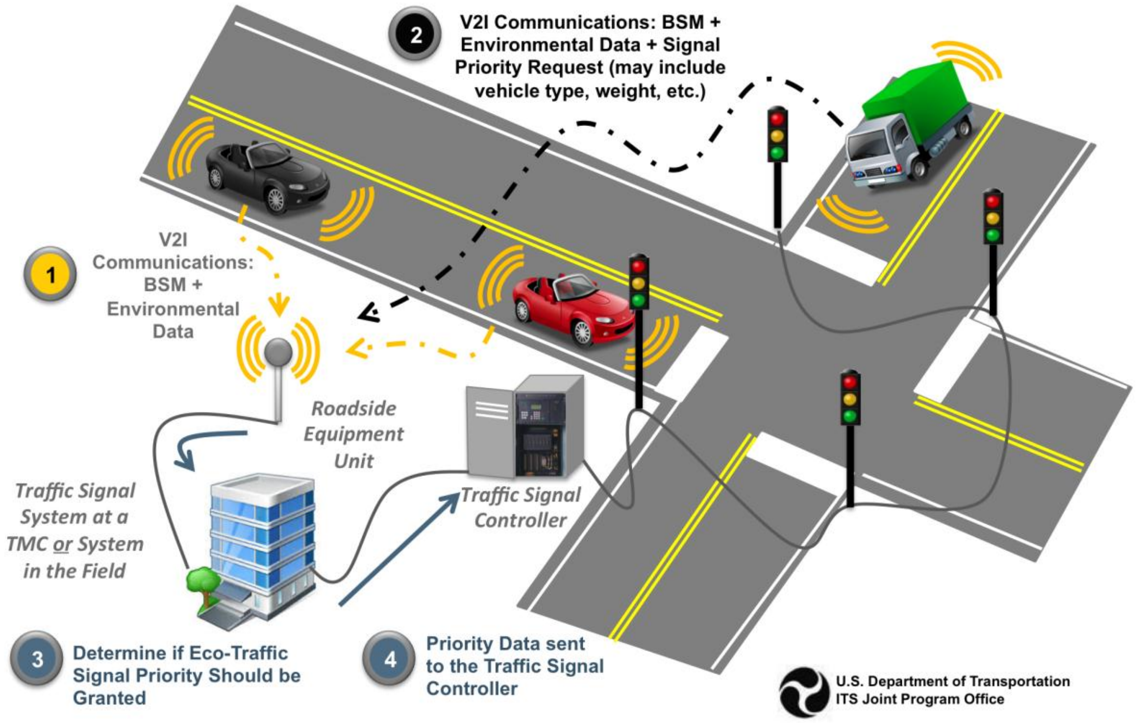


Figure 58: Eco-Freight Signal Priority Application Illustrated (Source: USDOT, February 2014).

Hypotheses

If the Eco-Traffic Signal Priority application is used to grant signal priority to selected transit and freight vehicles based on the transit vehicles' adherence to schedule, location, speed, size, vehicle class, and traffic and environmental characteristics of all vehicles at the signalized intersection, then there will be emissions reductions and lowered fuel consumption during congested traffic conditions in the range of 1–2 percent under partial connected vehicle penetration and 2–4 percent under full connected vehicle penetration.

Eco-Transit Signal Priority

Algorithm

This section describes the algorithm used to implement the Eco-Traffic Signal Priority application. The Eco-Traffic Signal Priority algorithm is an active transit signal priority algorithm that provides priority to transit vehicles by extending the current green time or truncating the red time of the phase immediately preceding the green phase favorable to the transit route. This method was chosen to minimize stop-and-go behavior that signalized intersections typically impose on the transit vehicle and therefore reduce the emissions it generates. A detailed flow chart of the Eco-Traffic Signal Priority algorithm is presented in Figure 59. The algorithm was implemented using the API available in the Paramics microsimulation software to simulate connected vehicle performance. The algorithm is called once for each simulation time step that the user defines. To properly simulate the DSRC technology range, a component of the algorithm depends on the communication range (also referred to as *communication distance*) of the public transit vehicle and the maximum extension of green time (or truncation of the red time) allocated to the transit vehicle at each intersection. Initially, the vehicle type of each individual vehicle present on every link of the network is assessed to determine whether the vehicle is a transit vehicle—in this specific case, a bus. This ensures that priority is granted only to the correct class of vehicles at the intersection. For equipped connected buses, the Eco-Traffic Signal Priority API keeps track of the real-time location of the buses in relation to any equipped signalized intersections. With the real-time location of the transit vehicle, the distance and time to the next intersection is calculated and available to the RSE to compare with the SPaT information. If the distance to the intersection is within the communication distance of the RSE, the provision of priority is assessed using the algorithm, which involves comparing the actual arrival time of the transit vehicle at the signalized intersection with the current phasing information received from the signal. Priority cannot be granted if the required extension or truncation time calculated for the bus is greater than the maximum threshold the user has set. The extension or reduction time is calculated for each vehicle using the following formula:

$$\begin{aligned} &Extension\ time = \\ &Time\ for\ transit\ vehicle\ to\ clear\ the\ next\ intersection - \\ &Time\ to\ red\ in\ the\ current\ related\ green\ phase\ for\ approach\ having\ transit\ vehicle \end{aligned}$$

$$\begin{aligned} &Truncation\ time \\ &= Time\ until\ transit\ vehicle\ arrives\ at\ the\ next\ intersection \\ &- Time\ for\ current\ red\ phase\ to\ terminate\ for\ the\ approach\ having\ transit\ vehicle \end{aligned}$$

If either of these formulas gives a positive result, it indicates that a priority is needed for the transit vehicle to not stop at the red signal. If the extension time is greater than the maximum extension time, then priority is not granted to prevent delays to the adjacent streets of the network and to limit the impact on the other phases of the signal cycle. However, if extension time is less than the maximum, either a green extension or red truncation is applied to that particular intersection to grant priority to the bus. This process is illustrated in the flow chart presented in Figure 59.

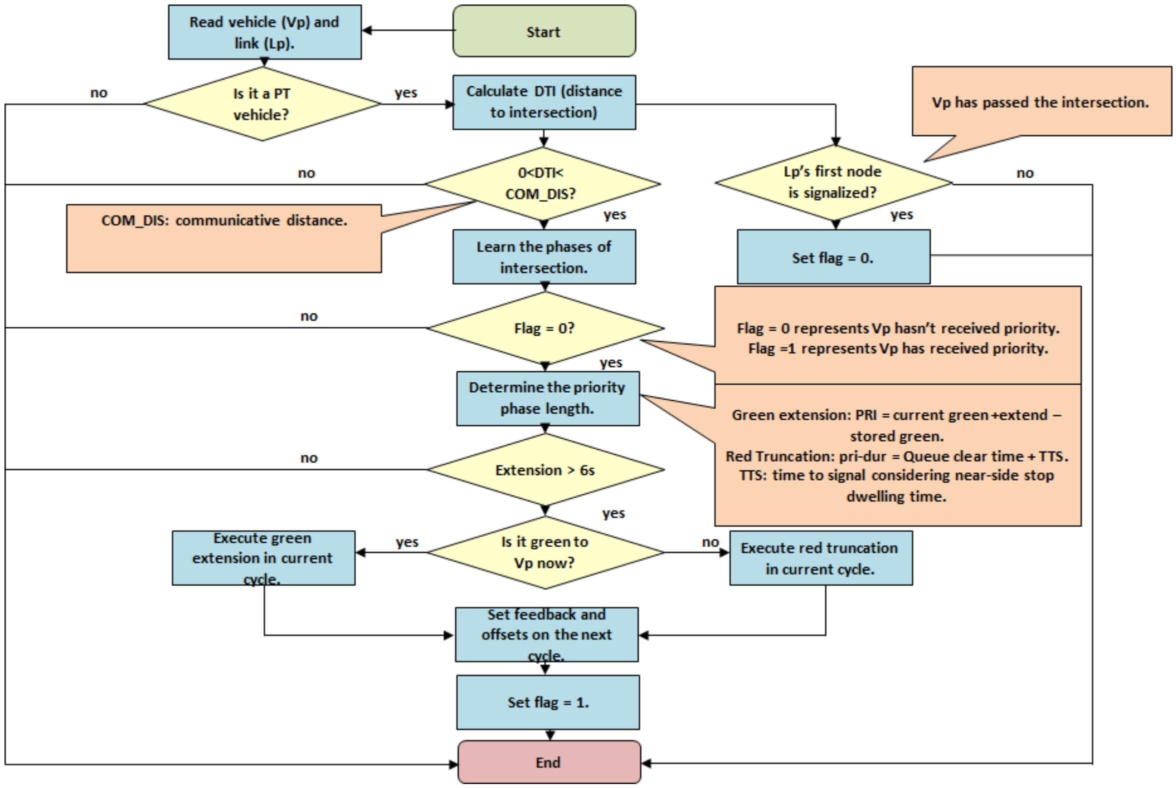


Figure 59: Flow Chart of the Structure of the E TSP Algorithm for the E TSP Application.

Influencing patrons to take transit rather than their personal vehicles is one of the ways that transportation agencies can reduce congestion and emissions along important, congested corridors. However, comfort and reliability are key parameters to the average person's adoption of public transportation. The assumption in this analysis is that if transit vehicles operate at or ahead of their schedule, more people will take transit, therefore reducing emissions in the larger scheme of operations. Therefore, for the Eco-Traffic Signal Priority algorithm, an important factor in determining whether to grant priority for the transit vehicle is the bus's adherence to its prescribed schedule. Buses that are unable to keep to schedule and are running late receive priority. This priority was implemented as a supplemental algorithm to ensure schedule adherence, which is shown in the flow chart in Figure 60.

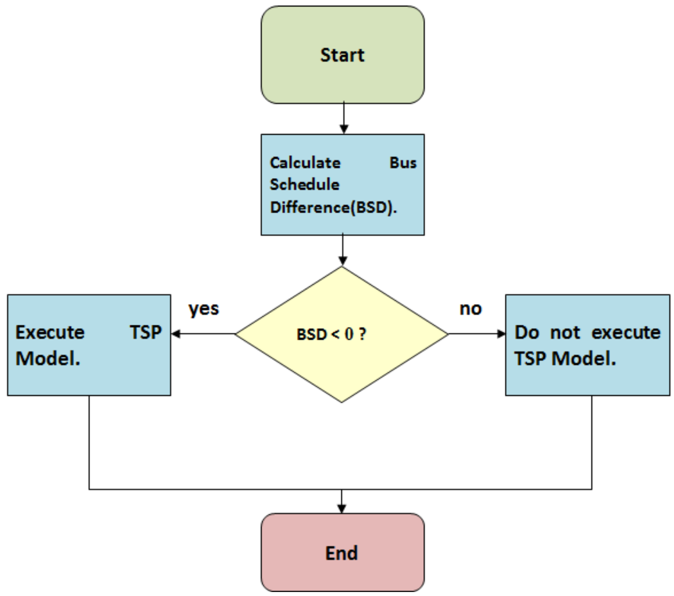


Figure 60: Extension of the Eco-Traffic Signal Priority Algorithm Accounting for Schedule Adherence.

Owing to the lack of bus schedule data and the difficulty that microsimulation models have in accurately modeling late events, the degree of schedule adherence was estimated using a comparative approach. To determine this measure of schedule adherence, the baseline performance of a transit vehicle was calculated using the following formula:

$$Bus\ Schedule = \frac{Distance\ Traveled}{Average\ Speed} + \left(Stops_{Encountered} \times \mu_{dwelling}\right) + \left(Intersections_{Encountered} \times \bar{x}_{crossing}\right)$$

For the Eco-Traffic Signal Priority API, the average values in the formula above were filled using assumed values determined from available data and sensitivity analyses, instead of pulling the data in real time. This significantly reduced the complication and computational time of the algorithm. For the analysis, it was assumed that the average speed of buses was 30 kph (18.64 mph), the mean dwell time was 10 s, and the mean intersection crossing time was 5 s for all buses along El Camino Real. The deviation from this expected schedule of the specific bus on a specific route was calculated as follows:

$$Bus\ Schedule\ Difference = Bus\ Schedule - Actual\ Bus\ Time\ in\ Network$$

As shown in Figure 60 if the bus schedule difference is less than zero, the bus is late and the traffic signal priority algorithm presented in Figure 59 is activated to determine whether to grant priority. However, if the schedule difference is less than or equal to zero, the bus is on time and no priority is granted. The algorithm presented uses connected vehicle technology to provide a real-time active traffic signal priority approach, accounting for schedule adherence and the environmental impact of the decision to provide priority on both the transit vehicle and the system as a whole.

Modeling Approach

The microscopic traffic simulation software Paramics was used to model the movement of individual vehicles and their interactions in detail. To be consistent with the modeling efforts on other AERIS applications, the latest version of Paramics (6.9.3) was used.

As part of the evaluation, detailed speed profiles of every vehicle were examined to estimate emissions and energy consumption. As part of the programming environment, Paramics supports the development of plug-ins using its API, which enables users to interface with its core simulation engine to perform specific tasks. The interaction between different models and the API used in this application is shown in Figure 61. The Eco-Traffic Signal Priority application plug-in is designed to fulfill the following functions:

1. Receive priority requests from transit vehicles.
2. Perform calculations to assign priority level.
3. Grant or deny priority.
4. Update signal timings.

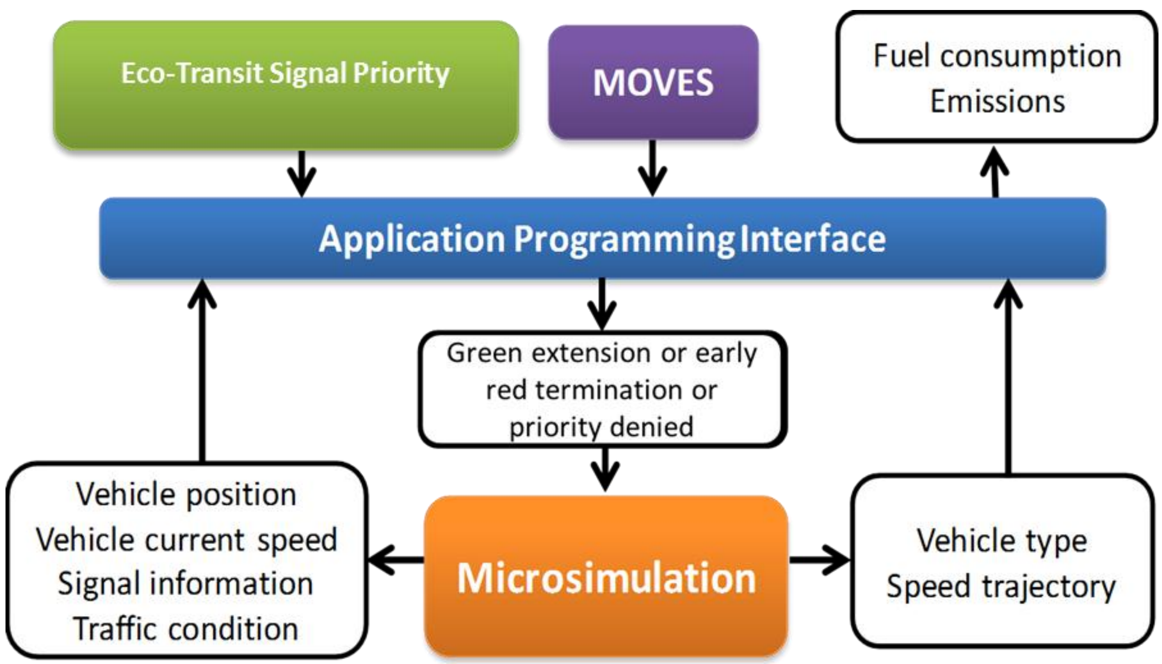


Figure 61: Diagram of Interactions Among the Models and the API.

Scenarios

An exhaustive set of scenarios was modeled for each application. The remainder of this section details the scenarios modeled. The modeling results that follow in the next section are organized in the same fashion.

The network used for modeling the scenarios was El Camino Real 27-Intersection Network (Referred to as ECR-27). For the Eco-Transit Signal Priority application, all of the following scenarios were modeled with and without consideration of schedule adherence. Scenarios with schedule adherence considered the bus schedule and how ahead or behind the schedule it was for granting priority. Buses that were behind schedule were given preference.

The following scenarios were modeled:

- **Eco-Transit Signal Priority on ECR-27—Communication Distance and Maximum Extension Time:** The scenarios were modeled on ECR-27 with a demand of 0.64 V/C ratio. Communication distances and the maximum extension times (i.e., the maximum duration a phase can be held or the maximum time that can be taken away from a phase). The values used for communication distance are 0, 20, 40, 60, 80, 100, and 120 meters. The values used for maximum extension times are 6, 8, 10, 12, and 14 s.
- **Eco-Transit Signal Priority on ECR-27—Greater Communication Distances:** These scenarios were an extension of tests carried out in the previous set of scenarios. The additional testing considered communication distances of 250, 300, 350, and 400 m in combination with all the maximum extension times considered for the previous communication distances.
- **Eco-Transit Signal Priority on ECR-27—Bus Frequency:** The Eco-Transit Signal Priority application was modeled on ECR-27 with a demand level of V/C = 0.64 used throughout. The transit frequencies used were10, 20, 50, and 100 buses/hour.
- **Eco-Transit Signal Priority on ECR-27—Demand:** The Eco-Transit Signal Priority was modeled with demand (V/C) = 0.77, lower demand (V/C) = 0.38, and higher demand (V/C) = 1.00. For each of these demand scenarios, three communication distance and maximum extension time combinations were selected for assessment based on their favorable performance with respect to emissions during a sensitivity test. These combinations were communication distance = 80 m and maximum extension time = 8 s (average emissions levels change); communication distance = 80 m and maximum extension time = 10 s (greatest reduction in emissions considering the “without schedule adherence” Eco-Traffic Signal Priority model); and communication distance = 120 m and maximum extension time = 8 s (greatest reduction in emissions considering the “with schedule adherence” Eco-Traffic Signal Priority model).

Modeling Results

To assess the benefits of the Eco-Traffic Signal Priority application, baseline models are developed with the assumption that there is no application deployment (i.e., connected vehicle penetration rate is 0 percent). The environmental impact of the Eco-Traffic Signal Priority algorithm implementation was assessed by comparing the emissions levels and delay that vehicles on the El Camino Real corridor experienced. For emissions, the analysis specifically focuses on the level of CO_2. Note that measuring the change in CO_2 levels is proportional to measuring the variation in fuel consumption the vehicles types within MOVES experience. Accordingly, it is important to remember this relationship when reading the results and conclusions associated with the modeling. The models used for the assessment were:

- Baseline model (without the use of any traffic signal priority)
- Eco-Traffic Signal Priority model without schedule adherence algorithm
- Eco-Traffic Signal Priority model with schedule adherence algorithm.

These models were investigated to understand not only the impact of this particular traffic signal priority algorithm but also what impact the inclusion of scheduling would have on the environmental and travel time measures for the transit vehicles and the other vehicles in the system. A variety of variables affect the performance of the Eco-Traffic Signal Priority model, including communication distance, maximum extension time provided, bus frequency, and the level of demand experienced within the network. Accordingly, the impact of these variables on the level of emissions and delay experienced throughout the network was assessed using three sensitivity testing scenarios.

Eco-Transit Signal Priority on ECR-27—Communication Distance and Maximum Extension Time

The first sensitivity test was conducted to determine the impact of communication distance and maximum extension time on the level of emissions for all vehicles on the network. It is important to consider the impact of these variables together to understand the trends, because not only is the communication distance varied but the maximum extension time affects these results. Table 29 lists communication distances and maximum extension times that were tested in every possible combination. Further analysis was conducted with larger values of communication distances later in the study.

Table 29: Scenarios Assessed for Communication Distance and Extension Time.

Communication Distance (m)					
20	40	60	80	100	120

Maximum Extension (or Truncation) Time (s)				
6	8	10	12	14

There are two types of intersections in El Camino Real: T section and cross-intersection. Figure 62 and Figure 63 represent the typical phase sequence of T section and cross-intersection, respectively.

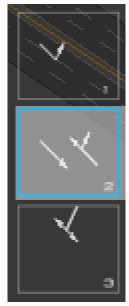


Figure 62: Typical Phase Sequence of T Intersection.

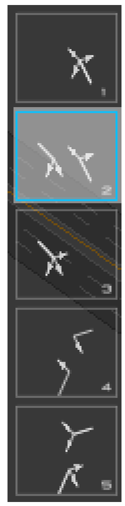


Figure 63: Phase Sequence in Cross-Intersection.

As detailed previously, schedule adherence of the transit services is an important factor in providing the decision to grant priority to the vehicle. Accordingly, the results from the sensitivity analysis compare the baseline environmental measures for all vehicles as well as transit vehicles (buses) in isolation, considering the Eco-Traffic Signal Priority models both with and without bus schedule adherence. In addition, the following parameters were held constant throughout the sensitivity assessment for consistency of results:

1. Five simulation runs were completed for each combination of communication distance and maximum extension time. Emissions and delay results from each simulation run were collected, and an average across all simulation results is presented in the following sections.
2. The demand level used for all models was based on the calibrated and validated base model with a V/C = 0.64.

Initially, the CO_2 emissions level results of comparing base conditions with both Eco-Traffic Signal Priority models are presented, followed by delay results. The analysis was conducted considering the performance of all vehicles within the network to identify the best performing combination of communication distance and maximum extension time for each environmental measure. These combinations were used to assess in greater detail the impact of the other variables described above.

Emissions Results without Bus Schedule Adherence

Table 30 and Figure 64 present the emissions improvement results of comparing the base conditions with the Eco-Traffic Signal Priority model without bus scheduling for all vehicles present on the network. The green shaded boxes show improvements compared with the base model, and the red, bold italics number shows the combination of communication distance and maximum extension time that showed the best performance.

Table 30: All-Vehicle Percentage Improvement in (CO_2) Emissions Considering the Without Schedule Adherence Eco-Traffic Signal Priority Model.

Percentage Improvement in (CO_2) Emissions		Maximum Extension Time (s) 6	8	10	12	14
Communication Distance (m)	20	-0.96%	-1.45%	-0.21%	-0.64%	-0.23%
	40	-0.60%	-0.49%	-0.30%	-0.72%	0.37%
	60	-0.47%	-0.37%	0.37%	-1.23%	-0.88%
	80	-0.29%	-0.62%	-0.93%	-1.13%	-0.05%
	100	-0.46%	-0.36%	0.00%	-0.34%	-0.03%
	120	-0.68%	0.43%	-0.29%	0.42%	-0.62%

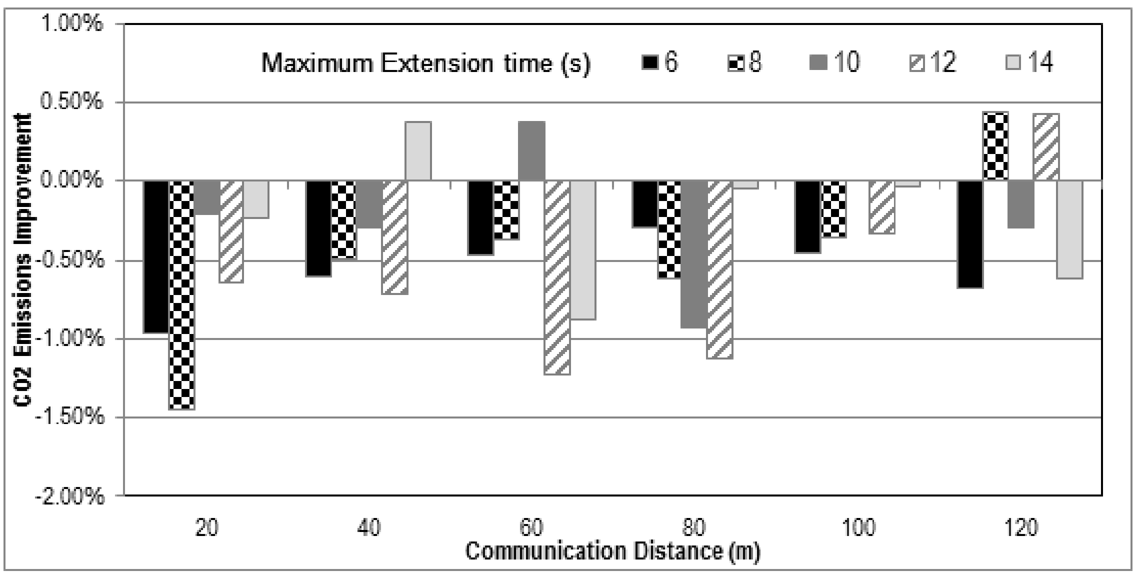


Figure 64: CO_2 Emissions Improvements for All Vehicles Across Various Extension Times and Communication Distances Considering the Without Schedule Adherence Eco-Traffic Signal Priority Model.

The results show an overall increase in the level of CO_2 emissions considering a majority of the communication distance and maximum extension combinations tested. However, note that the magnitude of these percentage deterioration ranges between 0.1 percent and 1 percent only. Only four cases shown in Figure 64 showed any sort of improvement.

Table 31 and Figure 65 present the emissions improvement results for transit vehicles (buses) in isolation. In contrast with the results considering all the vehicles on the network, transit vehicles experience a decrease in the level of CO_2 emissions, because providing priority reduces the stop-and-go behavior experienced. However, note that the improvements observed are minimal, with all percentage changes within 2 percent of the base case. The data do indicate that the best performance for transit vehicles occurs with a communication distance of 120 m.

There is a clear trend within the results: Improvements in emissions are observed when the communication distances are low, after which there is no improvement, and then increases with distance. This is evident, with communication distance equal to 120 m showing the greatest improvement in emissions levels across all maximum extension times. The trend can be explained as follows. With greater communication distances, there is more opportunity for the priority to be granted, therefore reducing fluctuations in the speed profiles of the bus. Because this is a corridor model, use of greater communication distances also minimizes the stop-and-go behavior of a majority of the other vehicles present on the network, thus reducing any negative impacts on the level of emissions. At low distances, this effect is also observed.

Table 31: Transit Vehicle Percentage Improvement in (CO_2) Emissions Considering the Without Schedule Adherence Eco-Traffic Signal Priority Model.

Percentage Improvement in (CO_2) Emissions		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	20	0.45%	0.65%	1.28%	1.40%	0.67%
	40	-0.53%	0.13%	0.43%	0.17%	-0.10%
	60	0.42%	0.77%	0.02%	0.05%	0.31%
	80	0.08%	0.00%	0.05%	0.18%	-0.17%
	100	0.48%	0.04%	0.51%	0.43%	-0.46%
	120	1.35%	1.32%	0.92%	1.51%	1.47%

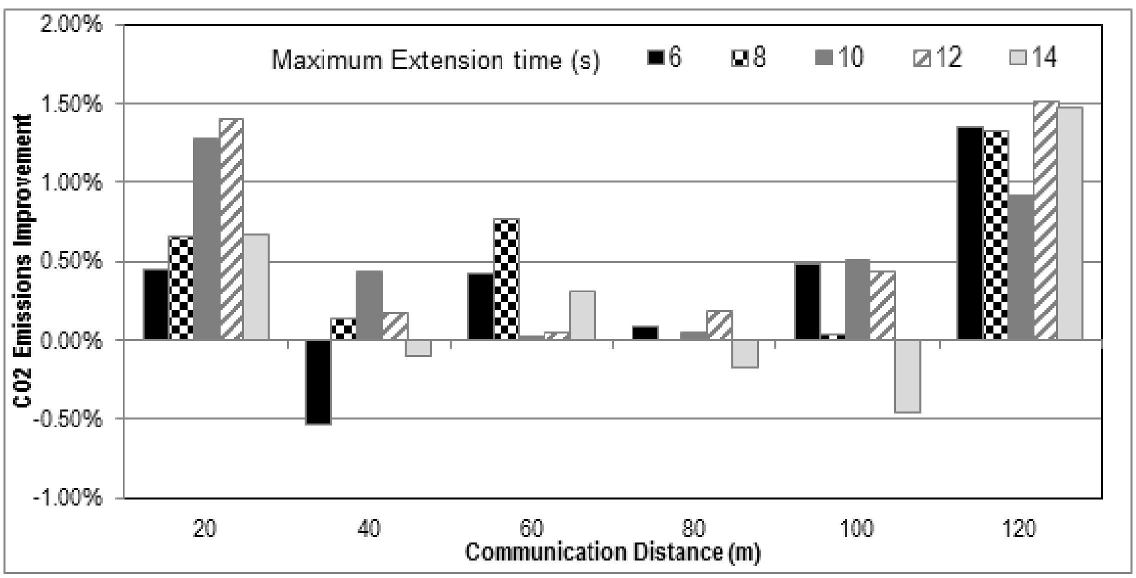


Figure 65: CO_2 Emissions Improvements for Transit Vehicles Only Across Various Extension Times and Communication Distances Considering the Without Schedule Adherence Eco-Traffic Signal Priority Model.

Emissions Results with Bus Schedule Adherence

Table 32 and Figure 66 present the emissions improvement results of comparing the base conditions against the Eco-Traffic Signal Priority model with bus scheduling, considering all the vehicles present on the network. As mentioned earlier, the green shaded boxes show improvements compared with the base model, and the red, bold italics number shows the combination of communication distance and maximum extension time that showed the best performance.

Table 32: All-Vehicle Percentage Change in (CO_2) Emissions Considering the With Schedule Adherence Eco-Traffic Signal Priority Model.

Percentage Change in (CO_2) Emissions		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	20	-0.21%	0.08%	-0.23%	-1.07%	-0.49%
	40	-0.57%	-1.06%	-1.26%	-1.05%	-0.96%
	60	-0.67%	-0.73%	-0.34%	0.08%	-0.49%
	80	0.93%	-1.13%	1.21%	0.26%	0.42%
	100	0.04%	0.00%	-0.21%	0.89%	0.75%
	120	-0.51%	0.09%	0.40%	-0.20%	-0.53%

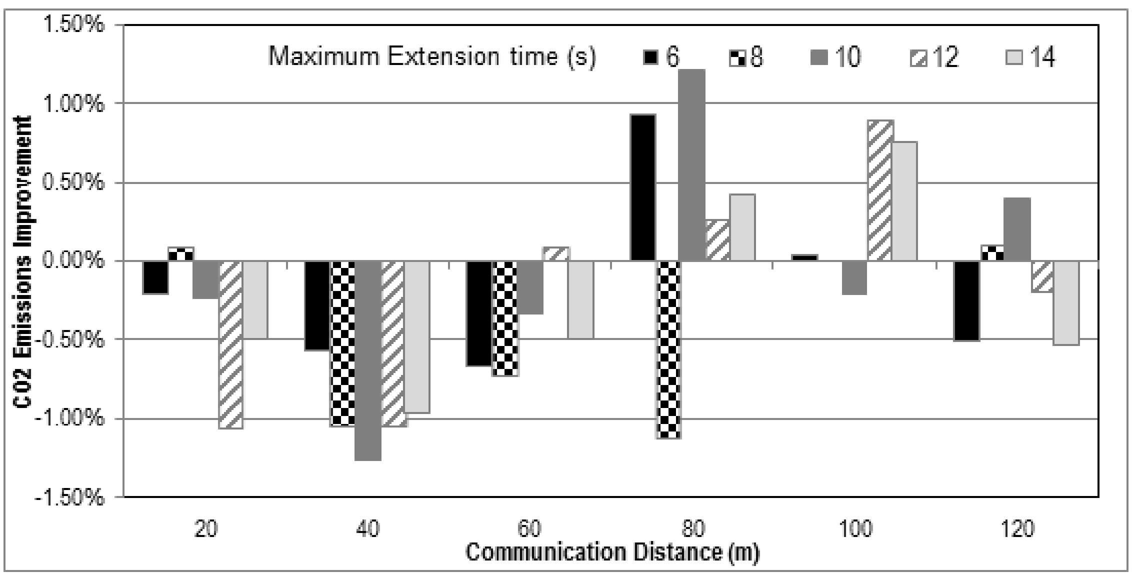


Figure 66: CO_2 Emissions Improvements for All Vehicles, Across Various Extension Times and Communication Distances Considering the With Schedule Adherence Eco-Traffic Signal Priority Model.

Overall, the emissions results of the Eco-Traffic Signal Priority model with bus schedule adherence outperform the Eco-Traffic Signal Priority model without scheduling. Communication distances greater than 80 m show some improvement in the level of CO_2 emissions, whereas without scheduling, improvements were observed only for the 120-m communication distance. However, the magnitudes of these improvements are all within 1 percent of the base conditions, indicating that the impact is minimal. The trends observed regarding communication distance are consistent with observations of the without scheduling results, where increased communication distance decreases the level of emissions.

Table 33 and Figure 67 present the emissions improvement results for transit vehicles in isolation, considering the Eco-Traffic Signal Priority model with bus schedule adherence. These results are similar to those observed without the implementation of scheduling. However, the results of the 20-m communication distance show a slight increase in the level of emissions between 0.4 percent and 1.2 percent. This finding may be because the increased sensitivity of requesting and granting priority with a short communication distance does not provide an emissions advantage for the transit vehicles. Generally, the changes are minimal, and the impact of the traffic signal priority algorithm on all vehicles on the network as well as transit vehicles in isolation is minimal.

Table 33: Transit Vehicle Percentage Improvement in (CO_2) Emissions Considering the With Schedule Adherence Eco-Traffic Signal Priority Model.

Percentage Improvement in (CO_2) Emissions		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	20	-0.67%	-0.40%	-0.72%	-1.02%	-1.21%
	40	1.23%	0.27%	0.40%	0.84%	0.93%
	60	0.60%	0.75%	0.24%	-0.28%	0.46%
	80	0.01%	0.62%	0.17%	0.40%	0.85%
	100	0.92%	-0.09%	0.77%	0.49%	0.51%
	120	1.07%	1.39%	0.92%	0.85%	1.52%

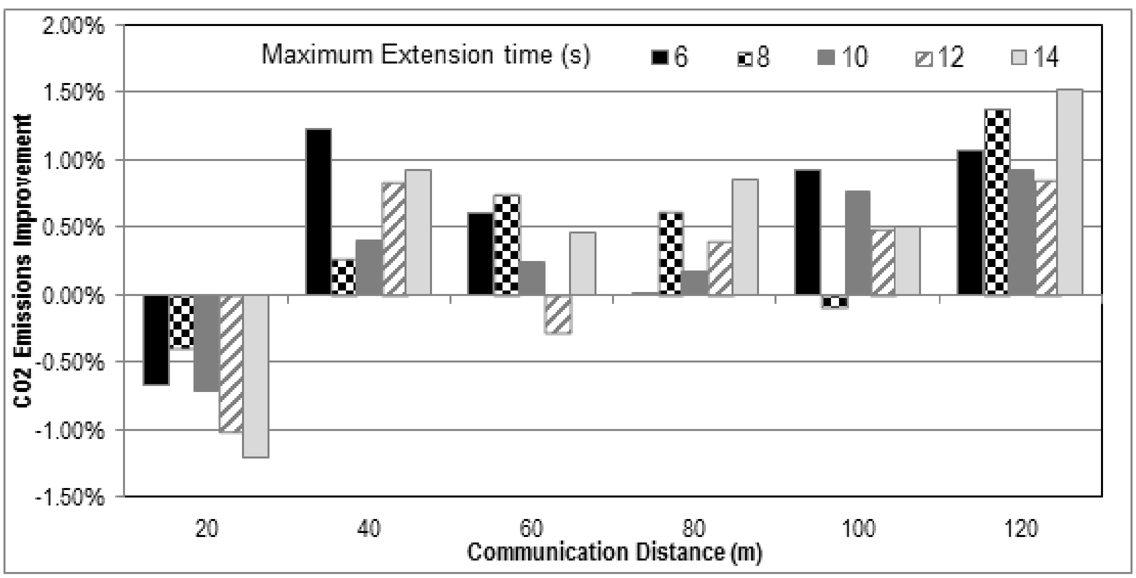


Figure 67: CO_2 Emissions Improvements for Transit Vehicles Only Across Various Extension Times and Communication Distances Considering the With Schedule Adherence Eco-Traffic Signal Priority Model.

Delay Results without Bus Schedule Adherence

Table 34 and Figure 68 present the delay improvement results for all vehicles, comparing the base conditions with the Eco-Traffic Signal Priority model without bus scheduling. As discussed earlier, the green shaded boxes show improvements compared with the base model, and the red, bold italics number shows the combination of communication distance and maximum extension time that showed the best performance.

Table 34: All-Vehicle Percentage Improvement in Delay Considering the Without Schedule Adherence Eco-Traffic Signal Priority Model.

Percentage Improvement in Delay		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	20	0.66%	0.76%	0.79%	1.18%	1.13%
	40	0.37%	0.68%	0.07%	0.51%	1.35%
	60	0.25%	0.38%	1.24%	-0.39%	0.19%
	80	0.57%	0.14%	0.15%	0.25%	0.29%
	100	0.39%	0.47%	0.58%	0.63%	0.59%
	120	0.19%	0.87%	0.83%	0.70%	0.28%

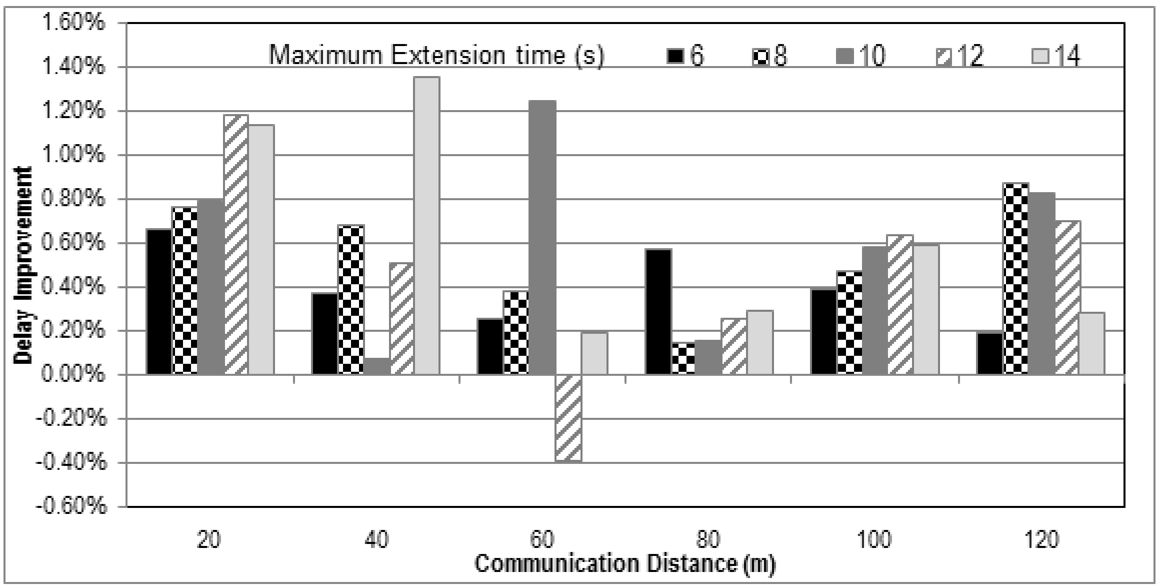


Figure 68: All-Vehicle Percentage Improvement in Delay Considering the Without Schedule Adherence Eco-Traffic Signal Priority Model.

The modeling shows a general reduction in delay throughout all combinations of communication distance and maximum extension times. The percentage improvements in the level of delay are all within 1.5 percent, indicating only a slight change from base conditions. These results are consistent with the implementation of the Eco-Traffic Signal Priority algorithm along a corridor model, because priority benefits the transit vehicles as well as the majority of the through traffic within the model. It was also found that apart from the extension times of 12 s, delay improvements are observed across all communication distances, with improvements ranging between 0.07 percent and 1.35 percent.

The impact on the delay of transit vehicles in isolation is an important factor to consider when discussing the feasibility and suitability of the Eco-Traffic Signal Priority algorithm. Table 35 and Figure 69 present the results for the improvement in delay relative to the base model conditions.

Table 35: Transit Vehicle Percentage Improvement in Delay Considering the Without Schedule Adherence Eco-Traffic Signal Priority Model.

Percentage Improvement in Delay		Maximum Extension Time (s) 6	8	10	12	14
Communication Distance (m)	20	1.67%	1.66%	2.12%	1.79%	1.25%
	40	1.70%	2.47%	2.07%	2.15%	2.80%
	60	2.41%	2.76%	2.14%	1.99%	2.86%
	80	2.12%	2.71%	3.13%	1.69%	2.68%
	100	1.93%	2.34%	2.18%	3.13%	2.07%
	120	2.24%	2.55%	3.28%	3.28%	2.88%

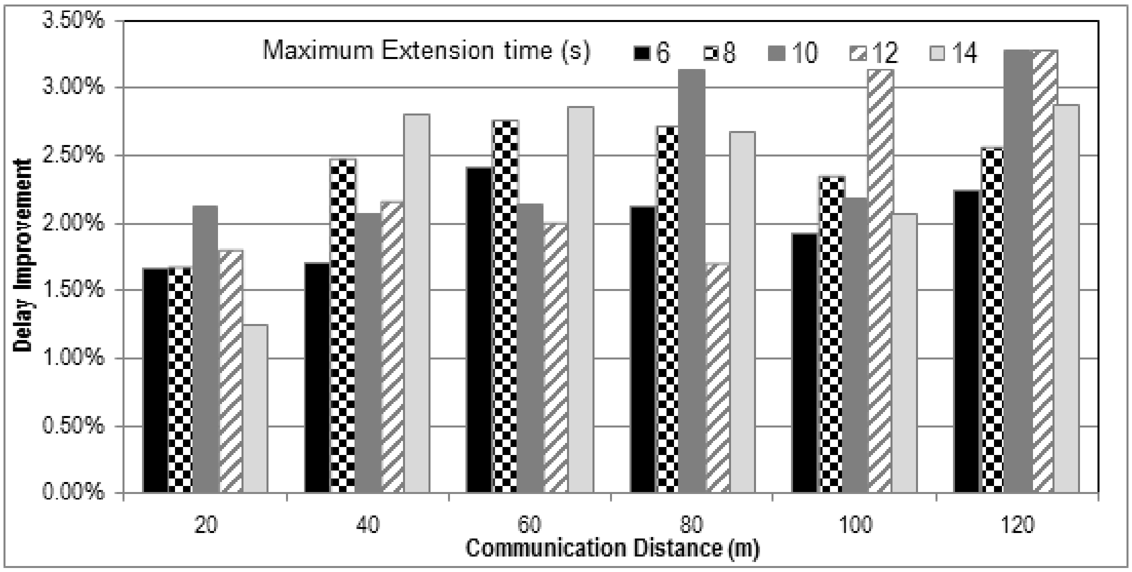


Figure 69: Transit Vehicle Percentage Improvement in Delay Considering the Without Schedule Adherence Eco-Traffic Signal Priority Model.

The results indicate that the introduction of the Eco-Traffic Signal Priority model without schedule adherence has improved the delay results across the board for all combinations of communication distance and maximum extension time. Improvements range between 1.25 percent and 3.28 percent, with greater communication distances and maximum extension times experiencing the greatest percentage improvement. As mentioned in the all-vehicle results, the reason for the improvement in delay for the buses on the network is that priority is granted to buses when required, reducing the delay experienced while waiting at signalized intersections. These results are consistent and more favorable than those observed when considering all vehicles on the network, because all bus routes occur along the corridor of the network.

Delay Results with Bus Schedule Adherence

Table 36 and Figure 70 show the delay improvement results of comparing the base conditions with the Eco-Traffic Signal Priority model with bus scheduling. As presented earlier, the green shaded boxes show improvements compared with the base model, and the red, bold, italic number shows the combination of communication distance and maximum extension time that showed the best performance.

Table 36: All-Vehicle Percentage Improvement in Delay Considering the With Schedule Adherence Eco-Traffic Signal Priority Model.

Percentage Improvement in Delay		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	20	0.39%	0.75%	0.21%	-0.17%	0.30%
	40	0.48%	-0.28%	-0.22%	-0.13%	-0.15%
	60	-0.04%	0.35%	-0.28%	0.68%	0.29%
	80	1.01%	0.12%	1.34%	1.44%	0.99%
	100	1.07%	1.02%	0.71%	0.99%	0.53%
	120	0.19%	0.64%	0.45%	0.49%	0.61%

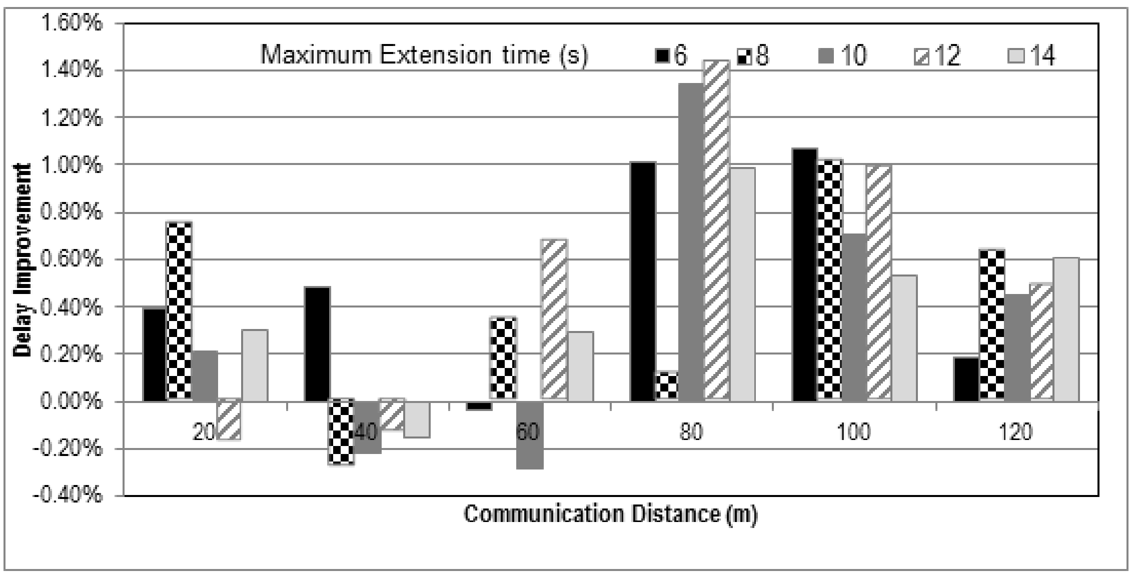


Figure 70: All-Vehicle Percentage Improvement in Delay Considering the Without Schedule Adherence Eco-Traffic Signal Priority Model.

The results accounting for bus schedule adherence also present a broad improvement in the level of delay that all vehicles within the network experienced. However, shorter communication distances have resulted in a small deterioration (less than 0.25 percent) that could be the result of ineffective granting of priority across short distances when attempting to maintain scheduling. Similar to the without bus scheduling results, the most consistent delay conditions are observed for maximum extension times of 8 s and 10 s.

Table 37 and Figure 71 present the results for the improvement in delay of transit vehicles relative to the base model conditions. Similar to the results of the without scheduling model, the delay of transit vehicles improves across the board for all combinations of communication distance and maximum extension time. However, in this case, improvements are slightly less than those experienced when comparing the results with the model without bus scheduling results, ranging between 0.22 percent and 2.88 percent. These observations are expected, because the Eco-Traffic Signal Priority algorithm without bus scheduling provides priority at every instance possible given the state of signals at each intersection, while the algorithm with bus scheduling provides priority only if the bus is not adhering to the schedule and running late. Accordingly, the opportunities to grant priority are fewer, limiting the advantages of priority to reduce the delay of the buses along the corridor.

Table 37: Transit Vehicle Percentage Improvement in Delay Considering the With Schedule Adherence Eco-Traffic Signal Priority Model.

Percentage Improvement in Delay		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	20	0.93%	0.22%	0.31%	0.28%	1.25%
	40	0.98%	1.71%	1.59%	2.23%	2.80%
	60	1.21%	1.77%	1.47%	0.84%	2.86%
	80	0.65%	1.36%	1.46%	1.30%	2.68%
	100	1.43%	1.33%	1.13%	2.44%	2.07%
	120	1.54%	1.78%	1.43%	2.21%	2.88%

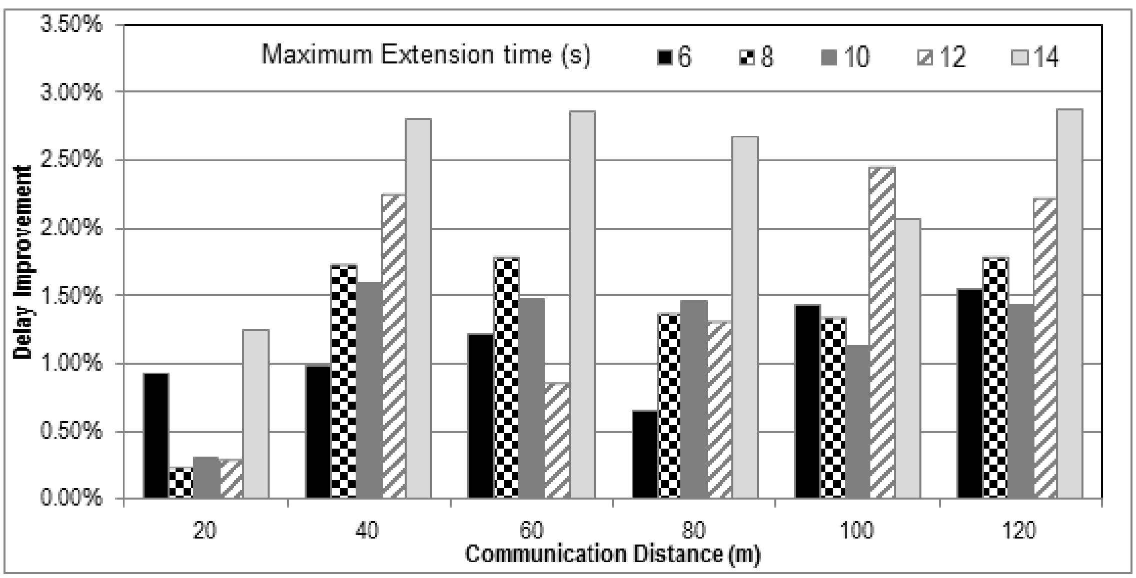


Figure 71: Transit Vehicle Percentage Improvement in Delay Considering the With Schedule Adherence Eco-Traffic Signal Priority Model.

Statistical Significance of Sensitivity Results

The results showed percentage changes, all within 4 percent, when comparing base conditions with those of models with the Eco-Traffic Signal Priority application. Accordingly, to further explore the statistical significance of these differences, a conventional “Z-test” was conducted comparing base model data with Eco-Traffic Signal Priority, with schedule adherence for both emissions and delay. These two models were compared, because the observations and trends described in the previous sections of the report indicated that the Eco-Traffic Signal Priority model with bus scheduling adherence outperformed the model without bus scheduling adherence when considering all vehicles on the network for delay and emissions level improvements. Two hypotheses were considered when conducting the statistical assessment:

1. The level of emissions after applying Eco-Traffic Signal Priority is statistically equal to that observed in base conditions.
2. The delay that all vehicles on the network experienced after applying Eco-Traffic Signal Priority is statistically equal to that observed in base conditions.

The *z*-value in this test is calculated by the following equation:

$$z = \frac{(\overline{x_1} - \overline{x_2}) - d_0}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}},$$

where $\overline{x_1}$ and $\overline{x_2}$ are mean values of samples.

d_0 is the expected difference—in our case, $d_0 = 0$.

σ_1 and σ_2 are the standard deviations of samples.

n_1 and n_2 are the sizes of samples.

Table 38 and

Table 39 present the *z*-values for the sensitivity test results, considering all vehicles on the network, with a 95 percent confidence level. The colored, bold, italic numbers show *z*-values that exceed 1.96 (or are less than -1.96), which indicates differences that are statistically significant at a confidence level of 95 percent. No statistical differences were observed for the variation in the level of emissions between the two models. Similarly for the delay results, 27 of the 30 combinations of communication distances and maximum extension times resulted in no significant differences.

Table 38: All-Vehicle Z-Scores for Emission Results.

Z-Score for Emissions Results		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	20	0.17	-0.06	0.22	1.17	0.47
	40	0.42	0.96	1.15	1.39	1.13
	60	0.60	0.73	0.34	-0.08	0.37
	80	-1.11	1.38	-1.12	-0.26	-0.49
	100	-0.04	0.00	0.25	-0.87	-0.99
	120	0.44	0.09	-0.44	0.17	0.51

Table 39: All-Vehicle Z-Scores for Delay Results.

Z–Score for Delay Results		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	20	-0.70	-1.10	-0.95	2.58	-2.73
	40	-0.05	0.70	0.73	0.35	3.06
	60	0.25	-0.05	0.94	-1.73	-0.33
	80	-0.55	-0.46	-0.63	-0.19	-0.16
	100	-0.07	-0.22	-0.37	-0.74	-0.60
	120	-0.26	-1.20	-1.32	-0.52	-0.16

Table 40 and

Table 41 present the *z*-values for the sensitivity test results, considering transit vehicles in isolation, with a 95 percent confidence level. When considering the emission level results, the trends are similar to the all-vehicle statistical test results, with 27 of the 30 combinations of emission level results showing no significant difference. However, the delay results are in contrast to those of the all-vehicle assessment, with 29 of the 30 combinations showing a statistically significant difference from the base model conditions.

Table 40: Transit Vehicle Z-Scores for Emission Results.

Z-Score for Emissions Results		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	20	0.85	0.61	0.97	1.59	2.02
	40	-2.33	-0.38	-0.55	-1.33	-1.00
	60	-0.99	-0.88	-0.34	0.32	-0.64
	80	-0.02	-1.04	-0.22	-0.54	-1.23
	100	-1.51	0.10	-1.07	-0.91	-0.56
	120	-1.62	-2.18	-1.38	-0.85	-1.69

Table 41: Transit Vehicle Z-Scores for Delay Results.

Z-Score for Delay Results		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	20	-2.04	-2.01	-3.58	-1.99	-1.61
	40	-1.98	-4.05	-3.11	-2.62	-4.08
	60	-3.99	-4.03	-3.83	-2.81	-3.02
	80	-3.38	-4.20	-4.85	-2.59	-3.82
	100	-2.58	-3.53	-3.42	-4.88	-3.40
	120	-3.25	-4.44	-5.93	-5.20	-4.70

Based on these results, it is evident that the Eco-Traffic Signal Priority model with bus scheduling shows significant transit delay improvements. However, the overall differences for emissions levels and delay between the base conditions and the Eco-Traffic Signal Priority model are statistically insignificant when considering all vehicles on the network. This means that the Eco-Traffic Signal Priority model with bus scheduling has a minimal impact on the environmental measures assessed.

Eco-Transit Signal Priority on ECR-27—Greater Communication Distances

The sensitivity test was extended to consider the impact of longer communication distances on the environmental measures assessed. This was completed to reflect other possible practical implementations of the Eco-Traffic Signal Priority model, and the results are similar to those observed earlier. The additional testing considered communication distances of 250, 300, 350, and 400 m in combination with all the maximum extension times considered for the previous communication distances. The results are presented for the percentage improvement in the level of emissions and delay in detail within the next subsections of the report. Table 42 presents the percentage improvement in emissions levels considering all the vehicles on the network when applying the without bus scheduling Eco-Traffic Signal Priority model. The results are consistent with those observed with shorter communication distances. Minimal increases in emissions, less than 2.5 percent, are observed for most combinations of the communication distance and maximum extension times tested. Increasing communication distance results in no improvement in the level of emissions for all vehicles on the network.

Table 42: All-Vehicle Percentage Improvement in Emissions Levels for Greater Communication Distances for the Without Bus Scheduling Eco-Traffic Signal Priority Model.

Percentage Improvement in (CO_2) Emissions		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	250	-0.23%	-0.03%	0.50%	-1.49%	-0.76%
	300	-1.20%	-0.60%	-0.33%	-1.30%	-0.79%
	350	-2.09%	-0.86%	-0.93%	-0.16%	-0.81%
	400	-0.93%	-0.98%	-1.43%	-1.14%	-0.71%

Table 43 presents the percentage improvement in emissions levels considering only transit vehicles on the network when applying the without bus scheduling Eco-Traffic Signal Priority model. The results are again consistent with those observed with shorter communication distances, with most combinations showing an improvement in the level of emissions when the Eco-Traffic Signal Priority algorithm is applied. However, as with the all-vehicle results, there are no additional benefits from the increase in communication distance, with all improvements less than 1.5 percent.

Table 43: Transit Vehicle Percentage Improvement in Emissions Levels for Greater Communication Distances for the Without Bus Scheduling Eco-Traffic Signal Priority Model.

Percentage Improvement in (CO_2) Emissions		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	250	0.35%	-0.13%	0.35%	-0.67%	0.42%
	300	0.35%	0.42%	1.27%	-0.29%	0.77%
	350	-0.20%	0.35%	0.12%	1.26%	0.10%
	400	-0.44%	0.10%	0.48%	0.58%	1.28%

Table 44 presents the percentage improvement in emissions levels, considering all the vehicles on the network, when applying the Eco-Traffic Signal Priority model with bus scheduling. These results differ from those observed with shorter communication distances; there are consistent increases in the level of emissions for all vehicles. The reason could stem from the increased opportunity to request and grant priority for the transit services on the network. The increase in granting of priority begins to adversely affect the entry of vehicles from the adjacent streets of the network into the corridor, increasing the stop-and-go behaviors of these vehicles, resulting in increased emissions for these vehicles and an overall increase in the all-vehicle levels.

Table 44: All-Vehicle Percentage Improvement in Emissions Levels for Greater Communication Distances for the with Bus Scheduling Eco-Traffic Signal Priority Model.

Percentage Improvement in (CO_2) Emissions		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	250	-1.43%	-1.06%	-1.02%	-1.53%	-2.62%
	300	-1.82%	-0.99%	-0.52%	-0.13%	-0.17%
	350	-1.45%	-1.06%	-0.92%	-0.56%	-0.97%
	400	-0.65%	-1.03%	0.22%	-1.02%	-1.33%

Table 45 presents the percentage improvement in emissions levels, considering transit vehicles, when applying the Eco-Traffic Signal Priority model with bus scheduling. Similar to the without scheduling results, these are consistent with those observed when considering shorter communication distances. As before, there are no additional benefits in terms of improvements to environmental measures with an increased communication distance.

Table 45: Transit Vehicle Percentage Improvement in Emissions Levels for Greater Communication Distances for the with Bus Scheduling Eco-Traffic Signal Priority Model.

Percentage Improvement in (CO_2) Emissions		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	250	0.47%	0.81%	1.60%	0.86%	0.28%
	300	0.26%	0.43%	0.77%	1.10%	0.77%
	350	0.73%	1.13%	0.26%	0.40%	1.09%
	400	0.57%	0.35%	0.50%	0.71%	0.05%

Table 46 presents the percentage improvement in delay considering all the vehicles on the network when applying the without bus scheduling Eco-Traffic Signal Priority model. The results of the shorter communication distances indicated that for most combinations tested, delay improvements were observed. This contrasts with what is observed in Table 44 where there are increases in the delay for all vehicles considering longer communication distances. The reason for such a trend follows from the increased opportunity to request and grant priority for the transit services on the network. As described earlier, the increase in granting of priority begins to adversely affect the entry of vehicles from the adjacent streets of the network into the corridor, resulting in increased delays for those vehicles and an overall increase in the all-vehicle levels of delay.

Table 46: All-Vehicle Percentage Improvement in Delay for Greater Communication Distances for the Without Bus Scheduling Eco-Traffic Signal Priority Model.

Percentage Improvement in Delay		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	250	0.52%	0.38%	0.33%	-0.90%	-0.76%
	300	-0.88%	0.45%	0.18%	-0.64%	-0.18%
	350	-0.33%	0.47%	-0.68%	0.38%	-0.26%
	400	-0.38%	0.14%	-0.02%	-0.36%	-0.30%

Table 47 presents the percentage improvement in delay considering only transit vehicles on the network when applying the without bus scheduling Eco-Traffic Signal Priority model. The results follow a similar trend to that observed when considering shorter communication distances. Improvements range between 1.74 percent and 5.10 percent, with greater communication distances and maximum extension times resulting in the greatest percentage improvement.

Table 47: Transit Vehicle Percentage improvement in Delay for Greater Communication Distances for the Without Bus Scheduling Eco-Traffic Signal Priority Model.

Percentage Improvement in Delay		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	250	2.16%	2.29%	2.44%	2.90%	2.73%
	300	2.74%	2.57%	3.07%	2.86%	4.23%
	350	2.41%	2.84%	3.21%	4.20%	4.41%
	400	1.74%	2.93%	2.85%	4.31%	5.10%

Table 48 presents the percentage improvement in delay considering all the vehicles on the network when applying the without bus scheduling Eco-Traffic Signal Priority model. Similar to what is presented in Table 46 for the without bus scheduling comparison, increases in communication distances negatively affect the delay all vehicles on the network experience.

Table 48: All-Vehicle Percentage Improvement in Delay for Greater Communication Distances for the with Bus Scheduling Eco-Traffic Signal Priority Model.

Percentage Improvement in Delay		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	250	-0.96%	-0.65%	0.24%	-0.27%	-1.35%
	300	-0.52%	-0.18%	0.05%	0.22%	0.00%
	350	-0.35%	-0.62%	-0.64%	-0.39%	-0.57%
	400	-0.22%	0.04%	0.05%	-0.66%	-1.41%

Table 49 presents the percentage improvement in delay considering only transit vehicles on the network when applying the without bus scheduling Eco-Traffic Signal Priority model. The results are consistent with those observed for shorter communication distances.

Table 49: Transit Vehicle Percentage Improvement in Delay for Greater Communication Distances for the with Bus Scheduling Eco-Traffic Signal Priority Model.

Percentage Improvement in Delay		Maximum Extension Time (s)				
		6	8	10	12	14
Communication Distance (m)	250	1.88%	1.36%	2.50%	2.30%	2.51%
	300	1.14%	1.36%	1.85%	2.13%	3.06%
	350	1.96%	1.36%	2.04%	2.35%	3.97%
	400	1.00%	1.77%	1.92%	2.57%	2.52%

Greater communication distances seem to reduce the level of emissions released and the delay that all vehicles within the network experience. Overall, the percentage variations in these results are minimal and, as with the initial testing of Sensitivity Test 1, the results were not statistically different from the results of the base modeling. However, transit vehicles experienced similar results in terms of emissions level improvements and further benefits in reduced delay with greater communication distances.

Performance of the Eco-Traffic Signal Priority Algorithm: Requesting and Granting Priority

The performance of the Eco-Traffic Signal Priority algorithm is another important consideration in assessing the validity of the previous results. Accordingly, the number of times priority a transit vehicle requests as well as the number of times priority is granted to the vehicles for each of the above combinations of communication distance and maximum extension time has been investigated.

Figure 72 presented the variation in mean requested priority across all the modeling combinations for the Eco-Traffic Signal Priority model without bus scheduling used for this sensitivity analysis. No clear trends were observed with priority request numbers across the different combinations of maximum extension times and communication distances and relatively random behavior. The request numbers fluctuate between 600 and 1,400 times, with a slight tendency toward an increase in the number of requests with increasing communication distance. The lack of trends in these numbers is most likely a result of the randomness of the arrival of buses at each intersection and the corresponding signal timing at that specific moment in time.

In contrast, a clear relationship is observed in the number of times priority is granted using the Eco-Traffic Signal Priority algorithm without bus scheduling. Increasing maximum extension time and communication distance increases the number of granted priorities for transit services, and this trend is clearly shown in Figure 72 and Figure 73. These results follow intuition; a greater communication distance and maximum extension time allow more time for a bus to be granted priority upon its request.

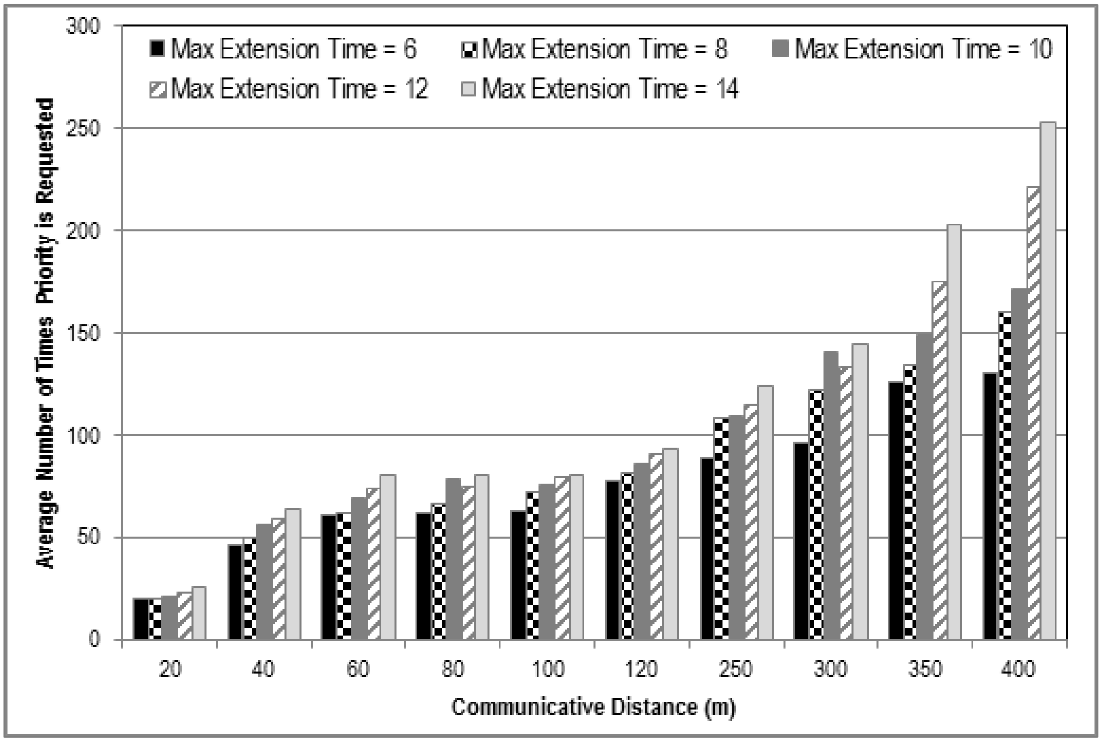


Figure 72: Variation in Requested Priority Across Communication Distance and Maximum Extension Combinations (Without Bus Scheduling Eco-Traffic Signal Priority Model).

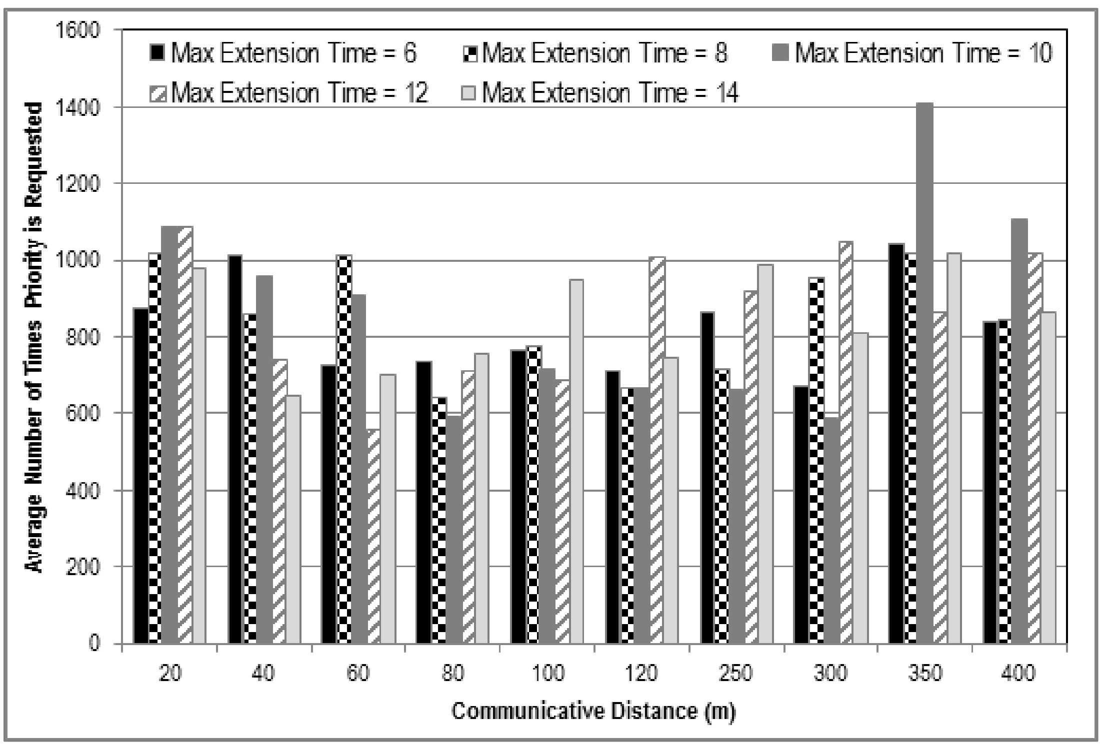


Figure 73: Variation in Granted Priority Across Communication Distance and Maximum Extension Combinations (Without Bus Scheduling Eco-Traffic Signal Priority Model).

Figure 74 and Figure 75 show the mean requested and granted priorities for with bus scheduling Eco-Traffic Signal Priority model, respectively. The trends are similar to those of the without bus scheduling Eco-Traffic Signal Priority model, but the number of times priority is granted is about half that observed in the without bus scheduling Eco-Traffic Signal Priority model. This is the result of the additional constraint of priority being provided only to the buses that do not adhere to the schedule, thus limiting the total number of priorities being granted.

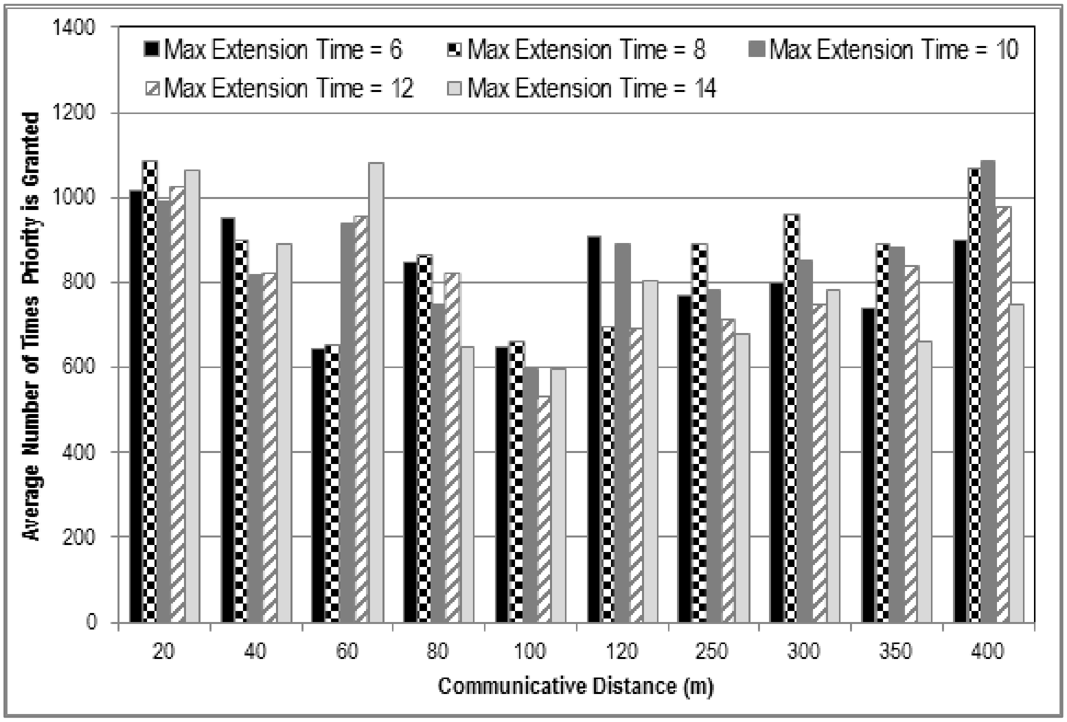


Figure 74: Variation in Requested Priority Across Communication Distance and Maximum Extension Combinations (with Bus Scheduling Eco-Traffic Signal Priority Model).

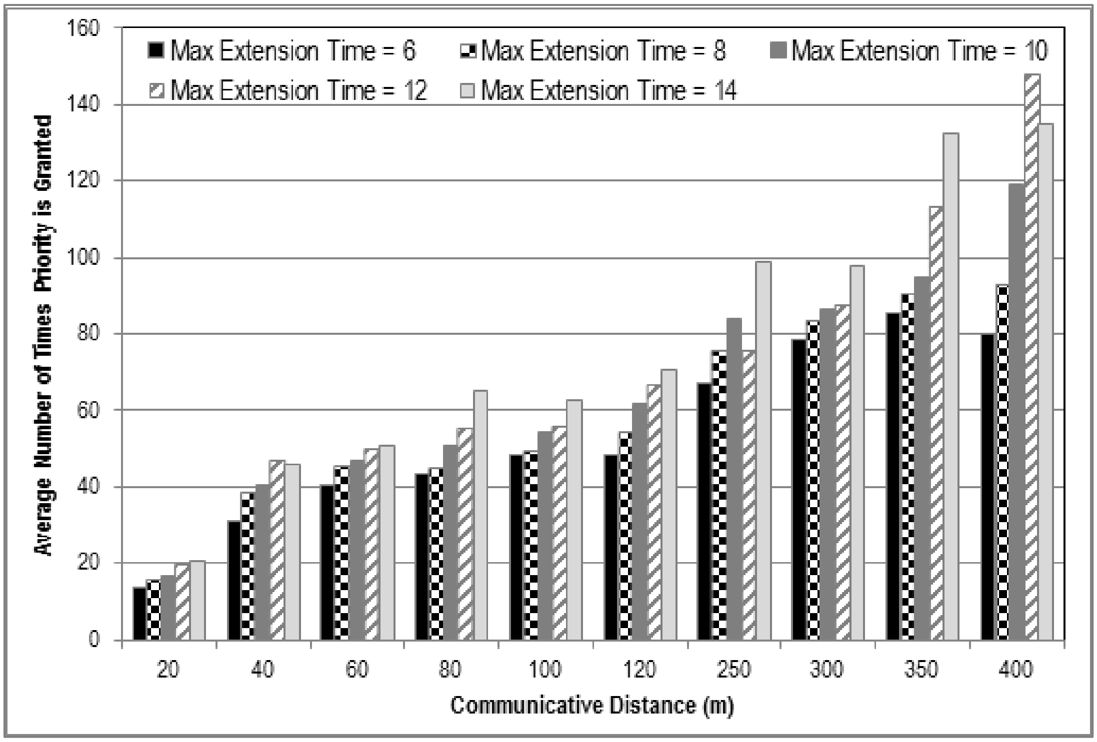


Figure 75: Variation in Granted Priority Across Communication Distance and Maximum Extension Combinations (Without Bus Scheduling Eco-Traffic Signal Priority Model).

Summary of Results

The sensitivity analysis provided detailed insight into the impact of communication distance and maximum extension time on the performance of the Eco-Traffic Signal Priority models with and without bus scheduling adherence. In addition, the modeling provided results and trends on the impact of each algorithm on the environmental measures of CO_2 emissions levels and delay network-wide. The results, trends, and observations are summarized as follows:

1. Overall, neither Eco-Traffic Signal Priority model provides a significant improvement in the level of emissions and delay for all vehicles on the network across the communication distances and maximum extension times. However, some combinations provide minimal improvements, on the order of 1–2 percent, across the network.
2. Communication distance = 80 m, and maximum Extension time = 8 s (was the most efficient based on reduction in average emissions levels).
3. Communication distance = 80 m, and maximum extension time = 10 s (greatest reduction in emissions considering the without schedule adherence Eco-Traffic Signal Priority model).
4. Communication distance = 120 m, and maximum extension time = 8 s (greatest reduction in emissions considering the with schedule adherence Eco-Traffic Signal Priority model).
5. Considering transit vehicles in isolation, both Eco-Traffic Signal Priority models show improvement in both the level of emissions and the level of delay. Although the emissions level differences are generally statistically insignificant, there is a 1–2 percent improvement throughout all combinations of communication distance tested. The delay improvements are statistically significant, on the order of 1–5 percent, with increasing communication distance, resulting in larger improvements. This trend is consistent with implementation of the Eco-

Traffic Signal Priority algorithm, as an increase in communication distance increases the probability of priority being granted and, thus, increases the likelihood that delay savings can be obtained for transit services.

6. Greater communication distances seem to have a negative impact on the emissions level and on the delay that all vehicles within the network experience. This trend results from the increased opportunity to request and grant priority for the transit services on the network. The increase in granting of priority begins to adversely affect the entry of vehicles from the adjacent streets of the network into the corridor, resulting in increased delays for these vehicles and an overall increase in all-vehicle levels. Accordingly, these greater communication distances were not used for the following sensitivity testing.
7. The results indicate that the Eco-Traffic Signal Priority model with bus scheduling outperforms the model without scheduling considering the all-vehicle assessment. This occurs because there are more instances of improvements in the level of emissions when considering the all-vehicle case for the Eco-Traffic Signal Priority with scheduling algorithm. This occurs because priority is granted only when it is absolutely necessary for the bus to remain on schedule, thus limiting the impact on links and vehicles entering from adjacent links to the network.

Eco-Transit Signal Priority on ECR-27—Bus Frequency

The results of the initial sensitivity analyses showed little, statistically insignificant, changes in emissions and travel time over the baseline model, considering all vehicles present on the network. It was hypothesized that these small, insignificant changes were the result of the small volumes of transit traffic in the El Camino Real corridor. The baseline transit vehicle schedule shows only about five or six buses per hour in each direction, leaving at about 10-minute evenly spaced intervals. To test the hypothesis, a sensitivity test was conducted to assess the impact of increasing bus frequency on the level of CO_2 emissions under base conditions and with the presence of the transit signal priority algorithm formulated throughout the project. For this analysis, the same demand level of V/C = 0.64 was used throughout, and the following frequencies (for each direction along the El Camino Real corridor) were tested:

1. 10 buses/hour
2. 20 buses/hour
3. 50 buses/hour
4. 100 buses/hour.

Before completing the sensitivity analysis, it was necessary to determine whether the transit signal priority algorithm could cope with the increase in frequency of buses. Table 50 presents the average transit signal priority requesting times and granting times for each bus frequency category assessed across all variables tested for the sensitivity analysis. Although the number of request times shows relatively random behavior, there is a general increase. It also can be shown that the granting times of transit signal priority increases linearly as the frequency of buses increases. Accordingly, the transit signal priority algorithm was shown to adapt to the increase in frequency of buses and was deemed satisfactory to conduct the sensitivity analysis.

Table 50: Transit Signal Priority Granting Times for Eco-Transit Signal Priority with Bus Schedule Model.

Bus Frequency (Buses per Hour)	Requested Priority Times	Granted Priority Times
10	815.9	70
20	2075.4	134.7
50	6416.4	353.8
100	6215.3	822.8

Delay and CO_2 emissions results for the base El Camino Real network and for the network including the transit signal priority are compared in the following section. The Eco-Transit Signal Priority algorithm used for the assessment included adherence to bus scheduling, because this provided optimal results in the previous testing conducted. The following tables and figures present the impact of varying bus frequency on emissions levels.

Emissions Results

Table 51 presents emissions results for the buses; this is shown graphically in Figure 76. When comparing the base model and the Eco-Transit Signal Priority model, buses across all frequency models produce minimal differences in the emissions levels; the greatest difference was an increase of 1.15 percent in emissions, which suggests that the transit signal priority algorithm does not have a significant impact on the level of emissions for a given bus frequency.

Table 51: CO_2 Emissions for Buses Only (g).

Bus Frequency (Buses per Hour)	Base Model	TSP with Bus Schedule	Difference	Percentage Improvement in Level of CO2 Emissions
10	250176.14	250068.60	-107.54	0.04%
20	476344.19	481840.21	5496.02	-1.15%
50	1371409.83	1363555.99	-7853.84	0.57%
100	2735447.28	2737423.85	1976.58	-0.07%

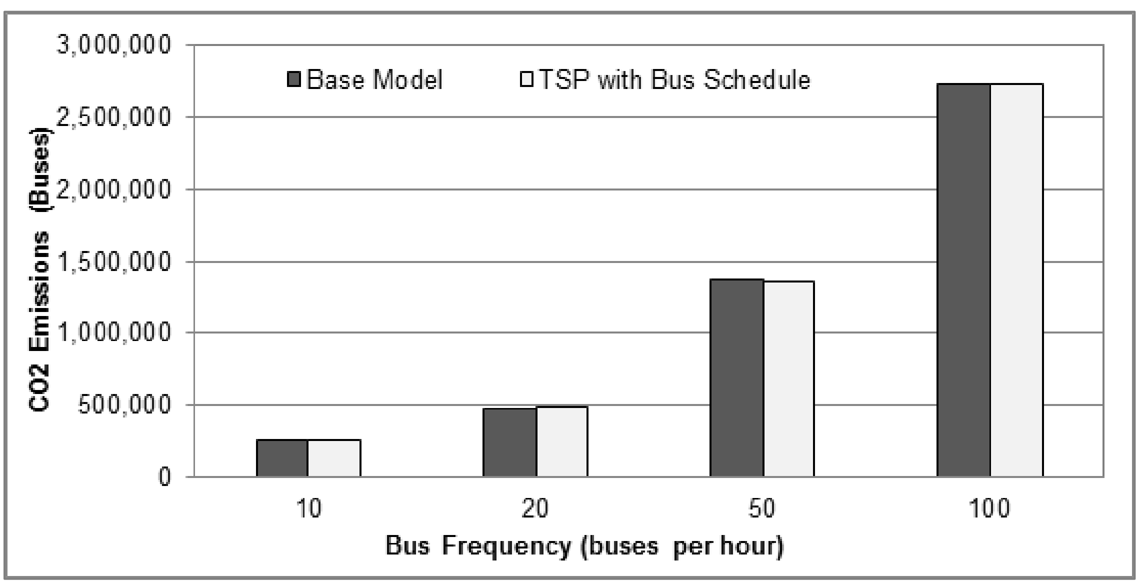


Figure 76: CO2 Emissions for Buses (g).

Table 52 presents the emissions results of all vehicles on the network, shown graphically in Figure 77. Similar to the results of the emissions of buses only, the difference between the base model and the Eco-Transit Signal Priority model are minimal (within 1 percent difference).

Table 52: CO_2 Emissions for All Vehicles (g).

Bus Frequency (Buses per Hour)	Base Model	TSP with Bus Schedule	Difference	Percentage Improvement in Level of CO_2 Emissions
10	5077854.10	5088566.70	10712.60	-0.21%
20	5311782.25	5334937.85	23155.60	-0.44%
50	5835802.80	5791518.90	-44283.90	0.76%
100	7222355.15	7196447.00	-25908.15	0.36%

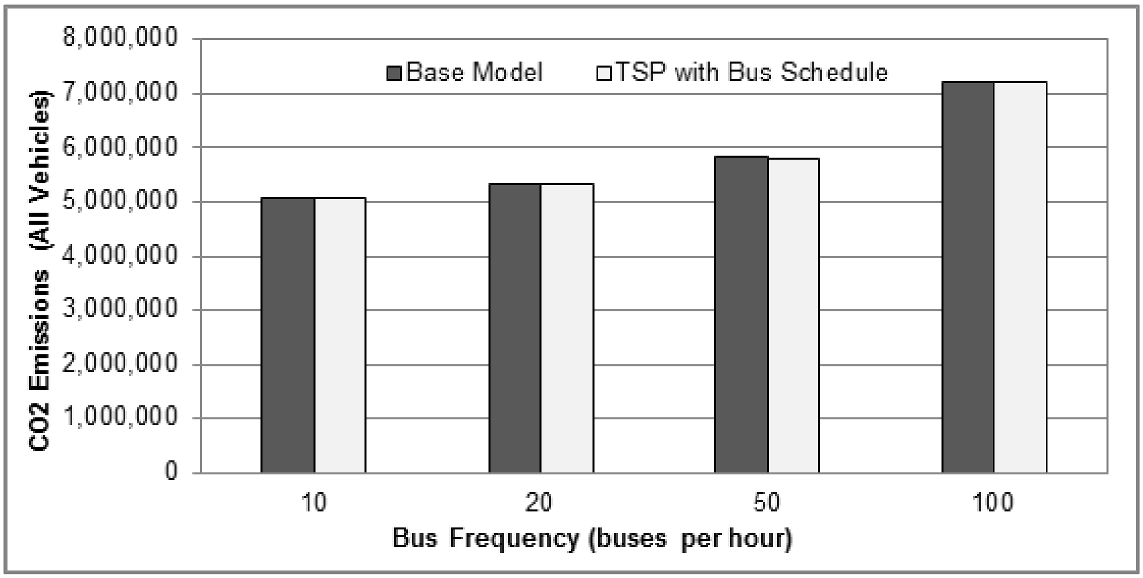


Figure 77: CO_2 Emissions for All Vehicles (g).

In addition, a statistical Z-test was conducted to determine whether the differences observed were significantly different from the base model. All results indicate that the emissions results for all vehicles were not significantly different from the base model at a 95 percent confidence level with *z*-values less than 1.96.

Delay Results

Table 53 and Figure 79 present the delay results of only the buses on the network. The results indicate that the Eco-Transit Signal Priority algorithm has a stable, positive impact on bus average delay, decreasing it by approximately 2 percent. The variation in the average delay of the buses is plotted as a parabolic curve, with the lowest point at 20 buses per hour. This means that as the frequency increases from 10 buses per hour to 20 buses per hour, the priority granted for a bus at the start of a queue might result in reducing uncertainty in delay for the following bus and, therefore, reducing overall bus delays. However, an increase in bus frequency then begins to contribute to congestion within the network, resulting in an increase in delays.

Although there is a reduction in average delay of buses when comparing the base model with the Eco-Transit Signal Priority model, there is no significant difference in the level of emissions the buses release, as presented in Table 53 and Figure 78. This can be explained by considering the size of the model and the absolute travel time savings of the bus. The greatest difference in average delay between the base model and the Eco-Transit Signal Priority model is only 32 s (for the 100 buses/hour case); this value does not markedly increase the average speed of the vehicle across the 10-km model. Accordingly, because the average speed is maintained, this does not have a significant impact on the level of emissions released. It would be beneficial for future work to understand the relationship between the level of emissions vehicles release and the average speed of the vehicle throughout the network.

Table 53: Average Delay for Buses (s).

Bus Frequency (Buses per Hour)	Base Model	TSP with Bus Schedule	Difference	Percentage Improvement
10	1486.99	1462.083	-24.907	1.67%
20	1432.008	1402.49	-29.517	2.06%
50	1443.302	1423.573	-19.729	1.37%
100	1502.347	1469.763	-32.584	2.17%

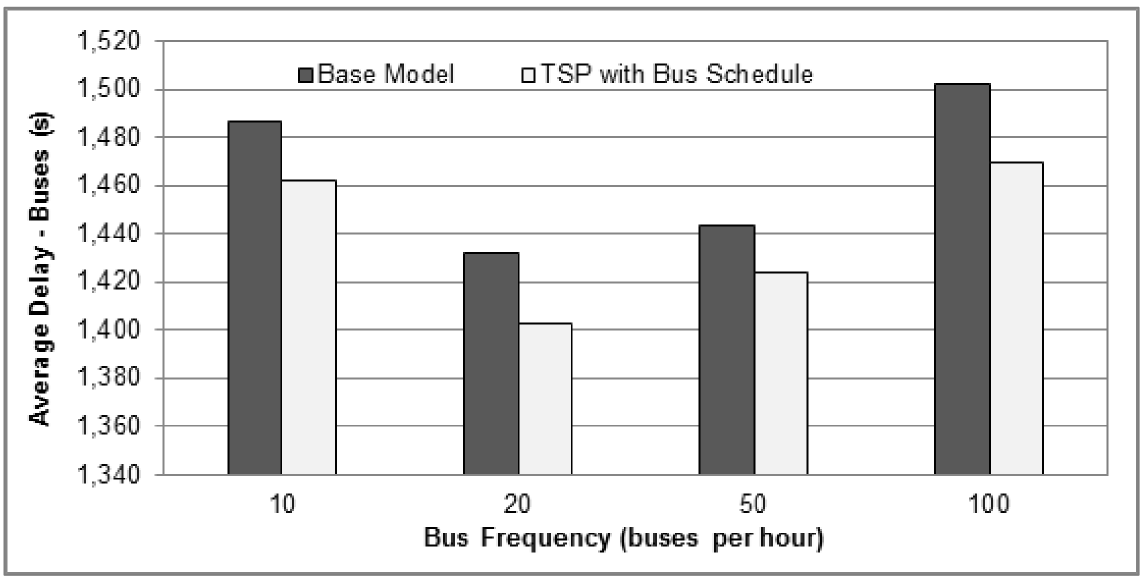


Figure 78: Average Delay for Buses (s).

Table 54 presents the delay results of all vehicles on the network, shown graphically in Figure 79. The results indicate that there is little difference (within 1 percent) between the delay of the base model and the transit signal priority model when considering all vehicles on the network. There also is a trend: As the number of buses increases (e.g., an increase from 50 buses per hour to 100 buses per hour), the delay of all vehicles decreases because of the application of the transit signal priority algorithm, possibly because bus priority reduces delays on El Camino Real, which carries the majority of the traffic.

Table 54: Average Delay for All Vehicles (s).

Bus Frequency (Buses per Hour)	Base Model	TSP with Bus Schedule	Difference	Percentage Improvement
10	207.379	207.972	0.593	-0.29%
20	209.176	210.348	1.172	-0.56%
50	220.814	219.731	-1.083	0.49%
100	238.841	237.715	-1.126	0.47%

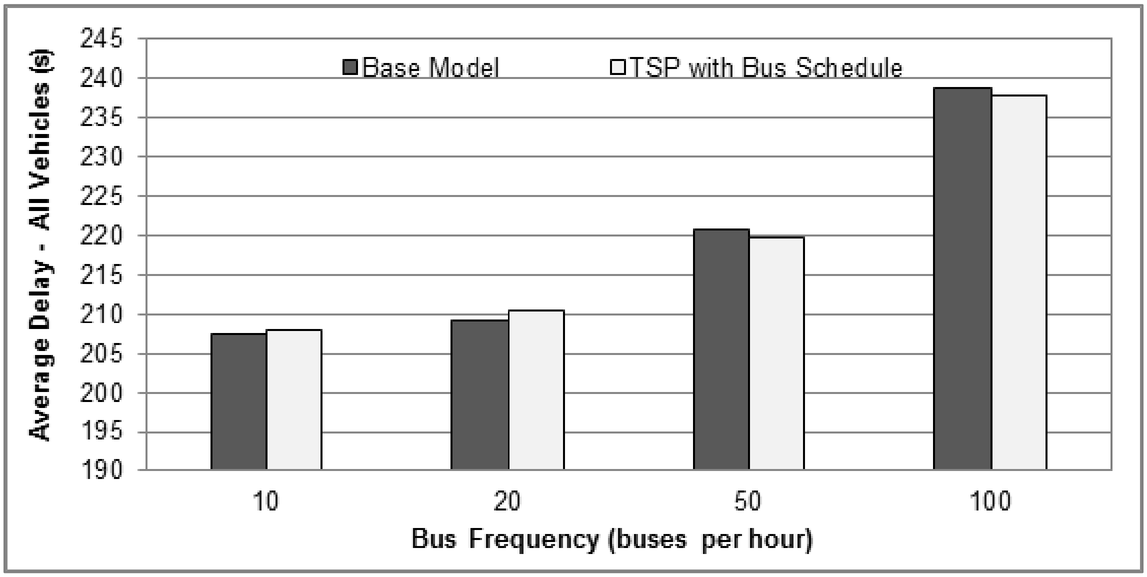


Figure 79: Average Delay for All Vehicles (s).

Summary of Results

The following section summarizes the results of Sensitivity Test 2 to provide an understanding of the impact of bus frequency on the level of emissions and on the delay vehicles within the network experience:

1. Overall, the impact of bus frequency on the level of environmental measures for all traffic on the network is minimal, similar to the findings of Sensitivity Test 1.
2. Emissions level improvements with application of the Eco-Transit Signal Priority model for all vehicles as well as for transit vehicles in isolation are minimal (within a 1 percent). This suggests that the transit signal priority algorithm does not have a significant impact on the level of emissions for a given bus frequency.
3. The results indicate that the Eco-Transit Signal Priority algorithm has a stable, positive impact on average delay of transit vehicles, with improvements of approximately 2 percent. The variation of the average delay of the buses, when plotted, shows a parabolic curve, with the lowest point at 20 buses per hour. The parabolic trend of the delay indicates the presence of congestion on the network with increasing bus frequencies.
4. An interesting result is observed with transit vehicles, where a reduction in delay occurs without a significant improvement in the level of emissions. The reason for that result is that the delay savings do not lead to a significant change in the average speed of the bus travelling through the corridor and thus does not affect the emissions of the vehicles.

Eco-Transit Signal Priority on ECR-27—Demand

The final sensitivity test was conducted to determine whether the level of demand on the network had an impact on the level of emissions and on delay. Similar to Sensitivity Test 2, this sensitivity testing also considered the emissions and delay impacts based on the vehicle type, separating transit vehicles (buses) from all other vehicles. Three separate demand scenarios were considered:

1. Moderate demand, V/C = 0.77
2. Half the demand, V/C = 0.38
3. Higher demand, V/C= 1.00.

For each of these demand scenarios, three communication distance and maximum extension time combinations were selected for assessment based on their favorable performance with respect to emissions during Sensitivity Test 1. These combinations were:

1. Communication Distance = 80 m, Maximum Extension Time = 8 s (average emissions levels change)
2. Communication Distance = 80 m, Maximum Extension Time = 10 s (greatest reduction in emissions considering the without schedule adherence Eco-Transit Signal Priority model)
3. Communication Distance = 120 m, Maximum Extension Time = 8 s (greatest reduction in emissions considering the with schedule adherence Eco-Transit Signal Priority model).

Emissions Results

The emissions results are presented in Table 55; Figure 80 and Figure 81 provide information about the percentage improvement in emissions levels when comparing the Eco-Transit Signal Priority model with the base model. Note that the results presented are specifically for the communication distance of 80 m and the maximum extension time of 8 s. Testing of the other combinations showed results similar to those presented below.

Table 55: Emissions Results for Varying Demand Levels.

Emissions Results (Communication Distance = 80 m; Maximum Extension = 8 s)			
Moderate Demand, V/C = 0.77	**CO_2, Total (gm)**	**CO_2, Buses (gm)**	**CO_2, Other Vehicles (gm)**
Base	6050723	217467.1	5909077
Eco-Transit Signal Priority without bus schedule	6034424	220919.5	5889083
Eco-Transit Signal Priority with bus schedule	6110348	217069.8	5971188
%Δ from Eco-Transit Signal Priority without bus schedule to base	-0.27%	1.59%	-0.34%
%Δ from Eco-Transit Signal Priority with bus schedule to base	0.99%	-0.18%	1.05%
Half Demand, V/C = 0.38	**CO_2, Total (gm)**	**CO_2, Buses (gm)**	**CO_2, Other Vehicles (gm)**
Base	2950869	197336.7	2770421
Eco-Transit Signal Priority without bus schedule	2957999	196016.5	2778857
Eco-Transit Signal Priority with bus schedule	2964743	195850.6	2786100
%Δ from Eco-Transit Signal Priority without bus schedule to base	0.24%	-0.67%	0.30%
%Δ from Eco-Transit Signal Priority with bus schedule to base	0.47%	-0.75%	0.57%
Higher Demand, V/C = 1.00	**CO_2, Total (gm)**	**CO_2, Buses (gm)**	**CO_2, Other Vehicles (gm)**
Base	8607029	229642.1	8545179
Eco-Transit Signal Priority without bus schedule	8777373	226509.8	8721315
Eco-Transit Signal Priority with bus schedule	8652577	227452.8	8593338

Emissions Results (Communication Distance = 80 m; Maximum Extension = 8 s)			
Moderate Demand, V/C = 0.77	**CO_2, Total (gm)**	**CO_2, Buses (gm)**	**CO_2, Other Vehicles (gm)**
%∆ from Eco-Transit Signal Priority without bus schedule to base	1.97%	-1.36%	2.06%
%∆ from Eco-Transit Signal Priority with bus schedule to base	0.53%	-0.95%	0.56%

Figure 82 and Figure 83 show that an increase in the level of demand increases the emissions impact across all vehicles within the network. In addition, implementation of the transit signal priority, in general, results in reduced emissions levels and improvement in environmental measures for buses, but it is a detriment for other vehicles and the overall network. The results of the comparison between the base model and the Eco-Transit Signal Priority model without bus scheduling provides interesting results in that implementation of the transit signal priority for the moderate demand of V/C = 0.77 results in an increase in the level of emissions for buses and a decrease for all other traffic, which is not consistent with all the other results. Furthermore, both Eco-Transit Signal Priority model comparisons indicate that an increase in demand to V/C = 1.00 will lead to considerable improvements in transit emissions but an increase in overall emissions. However, the impact on other vehicles and the overall network is reduced with implementation of bus schedule adherence within the Eco-Transit Signal Priority algorithm.

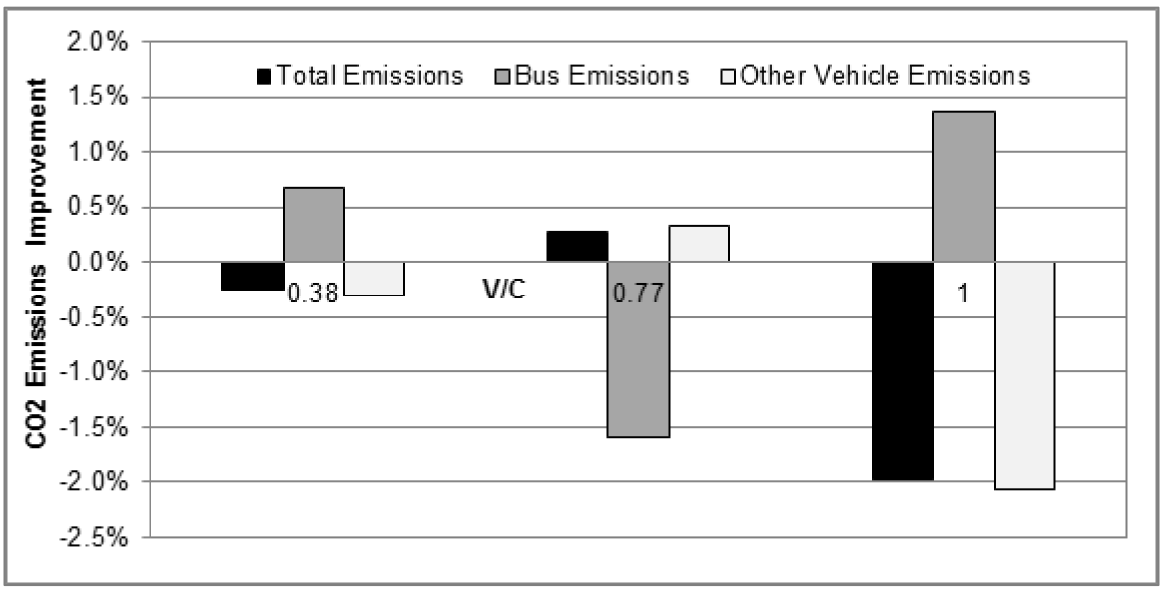


Figure 80: Percentage Improvement in Emissions for Varying Demand Levels Without Bus Scheduling Adherence.

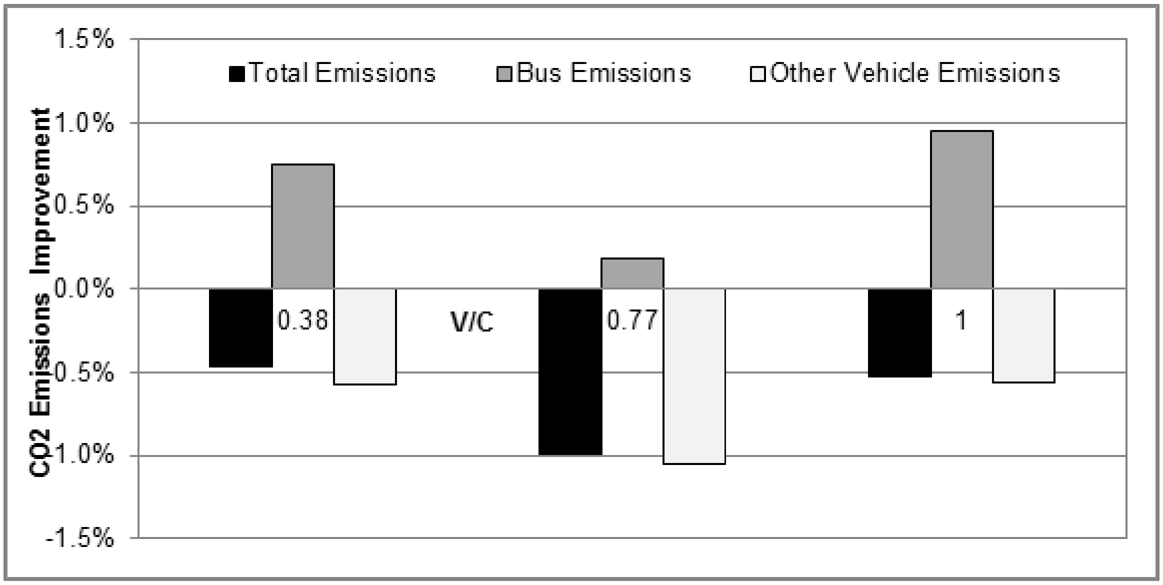


Figure 81: Percentage Improvement in Emissions for Varying Demand Levels with Bus Scheduling Adherence.

As in the first two sensitivity tests, a statistical Z-test was conducted to determine whether the above differences obtained were statistically significant. The results of the Z-test, shown in Table 56, indicate that the above results are statistically insignificant, at a confidence level of 95 percent.

Table 56: Z-Scores for Demand Testing in Network Emission.

Demand Level	Z-Scores (Without Bus Scheduling Adherence Comparison with Base)	Z-Scores (with Bus Scheduling Adherence Comparison with Base)
0.38	0.17	0.35
0.77	0.39	1.37
1	1.84	0.91

Delay results are presented in Table 57; Figure 82 and Figure 83 provide information about the percentage improvement in delay when compared with the base model. As stated before for the emissions results, the following results are presented specifically for the communication distance of 80 m and the maximum extension time of 8 s, and the other combinations provided similar results.

Table 57: Delay Results for Varying Demand Levels.

Delay Results (Communication Distance = 80 m, Maximum Extension = 8 s)					
Demand	**Moderate Demand, V/C = 0.77**				
Model	Base	Eco-Transit Signal Priority without bus schedule	Eco-Transit Signal Priority with bus schedule	%Δ from Eco-Transit Signal Priority without bus schedule to base	%Δ from Eco-Transit Signal Priority with bus schedule to base
Mean Vehicle Delay	213.3	212.354	213.122	-0.44%	-0.00%
Mean Bus Delay	1467.526	1443.586	1447.598	-1.63%	-0.01%
Total Mean Delay	214.68	213.708	214.476	-0.45%	-0.00%

Delay Results (Communication Distance = 80 m, Maximum Extension = 8 s)					
Demand	**Half Demand, V/C = 0.38**				
Model	Base	Eco-Transit Signal Priority without bus schedule	Eco-Transit Signal Priority With bus schedule	%∆ from Eco-Transit Signal Priority without bus schedule to base	%∆ from Eco-Transit Signal Priority with bus schedule to base
Mean Vehicle Delay	194.238	194.584	195.426	0.18%	0.00%
Mean Bus Delay	1402.774	1391.974	1389.312	-0.77%	-0.01%
Total Mean Delay	196.854	197.182	198.016	0.17%	0.01%

Delay Results (Communication Distance = 80 m, Maximum Extension = 8 s)					
Demand	**Higher Demand, V/C = 1.00**				
Model	Base	Eco-Transit Signal Priority without bus schedule	Eco-Transit Signal Priority with bus schedule	%∆ from Eco-Transit Signal Priority without bus schedule to base	%∆ from Eco-Transit Signal Priority with bus schedule to base
Mean Vehicle Delay	273.528	281.43	272.792	2.89%	-0.00%
Mean Bus Delay	1508.262	1476.062	1477.824	-2.13%	-0.02%
Total Mean Delay	274.622	282.492	273.866	2.87%	-0.00%

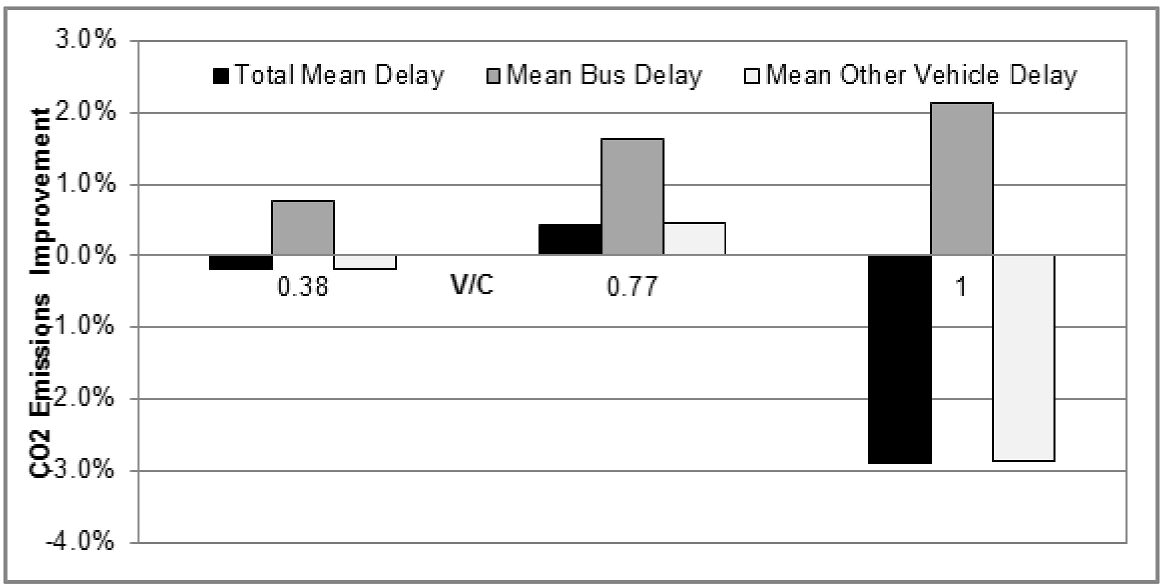


Figure 82: Percentage Improvement in Delay for Varying Demand Levels Without Bus Scheduling Adherence.

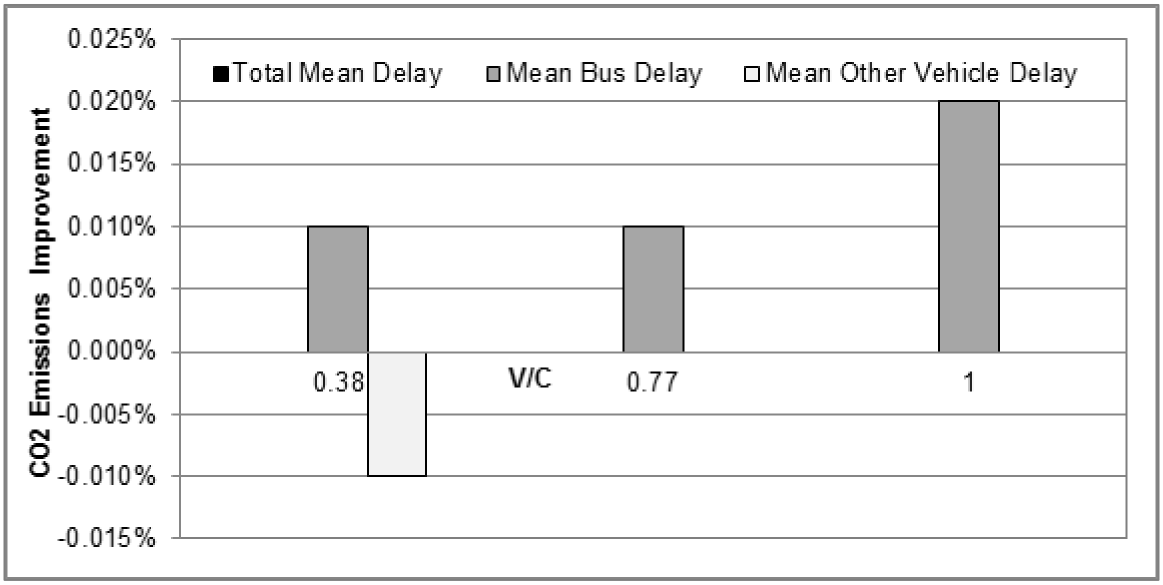


Figure 83: Percentage Improvement in Delay for Varying Demand Levels with Bus Scheduling Adherence.

Table 58: Z-Scores for Demand Testing in Network Delay.

Demand Level	Z-Scores (Without Bus Scheduling Adherence Comparison with Base)	Z-Scores (with Bus Scheduling Adherence Comparison with Base)
0.38	-0.72	-0.23
0.77	0.17	0.57
1	1.91	-0.22

The delay results further indicate that Eco-Transit Signal Priority with bus scheduling adherence outperforms Eco-Transit Signal Priority without bus scheduling adherence. Across all demand cases, Eco-Transit Signal Priority with bus scheduling adherence maintains the total base level of delay for all three delay measurements, with the greatest variation being a 0.02 percent improvement in bus delay.

Figure 82 shows that as demand increases, Eco-Transit Signal Priority without schedule adherence leads to a deterioration in other vehicle delay and in overall network delay by up to 3 percent. However, although there is an increase in delay for other vehicles, buses, in contrast, experience a 2 percent improvement in delay when compared with base conditions. As with the previous testing conducted, it is important to assess the significance of the differences in results between the models; this assessment was performed with a Z-test. Table 58 presents the Z-scores, which are between −1.96 and +1.96, indicating that there are no significant differences between the base model and the transit signal priority modeling.

Performance of the Transit Signal Priority Algorithm: Requesting and Granting Priority

Similar to what was conducted for previous sensitivity analysis with regard to communication distance and maximum extension time, performance of the Eco-Transit Signal Priority algorithm was investigated to assess the validity of the emissions and delay results obtained. As before, the number of times transit vehicles request priority as well as the number of times priority is granted to the vehicles for each of the above demand scenarios was investigated. Table 59 and Table 60 and present the number of requested and granted priorities for the without bus scheduling adherence model and the with bus scheduling adherence model, respectively (communication distance = 80 m and maximum extension time = 8 s). The results are consistent with those observed in the first two sensitivity test scenarios. Requested priority times show no specific trends; however, with increased demand, there is an increase in the number of requests by both models. Greater demand results in increased congestion within the network. As a consequence, buses are delayed on the network and will lie within the communication distance of 80 m for a longer period of time, resulting in more requests from the service. Similar to the other sensitivity tests, the Eco-Transit Signal Priority without bus scheduling model contains a higher number of granted priority numbers than the Eco-Transit Signal Priority with bus scheduling model. This is consistent with the algorithm structure, because priority is granted only for buses that are not adhering to schedule, thus limiting the number of priorities granted.

Table 59: Mean Transit Signal Priority Requested and Granted Times for Demand Testing (Eco-Transit Signal Priority Without Bus Schedule).

Demand Level	Requested Priority Times	Granted Priority Times
0.38	630.6	69
0.77	889.4	67
1	899	65

Table 60: Mean Transit Signal Priority Requested and Granted Times for Demand Testing (Eco-Transit Signal Priority with Bus Schedule).

Demand Level	Requested Priority Times	Granted Priority Times
0.38	717	50
0.77	735.6	43
1	814.4	50

Summary of Results

The following section summarizes the results of Sensitivity Test 3, which was conducted to gain an understanding of the impact of a change in the level of overall traffic demand on the level of emissions and delay that vehicles within the network experienced. The key findings are:

1. Increase in the level of demand increases the emissions impact across all vehicles within the network
2. Implementation of the transit signal priority, in general, results in reduced emissions levels and improvement in the environmental measures for buses; however, in some cases the transit signal priority was found to be detrimental for other vehicles and the overall network
3. The delay results further indicate that the Eco-Transit Signal Priority with bus scheduling adherence outperforms the Eco-Transit Signal Priority without bus scheduling adherence. Across all demand cases, Eco-Transit Signal Priority with bus scheduling adherence maintains the total base level of delay for all three delay measurements, with the greatest variation being a 0.02 percent improvement in bus delay
4. Overall, the differences in the results between the base model and both Eco-Transit Signal Priority models are statistically insignificant, indicating only a minor impact on the system.

Findings and Opportunities for Future Research

Prior to modeling, the hypothesis, generated based on a literature review, stated—

"If [the Eco-Transit Signal Priority] application is used to grant signal priority to selected transit vehicles based on their location, speed, size, vehicle class and traffic, and environmental characteristics of all vehicles at the signalized intersection, then there will be emissions reductions and lowered fuel consumption during congested traffic conditions in the range of 1 percent to 2 percent under partial connected vehicle penetration and 2 percent to 4 percent under full connected vehicle penetration."

The modeling results presented in this technical section are consistent with those reported in previous studies. It was found that the Eco-Transit Signal Priority application results in 1 percent to 2 percent energy savings both for transit vehicles and for the network as a whole while also providing benefit to mobility measures. Such benefit derives from the additional green time on the mainline, which the majority of traffic on the El Camino Real, both connected and unconnected vehicles, shares. The energy savings benefit of the application depends on a variety of factors, including congestion level, penetration rate of onboard and roadside equipment, and communication conditions:

1. Based on the present transit signal priority algorithm framework, a maximum extension time of Eco-Transit Signal Priority of 8 s or 10 s was found to improve performance both in emissions and in delay. These results indicate that there is an optimal maximum extension time that would result in efficient performance.
2. A communication distance of 80 m to 120 m in the case of Eco-Transit Signal Priority with bus scheduling adherence was found to provide maximum benefit for all vehicles on the network. This is significantly lower than the operational communication distance of 300 m and might be attributable to uncertainty in traffic conditions as the communication distance increases. Therefore, in the present algorithmic framework, an optimal communication distance remains to be identified.
3. The results indicate that the Eco-Transit Signal Priority model with bus scheduling outperforms the Eco-Transit Signal Priority model without bus scheduling considering the all-vehicle assessment. This occurs because there are more instances of improvements in the level of emissions when considering the all-vehicle case for the Eco-Transit Signal Priority with scheduling algorithm. The reason is that priority is granted only when it is absolutely necessary for the bus to remain on schedule, thus limiting the impact on links and vehicles entering from adjacent links to the network.
4. Increases in demand affect the environmental measures of the Eco-Transit Signal Priority model without bus scheduling adherence more significantly than they do the Eco-Transit Signal Priority model with bus scheduling adherence compared with base conditions. This is most likely a result of fewer priorities being granted with the scheduling limitation, thus minimizing the overall impact of the algorithm.
5. Overall, the impact of bus frequency on the level of environmental measures for all traffic on the network is minimal.
6. A small increase in average speed over a long corridor results in travel time savings; however, these small changes in speed would have minimal impact on emissions. Given this relationship between speed and travel time and between speed and emissions, a larger improvement in travel time was observed compared with emissions.

Based on the above findings from the modeling effort, the research team presents the following recommendations and remarks:

1. Given the inverse relationship between speed and travel time, a small change in speed could significantly influence delays without having a significant impact on emissions.
2. Among the scenarios tested, it was observed that incorporating bus scheduling into the transit signal priority framework provides the greatest benefit from an overall emissions perspective, and these benefits are greater under more congested conditions.
3. Only green extension and red truncation were used in the Eco-Transit Signal Priority model. In further investigations, more options may be applied, such as phase insertion and phase rotation.
4. A possible extension to gain maximum benefit from larger communication distances could involve providing a continuous beacon that re-computes the time at which the priority is granted as well as changes the extension dynamically. However, its impact on offsets and cycle length must be explored.
5. Expected average speed of buses in the bus scheduling model is preset to be 30 kph (18.64 mph), which decides the extent of the constraint on the Eco-Transit Signal Priority model. Further modeling is required to assess the sensitivity of this parameter.
6. Based on the results of sensitivity tests, which evaluated the impact of bus frequency, it would be beneficial to assess the relationship between the average speeds of vehicles and the change in the level of emissions.
7. Future investigations should consider passenger delay and number of passengers in the transit vehicle as criteria for assessing a priority request.

Eco-Freight Signal Priority

Algorithm

This section describes the algorithm and sub-algorithms used to implement the Eco-Freight Signal Priority application. The application was designed to simulate connected vehicle technology by detecting and monitoring a freight vehicle's position and characteristics in real time, using this information to detect and process priority requests from those vehicles. In addition to the main algorithm, it includes three complementary sub-algorithm modules that are called on as needed to assist in the process and determine if priority should be granted. Figure 84 shows the entire Eco-Freight Signal Priority algorithm, including the three sub-algorithms. The Paramics microsimulation model API calls this algorithm to start once per user time step (twice per second) for each vehicle in the network. This algorithm will only be activated when the vehicle is within the user-specified equipment communication range. For the majority of the analysis, the DSRC range of 300 m was used for the equipped traffic signals, but additional sensitivity analyses were conducted to show distances far beyond the current limitations.

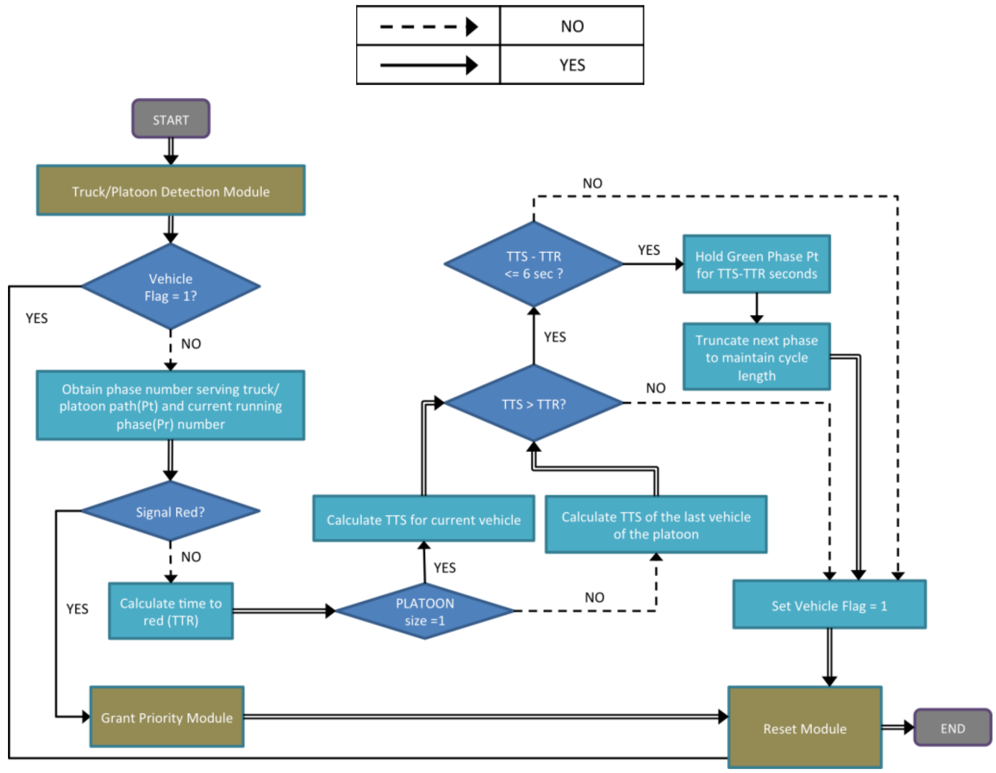


Figure 84: Detection, Priority Request, and Treatment of Freight Vehicles by the Eco-Freight Signal Priority Algorithm.

When the RSE detects a truck within range of the equipped signal, the Truck/Platoon Detection module is called, which is shown in detail in Figure 85. The Eco-Freight Signal Priority algorithm was designed to give priority based not only on a vehicle's location and speed but also on its size, weight, and emission rates as well as on whether it is within a platoon of similar freight vehicles. The Truck Platoon Detection module, by searching the link and by communicating with nearby freight vehicles, determines whether the vehicle is traveling as part of a platoon. In the Eco-Freight Signal Priority algorithm, *platooning* refers only to freight vehicles that are traveling in a vehicle platoon within a given headway threshold (T_p). In the case of the Eco-Freight Signal Priority algorithm, platoons were considered for trucks approaching the intersection in the same lane. This is important so that so that closely spaced platoons of freight vehicles can share the same priorities and have a greater impact on emissions and fuel savings. Therefore, higher priority is given to platoons of trucks on the same approach to the signalized intersection. The API coding in Paramics for the detection module was designed to have the lead truck on the approach to the intersection seek out any trucks within its V2V range and determine whether they are within a T_p of less than or equal to 2.5 s. This value was determined based on collected research about platooning in regard to priority from Liu et. al.

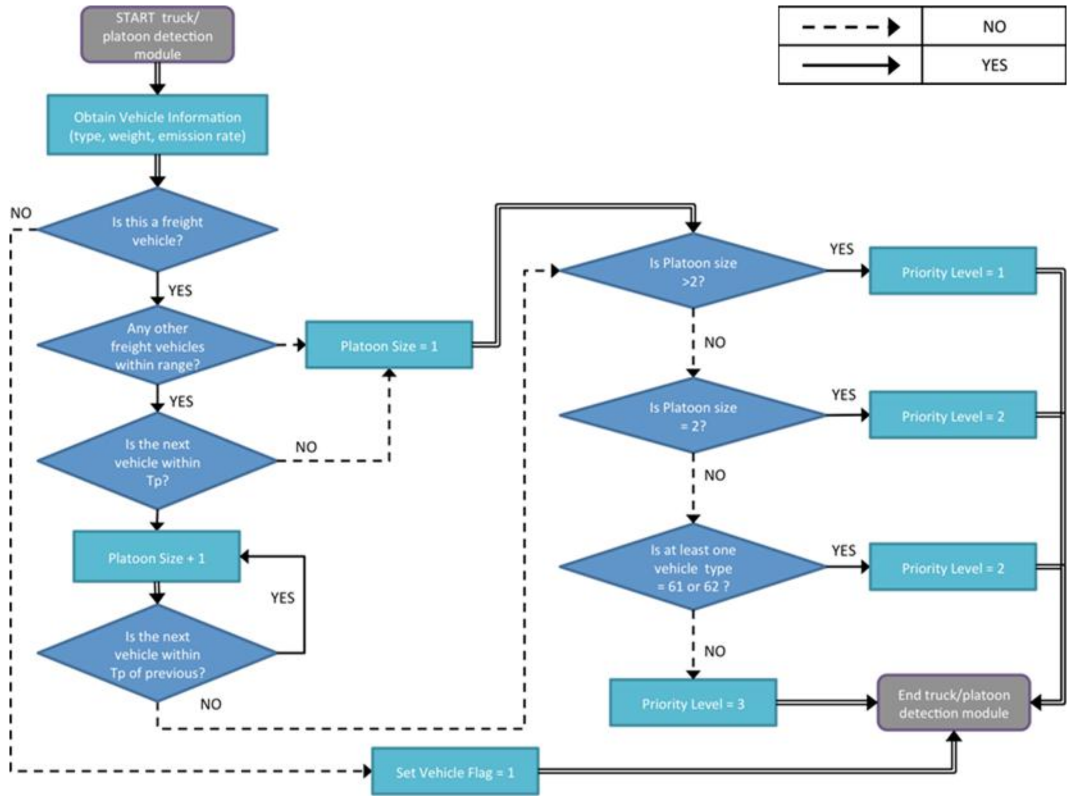


Figure 85: Truck/Platoon Detection Module.

The platoon information, in combination with the information about the freight vehicle's physical characteristics, is used to determine the freight vehicle's priority level. The assigned priority level is then used to determine what type of priority can be considered for this specific vehicle or platoon of vehicles. Table 61 shows the priority levels and the treatment applied to each. In this algorithm, all priority levels have the ability to request a green extension based on their proximity to the intersection and arrival profile on the approach. Priority Level 3 is not allowed to request an early red termination because it is the least important class. Priority Levels 1 and 2 get early red termination for 6 and 3 seconds, respectively. While researching traditional signal priority applications, it was determined that a maximum extension threshold was necessary to prevent significant damage to operations on the side streets or to damage coordination within the corridor. A value of 6 seconds was assumed for this analysis.

Table 61: Priority Levels and Their Treatment by the Freight Signal Priority Algorithm.

Priority Level	Treatment
Prio_level 1	Early red termination if the current phase ends in less than 6 seconds or hold green
Prio_level 2	Early red termination if the current phase ends in less than 3 seconds or hold green
Prio_level 3	Hold green only

As shown in Table 61, the highest priority level is assigned to platoons of more than two freight vehicles. The next priority level is assigned to combination trucks that are loaded or to a platoon of two freight vehicles in which at least one of them is either loaded or a combination vehicle. The lowest priority level is assigned to all other freight vehicles that do not meet any of the criteria mentioned above. The priority levels logic was inspired by research that used different treatments for platoons based on their size. Following similar logic, different treatments were applied to vehicles or platoons based on their emission levels. The vehicle types used in the analysis were based on the MOVES standard vehicle types, listed in Table 62 with their descriptions. For the purpose of this analysis, the MOVES vehicle type was used as a proxy for determining the emissions profile of vehicles approaching the intersection. Each MOVES vehicle type has a known emissions rate that was used instead of real-time monitoring of emissions to determine the eco-benefit of priority for a freight vehicle. For a given average speed of the vehicle, its vehicle-specific power is computed. Based on the vehicle specific power, a vehicle's emissions can be estimated. Using the MOVES vehicle type, emissions rates significantly reduced computational complexity and simplified the algorithm.

Table 62: Freight Vehicles Used in the Model.

MOVES Vehicle Type	Description	Unit
32	Light commercial truck	Single unit
52	Single-unit short-haul truck	Single unit
53	Single-unit long-haul truck	Single unit
61	Combination short-haul truck	Combination
62	Combination long-haul truck	Combination

In addition, for this analysis, the only fuel type that the MOVES model considered was modern gasoline engines for all types of freight vehicles. Any possible hybrid, alternative fuel, and electric freight vehicles that could be developed in the future could have an impact on the operations of the Eco-Freight Signal Priority algorithm when determining priority from conflicting approaches; however, this was not considered here. The introduction of alternative fuel types to the algorithm would require additional improvements to the algorithm to better benefit the priority types discussed above. Because the vehicles all have the same fuel type, the emissions can be classified simply by MOVES vehicle type, but with different fuel types, an electric vehicle of type 62 could have lower environmental impact than a gasoline type 32 freight vehicle. With the introduction of this complication, the priority types would have to be expanded to include additional considerations, including how vehicles on opposing approaches are considered with different fuel types.

After the Truck/Platoon Detection Module is run, the main algorithm (Figure 84) determines whether the freight vehicle or group of freight vehicles has already been granted or denied priority by checking the vehicle's flag. If the freight vehicle has already been given a flag, the algorithm is terminate, which was designed as a way to save on computational resources by preventing unneeded checks. If the vehicle has no flag, the algorithm gathers all relevant SPaT information from the signal, including current phase, phase number of serviced freight vehicle, time to red/green, and distance of vehicle to the signal. This information is used to determine on what phase the vehicle will arrive at the signalized approach. If the current phase is the desired green phase, the algorithm determines whether the vehicle will arrive before the termination of the phase. If the vehicle will arrive before the phase ends, then nothing is done and the algorithm is terminated; otherwise, the algorithm determines the difference between the time to signal (TTS) and the time to red. This difference is the amount of time that the green signal will need to be extended to service the freight vehicles. In the case of freight vehicles traveling in platoons, the TTS is calculated from the last vehicle in the platoon to make sure that the vehicles continue to travel together along the green wave in an effort to reduce emissions. The green time extension is also subject to the maximum threshold of 6 s, and no priorities will be granted that violate this maximum.

If the current phase on the approach of the freight vehicle is red, then the Grant Priority module is called to determine the probability of granting early red termination for a freight vehicle. This module is shown below in in detail.

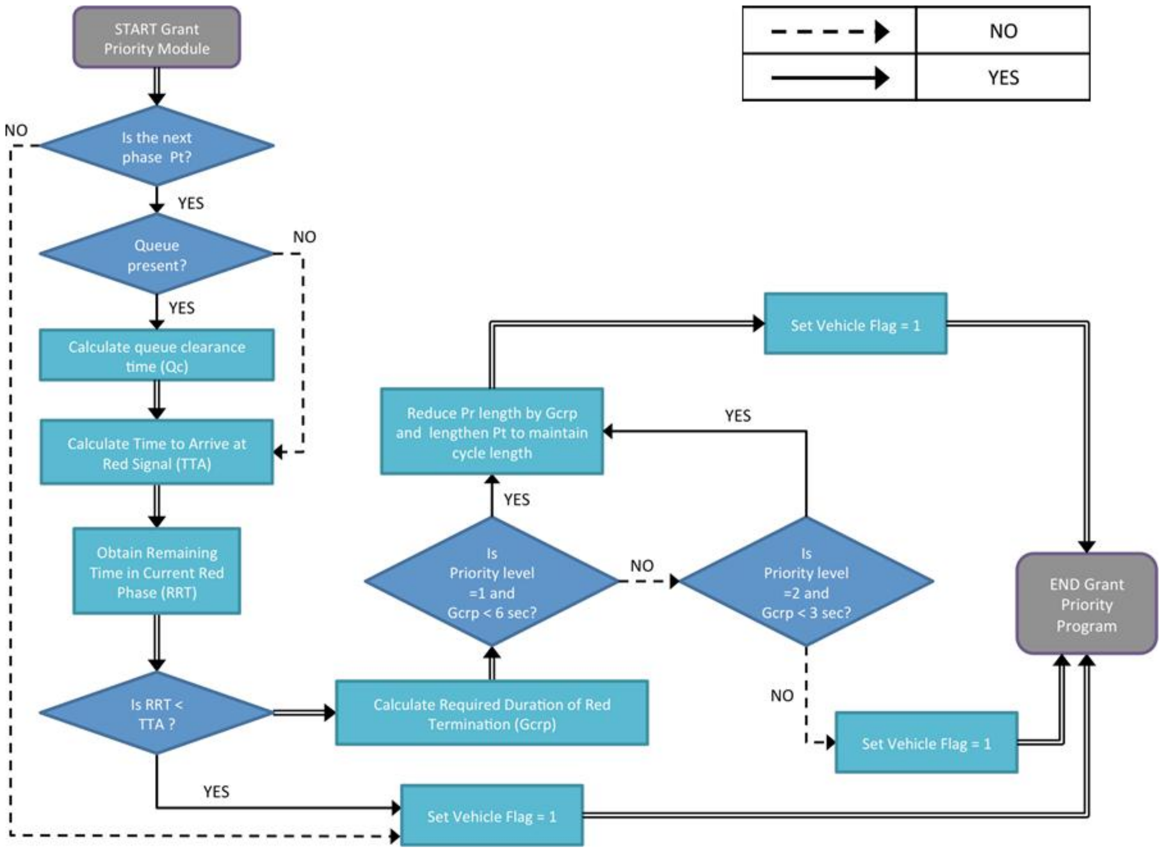


Figure 86: Grant Priority Module Algorithm.

The module uses a combination of speed profiles and the current queue dissipation time to determine when the vehicle will arrive at the stop line in relation to the end of the current red phase. The Eco-Freight Signal Priority algorithm did not consider reordering of phases or advanced pre-emption techniques in the interests of preserving corridor coordination. Therefore, the module in Figure 86 first determines whether the desired green phase (P_t) is the next phase that the controller services; if this is false, then the algorithm is terminated, and the vehicle is flagged. One of the most important features of the module that is needed to determine the time needed to be removed from the red phase in the case of early red termination is the queue dissipation calculation. A priority is not useful if the freight vehicle arrives to a green signal but the queue has not yet discharged. To this point, the module will determine whether a queue exists in the lane of the freight vehicle as it approaches, and then calculate the necessary queue clearance time (Q_c) with the following formula:

$$Q_c = \frac{(Number\ of\ Vehicles\ in\ Queue + 1)}{1800} \times 3600$$

The module then needs to calculate the required duration of the proposed early red termination priority. To do this, the SPaT information is obtained to determine the remaining time left in the red phase immediately preceding P_t as well as the actual time of arrival of the freight vehicle at the signal, taking into account the real-time queue times. The time for the freight vehicle to arrive at the signal (TTA) is given with the following formula:

$$TTA = TTS + Q_c$$

If the TTA is greater than the remaining time in the red phase (RRT), then there is no need to provide a priority, because the freight vehicle will arrive at the green phase, with the queue already dissipated in front of it. In this case, the vehicle receives a flag, and then the sub-algorithm module is terminated. If the TTA is less than RRT, then the module calculates the required duration of the early red termination priority (G_{prc}) as the difference between these two variables. The variable G_{prc} is the amount of time that the phase will be reduced. Depending on the priority level that was assigned to the freight vehicle in the Truck/Platoon Detection module, the algorithm determines whether G_{prc} is within the maximum thresholds to grant the priority. If G_{prc} is within the thresholds, then the phase duration is shortened, the vehicle is flagged, and the module is terminated back into the main Eco-Freight Signal Priority algorithm.

With regard to the complexity and computation time of the algorithm for a large corridor that has a large freight demand, a vehicle flag is added after a priority is either granted or denied to ensure that a vehicle does not continue to request priority when it is not necessary. Regardless of whether the algorithm is granting or denying an early red termination or a green extension, the last process is to call the Reset module to assess and clear any flags that remain on vehicles after the priority request has expired. The Reset module assesses whether the freight vehicle has just passed the signalized intersection for which priority was analyzed and resets the flag just as it crosses the center of the intersection. This is necessary so that the vehicle can begin to assess priority at the next intersection along the corridor. In addition, the Reset module serves to reset the green times to their stored values at the end of every cycle length. This is done to limit the damage to the coordination of signals along the corridor over time. The details of the Reset module are shown in Figure 87.

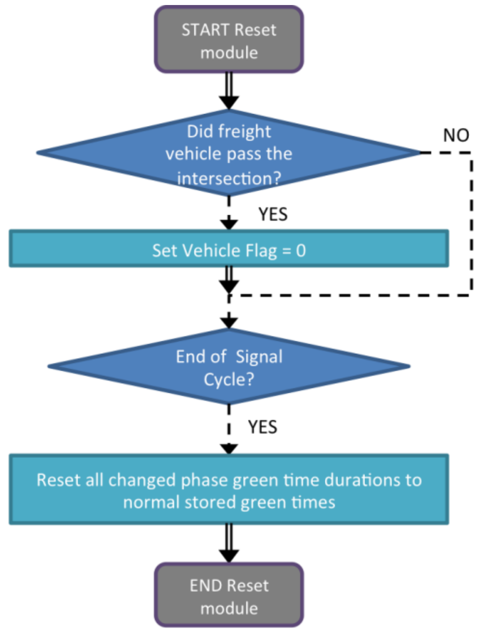


Figure 87: Reset Module.

The Eco-Freight Signal Priority algorithm shown in Figure 87 does not have any part that specifically limits the number of times a priority can be granted on the same approach during one cycle, but rather this is naturally accomplished by the nature of the process. Given the approach mechanics of the arrival on red, an early red termination priority can be granted only once to an approach in a given cycle, because after the first vehicle that is given this early termination, the following vehicles will now calculate that they will arrive at green and no longer need to request a priority. A green extension, however, can be granted for as many freight vehicles as possible on a single approach as long as the cumulative extension requested by all vehicles is less than the maximum threshold of 6 s.

Although rare, there is the possibility of two freight vehicles approaching the same signalized intersection from separate approaches, requesting a green extension and red termination at the same time. The algorithm shown in Figure 87 does not explicitly account for this situation, but the mechanics of the algorithm and the simulation would take care of the situation if it occurred. The algorithm will generally give priority based on the arrival time of the vehicle's proximity to the intersection, meaning that if the two vehicles are of similar priority, then the one that communicates with the signal first will be considered first. If priority is granted, then the opposing vehicle would be ignored to prevent a conflict or signal problems. If priority is denied to the first vehicle, then the second vehicle can be considered as usual. Other cases are taken care of naturally, such as a low-priority vehicle that cannot request early red termination. In the case of the corridor used for this analysis, the most common situation for this problem would be a side street freight vehicle requesting a green extension while a mainline vehicle is requesting an early red termination. However, the side-street traffic is relatively low, and the probability of this occurring is low.

One other aspect of the potential priority-granting process that is not considered in the Eco-Freight Signal Priority algorithm is the potential impact of hurting side streets when a large queue exists. If the freight vehicle is granted priority on the mainline while there is a large queue on the side street, this may be a worse decision in terms of environmental benefits than the decision to simply do nothing.

This aspect of the algorithm was not used for several reasons, most having to do with using the MOVES types as a proxy for real-time emissions profiles. Because the emissions are not being monitored on the side streets, this information is not currently available to the algorithm. Nevertheless, this information could be added as a secondary check within the algorithm and the Truck/Platoon module, as necessary, using the MOVES real-time APIs that the team designed. Another reason for this is that with the AERIS project, the team used the El Camino Real Paramics model, which is a corridor with light side-street traffic. Therefore, in this case, this situation would not exist for this analysis. This situation should be considered, however, when expanding this application to other possible areas in different cities.

Modeling Approach

The microscopic traffic simulation software Paramics was used to model in detail the movement of individual vehicles and their interactions. To be consistent with the modeling efforts on other AERIS applications, the latest version of Paramics (6.9.3) was used.

As part of the evaluation, detailed speed profiles of every vehicle were examined to estimate emissions and energy consumption. As part of the programming environment, Paramics supports the development of plug-ins using its API, which enables users to interface with its core simulation engine to perform specific tasks. The interaction among different models and the API used in this application is shown in Figure 88. The Eco-Freight Signal Priority application plug-in is designed to fulfill the following functions:

1. Freight vehicles submit priority requests.
2. Calculations are performed to assign priority level.
3. Grant or deny priority.
4. Update signal timings.

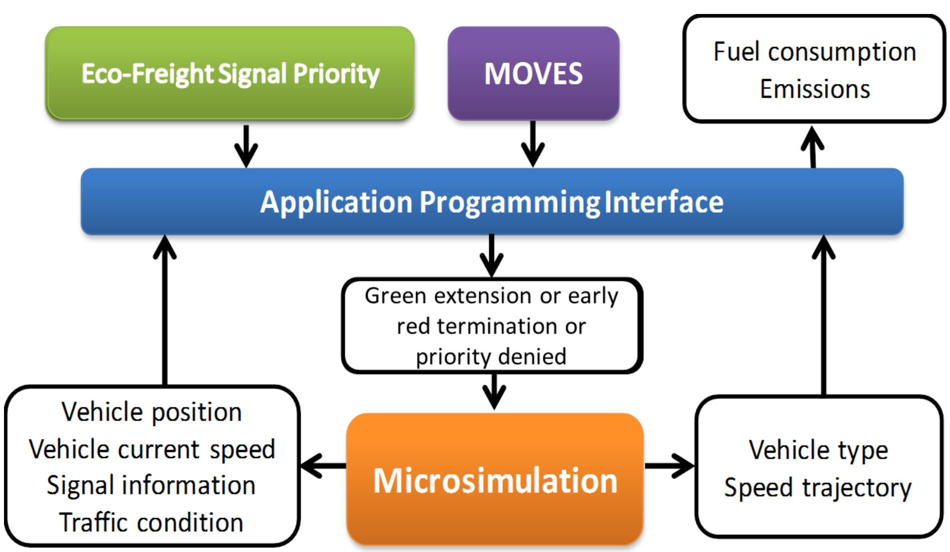


Figure 88: Diagram of Interactions between the Models and API.

Scenarios

An exhaustive set of scenarios was modeled for each application. The remainder of this section details the scenarios modeled. The modeling results that follow in the next section are organized in the same fashion.

The network used for modeling the scenarios was displayed in El Camino Real 27-Intersection Network (Referred to as ECR-27). The following scenarios were modeled:

- **Eco-Freight Signal Priority on ECR-27—Connected Vehicle On-Board Equipment Penetration Rate:** The Eco-Freight Signal Priority application was modeled on ECR-27 at the demand of V/C = 0.83. The truck percentages in the scenarios were varied, with values 1.2 percent from baseline and 10 percent. The OBE penetration rates used were 20 percent, 25 percent, 50 percent, 65 percent, 80 percent, and 100 percent.
- **Eco-Freight Signal Priority on ECR-27—Percentage Trucks:** The Eco-Freight Signal Priority application was modeled on ECR-27 at the demand of V/C = 0.83. The OBE penetration rate was assumed to be 100 percent. The truck percentage values used were 1 percent, 5 percent, 10 percent, 15 percent, 20 percent, and 25 percent.

- **Eco-Freight Signal Priority on ECR-27—Demand** Level**:** The Eco-Freight Signal Priority application was modeled on ECR-27 with a 100 percent OBE penetration rate. The demand levels were varied using V/C ratio values 0.38, 0.83, and 1.0.
- **Eco-Freight Signal Priority on ECR-27—Communication Range**: The Eco-Freight Signal Priority application was modeled on ECR-27 with a 100 percent OBE penetration rate and a demand of V/C = 0.83. The values used for communication distances were 50, 100, 200, 300, 400, 500, and 600 m.
- **Eco-Freight Signal Priority on ECR-27—Communication Delay:** The Eco-Freight Signal Priority application was modeled on ECR-27 with a 100 percent OBE penetration rate and a demand of V/C = 0.83. The values of communication delay used were 0, 1, 2, 5, and 10 s.
- **Eco-Freight Signal Priority on ECR-27—Additional Analyses on Granting of Priorities:** A comparative analysis of the number of priorities requested and those granted at different demand levels was carried out. The maximum extension time was also varied using values 4, 6, 8, 10, 12, 14, and 16 s.

Modeling Results

To assess the benefits of the Eco-Freight Signal Priority application, baseline models were developed with the assumption that there was no application deployment (i.e., connected vehicle penetration rate is 0). The environmental impacts were estimated by the MOVES API plug-in. Emissions and travel time statistics were collected from each baseline simulation run to establish the baseline conditions. The application benefits were then measured by comparing the performance of the networks with the Eco-Freight Signal Priority application algorithm active. Then, a variety of sensitivity scenarios were generated to characterize the detailed behavior of the application under different conditions, such as varying vehicle demand, percentage of trucks, communication range and delay, and OBE penetration rates.

For all of the modeling scenarios discussed in the following sensitivity analyses, one variable will be varied in each case while keeping the other variables constant, such as demand or percentage trucks. Unless otherwise stated, assume that the baseline demand ratio, percentage trucks, communications equipment, and others are set to the baseline value. As previously stated, many of the analyses used 10 percent trucks to simulate higher freight situations, but this will be stated in each analysis section. The communication technology used in this analysis is assumed to be a version of DSRC, with a maximum communication range of 980 feet (300 m), with no communication delay or lagging.

For purposes of the Eco-Traffic Signal Timing application, we assumed that all of the intersections along the El Camino Real in the microsimulation models are equipped with connected vehicle RSE technology. This assumption is based on the fact that the system infrastructure would need to be in place, because connected vehicle equipment will become commonplace on the roadways. These RSEs would serve to pass signal timing information to the vehicle approaching the intersection, and then the vehicle would be responsible for the calculations required to determine priority. The decision to grant priority would then be passed back to the RSE to implement the change in timing to the controller.

Eco-Freight Signal Priority on ECR-27—Connected Vehicle On-Board Equipment Penetration Rate

Connected vehicles will be released on a “rolling” implementation over time; therefore, it is important to analyze the impacts of the Eco-Freight Signal Priority application at varying levels of OBE penetration rates. This makes it is easy to determine whether the application will provide benefits to motorists and to the system as it is being introduced or whether it will provide benefits only after it has been fully adopted at some time in the future. As part of this analysis, freight vehicles were analyzed separately for connected and unconnected vehicles to assess the impact on both, because the penetration rate varies. The different levels of OBE implementation were tested on the El Camino Real network with the baseline demand ratio and OD patterns. The model was also tested for two conditions, one representing the baseline truck percentage of 1.2 percent and the second representing a heavier demand of trucks in the network at 10 percent of the total traffic volume.

Figure 89 presents the fuel savings results with increasing levels of OBE penetration rates of connected vehicle technology, considering both the mainline flow and cross-street traffic for the baseline freight demand condition of 1.2 percent of the total vehicular OD demand.

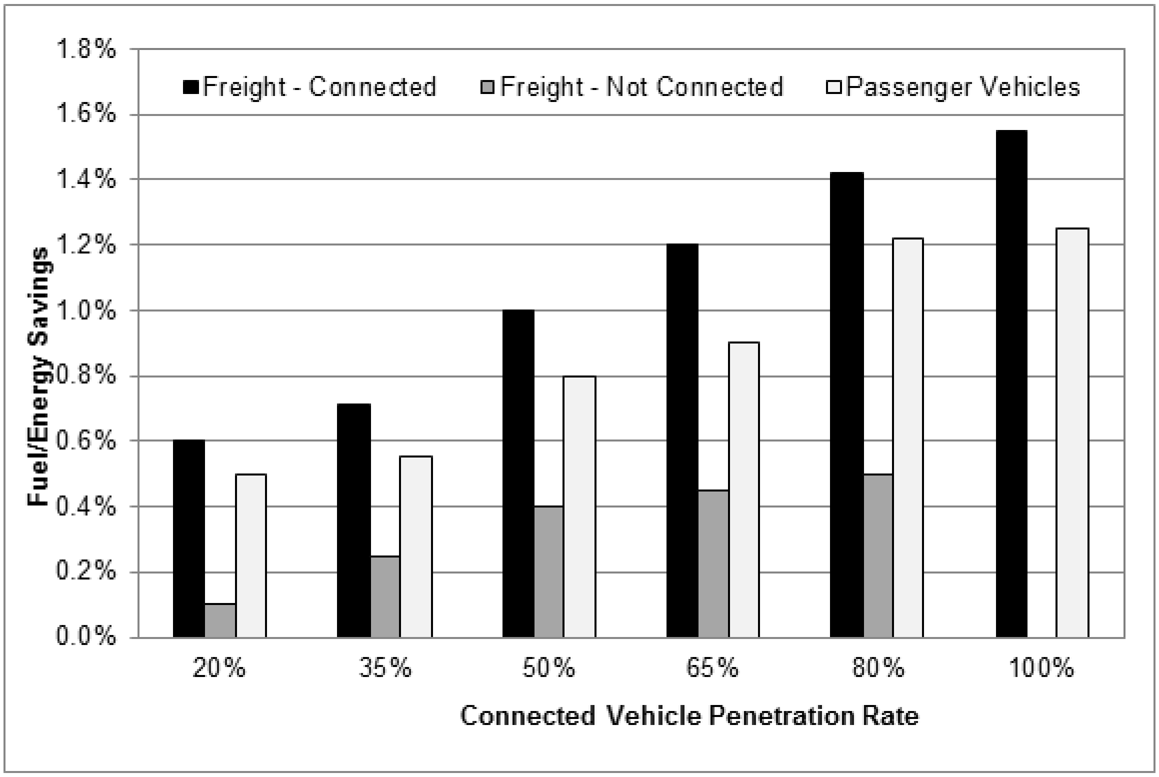


Figure 89: Fuel Savings vs. Connected vehicle OBE Penetration Rate During Morning Peak for Baseline Freight Demand.

The results indicate that increasing fuel and emissions savings can be achieved as the connected vehicle penetration rate increases. In addition to the savings in the connected freight vehicles on the mainline, the non-connected freight vehicles as well as the passenger cars are getting a small increase in fuel savings, as well, as the implementation rate increases. The maximum savings, however, are lower than were expected to be when granting priorities to freight vehicles in the network. It has been stated in this section that not only was the application intended to be modeled in a freight-heavy area but that it was expected that the application would be more useful as in this situation in general. To this end, the analysis was repeated to simulate a more used freight corridor to gain more insight into the situation.

To better understand the application in a higher freight demand situation, the connected vehicle OBE rate was tested for 10 percent freight demand. Figure 90 presents the fuel savings results with increasing levels of OBE penetration rates of connected vehicle technology, considering both the mainline flow and cross-street traffic for the increased freight demand condition. Like the previous analysis, results for passenger vehicles are shown in the figure in addition to results for freight vehicles.

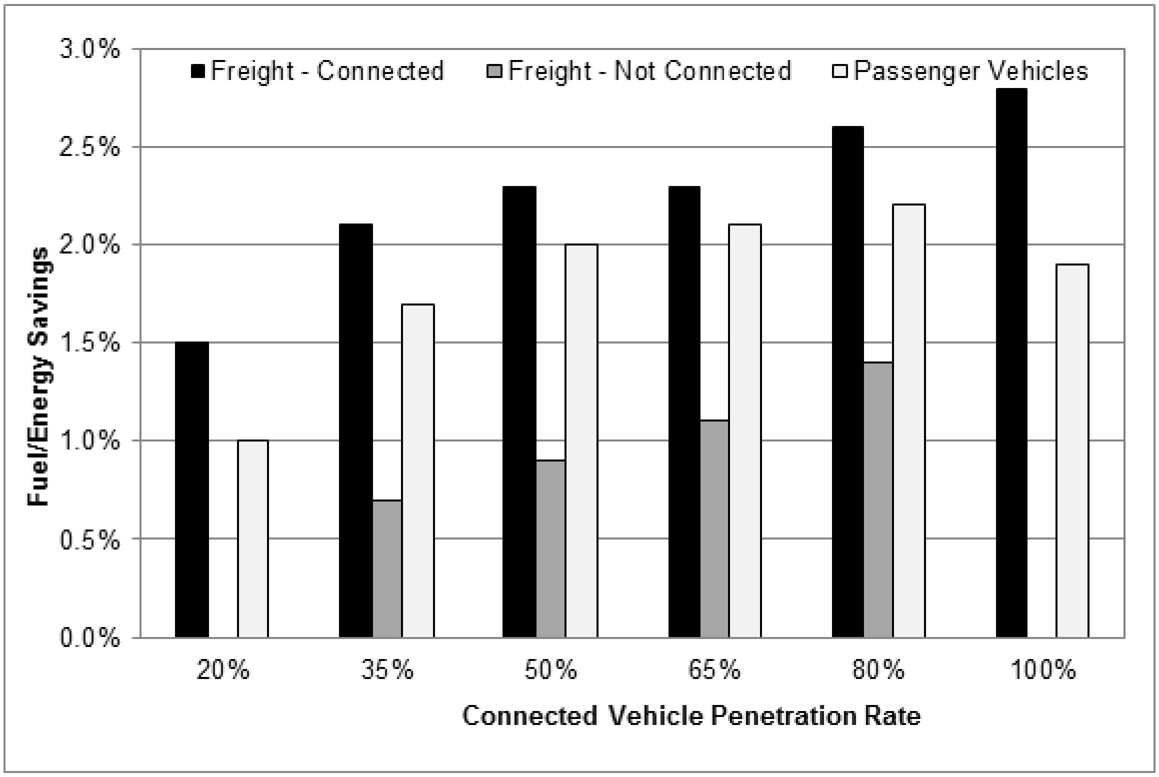


Figure 90: Fuel Savings vs. Connected vehicle OBE Penetration Rate during Morning Peak for 10 Percent Freight Demand.

Figure 90 shows other important results, as well, especially regarding the interaction among the three types of vehicles. Even at a low OBE penetration rate (i.e., 20 percent penetration), connected freight vehicles and all passenger vehicles along the corridor achieve significant savings. The results of all analyses indicate that there is a corollary improvement of non-freight vehicles along the mainline, because the granted freight signal priorities provide more green time, which is available to all vehicles using that approach. Because the majority of vehicles along the El Camino Real are non-freight passenger vehicles, they also receive significant benefits. However, as the connected vehicle penetration rate increases, the number of signal priorities granted for connected freight vehicles increases; therefore, the chances of an unconnected freight vehicle sharing a green priority increases as penetration increases, resulting in additional benefits.

An additional impact shown in the figure is that although passenger vehicle fuel savings increase as penetration levels increase, when the system reaches full penetration, there is a slight reduction in those savings, likely because there is a “tipping point” at which the impact on side-street traffic lessens the amount of improvement on the mainline. This effect would be more pronounced in passenger vehicles in than freight vehicles because of the ratio of the fleet mix. It would not be as equally pronounced in the freight vehicles, because the percentage of freight vehicles in the traffic demand would result in a lower probability of waiting freight vehicles on the side streets. Therefore, although there are occasionally freight vehicles on the side-street approaches, they are not equally subject to this phenomenon.

Additional results for fuel use and for emissions for different connected vehicle penetration rates are shown in more detail in Table 63. The results are presented separately for freight vehicles and for passenger vehicles in the network.

Table 63: Energy Consumption and Emissions with Penetration Rate from 0 Percent to 100 Percent for Freight Vehicles as Well as Total Vehicular Traffic.

Freight Vehicles						
Connected Vehicle Penetration (%)	**Energy (kJ)**	**CO_2 (g)**	**CO (g)**	**HC (g)**	**NOx (g)**	**PM (g)**
Baseline	57,666,880	4,103,858	53,397.8	1,982.4	10,216.3	45.79
20	57,514,731	4,103,412	53,608.1	1,970.5	10,206.9	45.86
35	56,974,522	4,048,408	53,026.1	1,954.7	10,151.6	45.43
50	56,754,320	4,037,880	52,795.4	1,942.8	10,068.2	45.00
65	56,561,573	4,025,349	52,684.6	1,938.1	10,052.8	45.13
80	56,315,226	3,992,731	52,349.2	1,912.9	9,972.4	44.94
100	56,055,963	3,989,193	52,220.4	1,919.6	9,945.1	44.87
Savings (%)						
20	-1.5%	-0.2%	-1.2%	-2.8%	-2.1%	-0.1%
35	-2.1%	-2.6%	-1.0%	-2.2%	-2.0%	-0.4%
50	-2.3%	-2.3%	-1.9%	-3.0%	-2.3%	-2.7%
65	-2.3%	-2.2%	-1.4%	-2.4%	-1.8%	-1.4%
80	-2.6%	-2.8%	-2.1%	-3.6%	-2.4%	-1.6%
100	-2.8%	-2.8%	-2.2%	-3.2%	-2.7%	-2.0%

Passenger Vehicles						
Connected Vehicle Penetration (%)	**Energy (kJ)**	**CO_2 (g)**	**CO (g)**	**HC (g)**	**NOx (g)**	**PM (g)**
Baseline	95,213,820	6,746,813	52,048.7	349.7	1,084.9	103.71
20	94,244,525	6,693,024	52,272.1	352.6	1,090.1	104.04
35	93,655,552	6,662,460	51,492.5	352.8	1,084.5	104.29
50	93,332,479	6,632,065	51,735.5	352.7	1,085.9	104.22
65	93,257,628	6,533,416	51,146.0	350.0	1,071.2	103.23
80	93,107,832	6,615,950	51,562.7	349.7	1,074.5	103.36
100	93,378,446	6,619,762	51,462.7	345.9	1,073.2	102.43
Savings (%)						
20	-1.0%	-0.8%	0.4%	0.8%	0.5%	0.3%
35	-1.7%	-1.3%	-1.1%	0.9%	0.0%	0.0%
50	-2.0%	-0.6%	-0.4%	-0.3%	-0.3%	-0.5%
65	-2.1%	-3.3%	-2.2%	-2.2%	-2.1%	-2.5%
80	-2.2%	-1.9%	-0.9%	0.0%	-1.0%	-0.6%
100	-1.9%	-1.9%	-1.1%	-1.1%	-1.1%	-1.3%

As shown in the results of this sensitivity analysis, there are improvements in the emissions and fuel consumption for all vehicles in the network, both freight and passenger and transit vehicles. Through these results, the patterns of who benefits from these improvements can be understood from the improvements in environmental measures. As stated previously in this section, the El Camino Real corridor is a mainline pass-through roadway, with the majority of the passenger, freight, and transit vehicles of the east and west approaches. As a result, when additional green time is allocated to the mainline approaches through the granting of signal priority, the majority of the vehicles benefit from this action. The only vehicles that experience a no benefit from this are the vehicles on the side streets that are queuing during the priority action. However, because there is a net positive benefit of around 3 percent, the benefits far outweigh the disadvantages.

Eco-Freight Signal Priority on ECR-27—Percentage Trucks

The Eco-Freight Signal Priority application was originally intended to be modeled in a freight-heavy corridor, the Port of Los Angeles Paramics model, but the model was unavailable for use. In addition, all other Eco-Signal Operations applications within the operational scenario were modeled in the El Camino Real network. It is understood that the number of freight vehicles in the system has a direct impact on the effectiveness and operation of the Signal Priority API. Therefore, the El Camino Real network was modified to run with a varying percentage of trucks to determine the impact of the number of freight vehicles in the network on the overall workings of the application. For this analysis, the connected vehicle OBE penetration rate was assumed to be 100 percent of the vehicles and all of the other baseline conditions were used, such as demand ratio and communication equipment.

Figure 91 presents the fuel savings with an increasing percentage of trucks (baseline levels to 25 percent), considering both the mainline flow and the cross-street traffic. The results are presented for the freight vehicle class separately and for passenger vehicles in the model.

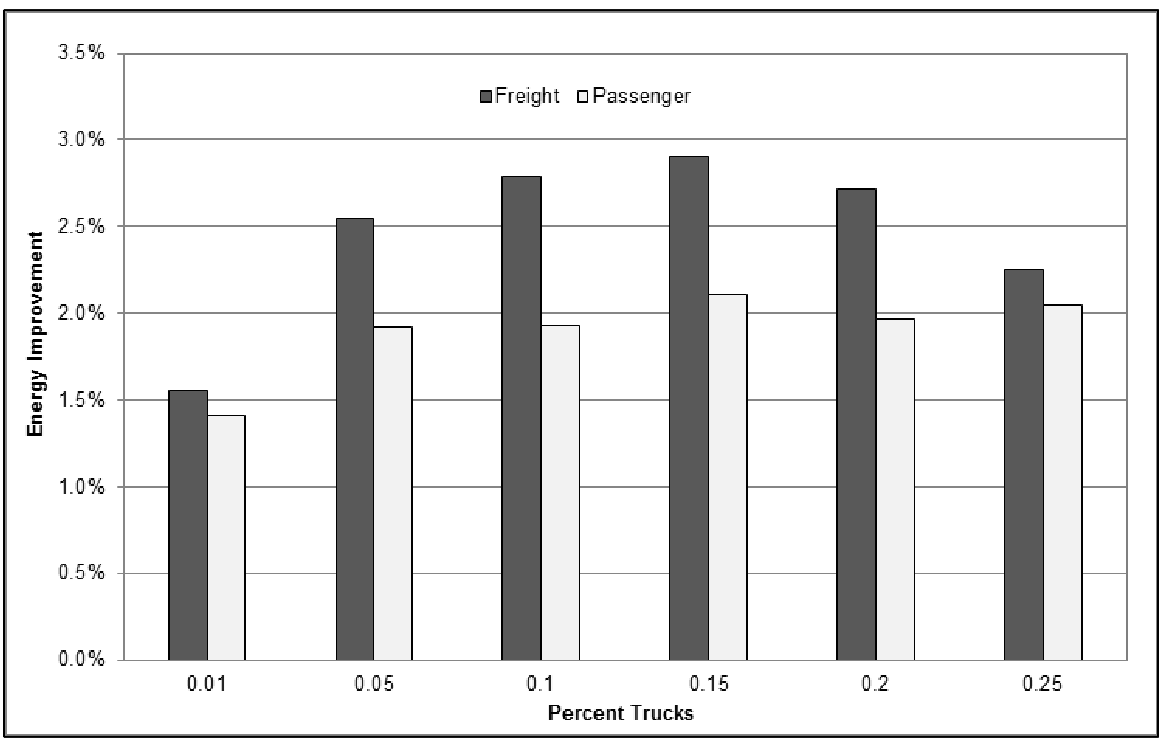


Figure 91: Energy/Fuel Savings vs. Percent Trucks During Morning Peak.

As shown in Figure 91, the fuel savings for freight vehicles increases with the percentage of trucks in the network. With more freight vehicles in the network, it is expected that more requests for priority will be granted; therefore, more green time will be available to vehicles on the mainline. Note that fuel savings for the baseline case of 1 percent trucks on the El Camino Real are much less than fuel savings for the other cases. It was found that the greatest effect on fuel savings for the application occurred at about 10 percent trucks in the network; 10 percent trucks in traffic is considered fairly high for urban areas, which is why this level was used for the other sensitivity analyses for the Eco-Freight Signal Priority application, although the maximum benefit was obtained with 15 percent trucks. An interesting find was that above 15 percent trucks, increasing the percentage of trucks had the opposite effect, reducing fuel savings over time. This occurs when the number of trucks in the system, especially on side streets, becomes burdened by the increasing number of priorities granted and the idling/dwell time that ensues. Truck percentages greater than 25 percent were not considered because they are rare and not feasible in most systems.

Although there are minor gains in the fuel savings of passenger vehicles with an increasing percentage of trucks on the corridor, the passenger class has significantly less sensitivity than freight vehicles. Above 5 percent to 10 percent trucks, varying the number of trucks does not lead to many additional improvements for passenger vehicles in the network. With additional priorities, it might be assumed that the mainline would benefit more from the additional green time, but this is not the case. Not only are freight vehicles much larger and take up more space on the corridor, especially in higher percentages, but with an increasing percentage of trucks, there are decreasing percentages of non-freight passenger vehicles. Therefore, fewer vehicles use the increased green time, which evens out the results in the end.

Additional results for fuel savings and emissions associated with an increasing percentage of trucks in the model are shown in more detail in Table 64. The results are presented separately for freight vehicles and for all passenger vehicles in the network.

Table 64: Energy Consumption and Emissions with Percentage Trucks from 1 Percent to 25 Percent for Freight Vehicles as Well as for Passenger Vehicle Traffic.

Freight Vehicles, Savings (%)						
Percent Trucks (%)	**Energy**	**CO_2**	**CO**	**HC**	**NOx**	**PM**
Baseline	-1.6%	0.5%	1.4%	0.1%	0.8%	-0.3%
5	-2.5%	-2.7%	-1.7%	-1.8%	-1.9%	-2.0%
10	-2.8%	-2.8%	-2.2%	-3.2%	-2.7%	-2.0%
15	-2.9%	-2.5%	-1.8%	-2.3%	-2.5%	-1.7%
20	-2.7%	-2.7%	-2.1%	-3.1%	-2.6%	-1.8%
25	-2.3%	-2.1%	-1.2%	-2.4%	-1.7%	-1.1%

Passenger Vehicles, Savings (%)						
Percent Trucks, %	**Energy**	**CO_2**	**CO**	**HC**	**NOx**	**PM**
Baseline	-1.4%	-1.4%	-0.9%	-1.0%	-1.3%	-1.4%
5	-1.9%	-1.9%	-0.6%	-1.2%	-0.9%	-1.5%
10	-1.9%	-1.9%	-1.1%	-1.1%	-1.1%	-1.3%
15	-2.1%	-2.1%	-1.4%	-1.3%	-1.3%	-1.5%
20	-2.0%	-1.9%	-1.3%	-1.2%	-1.3%	-1.5%
25	-2.0%	-2.4%	-2.2%	-2.3%	-2.3%	-2.7%

Eco-Freight Signal Priority on ECR-27—Demand Level

The ability to reliably track a freight vehicle's trajectory as well as to track and predict platooning and queuing on the approach to the signalized intersection is an important feature of the Eco-Freight Signal Priority application. It is understood that the approach to an intersection is different in undersaturated versus oversaturated conditions, so there is a need to understand the reliability of tracking algorithms. The baseline demand for the El Camino Real Paramics network currently operates at approximately a 0.83 V/C ratio. This ratio represents the average demand ratio at the mainline approaches to the intersection along the El Camino Real and does not represent the traffic on the side-street approaches. The side-street volumes are significantly lower than the mainline. To supplement the analysis of the application, the baseline and Eco-Freight Signal Priority application models were run for two additional scenarios: a low-demand scenario (V/C = 0.38) and a saturated network scenario (V/C = 1.00). For this analysis, the connected vehicle OBE penetration rate was assumed to be 100 percent of the vehicles, and the higher truck percentage of 10 percent was used in all three of the demand ratio conditions.

The results of the analysis are shown in Figure 92. The figure shows the fuel savings the application achieved versus the baseline condition at each demand level, both for freight vehicles and for passenger vehicles separately.

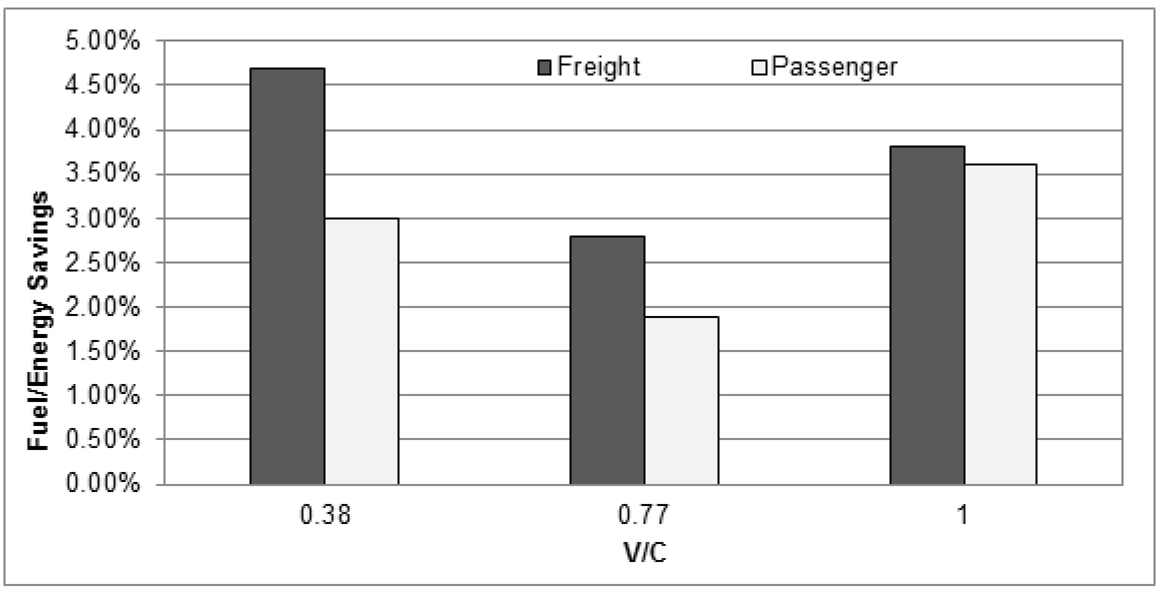


Figure 92: Fuel Savings for Freight and Passenger Vehicles for Varying Demand Levels.

As shown in Figure 92, there are significantly more fuel savings for the connected freight vehicles in the low-demand (0.38) scenario than in any of the other scenarios. This occurs because of the low demand on the approaches to the intersections, which means fewer queue and stoppage interactions that would cause a freight vehicle to miss the allotted priority green time granted by the application. Both the low-level and mid-level demand scenarios lead to noticeably more savings for freight vehicles than for non-freight vehicles on the mainline. In contrast, the highest demand level (1.00) shows high non-freight passenger vehicle savings that are similar to the savings of the connected freight vehicles. Because this scenario has more saturated approaches to the intersection, additional green time from the granted freight priorities is available to and used by all of the vehicles on that approach to the intersection.

Additional results for emissions and results for mobility for different demand ratios are shown in more detail in Table 65. The results are presented for freight and passenger vehicles in the network separately.

Table 65: Detailed Comparison of Varying V/C Demand Ratios for Freight Vehicles and Passenger Vehicles.

Freight Vehicles						
V/C	**Energy (kJ)**	**CO_2 (g)**	**CO (g)**	**HC (g)**	**NOx (g)**	**PM (g)**
Baseline						
1.00	81,042,759	5,766,832	72,198.7	2,825.5	14,176.3	61.31
0.83	57,666,880	4,103,858	53,397.8	1,982.5	10,216.3	45.80
0.38	25,518,708	1,815,913	23,821.7	865.5	4,519.1	20.04
Eco-Freight Signal Priority						
1.00	77,976,362	5,548,657	70,535.2	2,703.4	13,711.2	60.04
0.83	56,055,963	3,989,193	52,220.4	1,919.6	9,945.1	44.87
0.38	24,327,095	1,731,103	22,881.8	821.7	4,318.5	19.40
Savings, %						
1.00	-3.8%	-3.8%	-2.3%	-4.3%	-3.3%	-2.1%
0.83	-2.8%	-2.8%	-2.2%	-3.2%	-2.7%	-2.0%
0.38	-4.7%	-4.7%	-3.9%	-5.1%	-4.4%	-3.3%

Passenger Vehicles						
V/C	**Energy (kJ)**	**CO_2 (g)**	**CO (g)**	**HC (g)**	**NOx (g)**	**PM (g)**
Baseline						
1.00	140,660,168	9,693,056	67,981.1	455.1	1,440.6	135.08
0.83	95,213,821	6,746,813	52,048.7	349.7	1,085. 0	103.71
0.38	43,876,898	3,128,582	25,691.2	174.8	534.5	51.66
Eco-Freight Signal Priority						
1.00	135,559,090	9,308,540	66,633.8	445.9	1,409.6	132.68
0.83	93,378,446	6,619,762	51,462.7	345.9	1,073.2	102.43
0.38	42,550,147	3,034,523	25,100.7	170.9	523.1	50.36
Savings, %						
1.00	-3.6%	-4.0%	-2.0%	-2.0%	-2.1%	-2.3%
0.83	-1.9%	-1.9%	-1.1%	-1.1%	-1.1%	-1.3%
0.38	-3.0%	-3.0%	-2.3%	-2.2%	-2.1%	-2.5%

Eco-Freight Signal Priority on ECR-27—Communication Range

Given the current DSRC technology that is widely accepted for use in connected vehicle applications, the current range of communications is approximately 980 feet (300 m) for both V2V and V2I technology. It is not known what new technologies may be developed and implemented in the future before the Eco-Freight Priority Signal application is implemented. Therefore, it is necessary to explore the impact of communication range on the Eco-Freight Signal Priority application, especially at distances beyond 300 m, to show how other possible technologic extensions of the communications range could play a role. For the Eco-Freight Signal Priority application analysis, it is assumed that the freight vehicle will analyze and request priority the first chance it gets when in range, and then not reinvestigate its decision. This could lead to possible shortcomings in the prediction algorithm but will prevent double-counting and complex calculation time.

For this sensitivity analysis, the connected vehicle OBE penetration rate is assumed to be 100 percent equipped and baseline demand, with the increased truck percentage of 10 percent used in the El Camino Real network. Figure 93 shows fuel savings versus communication distance for freight and passenger vehicles separately. Communications distance is measured from 50 to 1,000 m.

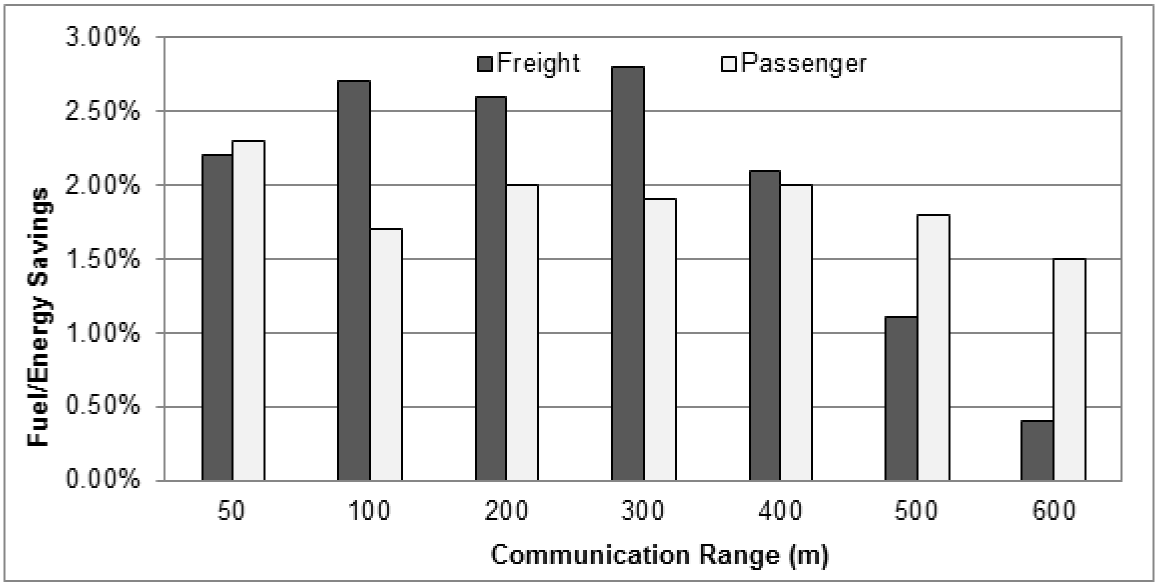


Figure 93: Fuel Savings with Different Communication Ranges vs. Baseline.

As shown in Figure 93, there is no significant difference for connected freight vehicles in terms of fuel savings up to about 400 m. These likely results from how the priority algorithm uses the available information to make a decision. Beyond 400 m, if the decision is made at the maximum communication distance, the savings begin to decrease because the “usefulness” of the connected vehicle information and SPaT information received decreases. In the case of the Eco-Freight Signal Priority application, the farther a vehicle is from the signal, the more uncertainty is introduced, such as queuing, unexpected stops, and transit vehicle interference, as well as the potential for the vehicle to “miss” its granted priority. This is discussed in detail in the section “Additional Analyses on Granting Priority.”

Although the freight vehicles cannot make their granted priorities at longer distances, the green time granted to the mainline is available to passenger vehicles on the approach to the intersection. That is why, at longer distances, there are significantly higher fuel savings for passenger vehicles when considering longer distances from the signalized intersection.

The figure also shows that the Eco-Freight Signal Priority application is not effective beyond the upstream intersection in the corridor. The logic of the algorithm is designed to obtain and analyze geometry and SPaT information only from the next signalized intersection; otherwise, the information would be too complicated for the priority request to be analyzed correctly. In the case of the El Camino Real segment, the maximum intersection spacing is 500–600 m on average, which is why the results reach a plateau at this point. Additional results for the fuel savings and for emissions based on communication distance are shown in more detail in Table 66. The results are presented for freight vehicles and passenger vehicles in the network separately.

Table 66: Fuel and Environmental Savings with Different Communication Ranges vs. Baseline.

Freight Vehicles, Savings (%)						
Communication Range (m)	Fuel	CO_2	CO	HC	NOx	PM
50	-2.2%	-2.2%	-1.6%	-2.5%	-2.0%	-1.9%
100	-2.7%	-2.7%	-1.7%	-3.0%	-2.4%	-1.4%
200	-2.6%	-2.6%	-1.9%	-3.0%	-2.4%	-1.5%
300	-2.8%	-2.8%	-2.2%	-3.2%	-2.7%	-2.0%
400	-2.1%	-2.1%	-1.4%	-2.2%	-1.7%	-1.7%
500	-1.1%	-1.1%	-0.3%	-1.3%	-0.8%	-0.7%
600	-0.4%	-0.4%	0.2%	-0.6%	-0.2%	0.1%

Passenger Vehicles, Savings (%)						
Communication Range (m)	Fuel	CO_2	CO	HC	NOx	PM
50	-2.3%	-2.2%	-1.5%	-1.5%	-1.5%	-1.6%
100	-1.7%	-1.7%	-0.8%	-0.7%	-0.8%	-1.0%
200	-2.0%	-1.9%	-1.2%	-1.1%	-1.1%	-1.3%
300	-1.9%	-1.9%	-1.1%	-1.1%	-1.1%	-1.3%
400	-2.0%	-2.0%	-1.2%	-1.1%	-1.1%	-1.3%
500	-1.8%	-1.7%	-1.2%	-1.2%	-1.2%	-1.3%
600	-1.5%	-1.5%	-1.3%	-1.3%	-1.3%	-1.3%

Eco-Freight Signal Priority on ECR-27—Communication Delay

In the real world, a communication delay is inevitable given the variety of software and hardware. The effect of communication delay was simulated in Paramics. In a zero-delay situation, vehicles place a priority request based on current information; in a Δt-second-delay situation, signals get that same priority request based on old information, which is Δt second earlier. For the purpose of the analysis, the *communication delay* is assumed to be the amount of time between when the vehicle sends the priority request and when the signal is changed or not changed based on the priority algorithm analysis. The vehicle continues to move forward in space during this delay.

Based on the analysis, there is only a slight effect on the energy savings results, as shown in Figure 94. This analysis assumes that there is a 100 percent connected vehicle OBE penetration rate as well as baseline traffic conditions and communication range.

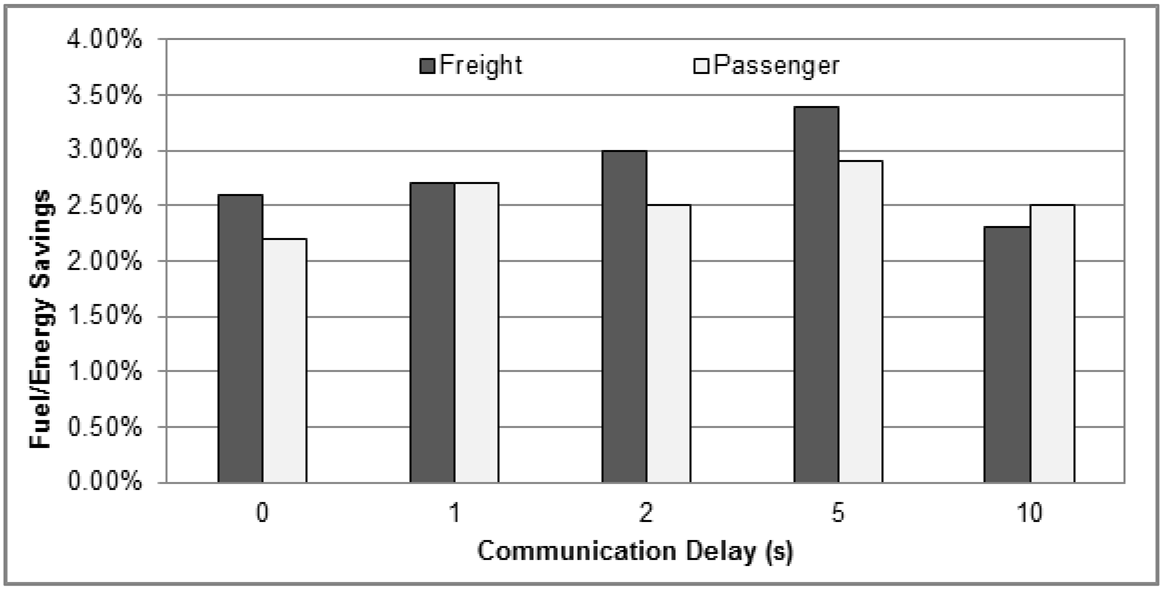


Figure 94: Fuel Savings with Different Communication Delays.

The analysis shows that the communication delay does not have a significant effect on application's performance, because the difference in time between the remaining phase time and the amount of time until arrival at the signal remains constant at a constant velocity. The extension or termination of a phase will be approximately the same number whether it makes the decision immediately or with a few seconds of delay. An exception to this explanation occurs if the delay time in calculation is more than the remaining travel time to the signal stop line. In such a case, the vehicle will either pass or stop at the intersection before the priority determination is made.

An interesting finding in this analysis was that there were slight improvements in the environmental benefits of freight vehicles with several seconds of communication delay because the vehicle is closer to the intersection at the time the priority determination is made. The closer the vehicle is to the intersection, the lower the chance that a vehicle encounters unexpected queuing or other traffic delays that interferes with its trajectory. However, the network environmental benefits for the other passenger vehicles show only marginal increases as extension time is increased, because the increased delay in processing time would not provide any additional benefits or green time than in the zero-delay case. This means that the additional green time provided to the non-freight vehicles on the approach would be the same regardless of how long it takes to implement.

Additional results for emissions and for mobility results for communication distance are shown in more detail in Table 67. The results are presented for freight vehicles and passenger vehicles in the network separately.

Table 67: Energy Savings with Different Communication Delays.

Freight Vehicles, Savings (%)						
Communication Delay (s)	**Energy**	**CO_2**	**CO**	**HC**	**NOx**	**PM**
0	-2.6%	-2.6%	-2.0%	-2.9%	-2.4%	-1.9%
1	-2.7%	-2.7%	-2.3%	-2.8%	-2.5%	-2.8%
2	-3.0%	-3.0%	-2.6%	-3.4%	-3.0%	-2.5%
5	-3.4%	-3.4%	-3.1%	-3.5%	-3.2%	-3.4%
10	-2.3%	-2.3%	-2.0%	-2.5%	-2.1%	-2.2%

Passenger Vehicles, Savings (%)						
Communication Delay (s)	Energy (kJ)	CO_2	CO	HC	NOx	PM
0	-2.2%	-2.2%	-1.6%	-2.7%	-2.3%	-1.4%
1	-2.7%	-2.6%	-2.2%	-3.4%	-3.2%	-1.9%
2	-2.5%	-2.5%	-1.9%	-3.1%	-2.8%	-1.6%
5	-2.9%	-2.9%	-2.5%	-3.3%	-3.1%	-2.2%
10	-2.5%	-2.5%	-1.8%	-2.3%	-2.1%	-1.9%

Eco-Freight Signal Priority on ECR-27—Additional Analyses on Granting of Priorities

The results of all sensitivity analyses performed as part of the Eco-Freight Signal Priority application occasionally raised other issues and indicated a need for additional clarity that was not immediately apparent from the data as presented above. Most of the need for clarification involved the granting of priorities in the system. As shown, there are notable savings in emissions, fuel, and idling time with implementation of the Eco-Freight Signal Priority application, but the question remains: Could there have been more savings? To better understand this application's granting of priorities, an analysis was performed on the Eco-Freight Signal Priority algorithm at 100 percent connected vehicle penetration and 10 percent trucks to determine how many priorities the algorithm was granting. The analysis used the three demand levels (0.38, 0.83, and 1.00) used in the previous analyses. It was hypothesized that as the level of demand increases, so would the number of priorities granted. The results are shown in Figure 95.

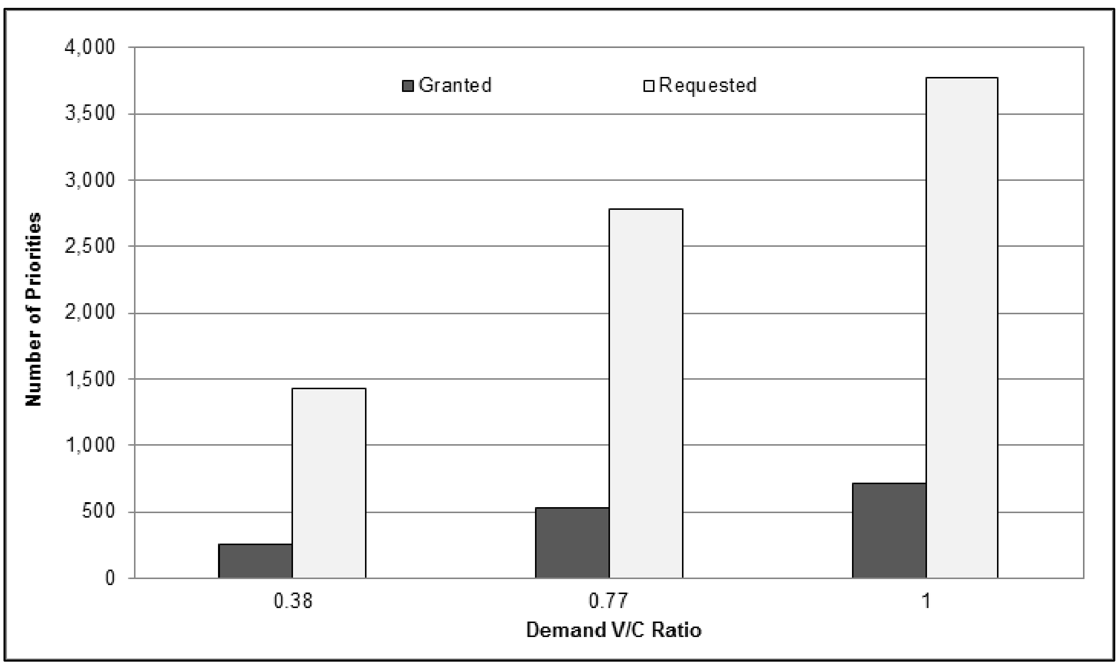


Figure 95: Granted vs. Requested Freight Vehicle Priorities for the Three Demand Levels.

As expected, the total number of priorities requested by freight vehicles increased as the amount of demand increased along the corridor. However, the number of priorities granted versus the number requested is only a fraction of the total. Note that for this analysis, only the priorities requested during the phase directly before or during the current desired phase were considered. To more easily visualize the trend, the actual percentage ratio of requested versus granted priorities is shown in Figure 96.

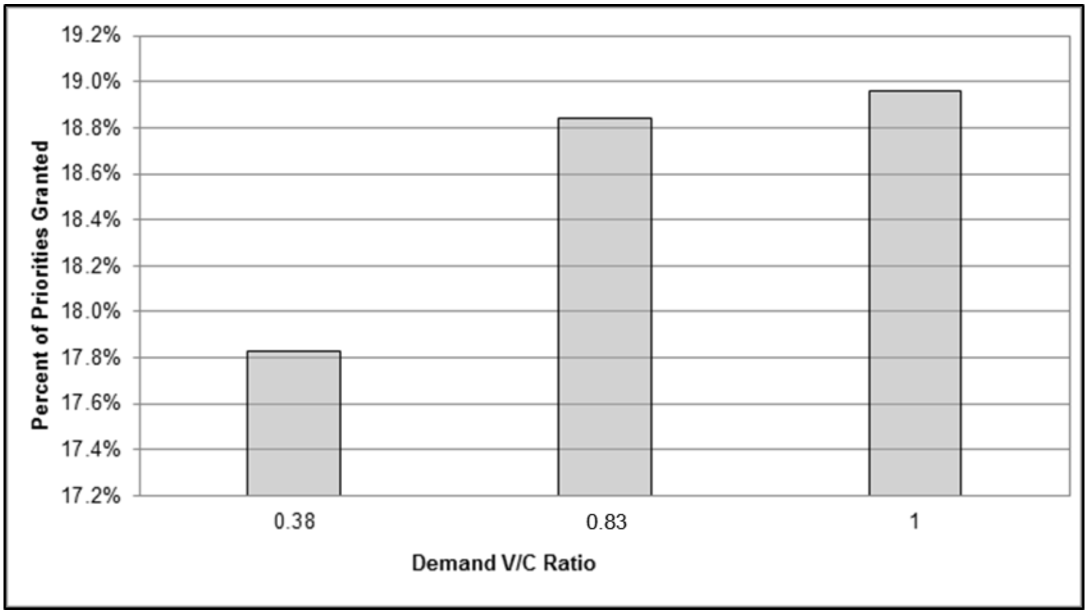


Figure 96: Percentage of Priorities Granted by Demand Level Ratio.

As shown in Figure 96, the number of requests granted is 18 percent to 19 percent of the total number requested for all three demand level ratios. This indicates that the relative change between the baseline and the application remain similar, regardless of the level of congestion or side-street demand. The approximately 80 percent of vehicles that were denied priority were too far outside the maximum threshold of extension/truncation provided for this application. This result indicates that additional work is needed to understand the role of the maximum extension threshold with regard to improving emissions along the corridor. The value of 6 s as a maximum threshold was used for this application.

As a result of this finding, it was decided to undertake another sensitivity analysis to determine the effect of smaller and larger extension thresholds and to obtain a better understanding of the effects on fuel and emissions savings along the corridor. To simplify the analysis, the green extension and red truncation thresholds were assumed to be the same. In future analyses, these thresholds could be varied to better understand the situation. According to research, the typical values of extension for priority vary from 5 s to a maximum of 10 s. For this experiment, extension maximum thresholds were tested for 4 s up to 16 s as a theoretical possible maximum. Figure 97 shows the results of this analysis in terms of fuel savings versus the baseline model.

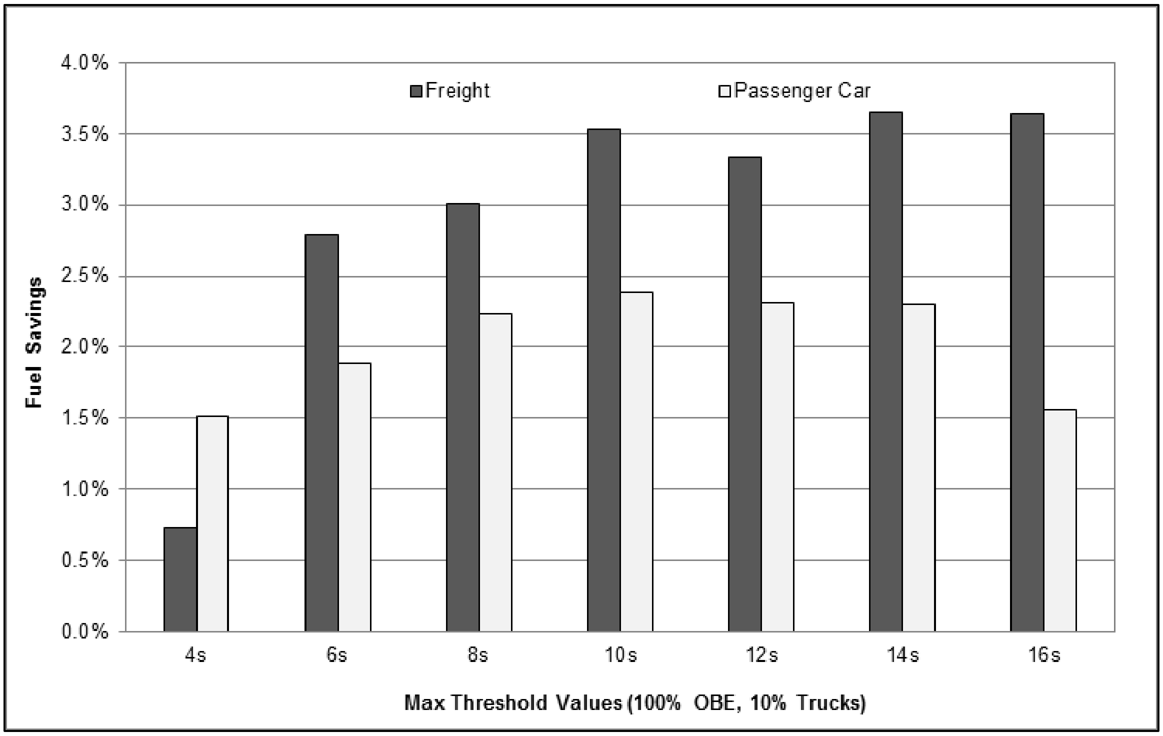


Figure 97: Fuel Savings by Maximum Extension Thresholds (100 Percent OBE, 10 Percent Trucks).

Figure 97 shows a clear trend that increasing the thresholds of maximum extension provides additional benefits in terms of fuel savings. Values less than 6 s provide significantly less savings, but it is interesting that this is the only experiment in which passenger cars receive greater benefit than freight vehicles. This is likely the result of several factors, from a short extension to the possibility of missing the granted priorities. The benefits increase to about 10 s, and then “plateau” at about a 3.6 percent improvement in fuel usage. An interesting trend is that the corollary improvement for passenger vehicles with the additional green time also shows improvement but only up to 10 s of extension maximum. The benefit then begins to decrease, presumably because of the increased wait time on the side streets that granted priorities cause, which are granted mainly on the mainline. This indicates that future research should consider a threshold of about 10 s for maximum benefit.

Finally, there is a possibility of freight vehicles “missing” the priorities they were granted. In the current version of the algorithm, the modules determine the speed and distance profiles as accurately as possible to determine the change necessary in the phase green time. There is a possibility of unknown factors, however, such as unexpected braking or other queue effects that can alter the trajectory of a vehicle. Because the algorithm does not have a “re-check” built in, it was hypothesized that some of the vehicles are stopping at the intersection even though the priority was granted for them. To test this hypothesis, an analysis API module was built into Paramics to determine whether a vehicle stopped at the light after it was given priority. The results of this analysis are shown in Figure 98.

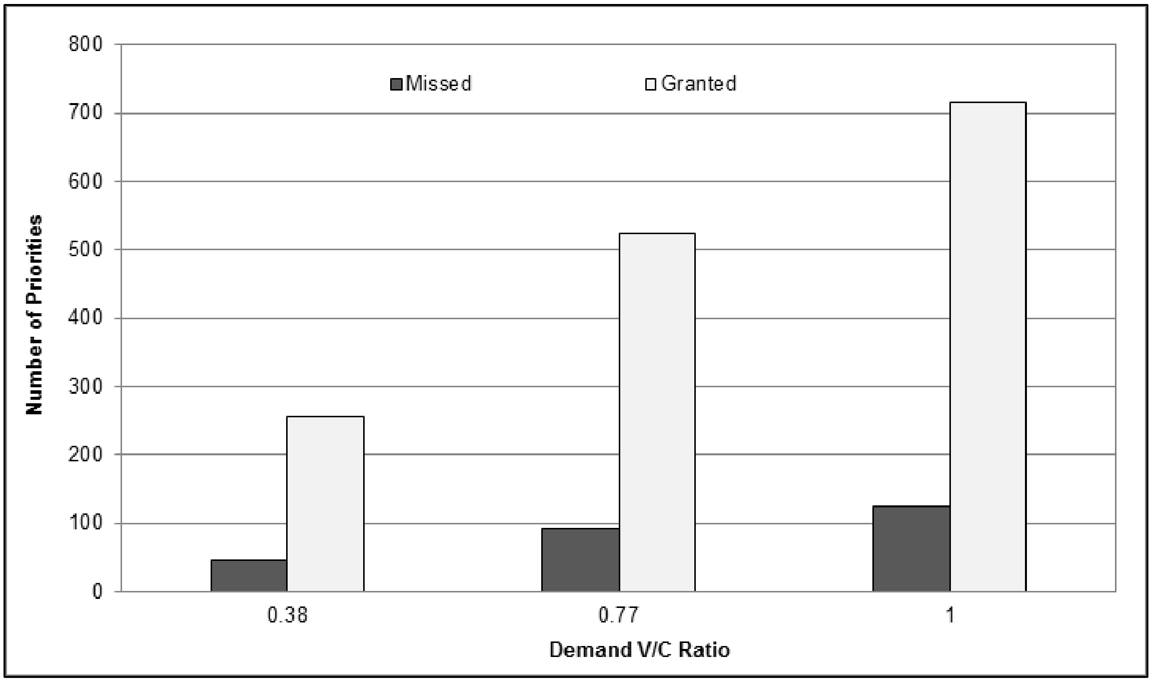


Figure 98: Number of "Missed" Priorities vs. Granted for the Three Demand Ratio Levels.

The percentage of "missed" priorities is similar relative to the baseline in all three demand ratio levels, with a value of approximately 17.5 percent. This value is significant enough to show a decrease in the savings of fuel and emissions, especially when a freight vehicle must stop suddenly when it misses the end of the phase only by a slight margin. This effect is exacerbated if the freight driver expects to get the priority and was surprised when the granted priority was missed. However, the corollary effect of passenger car savings would not be affected, because the additional mainline green would still be provided. This may help to explain why the ratio of freight improvement to passenger car improvement is not what was expected. The results of this analysis indicate future research into a "re-check" algorithm would be useful because this 17.5 percent of missed priorities would immediately be reinvested as additional fuel savings for the corridor.

Freight Idling Time

A traditional measure of effectiveness, especially in freight management of emissions and fuel savings, is the amount of time that a vehicle is not in motion (i.e., idling). Reducing the amount of time a vehicle idles at an intersection or is in a queue ultimately reduces delay and travel time; it is also believed to reduce overall vehicle emissions. Accelerating out of the idle or stop also uses more fuel than a constant speed profile. All of the reasons presented above contribute to the needs and wants of providing signal priority to freight vehicles; therefore, it was important to include them as measures of effectiveness in the analysis.

The total average network idling times for the different types of vehicles were analyzed at 100 percent connected vehicle penetration against the baseline. This analysis also was conducted for the three demand ratios mentioned previously in the analysis; the results are presented in Table 68. The values shown in the table are the summation of the average idling times at all of the approaches of all of the intersections in the El Camino Real network. The analysis is broken down to show the improvement of the passenger and freight traffic separately as well as the total difference in the combined traffic flow.

Table 68: Average Network Idling Time Savings for Different Vehicle Types in the Network for Freight Priority vs. Baseline.

Total Average Idle Time for Network (V/C = 0.38)				
Vehicle Type	Baseline (s)	Freight Signal Priority (s)	Absolute Difference (s)	Percentage Difference
Passenger	1,157.1	1,096.3	-60.8	-5.3%
Freight	1,131.5	1,054.2	-77.3	-6.8%
Total	1,137.9	1,064.7	-73.2	-6.4%

Total Average Idle Time for Network (V/C = 0.83)				
Vehicle Type	Baseline (s)	Freight Signal Priority (s)	Absolute Difference (s)	Percentage Difference
Passenger	1,195.9	1,184.3	-11.6	-1.0%
Freight	1,174.2	1,113.8	-60.4	-5.1%
Total	1,179.6	1,131.4	-48.2	-4.1%

Total Average Idle Time for Network (V/C = 1.00)				
Vehicle Type	Baseline (s)	Freight Signal Priority (s)	Absolute Difference (s)	Percentage Difference
Passenger	1,390.3	1,406.5	16.20	1.2%
Freight	1,377.9	1,271.8	-106.1	-7.7%
Total	1,381.0	1,305.5	-75.5	-5.5%

The results of the analysis show that significant savings in average idling time can be obtained from the Eco-Freight Signal Priority application. In the lowest demand scenario, there are significant improvements in both the freight vehicle and the passenger car vehicle types. In the El Camino Real network at the lowest demand levels, mainline passenger vehicles, connected vehicles, and non-connected vehicles share the benefits of the additional green time from the granted priorities. In addition, at the low demand level, granted priorities inconvenience fewer vehicles on the side streets. This translates into large net savings across the network.

At the baseline demand level, there are increasing levels of idle time for all vehicles, but this increase is not significantly higher than in the lower demand scenario. This indicates that there is still not a significant queue delay at the intersections along the corridor, and it still results mostly from control delay. However, the increase in side-street traffic and mainline traffic has an effect on the average idling time with the introduction of Eco-Freight Signal Priority application. The benefit to passenger cars decreases significantly as demand increases, but there remains a similar benefit to freight vehicles, because they are granted increasing numbers of priorities as demand increases. The savings in idling time for freight vehicles represent nearly 95 percent of the savings for the El Camino Real network.

In the highest demand scenario, the passenger car trend continues because the tipping point has been reached, where the idling time of vehicles inconvenienced by the signal priority is more than the idling time of those that benefit from it. In contrast, there is a noticeable increase in the savings that freight vehicles obtain in regard to idling time. For the saturated condition, the average idling time for freight vehicles is 15 percent higher than the baseline condition of 0.83, which provides the Eco-

Freight Signal Priority application with a better chance to improve and reduce the amount of time that the freight vehicles stand in a queue at the intersection.

Findings and Opportunities for Future Research

Prior to modeling, the hypothesis that was generated based on a literature review stated, "If the Eco-Freight Signal Priority application is used to grant signal priority to selected freight vehicles based on their location, speed, size, vehicle class, and traffic and environmental characteristics of all vehicles at the signalized intersection, then there will be emissions reductions and lowered fuel consumption during congested traffic conditions in the range of 1 percent to 2 percent under partial connected vehicle penetration and 2 percent to 4 percent under full connected vehicle penetration." The modeling results presented in this section are consistent with those reported in previous studies. It was found that the Eco-Freight Signal Priority application results in 1 percent to 5 percent energy savings for freight vehicles as well as for the network as a whole, while also providing benefit to mobility measures. Such benefit comes from the additional green time on the mainline, which the majority of traffic on the El Camino Real, both connected and unconnected vehicles, shares. The energy savings benefit of the application depends on several factors, including congestion level, penetration rate of OBE and RSE, and communication conditions specifically as follows:

1. The application is effective in all levels of congestion but provides greater fuel savings in both undersaturated and oversaturated conditions, as discussed previously. In addition to freight vehicles, passenger vehicles receive significant benefits because of the additional green time along the corridor. This effect is most noticeable in oversaturated conditions.
2. The higher the penetration rate of both OBE and RSE technology, the more energy savings and emission reductions can be achieved. It is interesting to note that even at low or moderate connected vehicle technology penetration levels; the application still has a positive network-wide effect that results from non-freight vehicles gaining energy/environmental benefits from the extra green time allotted to Eco-Freight Signal Priority.
3. Freight and passenger vehicle emissions show similar trends of environmental benefits in sensitivity analyses, because the majority of the priority extensions of green time are on the mainline, which contains the majority of vehicular traffic along the El Camino Real. Only at the highest levels of OBE and RSE penetration do freight vehicles receive greater net benefits than the other network vehicles; however, significant improvements are shown at all levels of penetration, which makes this a good candidate for early adoption.
4. The higher the percentage of trucks in the network system, the greater potential the Eco-Freight Signal Priority application has to improve freight vehicle and overall network emissions and to provide a larger range of fuel savings/ environmental benefits. However, as the percentage of freight vehicles and the resulting amount of priority time granted significantly increases, there is a noticeable decrease in fuel savings for passenger vehicles.
5. The results of the sensitivity analysis show that the farther from the signal the priority decision is made, the less accurate the information becomes, thus resulting in a lower environmental benefit for freight and passenger vehicles. In this analysis of the Eco-Freight Signal Priority application, it is assumed that the application makes the decision to grant priority at the maximum communication range.
6. The Eco-Freight Signal Priority algorithm is not effective when the distance is beyond the previous upstream intersection, because the application is designed to look only at the next signalized intersection in the vehicle's path. This was done to reduce the complexity of the

signal calculations and limits the vehicle's decision range to the physical distance between signalized intersections.

7. Communication delay is not a significant problem for this application, because the time between arrival and the remaining time in the phase are constant. Therefore, communication delay affects the decision to grant priority only if the communication delay is larger than the amount of travel time remaining to the intersection stop line.
8. The Eco Freight Signal Priority application can significantly reduce average idling time throughout the network. Idling is a major contributor to fuel loss and environmental problems and is the main feature that operators try to reduce. Similar improvements can be gained at all demand level ratios.
9. The number of priorities granted versus the number requested is 18 percent to 19 percent in all demand scenarios. It was hypothesized that longer maximum thresholds for extension would lead to more priorities being granted and, therefore, better fuel savings for freight vehicles. This hypothesis was demonstrated in a sensitivity analysis.
10. About 17 percent of priorities granted to freight vehicles are missed because of unforeseen queuing or shockwave scenarios. This represents lost time and lost opportunities that could potentially provide a significant boost in fuel savings for all vehicles in the network.

Based on the above findings from the modeling effort, the research team developed the following recommendations and remarks:

1. The current version of the Eco-Freight Signal Priority application's algorithm classifies freight vehicles into different emissions classes based on their MOVES vehicle emission type, which in turn specifies their emissions and fuel rates. This is a simplistic way of predicting the emissions of a freight vehicle and its impact on the system. Alternatively, a real-time predictive emissions module could be developed to provide the algorithm with a more accurate picture of the impact of granting or not granting priority to the freight vehicle in the application.
2. The current Eco-Freight Signal Priority application algorithm makes the decision to grant or not grant priority at the maximum communication range to make best use of the information as early as possible; however, the decision to grant or not grant priority is not revisited during the approach to the intersection. This was done to simplify calculations and because of the existing queuing and platooning procedures within the current application. However, as shown in the analysis, unexpected changes do occur; therefore, it might be useful to develop a more advanced trajectory determination and event-prediction algorithm to increase the accuracy of information at distances farther from the intersection.
3. The Eco-Freight Signal Priority application is limited to the next intersection that the freight vehicle will encounter because of the complexity of calculating the current priority status with respect to granting priority at the next intersection. It would be useful to conduct future research dedicated to determining the effect of granting priority at one intersection or the next in real time to answer the question, "Not only can we, but should we?"
4. The Eco-Freight Signal Priority application is designed for fixed-time signals. Under actuated signal control scenarios, it is more difficult to estimate SPaT information (e.g., the remaining time of the current phase), which in turn would make determining priority and estimating the trajectory of vehicles to the intersection difficult. It would be useful to develop an advanced prediction algorithm to predict changes in actuated timings based on real-time positions of all connected vehicles on the roadway.
5. The analysis showed that the overall network achieved energy/environmental improvements similar to those of the freight vehicles, but there may be a point where the amount of green

extension time will have a detrimental effect on the overall network. It would be useful to conduct more research on the effect of the maximum and minimum green time extension thresholds of priority granting to determine the relationship between freight vehicle and overall network emissions.

6. The application should be tested on a network system that is less of a main corridor and that has approximately equal amounts of traffic coming from different approach directions. This will test the ability of the application to balance network conditions that are different from the El Camino Real, where the vast majority of the emissions and traffic is on the mainline.
7. Another variation of the Eco-Freight Signal Priority application should be investigated that considers the entire corridor rather than signal by signal. If all the signals have the ability to coordinate and grant priority to heavy-polluting platoons of freight vehicles, environmental benefits may be achieved in corridors with heavy truck demand on the mainline.

Chapter 7. Connected Eco-Driving Application

Application Description

The description of the application is provided in the section “Connected Eco-Driving” on page 10. The application is illustrated in Figure 99.

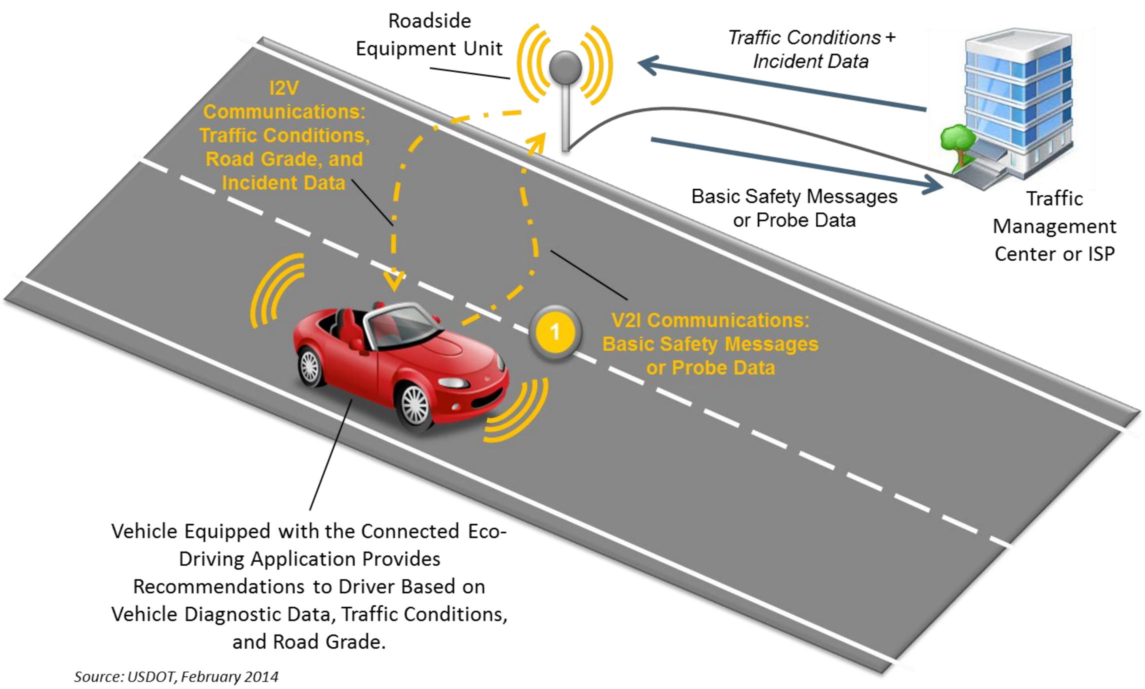


Figure 99: Connected Eco-Driving Application Illustrated

Hypotheses

If real-time driving advice (e.g., recommended driving speeds, optimal acceleration, optimal deceleration) is provided to drivers based on prevailing traffic conditions and interactions with nearby vehicles and feedback is provided to encourage drivers to drive in a more environmentally efficient manner, then there will be emissions reductions and lowered fuel consumption during congested traffic conditions in the range of 10 percent to 15 percent under partial connected vehicle penetration and 15 percent to 20 percent under full connected vehicle penetration.

Algorithm

This section describes the algorithm used to implement the Connected Eco-Driving application. As illustrated in Figure 100, the proposed algorithm consists of two major components: (1) General Eco-Driving Principles and (2) Eco-Approach and Departure at Signalized Intersection. An Eco-Speed Harmonization (for arterial) module was developed to supplement the Connected Eco-Driving application. However, the following section focuses on the description of General Eco-Driving Principles and Eco-Approach and Departure and the Eco-Speed Harmonization module will be described in the Appendix D. It should be pointed out that each component has its own effective region, as depicted in Figure 101. For example, the Eco-Approach and Departure module is effective within the communication range of traffic signal infrastructure (typically a radius of 300 m at a signal, based on the typical range of DSRC) because of the availability of SPaT information.

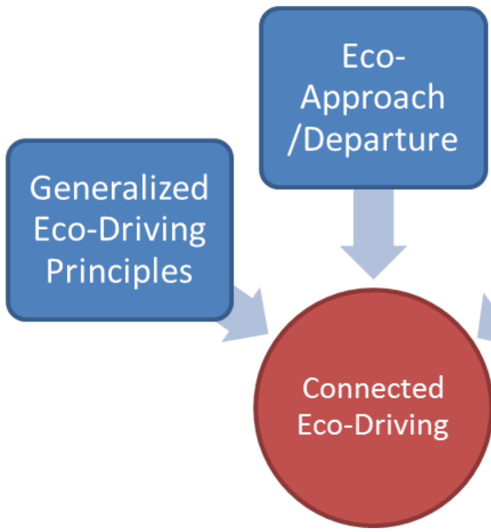


Figure 100: Modules of the Connected Eco-Driving Application.

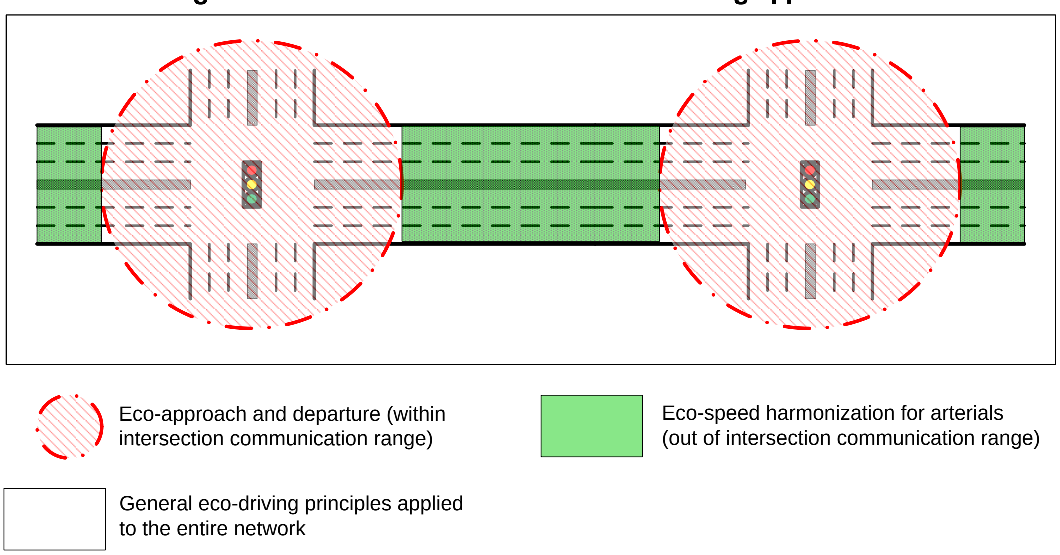


Figure 101: Effective Region of Each Component of the Connected Eco-Driving Application along a Signalized Corridor.

General Eco-Driving Principles

As previously mentioned, one simple way to reduce fuel consumption and pollutant emissions is to provide general eco-driving feedback principles to drivers on their driving behavior to encourage them to drive in a more environmentally efficient manner. To model the impacts resulting from use of the General Eco-Driving Principles system, the research team modified the acceleration and deceleration profiles in Paramics based on a real-world eco-driving field study, which was conducted in Riverside, California. In this study, GPS and fuel consumption data were collected from vehicles with and without eco-driving feedback application, which aims to reduce the acceleration and deceleration rates of vehicle operations. The study covered both freeways and arterials under a variety of traffic congestion levels. The data were used to evaluate the impacts of eco-driving feedback on driving behaviors and corresponding fuel consumption.

More specifically, Figure 102 illustrates a heuristic iterative procedure to calibrate the acceleration and deceleration profiles for Paramics inputs. Figure 103 presents examples of default acceleration profiles and eco-acceleration profiles used in Paramics for passenger cars. As can be seen from the figure, the accelerations under eco-scenarios (light gray) are milder than the default values (dark gray) across different speeds. Similar procedures have been applied to other vehicle types and deceleration-speed profiles, as well.

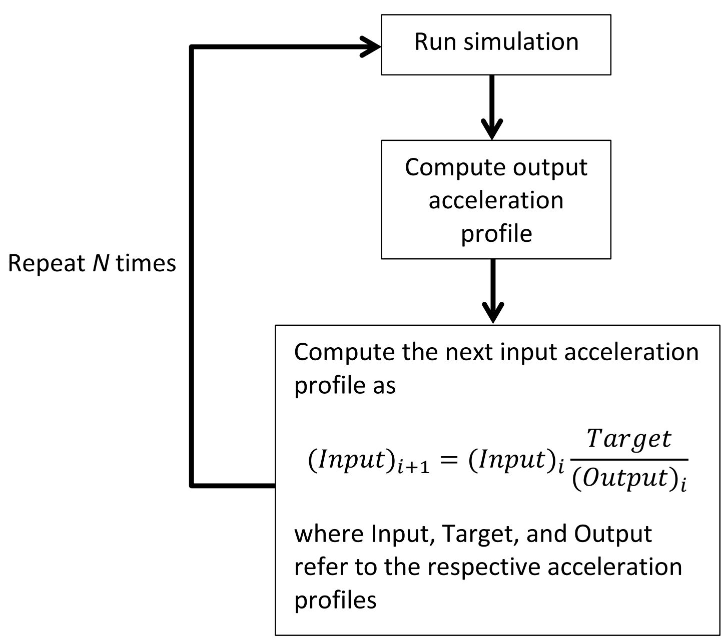


Figure 102: An Iterative Procedure to Calibrate Eco-Acceleration and Deceleration Profiles in Paramics.

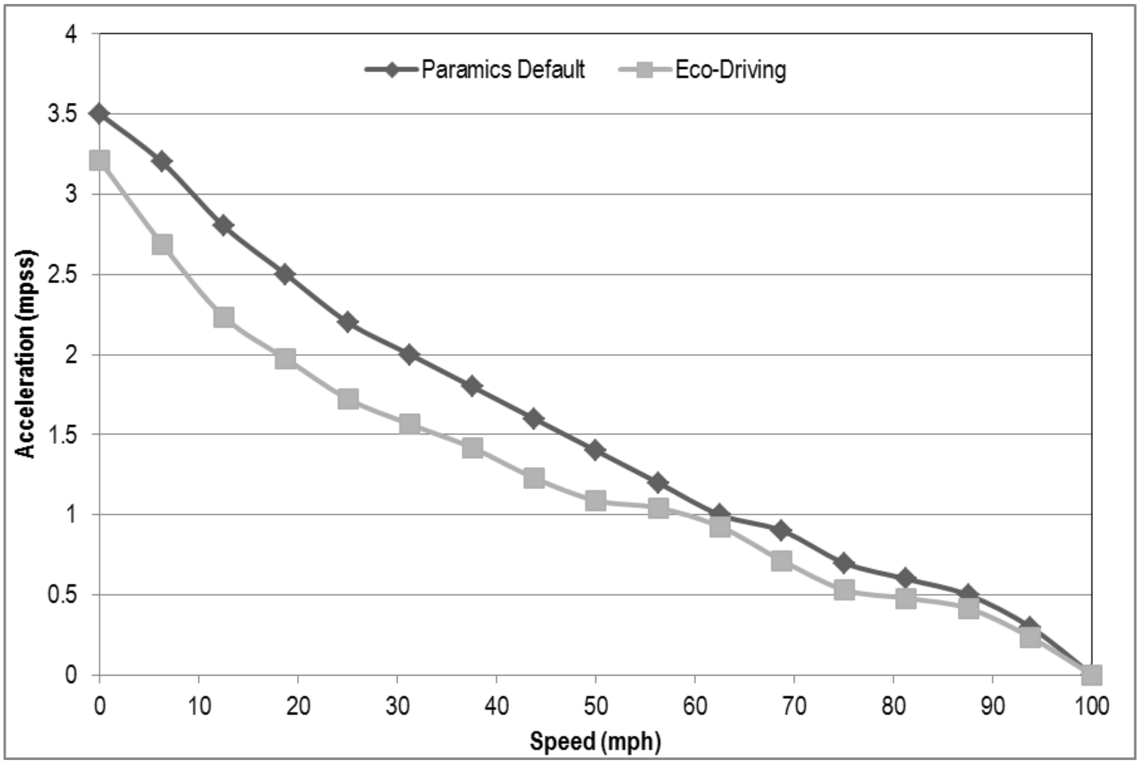


Figure 103: Example Acceleration and Deceleration Profiles in Paramics for Passenger Cars: Default vs. Eco-Driving.

Eco-Approach and Departure

As described in Chapter 4, the Eco-Approach and Departure at Signalized Intersections application (focusing primarily on the approach) uses wireless data communications sent from RSE to CVs to provide eco-friendly driving suggestions as CVs approach signalized intersections. As a part of this connected eco- driving application, the recommended speed profiles for vehicles both approaching and departing the signalized intersection were incorporated into the algorithm.

Instead of using the default driving behavior defined in Paramics, which results in a maximum acceleration event up to the speed limit, this application uses a smoother acceleration profile when a vehicle is departing an intersection and is still out of the communication range of the next signalized intersection. Based on the same sinusoidal function used in the Eco-Approach algorithm, the departure trajectory was designed to minimize travel time while still ensuring driving comfort by limiting the maximum jerk (da/dt). For an isolated intersection, this method can guarantee that the vehicle will not miss the earliest green time for the next signal (without knowing its SPaT). This avoids unrealistically slow acceleration, although it will favor the energy consumption for a single intersection only.

Modeling Approach

The microscopic traffic simulation software, Paramics, was used to model the movement of individual vehicles and their interactions in detail. To be consistent with the modeling efforts on other AERIS applications, the latest version of Paramics (6.9.3) was used.

As part of the programming environment, Paramics supports the development of plug-ins using its API, which enables users to interface with its core simulation engine to perform specific tasks. For example, detailed speed profile of every vehicle can be extracted by using the API. In addition, EPA's MOVES model was coded through an API to estimate emissions and energy consumption. The interaction between different models and the APIs used in this application are shown in Figure 104.

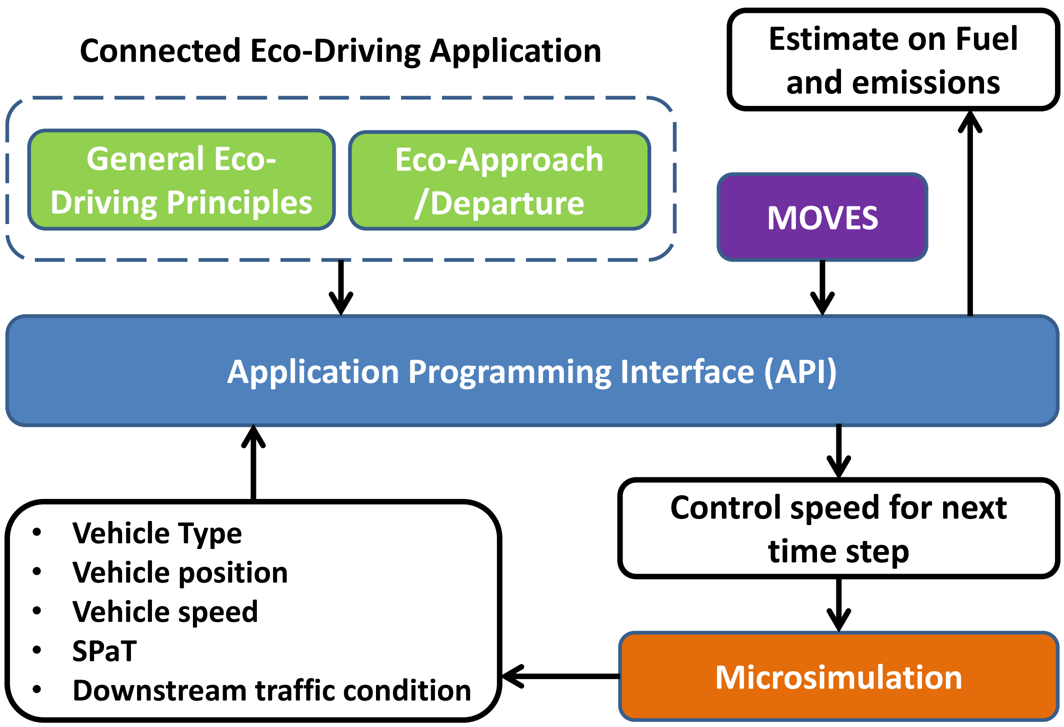


Figure 104: Diagram of Interactions Among the Models and API Within the Simulation Model.

More specifically, the Connected Eco-Driving application plug-in is designed to fulfill the following functions:

1. Collect vehicles' characteristics (e.g., type) and second-by-second speed data.
2. Collect SPaT information.
3. Estimate vehicles' energy consumption and pollutant emissions based on the MOVES model.
4. Generate vehicles' advisory speeds.
5. Calculate vehicles' control speeds.
6. Modify vehicles' acceleration profile.

Scenarios

An exhaustive set of scenarios was modeled for each application. The remainder of this section details the scenarios modeled. The modeling results that follow in the next section are organized in the same fashion. The network used for modeling the scenarios was El Camino Real 27-Intersection Network (Referred to as ECR-27).

A list of scenarios modeled is presented below.

- **Connected Eco-Driving on ECR-27—Demand:** The Connected Eco-Driving application was tested on the ECR-27 network with different demand levels of 0.38, 0.83, and 1.00 V/C ratios. The penetration rate of connected vehicle technology is assumed to be 100 percent.
- **Connected Eco-Driving on ECR-27—Penetration Rate:** The Connected Eco-Driving application was tested on the ECR-27 network with different connected vehicle penetration rates of 0 percent, 20 percent, 50 percent, 80 percent, and 100 percent. The traffic demand is assumed to be a 0.83 V/C ratio or the demand at morning peak on ECR-27.

Modeling Results

As described previously, the Connected Eco-Driving application consists of two major modules — General Eco-Driving Principles and Eco-Approach and Departure — each of which has a different effective region. To gain more in-depth insight into the application as well as its benefits, the 27-intersection El Camino Real network model was used (in Paramics). The sensitivity analysis on different roadway congestion levels or volume- to-capacity ratios (V/ C = 0.83 for the baseline traffic demand) and connected vehicle technology penetration rates were conducted by applying each individual module as well as the combined Connected Eco-Driving strategy. The environmental and mobility impacts were estimated by the aforementioned plug-ins.

Connected Eco-Driving on ECR-27—Demand

Figure 105 summaries the energy savings results from the simulation study for each individual module and the combined Connected Eco-Driving application. It can be observed that benefits from the General Eco-Driving Principles module varies from 0 percent to 1.1 percent, depending on the V/C. The Eco-Approach and Departure module can reduce energy consumption by up to 4 percent, especially in light traffic conditions (e.g., V/ C = 0.38).

In contrast, as shown in Figure 106, the General Eco-Driving Principles module is quite robust to demand variations in terms of penalizing the mobility of entire network. It gives rise to a slight increase in VHT (less than 3 percent), but mobility impacts resulting from the Eco-Approach and Departure module are sensitive to travel demands. When the network-wide V/ C = 0.83 (i.e., baseline demand), VHT can be increased by around 20 percent.

By further investigating the simulation tests, the research team realized that vehicles equipped with the Eco-Approach and Departure module can travel as a “moving bottleneck” when it has to be stopped by the signal because of the deceleration and acceleration smoothing effects. If the intersection spacing is not long enough, then it is likely that the equipped vehicle will “push” its followers back to the upstream intersection, resulting in queue spill-back. Figure 107 presents example snapshots from one microscopic simulation test, showing that queue spill-back does occur (and often) when the Eco-Approach and Departure module is applied, especially in congested scenarios. However, such a queue spill-back issue can be hardly witnessed in the baseline case (no equipped vehicles).

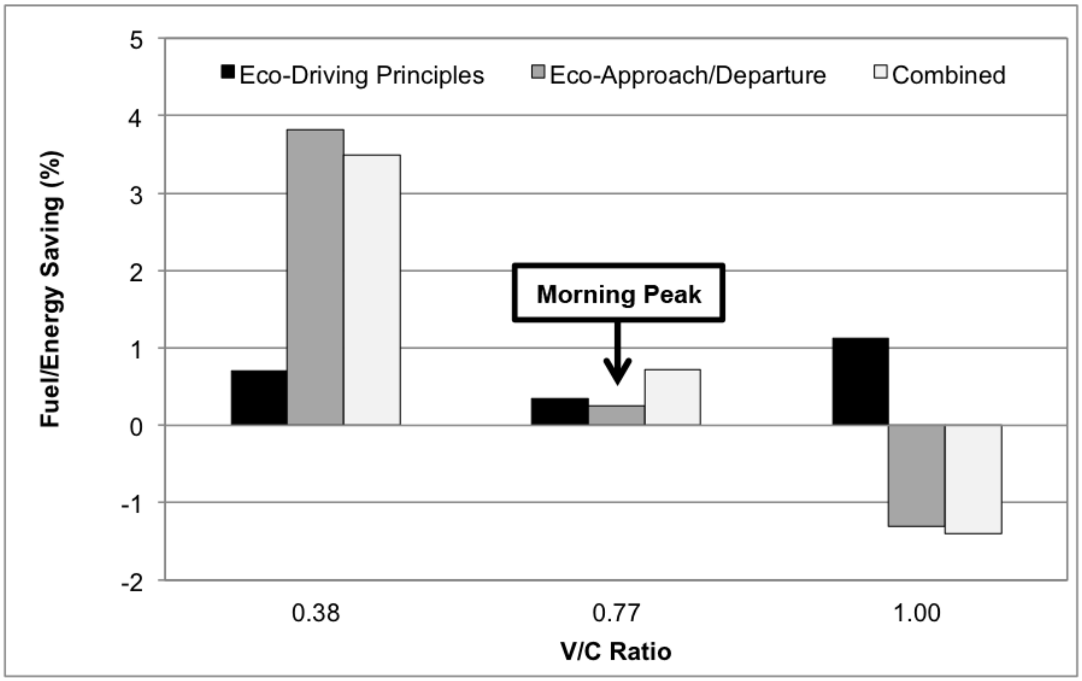


Figure 105: Performance of Different Modules and the Connected Eco-Driving Application on the 27-Intersection El Camino Real network under 100 Percent Penetration Rate: Energy Savings (%).

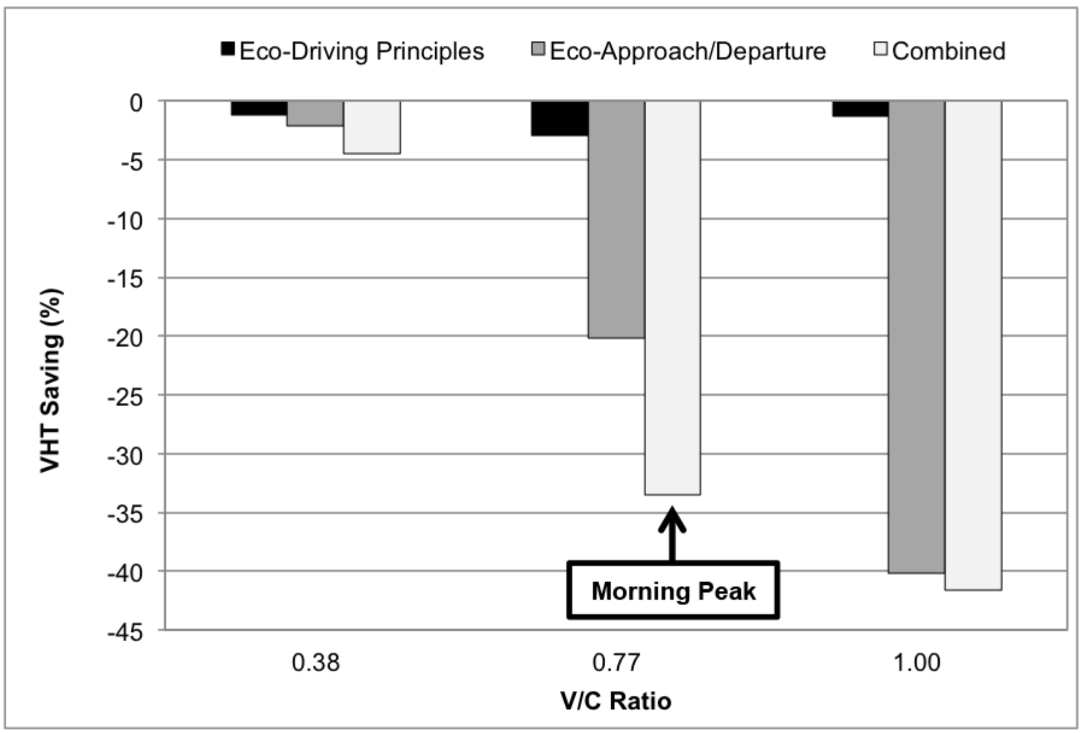


Figure 106: Performance of Different Modules and the Connected Eco-Driving Application on the 27-Intersection El Camino Real Network Under 100 Percent Penetration Rate: Changes in VHT (%).

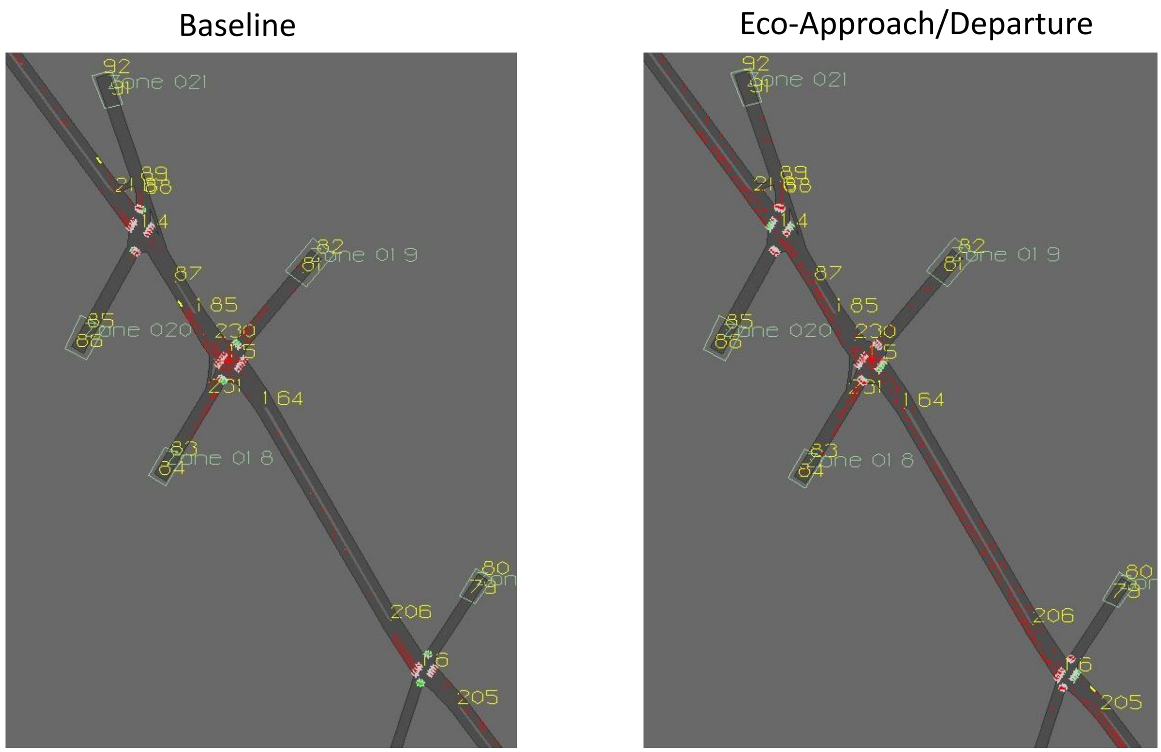


Figure 107: Snapshots from the Simulation Study To Show " Queue Spill-Back" Along the Short Link Caused by the Eco-Approach and Departure Module.

In addition, the overall benefits of Connected Eco-Driving (combined) are not simply the summation of two modules, but there are offsets in benefits when integrated. In this particular network, most of the intersection spacings are around 300 m, so the effectiveness of the Eco-Approach and Departure module dominates. The changes in MOEs over different congestion levels have been summarized in Table 69. As shown in the table, if the traffic demand is low (e.g., V/ C = 0.38), the proposed Connected Eco-Driving application can provide around 3.5 percent savings in energy consumption and significant reduction in other criteria pollutants (ranging from 5.7 percent to 26.8 percent), while the VHT per vehicle may increase by 5.0 percent. As the network becomes more and more congested, the benefits drop. For example, under the baseline (morning peak) traffic demand, where V/ C = 0.83, there is little improvement in energy consumption, although there are still significant reductions in other criteria pollutants. However, the VHT increases by about 33 percent.

Table 69: Changes (%) in MOEs Resulting from the Connected Eco-Driving Application Along the 27-Intersection El Camino Real Corridor (100 Percent Penetration Rate).

V/C	Energy	CO_2	CO	HC	NOx	PM-2.5	VHT	VMT
0.38	3.51	3.51	26.80	6.93	5.73	19.06	-4.96	0.89
0.83	0.73	0.85	24.51	4.45	5.59	19.86	-33.47	-0.21
1.00	-1.44	-1.42	21.24	0.49	4.16	18.28	-41.49	0.15

To get better understandings of the interaction among different modules, the research team conducted an additional sensitivity analysis on module combinations. The results are summarized in Table 70, where the baseline traffic demand (i.e., V/ C = 0.83) is modeled. As illustrated in the table, under the baseline traffic demand, the benefits in energy savings from the General Eco-Driving Principles module and Eco-Approach and Departure module are not so significant (less than 1 percent).

Table 70: Changes (%) in MOEs Under Different Module Combinations (Morning Peak ; Baseline Traffic Demand, where V/C = 0.83) Along the 27- Intersection El Camino Real Corridor (100 Percent Penetration Rate).

Module	Energy	CO_2	CO	HC	NOx	PM-2.5	VHT	VMT
A	0.26	0.37	9.32	0.39	3.57	8.86	-20.53	-0.11
P	0.36	0.45	18.43	6.17	1.04	11.54	-3.42	-0.50
A+P	0.73	0.85	24.51	4.45	5.59	19.86	-33.47	-0.21

A: Eco-Approach and Departure; P: General Eco- Driving Principles

Connected Eco-Driving on ECR-27—Penetration Rate

The research team further investigated the impacts of penetration rate on the effectiveness of each individual module. The results of the Generalized Eco-Driving Principles module are presented in this section.

Table 71 summarizes the relative changes in a variety of measures of effectiveness of the Generalized Eco-Driving Principles module under different levels of penetration : 0%, 20%, 50%, 80%, and 100%, when V/C = 0.83 (baseline demand). It is expected that there is not too much variation (all within 0.4 percent) in energy savings, because the greatest gain (fewer than 100 percent penetration rate) is not significant.

Table 71: Changes (%) in MOEs of the Generalized Eco-Driving Principles Module Under Different Penetration Rates (Morning Peak; Baseline Traffic Demand, Where V/C = 0.83) Along the 27-Intersection El Camino Real Corridor.

Penetr %	Energy	CO_2	CO	HC	NOx	PM-2.5	VHT	VMT
0	—	—	—	—	—	—	—	—
20	-0.36	-0.27	4.66	1.40	-0.76	2.29	-2.84	-0.58
50	0.12	0.21	10.77	4.32	-0.25	5.25	0.53	-0.03
80	-0.18	-0.09	15.35	5.17	-0.42	8.02	-2.59	-0.03
100	0.36	0.45	18.43	6.17	1.04	11.54	-3.42	-0.50

Findings and Opportunities for Future Research

Prior to modeling, the hypothesis that was generated based on literature review stated, "If real-time driving advice (e.g., recommended driving speeds, optimal acceleration, optimal deceleration) were provided to drivers based on prevailing traffic conditions and interactions with nearby vehicles and feedback were provided to encourage drivers to drive in a more environmentally efficient manner, then there will be emissions reductions and lowered fuel consumption during congested traffic conditions in the range of 10 percent to 15 percent under partial connected vehicle penetration and 15 percent to 20 percent under full connected vehicle penetration." The modeling results shown in this chapter indicate that the proposed Connected Eco-Driving application (created by integrating the General Eco-Driving Principles and Eco-Approach and Departure modules) may reduce the emissions and lower fuel consumption by up to 6 percent under full connected vehicle penetration, which is less than those reported in previous studies. It was found that the quantitative benefits are site specific. More specifically, this study found the following:

1. The analyses on the 27-intersection El Camino Real network show that as traffic becomes increasingly congested, the benefits from the Connected Eco-Driving application decrease. This is logical, because there is less room along the arterial for the application to improve system performance when the traffic demand increases. In addition, the implementation of this overall application may cause "moving bottlenecks" under high traffic volumes because of the smoothed deceleration and acceleration by the leading and preceding vehicles, which may result in queue spill-back when the storage space (intersection spacing) is not long enough. This has been verified by the Snapshots of simulation runs (see Figure 107).
2. The benefits of Connected Eco-Driving are *not* simply the summation of benefits from each individual component. Interactions between different modules may offset their own benefits when integrated. For example, the progression speeds of traffic flows may be changed because of the implementation of some modules (e.g., General Eco-Driving Principles), which may affect the coordination levels along the corridor.
3. By investigating each module of the Connected Eco-Driving application, it can be shown that the Eco-Approach and Departure module works well in light traffic condition, but its effectiveness diminishes when the network becomes congested. The General Eco-Driving Principles component is quite robust to the demand variations, and the changes in energy consumption and VHT are within 3 percent.
4. The sensitivity analyses on penetration rate show little variation in MOE changes for the Generalized Eco-Driving Principles module when applying the 27-intersection El Camino Real corridor (baseline traffic demand).
5. Note that in most of the results for the 27-intersection El Camino Real corridor, the changes in energy consumption and CO_2 emissions are much smaller than the changes in other criteria pollutant emissions. A possible explanation is that the emissions factors of these criteria pollutants are much more sensitive to the changes in vehicles' trajectories because of the implementation of these modules.
6. Based on the above findings from the modeling effort, the research team has the following recommendations and remarks:
7. The Eco-Approach and Departure module needs further improvement, taking into account the real-time information of the preceding vehicle.
8. Connected adaptive cruise control can be integrated to further improve the performance of the entire system.

Chapter 8. Combined Modeling of the Eco-Signal Operations Applications

Application Combination Description

Following the individual modeling of the five applications within the Eco-Signal Operations Operational Scenario, the applications were then combined to function simultaneously within the same modeling environment. To properly understand the impacts of the applications in this operational scenario, it was important to model the interactions of the applications and estimate the overall benefits to ensure that the applications under the operational scenario are compatible and do not significantly negate the benefits of other applications in the same operational scenario. While the compatibility of the applications within the operational scenario is not expected to result in additive improvements of their individual improvements when combined, it is important to have knowledge of incompatibility to understand future implementation.

To combine the applications in the modeling environment to test the impacts of the combined operational scenario, additional technical improvements were carried out on the individual algorithms and APIs used for the Paramics program. This includes combination of similar applications in to a single interface while making minor improvements to help understand the interactions and reduce technical conflicts in the technology. The following subsections detail the improvements, combinations, and assumptions made for the five applications within this operational scenario to complete the combined modeling of applications.

Eco-Traffic Signal Timing Application Integration

The Eco-Traffic Signal Timing application that was developed during the course of this project, as described in Chapter 5, is an “offline” method of signal timing optimization using the GA that was created. As a result, the GA needed to be run ahead of time for all of the desired sensitivity analyses to be conducted during the combining of applications. The resulting signal timing plans for the 27-intersection El Camino Real model were used as a starting point for combining of applications and added to the model before the other four applications were combined into the model to run in real time. Because the application is an offline method, it was therefore not running in real time with the other four applications but more as an application baseline timing that could be modified by the signal priority applications as their respective algorithms required. As a result, timing plans were developed for different levels of connected vehicle penetration (20 percent, 35 percent, 50 percent, 65 percent, 80 percent, and 100 percent) as well as for the three demand levels (0.38, 0.83, and 1.00 V/C ratio). Any new timing plans produced in addition to those from the individual modeling phase were developed using the same method and algorithms and subject to the same requirements and restrictions described in the Eco-Traffic Signal Timing application in Chapter 5.

During the course of combined modeling analyses and development, it was hypothesized that running the signal timing optimization algorithms separately from the Connected Eco-Driving and Eco-Approach and Departure applications may cause a conflict in the progression of vehicles through the network. In short, the Eco-Traffic Signal Timing application was designed to improve the flow of traffic to improve the environmental measures using the baseline vehicle trajectories, so if the other applications change the trajectories and speed a vehicle travels through the network, then it is possible that the improvements from the optimized signal timings might be lost. This could be studied in more detail in the future but would rely on improved algorithms and computer resources, as the speed advice and trajectory planning would considerably slow down the GA optimization process.

Eco-Signal Priority Applications Integration

Eco-Signal Priority is the umbrella description of the combination of the two signal priority-based applications: the Eco-Freight Signal Priority and the Eco-Transit Signal Priority application. Although the criteria for granting priority to freight or transit vehicles in the network are quite different (described in detail in the individual modeling in Chapter 6), the core implementation of the vehicle-tracking algorithms, SPaT communication methods, and signal timing override commands are virtually identical for both applications. Because of technical implementation requirements in Paramics for these methods and computational efficiency in the modeling, it made sense to combine the two applications in to one API for use in the combined modeling. For the purpose of this report, this algorithm is referred to as the *Combined Signal Priority algorithm,* shown in Figure 108. Because the logic of determining and granting the priorities is explained in great detail in this report, it is shown only in a simplified view here.

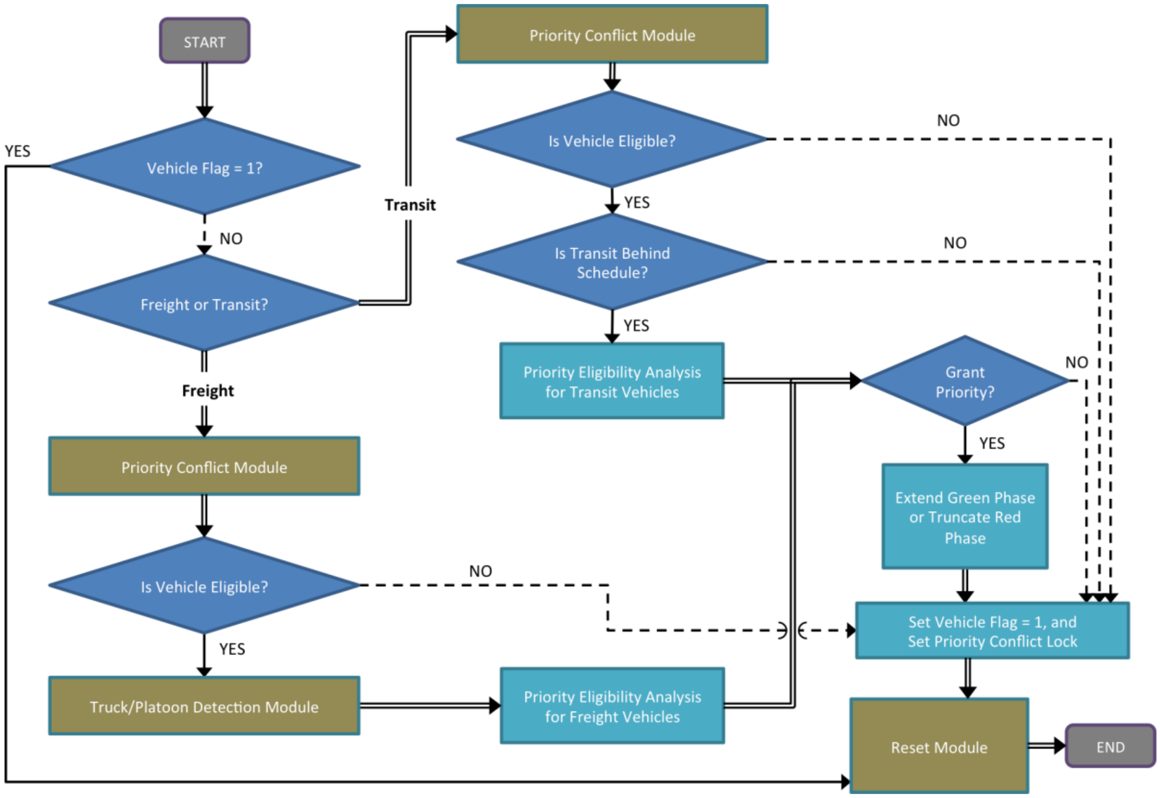


Figure 108: The Combined Signal Priority Algorithm.

The Combined Signal Priority algorithm takes the main features of the Eco-Freight Signal Priority and Eco-Transit Signal Priority applications to create an efficient monitoring algorithm to determine eligibility. When an eligible vehicle is within communication range of the signalized intersection, the algorithm first determines whether the vehicle is a freight vehicle or a transit vehicle. If it is a transit vehicle, then the eligibility is determined by two factors: Is in in conflict with a vehicle that has already been granted priority (Priority Conflict Module), and is the vehicle behind schedule. If the vehicle meets both eligibility requirements, then the same analysis is carried out as in the Eco-Transit Signal Priority individual application (see Figure 57 in Chapter 6). If the approaching vehicle is a freight vehicle, eligibility is determined based on the same Priority Conflict Module. If eligible, the vehicle information is immediately passed to the Truck/Platoon Detection Module (see Figure 58 in Chapter 6), and then analyzed the same way as the in the Eco-Freight Signal Priority individual application. When priority has been granted, a lock is placed on other approaches to the intersection to prevent conflicts with other vehicles at the same intersection, which the Priority Conflict Module can detect. This module is the most important addition to the Combined Signal Priority application algorithm and can be seen in Figure 109.

Figure 109: Priority Conflict Module Algorithm.

This algorithm is designed to prevent conflicting approaches being granted a conflicting priority at the same intersection. Such actions would consequently prevent the trajectory-planning algorithms from providing accurate SPaT information to and from the vehicles in real time. The first thing that the module searches for is whether there is a vehicle type conflict lock; if there is none, then the module determines whether there is an approach type conflict. If the vehicle passes both tests, then it is marked "Eligible," and this information is passed back to the main algorithm. Otherwise, the vehicle is marked "Ineligible" and ultimately terminates the main algorithm, not granting priority (the vehicle will also receive flag = 1).

This approach is a simplified way to solve the problem of conflicting priority requests by considering a first-come, first-served mentality for handling the requests. The Priority Conflict Module will also not prevent similar vehicle types from requesting priorities on the same approach. The limitation in this approach is that the algorithm does not consider whether the vehicle on the conflicting approach may have a worse environmental footprint than the vehicle that first requests the priority. This simplified approach is acceptable in many situations, especially the El Camino Real, because the lower freight volumes and transit headways do not cause a large number of conflicts that must be resolved. Future research may be warranted to shed more light on situations in which large differences in emissions could be approaching from different directions at the same intersection.

To help accommodate the interaction of transit and freight when combined in the same API algorithm and the addition of the Priority Conflict Module, the Reset Module was updated in the Combined Signal Priority algorithm, shown in Figure 110.

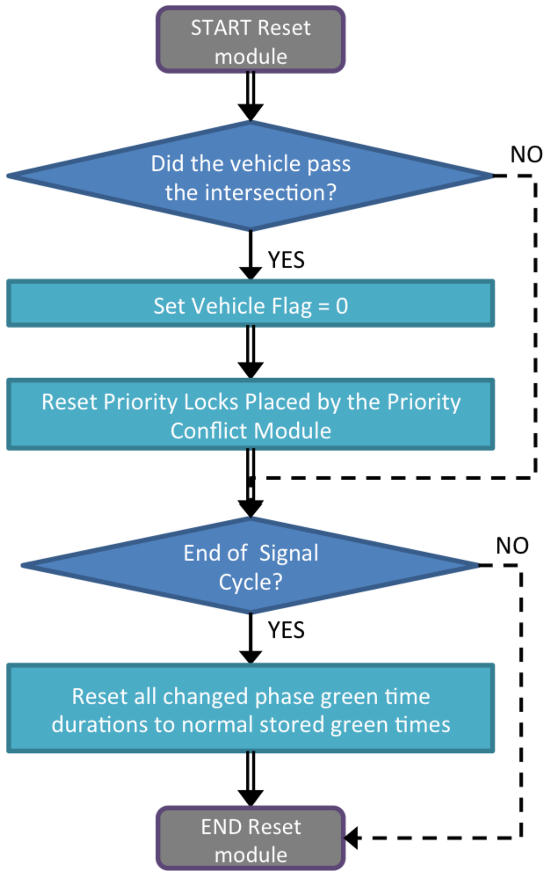


Figure 110: Reset Module Algorithm.

The main purpose of the module update is to add the ability to reset the priority lock that the Priority Conflict Module analyzes. When the vehicle to which the algorithm has granted priority passes the signalized intersection, the lock on the approach is released, and conflicting approaches can now be considered.

Eco-Approach and Departure Application Integration

The Eco-Approach and Departure application logic required setting up a memory bank for each vehicle in the model that would store emissions and vehicle-specific data that can be used and updated in real time to achieve the application's goal. Because the Paramics software does not allow two API plug-ins to assign and access such a memory bank on the same vehicle, it was necessary to combine the Eco-Approach and Departure application with the MOVES emission model plug-in, which also needs to store data with each vehicle. This greatly improved the computational efficiency of the applications, allowing all calculations to take place simultaneously in a second-by-second methodology in the same API plug-in. The logic used in combining these two plug-ins is shown in Figure 111. The detailed operation of each plug-in is not shown in this figure, because explanation of the operation is provided in Chapter 4, *Eco-Approach and Departure at Signalized Intersections Application*, and Appendix B, Development of MOVES Plug-In.

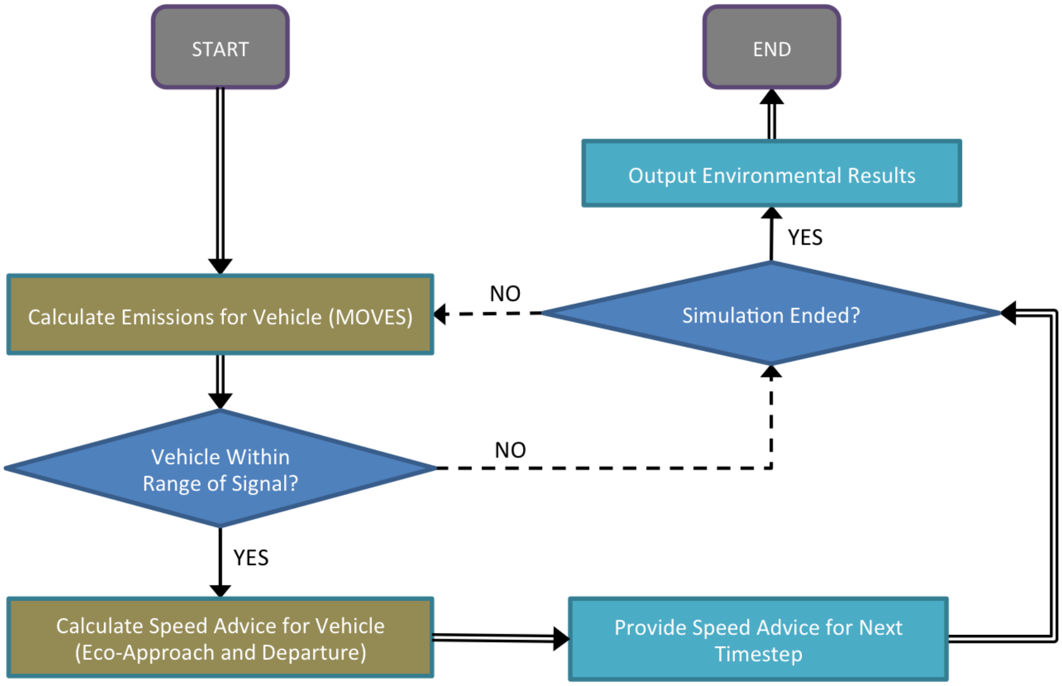


Figure 111: Combined Eco-Approach and Departure Signalized Intersections and MOVES Emission Model Algorithm.

Using this logic, the vehicle's emissions are calculated at every time step (once per second), regardless of whether the connected vehicle is within DSRC range of the signalized intersection. This information is stored in the vehicle for use in the application or for calculations of total emissions within the corridor. When the vehicle is within range, the vehicle speed would be calculated at each time step in addition to its emissions within the same process. When the simulation is complete, the stored emissions information is compiled and sent as an output from the model to be used for application sensitivity analysis results.

For this application, the compliance rate is assumed to be 100 percent for vehicles that are equipped with connected vehicle OBE technology and are receiving the Eco-Approach and Departure advice from the system. Because the vehicles in the system are not autonomous, driver compliance is important to the success of the application as well as the drivers' ability to follow the advice they have received to drive more "eco-friendly." Future research in to compliance rates could help to better show the impact of equipped drivers not following the driving advice.

Connected Eco-Driving Application Integration

The logic of the Connected Eco-Driving Application is not a real-time API within the Paramics environment, so its implementation in the combined modeling of the Eco-Signal Operations Operational Scenario applications is straight forward. For the Eco-Signal Operations Operational Scenario, the Connected Eco-Driving Application consists of the General Eco-Driving Principles, which are the desired acceleration and deceleration profiles for each type of vehicle to achieve the best fuel efficiency and emission rates as they drive along the corridor. These values are not dynamic or real time, meaning that they are not updated based on current or changing traffic conditions within the model; rather, these ideal values are applied to each vehicle when they are created during the simulation. When each vehicle is created, if it is a connected vehicle —meaning that it has on-board connected vehicle technologies —then it is assigned the environmentally friendly profiles, while non-connected vehicles are assigned the baseline calibrated driving profiles. The development of these General Eco-Driving Principles for the Connected Eco-Driving application is explained in more detail in Chapter 7. When the Eco-Approach and Departure application is providing the real-time speed advice to the vehicles as they approach the intersection, the maximum and minimum acceleration and deceleration values these Eco-Driving principles provide affect how quickly the vehicle is allowed to react to the recommendation. Therefore, there will be a difference in how the applications achieve results when combined as opposed to the individual modeling.

For this application, again, the compliance rate is assumed to be 100 percent for vehicles that are equipped with connected vehicle OBE technology and are receiving the Eco-Driving advice from the system. Because the vehicles in the system are not autonomous, driver compliance is important to the success of the application as well as the drivers' ability to follow the advice they have received to drive more "eco-friendly." Future research in to compliance rates could help to better show the impact of equipped drivers not following the driving advice.

Hypotheses

If all five applications in the Eco-Signal Operations Operational Scenario are implemented together, then there will be emissions reductions and lowered fuel consumption during congested traffic conditions in the range of 15 percent to 20 percent under partial connected vehicle penetration and 20 percent to 25 percent under full connected vehicle penetration. The percentage saving estimates considers operational improvements only; potential mode shift and route changes are assumed to have a minimal impact.

Modeling Approach

The overall modeling approach for the combined modeling of applications within the Eco-Signal Operations Operational Scenario was completed using similar methods as the individual application modeling using the Paramics micro simulation modeling package to model the environmental impacts. All of the modeling was carried out on the 27-intersection corridor model of the El Camino Real, as explained in Chapter 3, which was intended to show the maximum attainable benefits in a real-life, urban environment. The interactions between the different Eco-Signal Operations applications within the technical infrastructure, however, are much more detailed and complicated than those of the individual models. As described in "Application Combination Description" section, there was some effort to combine APIs and interweave the infrastructure of the applications to help them to work in combination.

As part of the evaluation, detailed speed profiles of every vehicle were examined to estimate emissions and energy consumption as a goal measure. The interaction among the different applications and the API used in is shown below in Figure 112. The Eco-Signal Operations Operational Scenario plug-ins are designed to fulfill the following functions:

1. Freight and transit vehicles can submit priority requests, which are reviewed and provided to the signal system in the microsimulation, if approved.
2. Provide vehicles with second-by-second approach and departure speed advice to promote eco-friendly driving.

3. Be able to query and modify signal and other infrastructure traits in response to connected vehicle technology.
4. Vehicle information and trajectories are recorded every second to determine their emission rate and fuel efficiency to develop environmental resultant measures.

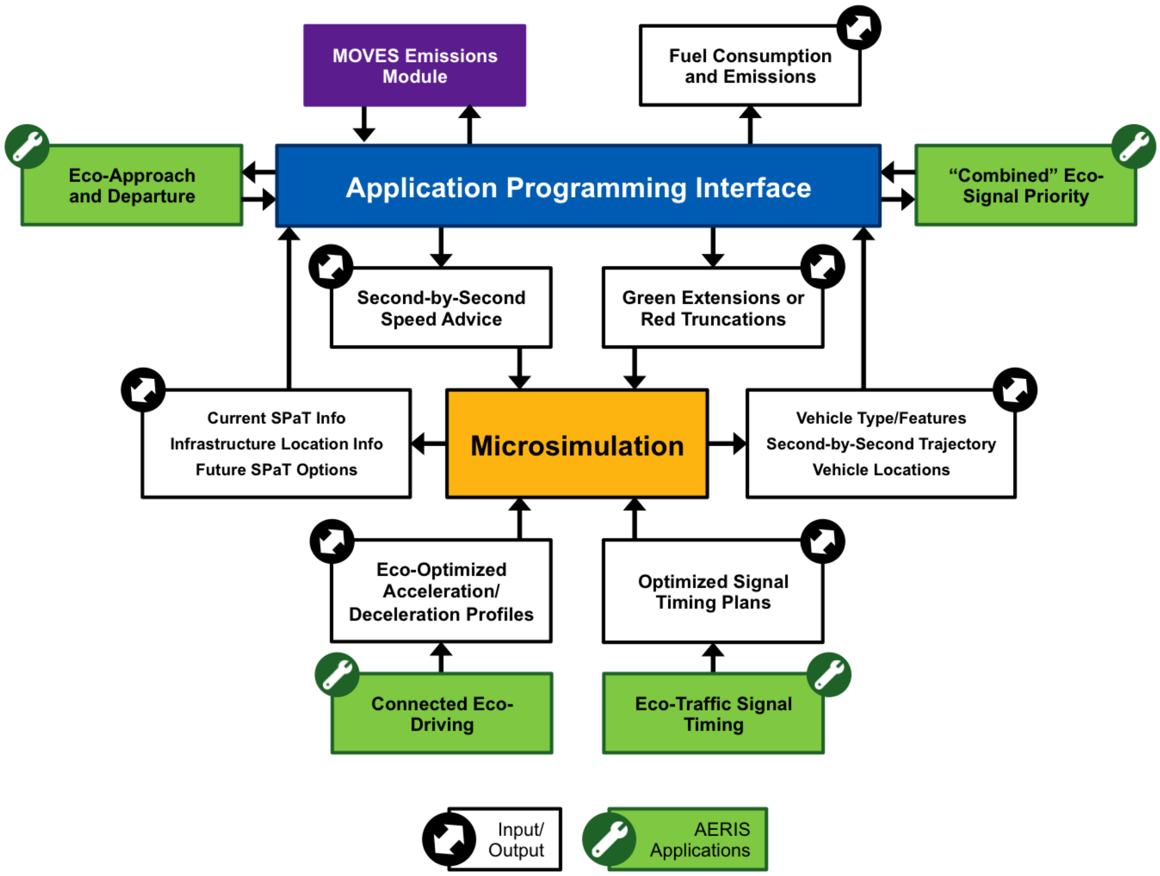


Figure 112: Diagram of Interactions Among the Models and API.

When the microsimulation model is initialized, it is provided with the optimized signal timings from the GA optimization in the Eco-Traffic Signal Timing application as well as the eco-optimized acceleration and deceleration profiles for connected vehicles. These values are locked in to the simulation parameters and do not change during the simulation run or interact with the Paramics API. As the simulation runs, the model provides the Paramics Programmer API with second-by-second vehicle information, trajectory, and speed profiles as well as the vehicles' locations in relation to the infrastructure. The API also communicates with the model requesting information on SPaT status as well as requesting changes to the infrastructure. The Combined Signal Priority application (Eco-Freight Signal Priority and Eco-Transit Signal Priority) as well as the Eco-Approach and Departure application use this connection to the API to make judgments and requests to the infrastructure based on each application's intention. When the application has made a decision, the API sends the information, whether a signal priority or speed advice, back to the microsimulation model. The MOVES environmental plug-in is active throughout the simulation, all the time calculating and storing the resultant fuel consumption and emissions information to be output at the end of the simulation.

More information on the microsimulation model calibration and other information on the baseline model can be found in Chapter 3.

Scenarios

An exhaustive set of scenarios was modeled as part of the combined modeling of applications. The remainder of this section details the scenarios modeled. The modeling results that follow in the next section are organized in the same fashion. The network used for modeling the scenarios was El Camino Real 27-Intersection Network (Referred to as ECR-27).

A list of scenarios modeled is presented below.

1. **Combined Eco-Signal Operations Applications:** The Eco-Signal Operations applications were tested on the ECR-27 network at baseline demand of 0.83 V/C ratio. The penetration rate of connected vehicle technology is assumed to be 100 percent.
2. **Combined Eco-Signal Operations on ECR27 – Connected Vehicle On-Board Equipment Penetration Rate:** The Eco-Signal Operations applications were tested on the ECR-27 network at baseline demand of 0.83 V/C ratio. The penetration rate of connected vehicle technology was varied using values 20%, 35%, 50%, 65%, 80% and 100%.
3.
4. **Combined Eco-Signal Operations on ECR27 – Demand** Level**:** The Eco-Signal Operations applications were tested on the ECR-27 network at 100% connected vehicle penetration rate. The demand levels expressed as V/C ratio were varied using three levels: baseline (V/C = 0.83), undersaturated (V/C = 0.38), and at saturation (V/C = 1.00).
5. **Combined Eco-Signal Operations on ECR27 – Analysis of Future Fleet Mix:** The Eco-Signal Operations applications were tested on the ECR-27 network at baseline demand of 0.83 V/C ratio. The penetration rate of connected vehicle technology is assumed to be 100 percent. A sensitivity analysis was undertaken to compare the 2005 baseline fleet mix with a future fleet mix in the year 2030. For the sake of simplicity, the traffic volumes were not grown to represent the increase in traffic demand; rather, the sensitivity analysis focused purely on the change in emissions of the same amount of vehicles with improved fuel consumption and environmental profiles.

Modeling Results

To assess the environmental benefits of the combined modeling of the five applications in the Eco-Signal Operations Operational Scenario, baseline models were developed with the assumption that there was no application deployment with any of the five applications. The MOVES API plug-in developed for the AERIS program estimated the environmental impacts and fuel consumption. Emissions and travel time statistics were collected from each baseline simulation run to establish the baseline conditions. The application impacts and benefits were then measured by comparing the performance of the networks with applications active. Because extensive sensitivity analyses had been completed previously on all applications during the individual modeling phase of the operational scenario, the combined modeling focused on a more targeted sensitivity analysis to better understand the impact of the applications on each other. The three primary sensitivity analyses that were examined were —

- Penetration rate of the connected vehicle technology —specifically, the penetration of the OBE
- Congestion ratio (V/C ratio)
- Impact of applications in the future fleet mix (2030) versus the baseline fleet mix (2005).

For this analysis, it is assumed that if a vehicle were equipped with connected vehicle OBE technology it would have access to and use all of the applications available in the Eco-Signal Operations Operational Scenario. Sensitivity analyses were not undertaken as a part of this analysis to show what impacts would be undertaken if certain vehicles had only a few of the total applications installed or active in their vehicle when traveling through the model. So, for the purposes of this report, the vehicle penetration rate represents vehicles that will use and provide V2I information for all applications within the operational scenario. The Eco-Traffic Signal Timing and Eco-Traffic Signal Priority applications are “passive,” in that the operator of the equipped vehicle does not need to actively comply with or provide active responses to the applications to use them. As stated in Chapter 3, the compliance rate was also assumed to be 100 percent for the Eco-Approach and Departure and Connected Eco-Driving Applications that provide real-time speed and acceleration advice to drivers. All of these additional parameters should provide interesting information in future research to help supplement the real-life implementation of these applications.

Combined Eco-Signal Operations Applications on ECR27

Before detailed sensitivity analyses could be undertaken on the combined applications of the Eco-Signal Operations Operational Scenario, the five applications first needed to be run in the modeling environment together to check for technical implementation issues and to see the overall “total improvement” of the applications against the baseline conditions. To compare how the “bundling” of applications compared with the individual results obtained and explained in this report, all five Eco-Signal Operations applications were finalized and run individually in the 27-intersection El Camino Real baseline model (as described in Chapter 3) to show the best obtainable result of the applications. The five applications were then combined in the same model and run at a 100 percent connected vehicle OBE penetration rate, baseline demand and freight percentages, and transit schedule to show the maximum expected benefit of the combined applications. The results of this analysis are shown in Figure 113 for each application and for each fuel/emissions type for all of the vehicles in the network.

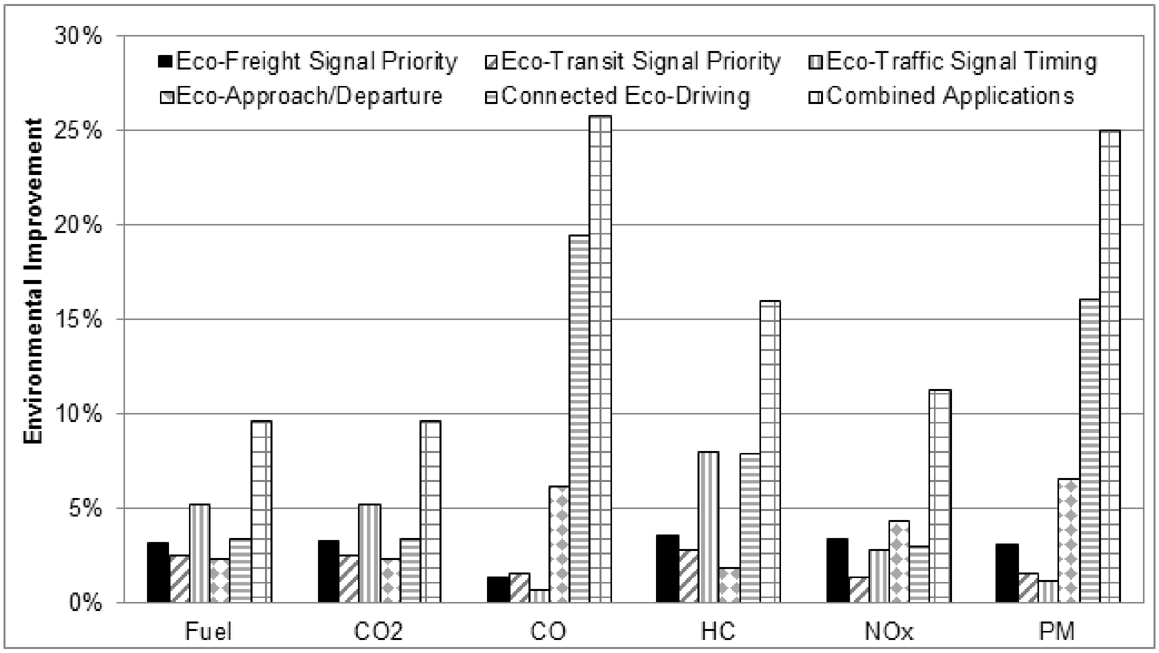


Figure 113: Fuel and Emissions Savings Against the Baseline for the Combination of Eco-Signal Operations Applications.

As shown, the combination of the five applications within the Eco-Signal Operations Operational Scenario results in significantly improved fuel consumption and environmental measures across all types of pollutants. One of the most important and interesting questions about the combination of the applications was whether all of the individual results would be additive or whether one application could hinder or nullify the improvements of another within the same operational scenario. The result above shows that the individual results are not exactly additive but that no one application significantly hinders any of the others. The results of the application combination show that all five of the Eco-Signal Operations applications complement each other to receive a roughly 10 percent improvement in fuel consumption and CO_2 savings on the El Camino Real corridor as well as significant improvements in all other pollutant types.

Another major takeaway from the results shown in Figure 113 is that there are different patterns in the improvement of different environmental measures for each of the different applications, which is a direct result of the individual applications' intended purpose. One major purpose of all of the Eco-Signal Operations applications is to reduce the number of stops, queuing, and decelerating along the approaches to the signalized intersections along the El Camino Real roadway. These activities all have a real and direct effect on fuel consumption and CO_2 measures, which are the best known and most interesting to those investing in environmentally friendly applications. The Eco-Traffic Signal Timing application has the largest effect on these resultant measures, because changing the baseline timing plan has a major effect on the amount of delay at the approach and the travel time through the corridor. In contrast, the other four applications have similar and significant improvements in fuel consumption. The applications that are intended to smooth out the trajectories of drivers and provide them with advice on speed, acceleration, and deceleration—the Eco-Approach and Departure and Connected Eco-Driving —have a completely different effect on the emissions. Pollutants, such as CO and particulate matter, are greatly affected by the smoothing of these trajectories, so a significant improvement can be seen in these pollutants. As shown in the individual modeling and Figure 124, applications such as Eco-Traffic Signal Timing and Eco-Signal Priority only change the signal settings; therefore, they have no significant impact on these pollutant types.

The results above also show that there are larger improvements for CO_2, hydrocarbons, and particulate matter than are seen for CO_2 and fuel consumption measures because of the total magnitude of the volume of these pollutants compared with each other. The fuel and CO_2 baseline numbers are orders of magnitude larger, meaning that the percentage increases can be misleading. Absolute volumes of these pollutants can be seen in Figure 114. The improvement in fuel on the left side represents a 10 percent improvement, while the improvement in particulate matter on the right is a little more than 25 percent improvement over the baseline for the combined applications.

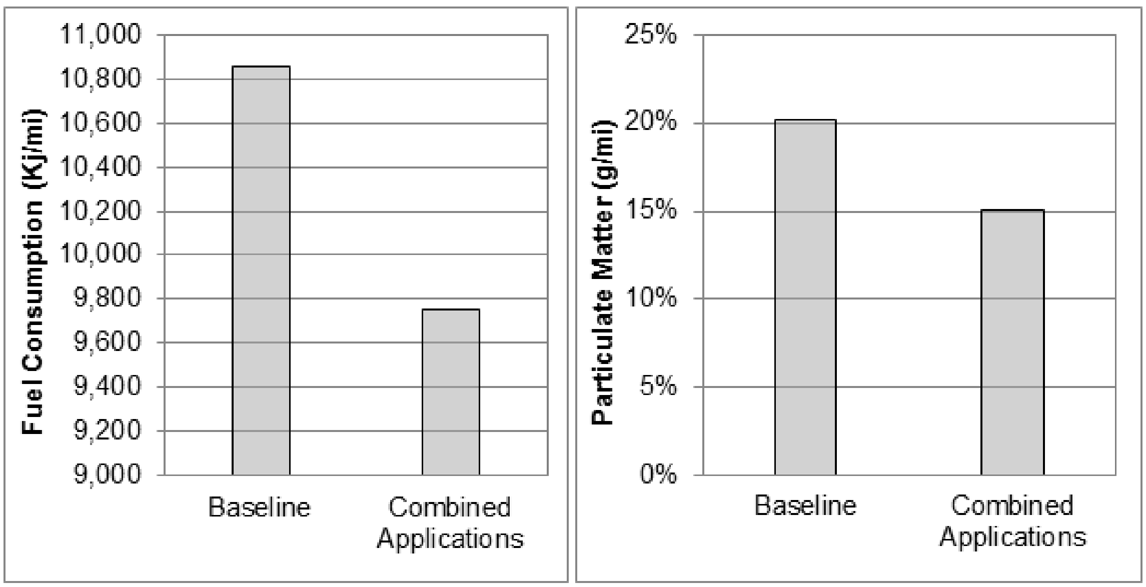


Figure 114: Comparison of Volume Magnitude Between Fuel Consumption and Particulate Matter in the Combined Modeling Results.

Table 72 provides detailed emissions and fuel consumption information for the combination of applications in the Eco-Signal Operations Operational Scenario relative to the baseline.

Table 72: Detailed Comparison of the Combined Applications vs. Baseline for All Network Vehicles.

All Vehicles						
Eco-Signal Operations Application	**Fuel, (kJ/mi)**	**CO_2 (g/mi)**	**CO (g/mi)**	**HC (g/mi)**	**NOx (g/mi)**	**PM (g/mi)**
Baseline	10,859.7	785.03	11.34	0.531	3.915	0.202
Eco-Freight Signal Priority	10,504.9	759.34	11.19	0.512	3.782	0.196
Eco-Transit Signal Priority	10,576.4	764.58	11.17	0.516	3.849	0.198
Eco-Traffic Signal Timing	10,280.9	743.27	11.25	0.488	3.781	0.198
Eco-Approach and Departure	10,580.6	764.74	10.65	0.520	3.724	0.188
Connected Eco-Driving	10,566.3	763.92	9.18	0.494	3.865	0.175
Combined Applications	9,749.9	704.68	8.41	0.444	3.432	0.151
% Improvement Compared with the Baseline						
Eco-Freight Signal Priority	3.3%	3.3%	1.4%	3.6%	3.4%	3.1%
Eco-Transit Signal Priority	2.6%	2.6%	1.5%	2.9%	1.7%	1.8%
Eco-Traffic Signal Timing	5.3%	5.3%	0.8%	8.2%	3.4%	1.9%
Eco-Approach and Departure	2.6%	2.6%	6.1%	2.1%	4.9%	7.0%
Connected Eco-Driving	2.7%	2.7%	19.0%	7.1%	1.3%	13.5%
Combined Applications	10.2%	10.2%	25.8%	16.4%	12.3%	25.1%

Combined Eco-Signal Operations on ECR27 – Connected Vehicle On-Board Equipment Penetration Rate

During the individual modeling of applications in the Eco-Signal Operations Operational Scenario and their corresponding sensitivity analyses, it was found that perhaps the most important sensitivity parameter for connected vehicle technologies is the connected vehicle OBE penetration rate in the network. The rolling implementation of the application technology will enable an understanding of whether the operational scenario provides environmental benefits to motorists and the system as vehicles are being introduced over time or only after they have been fully adopted in the future. Because it was shown in the previous section that different vehicles and pollutant types respond differently for different applications, this sensitivity analysis is even more interesting when the applications are combined. With this, it can be seen whether having speed and acceleration advice as well as timing and signal priority changes can be effective or detrimental when only communicating with a small portion of vehicles in the network. For this analysis, it is assumed that the connected vehicle OBE penetration rate represents the amount of information each application is using —for example, a 20 percent penetration rate means that only 20 percent of the vehicles are receiving speed and acceleration advice or that only 20 percent of the vehicles are contributing environmental information to the signal timing optimization algorithm.

This sensitivity analysis was undertaken on the same El Camino Real baseline network; as previously mentioned, an equipped vehicle in this analysis will take advantage of all five of the Eco-Signal Operations applications. The results of this analysis are shown in Figure 115, which is shown as the improvement in fuel consumption for each major vehicle class in the network to help better understand the results of the analysis.

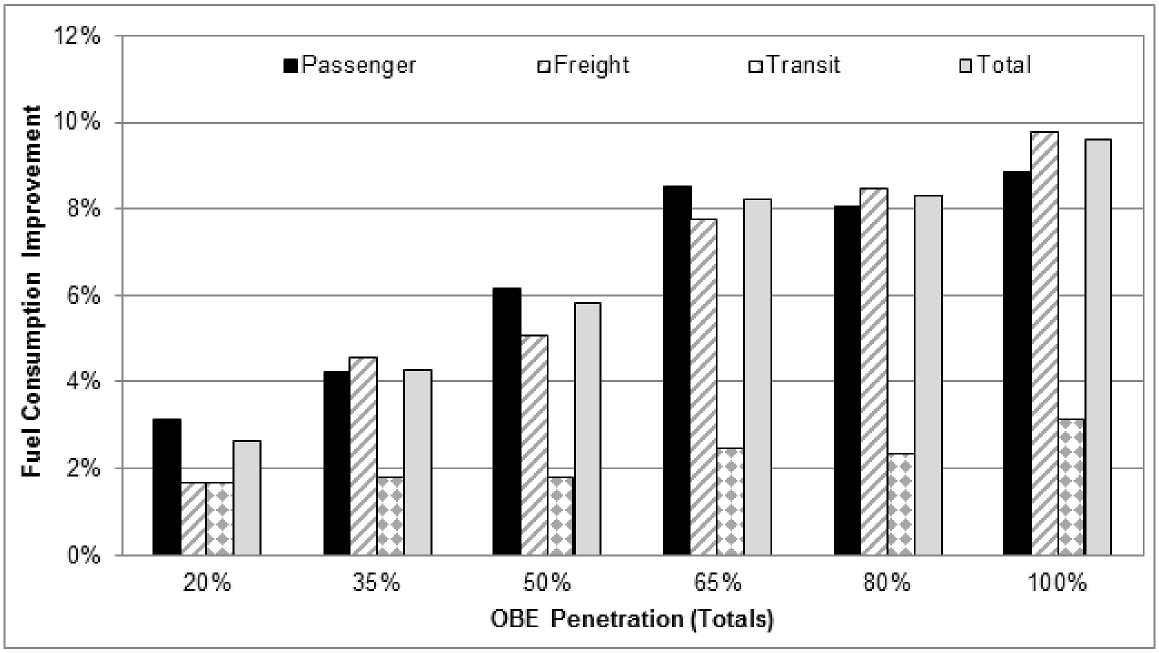


Figure 115: Fuel Savings Against the Baseline for Increasing Levels of Connected vehicle OBE Penetration Rate by Vehicle Type.

The results in Figure 115 from the sensitivity analysis show the same trend that has been apparent in all of the individual modeling of applications within the Eco-Signal Operations Operational Scenario, which is that an increasing level of connected vehicle technology OBE penetration rates results in increasing improvements in environment improvement. The results for the total vehicles in the network is the sum of all vehicles in the network, and it can be seen that even at the lowest levels of connected vehicle penetration, there are noticeable environmental benefits when looking at the network as a whole, increasing to a maximum benefit of about 10 percent improvement in fuel consumption at full implementation. The figure helps us understand the detailed impacts of the applications in lower penetration rates, however, as it is broken down in to the three major vehicle classes in the network. This shows the contribution of benefits from the different types of vehicles in the lower levels of connected penetration rate increasing over time. It can be seen at the lowest levels of connected vehicle OBE penetration rate that passenger vehicles are receiving the greatest benefit from the combined applications, but there is still almost 2 percent improvement for freight and transit vehicles. It can also be seen that the passenger vehicle improvement plateaus at about a 65 percent penetration rate and holds steady at about 8 percent to 8.5 percent improvement at higher penetration rates. The benefit that transit vehicles see stays roughly constant among the increasing implementation of connected vehicle technology, increasing only slightly as the penetration rate nears 100 percent. This is likely because the transit demand in the network is small compared with all the other vehicle types (see Chapter 3 for more information about demand in the network). The environmental improvements freight vehicles gain follow the same general trend as passenger vehicles, except that they experience slightly higher improvements in full penetration. Freight vehicles contribute much larger volumes of pollutants, so the improvements the combined applications gain are greater in full connected vehicle penetration.

In addition to the total passenger vehicle improvements, the results obtained for connected and non-connected vehicles helps us to better understand the impact of the applications on the vehicles in the network. The fuel consumption improvements for connected and non-connected passenger vehicles are shown in Figure 116.

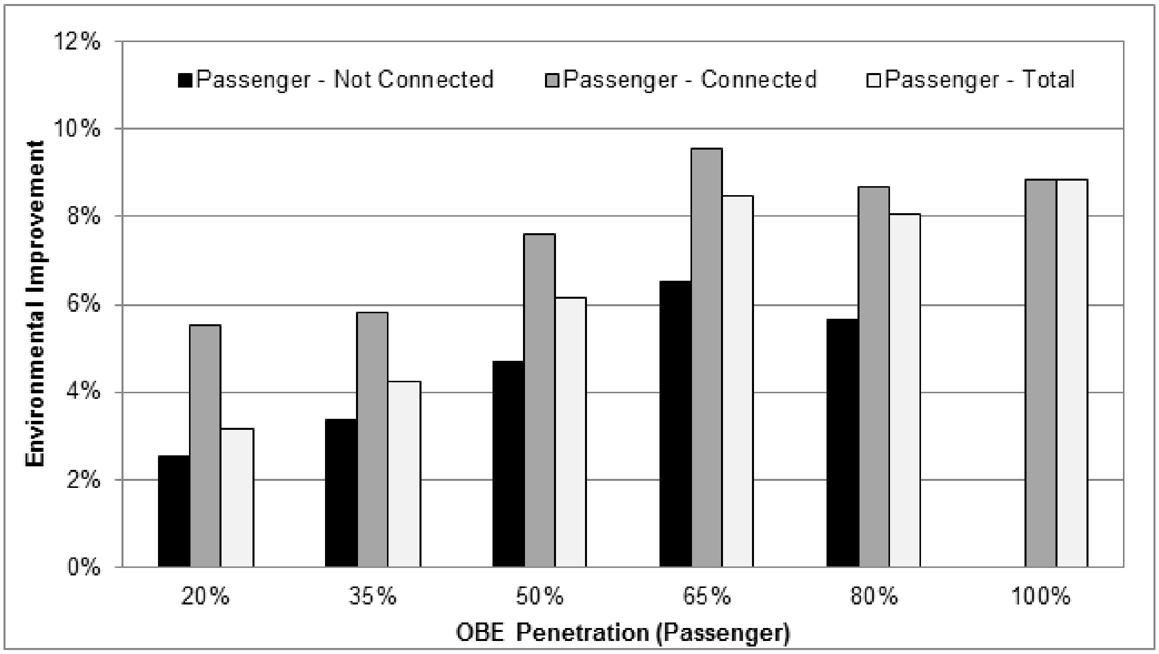


Figure 116: Fuel Savings Against the Baseline for Increasing Levels of Connected Vehicle OBE Penetration Rate for Passenger Vehicles.

This figure shows that there are significant improvements in both the connected and non-connected passenger vehicles in the network, even at the lowest levels of connected vehicle OBE penetration. The majority of the vehicles in the network are passenger vehicles (see Chapter 3 for more information about demand rates), and the uniformity of the traffic stream allows all vehicles to obtain some benefit from the applications, even when not connected. As the connected vehicle OBE penetration rate increases, the benefits increase for connected and non-connected vehicles until about a 65 percent penetration rate, where the benefits plateau at their maximum values of about 9 percent to 9.5 percent. This would indicate that there is a maximum level of benefit that the passenger vehicle traffic stream can obtain with these applications when smoothing the trajectory of the stream with speed and acceleration advice. These maximum benefits being reached at lower levels of connected vehicle OBE penetration rate indicate that these combined applications would be useful for implementation at the early introductions of connected vehicle technology to provide great benefits to the system.

In addition to passenger vehicles, the results were collected for connected and non-connected freight to understand their impacts. The fuel consumption improvements for connected and non-connected freight vehicles are shown in Figure 117.

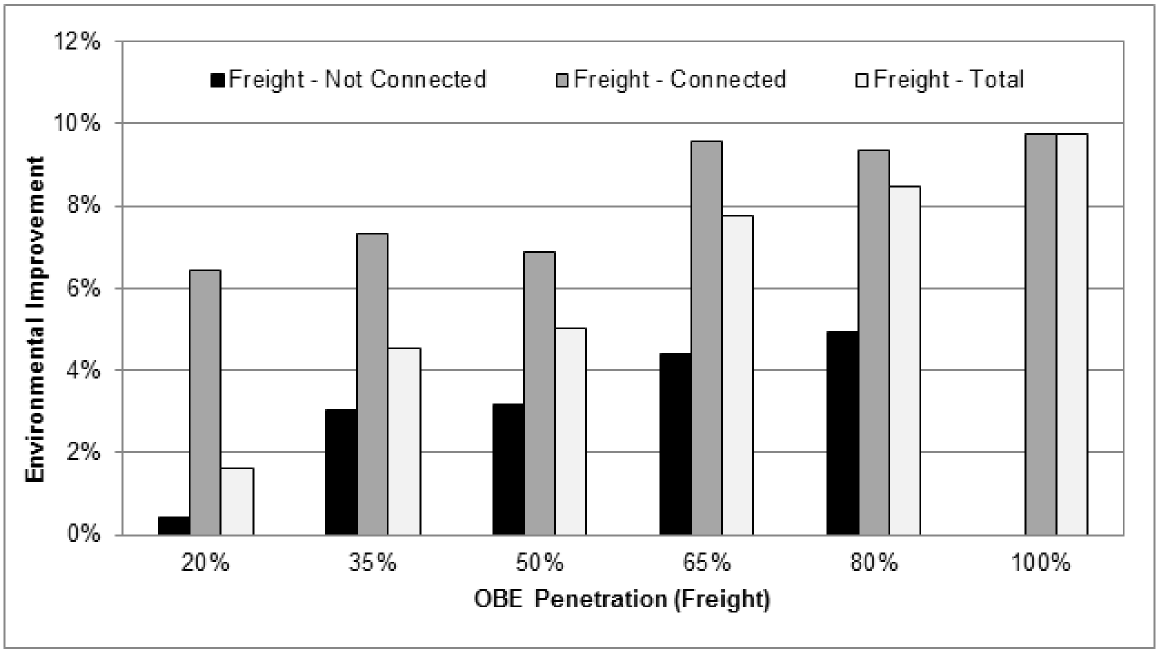


Figure 117: Fuel Savings Against the Baseline for Increasing Levels of Connected Vehicle OBE Penetration Rate for Freight Vehicles.

The results show that even at low levels of connected vehicle penetration, connected freight vehicles gain significant improvements in fuel consumption with the combined applications of the Eco-Signal Operations Operational Scenario. This level of improvement stays constant at the lower levels of penetration, but after 65 percent OBE penetration rates, the improvement increases up to nearly 10 percent at full implementation. The results for the connected and non-connected vehicles are not weighted in the analysis by their total size and effect on the overall freight numbers, so the total combined freight contribution is also shown in the figure in green. This was done so that the contribution of the connected versus non-connected vehicles could be understood in relation to their volumes in the traffic demand. For the non-connected vehicles, minor improvements can be seen at the lower levels of penetration, because the vehicles are able to take advantage of priorities, improved signal timings, and speed advice given to other connected vehicles in the network. At the lowest levels of penetration, it can be seen that because only minor improvements are gained, the total freight improvements are also minor. As the number of connected vehicles increases, the incidental benefits to the non-connected vehicles improve as a consequence. The trend holds that with increasing penetration there are increasing environmental improvements because of the combined Eco-Signal Operations applications.

More detailed emissions and fuel consumption information for each level of connected vehicle OBE penetration rate implementation relative to the baseline is available in Table 73, Table 74, Table 75, and Table 76.

Table 73: Detailed Comparison of Increasing Connected Vehicle OBE Penetration Rate with Baseline (All Network Vehicles).

OBE Penetration Rate (%)	Fuel (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)
0	10,859.7	785.04	11.34	0.531	3.915	0.202
20	10,499.7	758.99	10.48	0.503	3.778	0.188
35	10,336.3	747.11	10.09	0.494	3.683	0.179
50	10,178.2	735.73	9.72	0.477	3.659	0.175
65	9,952.7	719.49	9.24	0.455	3.616	0.169
80	9,923.4	717.27	8.89	0.454	3.539	0.162
100	9,749.9	704.68	8.41	0.444	3.432	0.151
% Improvement Compared with the Baseline						
20	-3.3%	-3.3%	-7.6%	-5.4%	-3.5%	-6.7%
35	-4.8%	-4.8%	-11.0%	-7.0%	-5.9%	-11.1%
50	-6.3%	-6.3%	-14.3%	-10.2%	-6.6%	-13.3%
65	-8.4%	-8.4%	-18.5%	-14.3%	-7.6%	-16.0%
80	-8.6%	-8.6%	-21.6%	-14.5%	-9.6%	-20.0%
100	-10.2%	-10.2%	-25.8%	-16.4%	-12.3%	-25.1%

Table 74: Detailed Comparison of Increasing Connected Vehicle OBE Penetration Rate with Baseline (Passenger Vehicles).

OBE Penetration Rate (%)	Fuel (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)
0	8,057.9	579.12	10.41	0.392	1.195	0.064
20	7,804.3	560.89	9.54	0.370	1.153	0.056
35	7,716.8	554.60	9.11	0.361	1.131	0.052
50	7,562.5	543.51	8.70	0.345	1.124	0.049
65	7,367.7	529.52	8.24	0.328	1.102	0.045
80	7,407.7	532.39	7.88	0.327	1.088	0.040
100	7,343.5	527.77	7.38	0.318	1.068	0.035
% Improvement Compared with the Baseline						
20	-3.1%	-3.1%	-8.3%	-5.7%	-3.5%	-12.6%
35	-4.2%	-4.2%	-12.4%	-8.0%	-5.4%	-19.2%
50	-6.1%	-6.1%	-16.4%	-12.0%	-5.9%	-24.3%
65	-8.6%	-8.6%	-20.9%	-16.2%	-7.8%	-30.3%
80	-8.1%	-8.1%	-24.3%	-16.7%	-9.0%	-37.1%
100	-8.9%	-8.9%	-29.1%	-19.0%	-10.6%	-45.1%

Table 75: Detailed Comparison of Increasing Connected Vehicle OBE Penetration Rate with Baseline (Freight Vehicles).

OBE Penetration Rate (%)	Fuel (kJ/mi)	CO2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)
0	33,910.40	2,478.80	19.77	1.721	26.01	1.306
20	33,353.90	2,438.30	19.15	1.668	25.771	1.282
35	32,365.00	2,365.60	19.04	1.658	24.889	1.224
50	32,200.90	2,353.70	19	1.632	24.733	1.211
65	31,206.50	2,281.10	18.27	1.54	24.041	1.17
80	31,039.50	2,268.80	18.17	1.571	23.87	1.15
100	30,596.40	2,236.20	18.07	1.584	23.474	1.118
% Improvement Compared with the Baseline						
20	-1.60%	-1.60%	-3.10%	-3.10%	-0.90%	-1.80%
35	-4.60%	-4.60%	-3.70%	-3.60%	-4.30%	-6.30%
50	-5.00%	-5.00%	-3.90%	-5.20%	-4.90%	-7.30%
65	-8.00%	-8.00%	-7.60%	-10.50%	-7.60%	-10.40%
80	-8.50%	-8.50%	-8.10%	-8.70%	-8.20%	-11.90%
100	-9.80%	-9.80%	-8.60%	-8.00%	-9.80%	-14.40%

Table 76: Detailed Comparison of Increasing Connected Vehicle OBE Penetration Rate with Baseline (Transit Vehicles).

OBE Penetration Rate (%)	Fuel (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)
0	45,510.2	3,337.4	10.90	1.528	42.146	2.366
20	44,757.5	3,292.2	10.80	1.512	41.094	2.304
35	44,698.3	3,277.9	10.90	1.527	41.442	2.313
50	44,694.0	3,272.2	10.92	1.523	41.600	2.315
65	44,446.1	3,259.4	10.65	1.436	41.074	2.285
80	44,448.8	3,278.8	10.69	1.449	41.215	2.283
100	44,095.5	3,283.5	10.73	1.451	41.414	2.291
% Improvement Compared with the Baseline						
20	-1.7%	-1.4%	-0.9%	-1.0%	-2.5%	-2.6%
35	-1.8%	-1.8%	0.0%	-0.1%	-1.7%	-2.2%
50	-1.8%	-2.0%	0.2%	-0.3%	-1.3%	-2.2%
65	-2.3%	-2.3%	-2.3%	-6.0%	-2.5%	-3.4%
80	-2.3%	-1.8%	-1.9%	-5.2%	-2.2%	-3.5%
100	-3.1%	-1.6%	-1.6%	-5.0%	-1.7%	-3.2%

Combined Eco-Signal Operations on ECR27 – Demand Level

Another sensitivity factor of great importance when considering the impact of connected vehicle technology is the amount of congestion and the number of vehicles in the network. It can be seen in the individual modeling of applications that the different applications of the Eco-Signal Operations Operational Scenario react differently and with different levels of sensitivity to increasing amounts of traffic saturation in the El Camino Real corridor. Therefore, the traffic congestion was again tested as a sensitivity parameter, expressed in terms of V/C ratio, for three levels of traffic demand: baseline (V/C = 0.83), undersaturated (V/C = 0.38), and at saturation (V/C = 1.00). The combined applications were modeled at a 100 percent connected vehicle OBE penetration rate, baseline freight percentages, and transit schedule. The results of this analysis are shown in Figure 118 for each major vehicle class at each level of congestion ratio in the network to help better understand the results of the analysis.

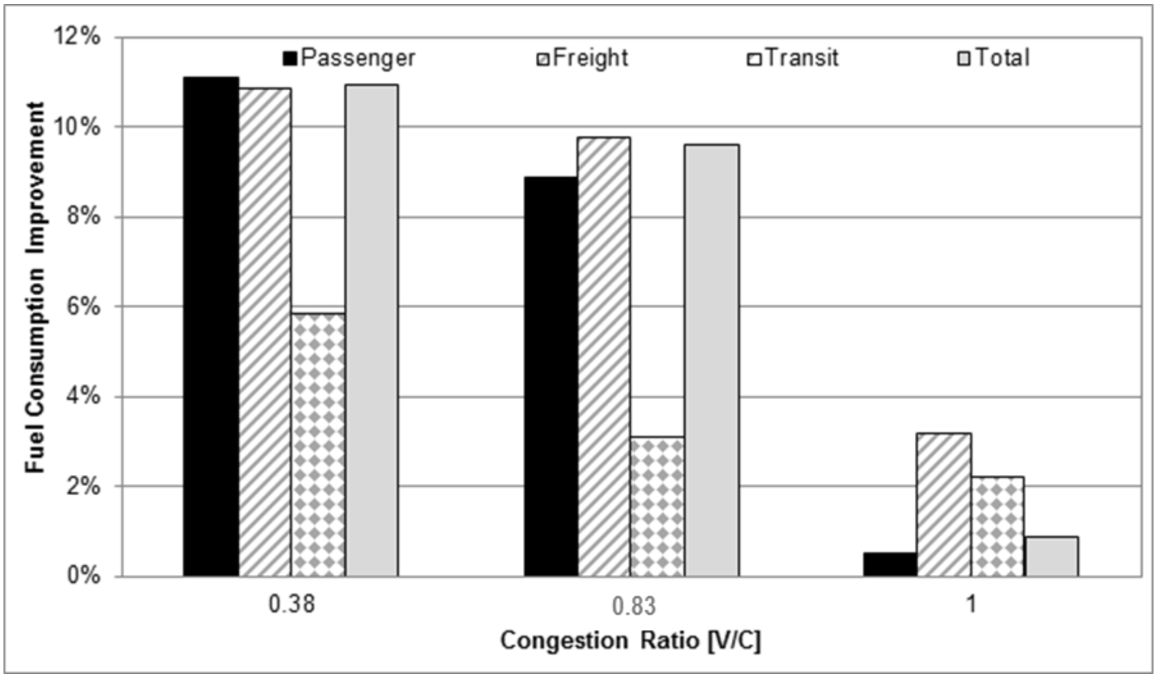


Figure 118: Fuel Savings Against the Baseline for Varying Levels of Demand by Vehicle Type.

The results for the sensitivity analysis show that the level of congestion plays a big role in the effectiveness of the combined Eco-Signal Operations applications, as shown in the figure. At the baseline level of congestion (V/C = 0.83), all three vehicle types receive significant benefits from the combined applications. Transit vehicles experience less improvement than the other vehicles, but their small numbers do not have a significant impact on overall network environmental improvement. The undersaturated traffic conditions (V/C = 0.38) show slightly better improvements than the baseline because of the lack of congestion and queuing in that situation. With less queuing and congestion along the mainline of the El Camino Real corridor, it would be easier to plan trajectories for approach speed and acceleration as well as for granting priorities for freight and transit vehicles. This would allow for less stoppage and an increased ability to provide better fuel consumption for types of vehicles in the network. The overall pattern of improvement among the different classes of vehicles is similar in both the baseline and undersaturated conditions, indicating that the applications in combination work in a similar fashion in the two situations.

In contrast, the saturated conditions model shows the same trend as seen in the individual modeling of applications throughout the report. Much less can be improved in terms of throughput and signal timing when the mainline approaches are at saturation. This is particularly apparent for passenger vehicles, as they represent the majority of vehicles in the network. Surprisingly, the freight and transit vehicles still get a significant amount of improvement in their fuel consumption as a direct result of their improved acceleration and deceleration as well as the ability to request a priority to dissipate the queue ahead of them at the saturation intersection approaches.

More detailed emissions and fuel consumption information for the different levels of congestion based on volume-to-capacity ratio relative to the baseline are provided in Table 77, Table 78, Table 79, and Table 80.

Table 77: Detailed Comparison of Varying V/C Demand Ratios with Baseline (All Network Vehicles).

V/C	Fuel (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)
Baseline						
1.00	11,533.2	833.32	11.53	0.583	3.890	0.194
0.83	10,859.7	785.04	11.34	0.531	3.915	0.202
0.38	10,455.0	756.03	11.60	0.501	3.963	0.213
Combined Eco-Signal Operations Applications						
1.00	11,315.95	817.47	9.22	0.550	3.677876	0.158
0.83	9,749.963	704.68	8.41	0.444	3.432089	0.151
0.38	9,280.678	671.08	7.91	0.408	3.481026	0.156
% Improvement Compared with the Baseline						
1.00	1.9%	1.9%	20.0%	5.7%	5.5%	18.5%
0.83	10.2%	10.2%	25.8%	16.4%	12.3%	25.1%
0.38	11.2%	11.2%	31.8%	18.5%	12.2%	27.0%

Table 78: Detailed Comparison of Varying V/C Demand Ratios with Baseline (Passenger Vehicles).

V/C	Fuel (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)
Baseline						
1.00	8,830.6	634.65	10.57	0.433	1.226	0.061
0.83	8,057.9	579.12	10.41	0.392	1.195	0.064
0.38	7,606.2	546.66	10.74	0.373	1.185	0.071
Combined Eco-Signal Operations Applications						
1.00	8,783.7	631.28	8.19	0.398	1.128	0.034
0.83	7,343.5	527.77	7.38	0.318	1.068	0.035
0.38	6,761.8	485.97	6.91	0.284	0.991	0.034
% Improvement Compared with the Baseline						
1.00	0.5%	0.5%	22.5%	8.1%	7.9%	43.4%
0.83	8.9%	8.9%	29.1%	19.0%	10.6%	45.1%
0.38	11.1%	11.1%	35.6%	23.9%	16.4%	51.9%

Table 79: Detailed Comparison of Varying V/C Demand Ratios with Baseline (Freight Vehicles).

V/C	Fuel (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)
Baseline						
1.00	35,332.7	2,582.5	20.59	1.951	27.117	1.345
0.83	33,910.5	2,478.8	19.77	1.721	26.010	1.306
0.38	32,606.6	2,383.4	19.76	1.573	25.049	1.260
Combined Eco-Signal Operations Applications						
1.00	33,875.3	2,475.9	18.96	1.955	26.175	1.238
0.83	30,596.4	2,236.2	18.07	1.584	23.474	1.118
0.38	29,068.6	2,124.8	17.06	1.457	22.627	1.061
% Improvement Compared with the Baseline						
1.00	4.1%	4.1%	7.9%	-0.2%	3.5%	7.9%
0.83	9.8%	9.8%	8.6%	8.0%	9.8%	14.4%
0.38	10.9%	10.9%	13.7%	7.4%	9.7%	15.8%

Table 80: Detailed Comparison of Varying V/C Demand Ratios with Baseline (Transit Vehicles).

V/C	Fuel (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)
Baseline						
1.00	46,381.3	3,401.3	11.33	1.640	43.093	2.393
0.83	45,510.2	3,337.4	10.90	1.528	42.146	2.366
0.38	45,478.8	3,335.1	10.63	1.447	42.082	2.378
Combined Eco-Signal Operations Applications						
1.00	45,351.6	3,325.8	11.30	1.620	42.283	2.292
0.83	44,095.5	3,283.5	10.73	1.451	41.414	2.291
0.38	42,825.9	3,140.6	10.46	1.460	39.967	2.136
% Improvement Compared with the Baseline						
1.00	2.2%	2.2%	0.3%	1.2%	1.9%	4.2%
0.83	3.1%	1.6%	1.6%	5.0%	1.7%	3.2%

V/C	Fuel (kJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)
0.38	5.8%	5.8%	1.6%	-0.9%	5.0%	10.2%

Combined Eco-Signal Operations on ECR27 – Analysis of Future Fleet Mix

The baseline model was calibrated for the 2005-year demands and traffic conditions, and the MOVES model was originally designed with emissions rates based on the 2005 fleet mix. It is important to consider, however, that connected vehicle technology is a modern implementation that will take many years to come to fruition. Therefore, it is important to consider the improvements in fuel consumption and the increasing penetration of electric vehicles in the future fleet mixes to make sure that the improvements seen in the applications are not nullified by improved fleets. A sensitivity analysis was undertaken to compare the 2005 baseline fleet mix with a future fleet mix in the year 2030, assuming that this is the time of near-full connected vehicle OBE penetration in the United States. For the sake of simplicity, the traffic volumes were not grown to represent the increase in traffic demand; rather, the sensitivity analysis focused purely on the change in emissions of the same amount of vehicles with improved fuel consumption and environmental profiles. The baseline and future fleet mixes that were used to develop the MOVES emission table were determined from the 2011 California Emissions Factor (EMFAC2011) model. In Table 81, the distribution of fuel types is shown for all vehicles in the fleet for 2005 and 2030.

Table 81: Distribution of Vehicle Fuel Types for Baseline and Future Fleets.

Fleet	Gasoline	Diesel	Electric
2005 Baseline	97.78%	2.22%	0.002%
2030 Future	97.17%	1.50%	1.34%

In the table, it can be seen that there are almost no electric vehicles in the traffic fleet and a number of diesel vehicles, mostly freight and transit vehicles. The future 2030 fleet mix retains a majority of gasoline vehicles, as predicted by the EMFAC2011 model, despite representing the improvements in the future. A large chunk of the diesel vehicles in the future are expected to be converted to electric, while less than 1 percent of future gasoline vehicles will be converted to electric. Despite the small percentage of the total fleet becoming zero emission, this still represents a large increase over the baseline fleet. In addition to the fuel type of the vehicles, the age distribution of the vehicles of each fuel type contributes to how the MOVES model emission table is determined. The age distribution for the three fuel types for the 2005 and 2030 fleet mixes are shown in Table 82.

Table 82: Age Distribution of Vehicles for Baseline and Future Fleets.

Fuel Type	Vehicle Age				
	0 – 5 Years	6 – 10 Years	11 – 20 Years	21 – 30 Years	> 30 Years
2005 Baseline Fleet					
Gasoline	34.0%	31.6%	28.1%	3.8%	2.6%
Diesel	30.9%	25.0%	27.7%	15.4%	1.1%
Electric	100.0%	0.0%	0.0%	0.0%	0.0%
2030 Future Fleet					
Gasoline	28.7%	24.7%	30.9%	10.2%	5.5%
Diesel	24.0%	21.8%	30.8%	14.4%	8.9%
Electric	36.0%	30.9%	31.1%	1.9%	0.0%

Electric vehicles were a relatively new concept in 2005, so not only do they represent a small fraction of the fleet, but they are all relatively new. The baseline fleet also has few vehicles over 20 years old, except for the diesel transit and freight vehicles. In the future fleet, a nice distribution of electric vehicles can be seen between 0 and 20 years of age as they are adopted over the years. In the future fleet, fewer gasoline and diesel vehicles are brand new, with people who are replacing their vehicles choosing electric vehicles, while others are still using their aging vehicles.

The first step of the sensitivity analysis was to determine the background changes in the emissions and fuel consumption from 2005 to 2030 before considering the impacts of the Eco-Signal Operations combined applications. To accomplish this, the baseline El Camino Real model was run with the MOVES model from the 2005 fleet mix emission rate table, and then once again with the 2030 MOVES table. The results were compared for all the resultant emissions and are shown below in Figure 119, which represents all vehicles in the model, with all baseline demand and traffic conditions kept constant between the two models.

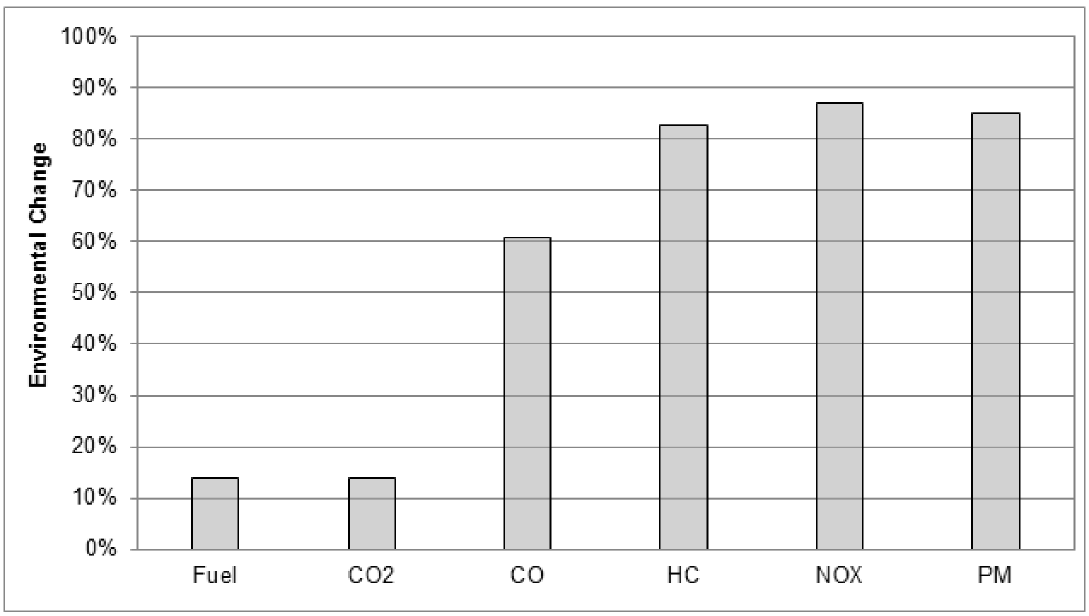


Figure 119: Difference in Baseline Emissions for the El Camino Real for the 2030 Future Fleet over the 2005 Baseline Fleet.

For the future year 2030 fleet mix, the changes in age distribution and fuel efficiency are shown to improve the overall baseline fuel consumption and CO_2 emissions by about 14 percent to 15 percent without the help of any AERIS applications. However, as shown in the figure, these two resultant emissions show significantly less improvement in the future fleet mix than the other four resultant pollution types analyzed in the corridor. This happens for several reasons that have already been explained to some extent in this report. The first is that CO, hydrocarbons, nitrogen oxides, and particulate matter total output are magnitudes smaller in volume than CO_2. A 15 percent improvement in fuel consumption would constitute a nearly 1,600 KJ/mile improvement, while an 85 percent improvement in NOx over the baseline fleet mix would represent only about 3 grams/mile. The other reason is how the fuel types respond to different vehicle types, which was explained earlier in this report. As shown in Table 82, the major expected change in vehicle types in the model represents a shift of diesel transit and freight vehicles to newer electric counterparts but only a small change in the gasoline vehicles. These large diesel vehicles heavily pollute, especially hydrocarbons, NOx, and particulate matter, which is why nearly all of their resultant emissions are reduced in the future fleet.

With an understanding of the future improvements in fuel consumption and environmental measures with the resultant emissions, a sensitivity analysis was undertaken to look at the impacts of the combined Eco-Signal Operations applications between the 2005 and 2030 fleet mixes. The same analysis was completed as above, except that all five of the applications were active using the 2005 MOVES model and the 2030 MOVES model. The results of the two runs are provided in Figure 120, which shows the total resultant emissions for each type, representing all of the vehicles in the model.

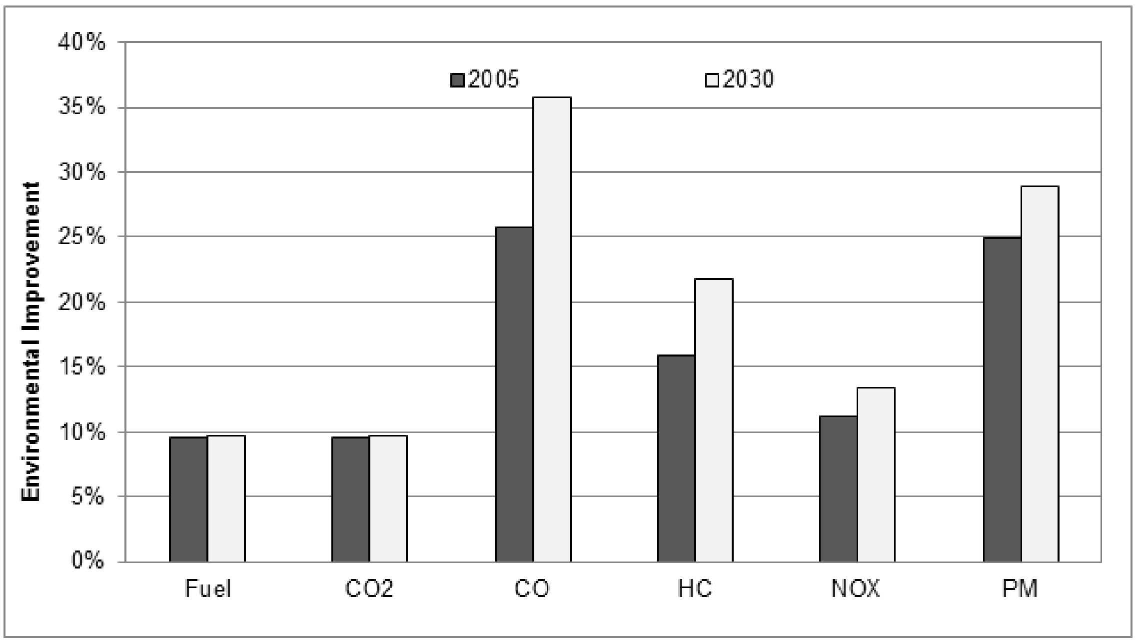


Figure 120: Difference in Environmental Impacts Between the Baseline 2005 Fleet Mix and the Future 2030 Fleet Mix for All Vehicles.

The results of the sensitivity analysis show that even though there is a significant improvement in emissions in the future caused by the improvement in the fleet mix (as shown in Figure 120), similar overall improvements can be gained with the combined applications over the baseline. There is only a slight loss in improvement for the fuel consumption and CO_2 in the future 2030 fleet, which is overall statistically the same, while the major differences come in the other four pollutant types. As explained above, the overall volume of emissions for these pollutant types is much lower, and the improvements gained in the 2030 improvements in fuel type result in the baseline values being even lower. As a result, larger percentage improvements for these pollutant types are seen in the future, even though the overall volume improvement is much lower than in the 2005 baseline fleet mix.

The fact that the improvements are similar in both fleet mixes is important for the future of the AERIS applications, because implementation will still take many years for connected vehicle technologies. The combined applications of the Eco-Signal Operations Operational Scenario will achieve a similar magnitude of results, regardless of the baseline emission or fuel type profile.

Findings and Opportunities for Future Research

Prior to modeling, the hypothesis that was generated based on literature review stated that, "If all five applications in the Eco-Signal Operations Operational Scenario are implemented together, then there will be emissions reductions and lowered fuel consumption during congested traffic conditions in the range of 15 percent to 20 percent under partial connected vehicle penetration and 20 percent to 25 percent under full connected vehicle penetration." The results of sensitivity analyses on the combined modeling of applications show that for the El Camino Real corridor, fuel consumption and emissions reductions can be obtained of around 1 percent to 7 percent for partial vehicle penetration and about 2 percent to 11 percent for full connected vehicle penetration when compared with baseline models. The amount of environmental benefit from the combined applications that were obtained depend on a variety of factors, including congestion level, penetration rate of connected vehicle OBE, and the composition of the fleet mix in relation to fuel type and age distribution :

1. The combined applications of the Eco-Signal Operations Operational Scenario work well together, and though the environmental benefits of the combination of the five applications are not exactly additive of the results of the individual modeling results, none of the applications is seen to conflict with or nullify the results of any of the applications within the operational scenario.
2. The applications within the operational scenario that aim to reduce stop time and queuing at the intersection approaches, such as Eco-Traffic Signal Timing and Eco-Signal Priority, better improve resultant pollutant emissions such as CO_2 and fuel consumption, while the applications that aim to smooth speed and acceleration trajectories show greater improvements in pollutants such as CO and particulate matter. When combined, they help to significantly reduce all type pollutant emissions.
3. The overall pollutant volume of emissions can skew the results of the environmental improvements the application gains. Because particulate matter, hydrocarbons, and CO have orders of magnitude less total volume, a 25 percent improvement in these pollutants may be significantly smaller than a 10 percent improvement in CO_2 or fuel consumption.
4. Unlike some of the individual modeling scenarios, noticeable benefits can be gained with the combined modeling of applications even at the lowest level of connected vehicle OBE penetration (i.e., 20 percent OBE rate). Passenger vehicles obtain around 3 percent improvement, while freight and transit vehicles receive a little less than 2 percent each in fuel consumption improvement.
5. Both passenger vehicles and transit vehicles experience significant environmental benefits at all levels of connected vehicle OBE penetration rate, which increases as the implementation level increases.
6. Passenger and freight vehicles in the network that are not connected receive incidental benefits from the combined Eco-Signal Operations applications that are seeking to improve the environmental conditions of connected vehicles. The improved signal timings, granted priorities, and speed advice meant for the connected vehicles is shared by non-connected vehicles in the traffic stream and approaches to intersections, resulting in additional benefits.
7. Significant and similar environmental improvements are gained in both the baseline and undersaturated congestion conditions in the El Camino Real model for all three vehicle classes. The undersaturated conditions (V/C = 0.38) achieve slightly better results than the baseline because there is little to no queuing or congestion in the model. The saturated condition has significantly less improvements over the baseline, because the approaches are already at saturation; therefore, less can be done to improve the conditions.

8. The future 2030 fleet mix has a baseline reduction in fuel consumption and CO_2 of about 15 percent over the 2005 baseline calibrated fleet mix and a 60 percent to 85 percent reduction in the other pollutants. This large reduction in these pollutants is because the EMFAC2011 predicts that the largest shift of vehicles is diesel freight and transit vehicles being converted to electric or electric hybrid, which would greatly reduce pollutants such as CO and particulate matter.
9. The overall percentage impact of the combined applications is similar for both the current 2005 and the future 2030 fleet mixes for all pollutant types, indicating that the applications would be beneficial even in future conditions, where the improved fuel mix is thought to possibly nullify environmental gains.

Based on the above findings from the combined modeling effort, the research team has the following recommendations and remarks about the applications that were determined in addition to those found in the individual modeling effort:

1. The compliance rate of the willingness for drivers to actively follow the eco-speed, acceleration, and deceleration advice given to them from connected vehicle technologies will greatly affect the results in relation to future implementation of the applications. Future modeling efforts could and should focus on drivers' willingness and ability to follow the advice as presented.
2. The eco-friendly acceleration and deceleration values were determined through research and hard-coded to the connected vehicles at the beginning of the simulation runs. Future research and improvements in eco-algorithms could yield a method of providing this advice dynamically to conform to changing traffic conditions.
3. It is hypothesized that the performance of the Eco-Approach and Departure and the Eco-Traffic Signal Timing applications in combination could be greatly improved if the optimization process included the eco-friendly speed advice to vehicles during the runs. Because the Eco-Approach and Departure changes the trajectories of the vehicles, it is possible that the signal timings would be able to better adapt. Initial tests showed this significantly added to the complexity of the GA runs, and additional tests are necessary.
4. More research could yield fixes and improvements to the combined applications that will help mitigate the disadvantages that freight vehicles in lower levels of connected vehicle OBE implementation see. This will make early implementation of applications more attractive to freight operators.
5. Additional research could be conducted on the composition of the future fleet mixes using sources of information other than the EMFAC2011 model to determine fuel type percentages. Modeling runs with fleet estimates that have more aggressive assumptions of electric and hybrid fuel vehicles in the future 2030 model may yield additional interesting results.
6. Again, additional application testing should be done for the combined modeling on a network system that is less a main corridor and has roughly equal traffic approaching from different directions. This will test the ability of the application to balance network conditions, unlike with the El Camino Real, which has the vast majority of the emissions and traffic on the mainline.
7. Initial analyses of using the Eco-Speed Harmonization module as part of the Connected Eco-Driving application (Appendix D) as part of the combined modeling of the applications was performed to help better understand the possibilities. Although this was not part of the original Eco-Signal Operations Operational Scenario, it was discovered and showed great promise along the way. The preliminary results that were obtained for this effort are discussed in Appendix D. Additional research should focus on this possible application when looking in to signal operations connected vehicle applications.

Chapter 9. Conclusions

The results that we obtained from the variety of sensitivity analyses of the Eco-Signal Operations applications allow us to draw significant conclusions. The modeling exercises allowed for insight into the interactions of the combined applications as well as the performance of stand-alone 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. As described at the beginning of the document, the focus of the Eco-Signal Operations Operational Scenario was to study the benefits of deploying environmental applications on an arterial segment. A majority of the study uses a segment of the El Camino Real corridor, as described in Chapter 3. A small hypothetical network was used for some parts of the study.

Each application was reduced to an algorithm that accurately represented the working of the application as described by the AERIS program (refer to Chapter 2). The algorithms were modeled using the API of Paramics microsimulation software.

The details of the individual algorithms were implemented using the tools, and details are provided earlier in this document and can be found in the individual sections of this report. Extensive sensitivity analyses were carried out to study the impacts of the applications in a variety of situations that could potentially be encountered from location to location when the applications are implemented in the future. Each section of the report details all of the conclusions found for the individual modeling as well as the combined modeling of applications; therefore, they will not be shown here again in great detail. Rather, an overall summary of the major findings and suggestions for future research for each application within the Eco-Signal Operations Operational Scenario is provided in this section. The major findings for each application are presented in Table 83.

Table 83: Summary of Results of the Eco-Signal Operations Applications.

Application	Range of Benefit	Effect of Congestion	Effect of Technology Penetration	Effect of Communication Distance	Others
Eco-Approach and Departure at Signalized Intersections	2% to 8% energy savings for all vehicles	Less effective when corridor is congested because of queuing at the approach to the intersection	Benefits increase with technology penetration, though benefits seen at low penetration	Benefits increase with longer communication distance because of better trajectory planning	Provides greater benefits for the corridor on which traffic signals are less coordinated
Eco-Traffic Signal Timing	1% to 5.5% emissions reductions for all vehicles	Effective at most levels of congestion, but improvements drop off as the system reaches saturation	Benefits increase with technology penetration, with almost no significant improvement at lowest levels of penetration	The effect of communication distance was not relevant for this application	Resulting Eco-Optimized Signal Timing plans have significantly shorter cycle lengths than traditionally optimized corridor timing plans

Application	Range of Benefit	Effect of Congestion	Effect of Technology Penetration	Effect of Communication Distance	Others
Eco-Traffic Signal Priority	1% to 4% fuel savings for freight vehicles 2% to 4% fuel savings for transit vehicles	Most effective in low congestion scenarios because of less queuing at the intersection approaches	Benefits increase with technology penetration, though benefits seen for freight vehicles even at low penetration rates	Longer communication distances do not increase the benefits, because the approach trajectory can be calculated reliably at any distance from the signal	Similar fuel savings achieved for non-connected vehicles as well as passenger vehicles that share additional green time
Connected Eco-Driving	1% to 18% emissions reductions, 1% to 6% fuel savings for all vehicles	Most effective in low-congestion scenarios, because softer decelerations and accelerations are better achieved in lower saturation	No effect on energy consumption, but emission reductions increase with increasing penetration rate	The effect of communication distance was not assessed	The Connected Eco-Driving application works best when intersection distances are longer than the range of DSRC communication systems

The majority of the applications in the Eco-Signal Operations Operational Scenario show greater benefits with higher levels of connected vehicle technology. The technology provides the applications with more information that help it perform better, with any detrimental side effects of non-connected vehicles falling off quickly at higher levels of implementation. In most cases, even at lower penetration rates, the other surrounding vehicles derived a benefit from the connected vehicles. For example, in the case of Eco-Traffic Signal Priority, non-connected vehicles on the mainline benefited from the priority granted. In the case of Connected Eco-Driving and the Eco-Approach and Departure applications, non-connected vehicles could follow vehicles that were following eco-driving principles and benefit from them. With all of these benefits at the lower levels of connected vehicle penetration, it shows that the Eco-Signal Operations Operational Scenario will be useful for implementation even in the early stages of connected vehicle OBE and RSE technology being available to the public.

The combined modeling of applications within the Eco-Signal Operations Operational Scenario was completed for two major purposes: to understand what the operational scenario would look like in real-life operation and whether any of the applications would nullify the improvements of any other application within the operational scenario. The major finding of the combined modeling showed that although the improvements in the combined modeling of applications were not exactly the additive improvements of all the individual, no conflicting elements nullify the effects of any of the applications. When combined, the applications of the Eco-Signal Operations Operational Scenario result in fuel consumption improvements of about 10 percent using the 27-intersection El Camino Real corridor model. There are also emissions improvements of other resultant pollutants of 15 percent to 25 percent. The combined modeling also shows that different applications improve different emissions in different ways because of the goal of each application, whether to improve vehicle trajectory or to reduce queuing time at the intersection approach. The other sensitivity analyses of the combined modeling show similar results to those of the individual modeling, such as the increasing benefits with increasing penetration rate and that the improvements are reduced in higher levels of congestion when the corridor reaches full saturation.

In addition to the sensitivity analyses that were conducted on the El Camino Real calibrated model, there was concern that the improvements in fuel and vehicle operations in the future would nullify any environmental improvements from connected vehicle applications. To better understand this, additional analyses were done on some of the applications, including the combined modeling, to better understand the impacts of the applications in future conditions. While carrying out analysis with 2030 future fleet mixes, it was observed that the Eco-Signal Operations applications reduced certain criteria emissions, like hydrocarbons and carbon monoxide, more than in the current-year fleet mix because of the expected change in operation of vehicles and different mixes of hybrids expected in the year 2030. Also, this has an impact on the differences in improvements of resultant emissions, as these show greater reductions over the baseline model than fuel consumption in future fleets with the Eco-Signal Operations applications. However, overall, the future fleet shows similar improvements in the applications over the baseline model, meaning that relatively similar percentage environmental improvements can be gained regardless of the baseline fuel mixes.

Finally, although the AERIS project is intended to lay the groundwork of how to use connected vehicle technology to improve the environment and improve fuel efficiency for vehicles across the nation, the development of applications within the Eco-Signal Operations Operational Scenario was not envisioned to be the catch-all, finalized version of these potential applications. The information provided in this report is intended as a first step in a line of research to improve the environment using connected vehicle technology, so there is great potential in the next steps of research in future AERIS or other work. Each section of the report, for each individual application and the combined modeling, details potential future opportunities and proposed research to help guide future endeavors by what was learned from the design and modeling of the Eco-Signal Operations Operational Scenario. Overall, it was found that many impacts or interesting findings of several of the applications, especially the Eco-Signal Timing and Eco-Signal Priority applications, depend strongly on the shape and configuration of the roadway on which they are implemented. The fact that the El Camino Real is a corridor, with the majority of the heavy traffic on the mainline and only minor side-street traffic, could have an impact on the operations of the applications. As a result, there should be more research on different types and configurations of roadways to better represent a chunk of the United States. In addition, many of the application algorithm pieces either had assumptions, like “offline” or hard-coded values, rather than more “online”/real-time processes, which would be more realistic with the future implementation of connected vehicle technologies. The results of the sensitivity analyses have given a better understanding of the unknowns from the beginning of the project, so these insights, in combination with future research, could yield significantly more improvements and more dynamic environmental connected vehicle technologies.

Appendix A. List of Acronyms

Acronym	Definition
AERIS	Applications for Environment Real Time Information Synthesis
API	Application Programming Interface
BAA	Broad Agency Announcement
BCA	Benefit- Cost Analysis
CACC	Cooperative Automated Cruise Control
CMEM	Comprehensive Modal Emissions Model
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CV	Connected Vehicle
DSRC	Dedicated Short-Range Communication
ECR-27	27-Intersection of El Camino Real
ECR-3	3-Intersection of El Camino Real
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
FTA	Federal Transit Administration
GA	Genetic Algorithm
GASTO	Genetic Algorithm for Signal Timing Optimization
GHG	Greenhouse Gas
GID	Geographic Information Description
Gprc	Early Red Termination Priority
GPS	Global Positioning System
HC	Hydrocarbon
HCM	Highway Capacity Manual
HPN	Hypothetical Network
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
LDV	Light Duty Vehicles
LOS	Levels of Service
MOE	Measure of Effectiveness
MOVES	Motor Vehicle Emission Simulator
MPG	Miles Per Gallon
NOx	Nitrogen Oxide
OBE	On-Board Equipment
OD	Origin-Destination
OpMode	Operating Mode
PATH	Partners for Advanced Transportation Technology
Pt	Desired Green Phase
Qc	Queue Clearance Time

RRT	Remaining Time in the Red Phase
RRT	Red Phase
RSE	Roadside Equipment
SCATS	Sydney Coordinated Adaptive Traffic System
SCOOT	the Cycle Offset Optimization Technique
SOx	Sulfur Oxide
SPaT	Signal Phase and Timing
SUV	Sport Utility Vehicles
TFHRC	Turner Fairbank Highway Research Center
TTA	Time for the Vehicle to Arrive at the Signal
TTPM	Travel Time Per Mile
TTS	Time to Signal
USDOT	U. S. Department of Transportation
V/C	Volume-to-Capacity
V2G	(V2I), and Vehicle-To-Grid
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VHT	Vehicle Hours Traveled
VMT	Vehicle Miles Traveled

Appendix B. Development of MOVES Plug-In

To support the modeling and evaluation of all AERIS applications, UCR team has made a significant effort to develop the emission estimation plug-in for Paramics based on the MOVES by EPA. Figure 121 depicts the work flow of MOVES plug-in development. Basically, the user will input the network model information, such as the geographic region (e.g., Santa Clara County in California) of the model and the calendar year (e.g., Year 2005). This configuration information will be coded into settings files in the XML format, which then feed into MOVES. The outputs from MOVES are the emission rate tables for different source types (e.g., passenger car and transit bus) defined by EPA, taking into account various factors, such as model year distribution, fuel type/engine technology market share, and temperature and/or humidity adjustment. All these emission rate tables will be coded as the configuration files for Paramics network model. Another developed API will calculate the OpMode distribution based on second-by-second vehicle trajectories and estimate the energy/emissions by using these configuration files.

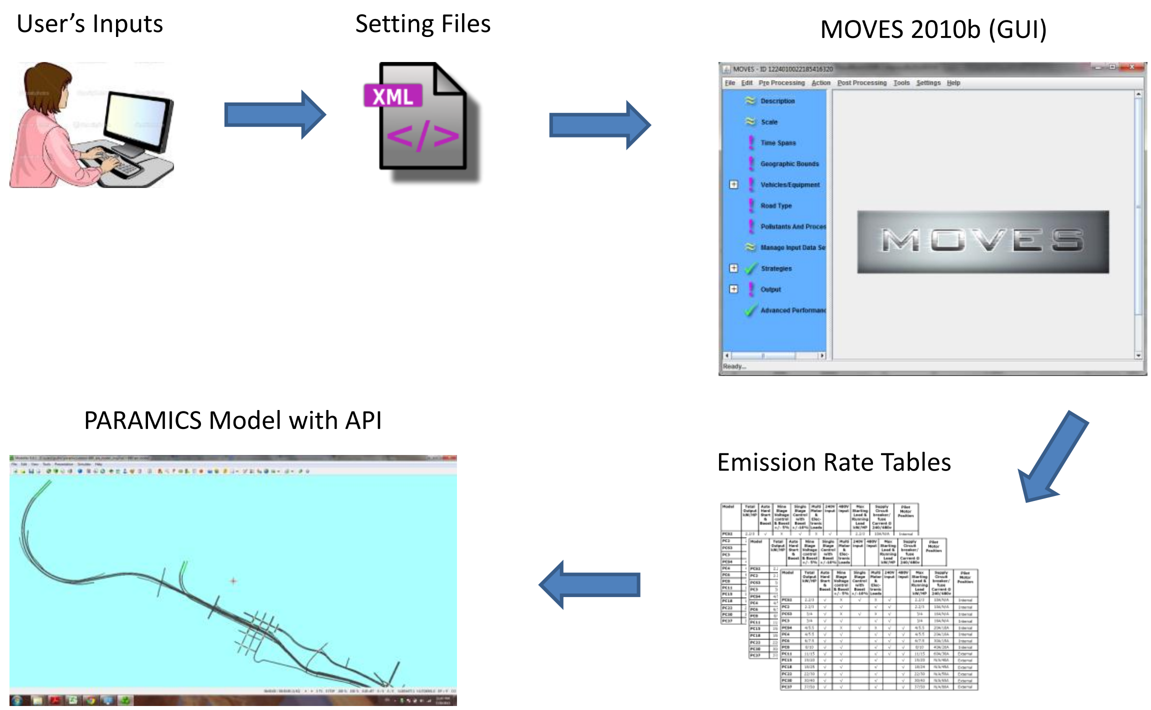


Figure 121: Work Flow of MOVES Plug- In Development.

To further investigate the impact of application(s) for future fleet, we have developed MOVES plug-in for not only Year 2005 (for baseline scenario) but also Year 2020 (for future projection). As one of the inputs to MOVES, fuel type/engine technology share are quite different between Year 2005 and Year 2020. Figure 122 presents the typical California fuel use type proportion for passenger cars in Year 2005 and Year 2020, respectively. As shown in the figure, electric vehicles' share (projected) will increase up to 16 percent by Year 2020 (compared to almost 0 percent in Year 2005).

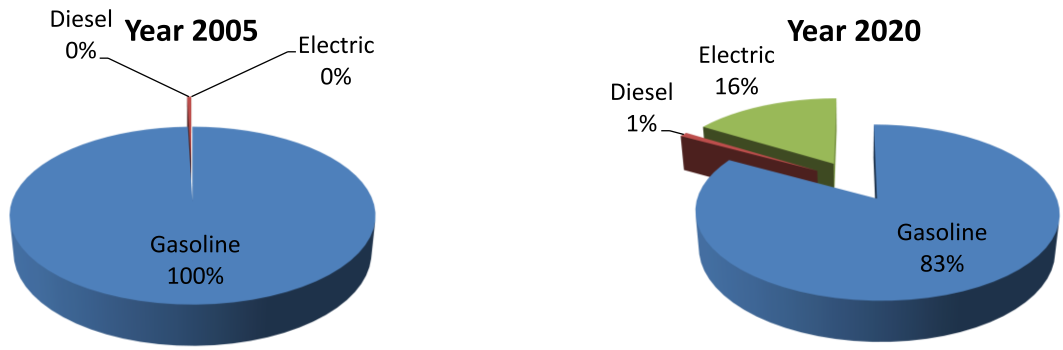


Figure 122: Proportion of Fuel Use Type for Passenger Cars in Year 2005 and Year 2020 in California (Source: EMFAC 2007).

Appendix C. Baseline and Optimized Signal Timing Plans and OD Data

Table 84: Baseline Signal Timings for the El Camino Real 3-Intersection Network.

Cross Street	Southbound		Northbound		Eastbound		Westbound		Offset
	L	TR	L	TR	L	TR	L	TR	
Curtner	32		-	-	22	66	-	66	75
Los Robles	18	27	18	27	20	53	20	53	54
Maybell	17	27	17	27	23	57	15	49	120

Table 85: Default Signal Plan During Morning Peak (7:15 am to 9:30 a.m.) in July 2005.

Intersection	Southbound			Northbound			Eastbound			Westbound		
	G	Y	R	G	Y	R	G	Y	R	G	Y	R
Ventura Ave.	65.5	4	60.5	65.5	4	60.5	32	3	95	32	3	95
Los Robles Ave.	53	4	73	53	4	73	25	3	102	25	3	102
Maybell Ave.	57	4	69	49	4	77	26	3	101	26	3	101

Table 86: Environmentally Optimized Signal Timings for the El Camino Real 3-Intersection Network With 100% OBE and 0.38 V/C Ratio.

Cross Street	Southbound		Northbound		Eastbound		Westbound		Offset
	L	TR	L	TR	L	TR	L	TR	
Curtner	17		-	-	11	28	-	28	63
Los Robles	6	17	6	17	7	24	6	23	53
Maybell	6	17	6	17	6	24	6	24	20

Table 87: Environmentally Optimized Signal Timings for the El Camino Real 3-Intersection Network With 100% OBE and 0.77 V/C Ratio.

Cross Street	Southbound		Northbound		Eastbound		Westbound		Offset
	L	TR	L	TR	L	TR	L	TR	
Curtner	17		-	-	18	20	-	20	6
Los Robles	6	17	6	17	6	23	6	23	58
Maybell	6	17	6	17	6	23	6	23	30

Table 88: Environmentally Optimized Signal Timings for the El Camino Real 3-Intersection Network With 100% OBE and 1.00 V/C Ratio.

Cross Street	Southbound		Northbound		Eastbound		Westbound		Offset
	L	TR	L	TR	L	TR	L	TR	
Curtner	17		-	-	8	41	-	41	36
Los Robles	8	17	8	17	11	32	6	27	14
Maybell	6	17	6	17	9	34	15	31	40

Table 89: Delay-Optimized Signal Timings for the El Camino Real 3-Intersection Network With 100% OBE and 0.38 V/C Ratio.

Cross Street	Southbound		Northbound		Eastbound		Westbound		Offset
	L	TR	L	TR	L	TR	L	TR	
Curtner	17		-	-	10	53	-	53	75
Los Robles	10	17	10	17	34	16	34	66	66
Maybell	6	17	6	17	7	47	7	47	30

Table 90: Delay-Optimized Signal Timings for the El Camino Real 3-Intersection Network With 100% OBE and 0.77 V/C Ratio.

	Southbound		Northbound		Eastbound		Westbound		
Cross Street	L	TR	L	TR	L	TR	L	TR	Offset
Curtner	17		-	-	9	27	-	27	33
Los Robles	6	17	6	17	6	21	6	21	19
Maybell	6	17	6	17	6	21	6	21	40

Table 91: Delay-Optimized Signal Timings for the El Camino Real 3-Intersection Network With 100% OBE and 1.00 V/C Ratio.

	Southbound		Northbound		Eastbound		Westbound		
Cross Street	L	TR	L	TR	L	TR	L	TR	Offset
Curtner	17		-	-	9	35	-	35	13
Los Robles	6	17	6	17	6	23	6	23	32
Maybell	6	17	6	17	6	23	6	23	39

Table 92: Baseline Signal Timings for the El Camino Real 27-Intersection Network.

	Southbound		Northbound		Eastbound		Westbound		
Cross Street	L	TR	L	TR	L	TR	L	TR	Offset
Churchill	28		-	-	25	76	-	76	94
Park Serra	15	25	15	25	18	60	18	60	81
Stanford	17	25	17	25	18	61	15	58	66
Cambridge	16	25	16	25	18	61	16	59	7
California	16	25	16	25	18	61	16	59	128
Pagemill	17	33	17	33	17	51	17	51	125
Portage	31		-	-	26	64	-	64	128
Hansen	-	-	32		-	64	26	64	128
Matadero	18	18	18	18	16	59	23	66	59
Curtner	32		-	-	22	66	-	66	75
Los Robles	18	27	18	27	20	53	20	53	54
Maybell	17	27	17	27	23	57	15	49	120
Arastradero	17	31	17	31	26	55	15	44	3
Dinah	20	30	20	30	23	49	19	45	0
Los Altos	17	26	17	26	16	59	16	59	67
Del Medio	16	19	16	19	19	64	19	64	61
San Antonio	17	27	17	27	22	55	19	52	51
Showers	30		-	-	28	63	-	63	2
Jordan	17	25	17	25	18	59	16	57	0
Ortega	22	25	22	25	23	56	15	48	16
Distel	-	-	30		-	65	26	65	0
Rengstroff	21	27	21	27	25	52	18	45	121
Escuela	30		-	-	25	66	-	66	72
El Monte	-	-	30		-	65	26	65	81
Miramonte	20	25	20	25	21	54	19	52	121
Castro	22	30	22	30	18	49	17	48	116
Calderon	20	23	20	23	20	54	21	55	53
Grant	17	27	17	27	22	57	17	52	59

Table 93: Environmentally Optimized Signal Timings for the El Camino Real 27-Intersection Network With 100% OBE and 0.83 V/C Ratio.

	Southbound		Northbound		Eastbound		Westbound		
Cross Street	**L**	**TR**	**L**	**TR**	**L**	**TR**	**L**	**TR**	**Offset**
Churchill	20		-	-	17	20	-	20	12
Park Serra	6	20	6	20	6	22	6	22	58
Stanford	7	20	7	20	6	21	6	21	40
Cambridge	6	20	6	20	6	22	6	22	24
California	8	20	8	20	6	20	6	20	20
Pagemill	6	20	6	20	7	22	6	21	2
Portage	20		-	-	11	26	-	26	59
Hansen	-	-	20		-	23	14	23	59
Matadero	7	20	7	20	6	21	6	21	25
Curtner	20		-	-	17	20	-	20	9
Los Robles	6	20	6	20	7	21	7	21	55
Maybell	6	20	6	20	6	22	6	22	27
Arastradero	6	20	6	20	6	22	6	22	17
Dinah	6	20	6	20	6	22	6	22	57
Los Altos	7	20	7	20	9	20	7	18	42
Del Medio	7	20	7	20	6	19	8	21	34
San Antonio	6	20	6	20	6	22	6	22	14
Showers	20		-	-	12	25	-	25	59
Jordan	8	20	8	20	7	20	6	19	50
Ortega	6	21	6	21	6	17	8	21	40
Distel	-	-	25		-	20	12	20	42
Rengstroff	7	20	7	20	6	21	6	21	17
Escuela	20		-	-	10	27	-	27	57
El Monte	-	-	20		-	16	21	16	39
Miramonte	6	20	6	20	7	22	6	21	5
Castro	8	20	8	20	7	18	8	19	48
Calderon	6	20	6	20	6	21	7	22	13
Grant	6	20	6	20	6	22	6	22	53

Table 94: Synchro-Optimized Signal Timings for the El Camino Real 27-Intersection Network for Green Times Only With 0.83 V/C Ratio.

	Southbound		Northbound		Eastbound		Westbound		
Cross Street	**L**	**TR**	**L**	**TR**	**L**	**TR**	**L**	**TR**	**Offset**
Churchill	31		-	-	14	84	-	84	94
Park Serra	5	63	5	63	5	42	8	45	81
Stanford	5	55	5	55	5	47	11	53	66
Cambridge	5	29	5	29	12	73	11	72	7
California	18	10	22	14	10	64	22	75	128
Pagemill	19	36	19	36	10	39	24	63	125
Portage	36		-	-	18	67	-	67	128
Hansen	-	-	32		-	69	21	69	128
Matadero	5	28	5	28	9	62	23	76	59
Curtner	32		-	-	24	65	-	65	75
Los Robles	15	21	15	21	16	57	25	66	54
Maybell	22	29	12	19	9	66	11	68	120
Arastradero	20	27	20	27	14	49	22	57	3
Dinah	5	19	5	19	17	67	24	74	0
Los Altos	5	21	5	21	10	63	27	79	67
Del Medio	5	34	5	34	15	53	25	63	61
San Antonio	21	39	21	39	22	34	24	36	51
Showers	37		-	-	23	61	-	61	2
Jordan	14	17	14	17	9	64	21	76	0
Ortega	14	19	14	19	12	61	21	70	16
Distel	-	-	27		-	72	22	72	0
Rengstroff	19	23	19	23	12	51	22	61	121

Cross Street	Southbound		Northbound		Eastbound		Westbound		Offset
	L	TR	L	TR	L	TR	L	TR	
Escuela	31		-	-	49	90	-	41	72
El Monte	-	-	36		-	47	38	88	81
Miramonte	34	34	19	19	22	45	17	40	121
Castro	22	21	22	21	14	44	31	61	116
Calderon	17	19	17	19	9	54	25	70	53
Grant	20	33	20	33	12	42	20	50	59

Table 95: Synchro-Optimized Signal Timings for the El Camino Real 27-Intersection Network for Full Optimization With 0.83 V/C Ratio.

Cross Street	Southbound		Northbound		Eastbound		Westbound		Offset
	L	TR	L	TR	L	TR	L	TR	
Churchill	25		-	-	6	75	-	75	0
Park Serra	5	19	5	19	5	19	5	19	20
Stanford	5	18	5	18	5	20	5	20	44
Cambridge	5	17	5	17	5	21	5	21	20
California	17	5	17	5	19	31	5	17	46
Pagemill	7	17	7	17	5	17	17	29	40
Portage	17		-	-	5	19	-	19	0
Hansen	-	-	18		-	17	17	17	0
Matadero	5	17	5	17	5	14	17	26	0
Curtner	17		-	-	17	17	-	17	0
Los Robles	5	17	5	17	6	19	17	30	0
Maybell	7	17	7	17	5	19	5	19	0
Arastradero	7	17	7	17	6	17	17	28	36
Dinah	5	17	5	17	19	19	19	19	9
Los Altos	5	17	5	17	5	19	17	31	59
Del Medio	5	17	5	17	5	18	10	34	24
San Antonio	7	17	7	17	9	17	17	25	9
Showers	17		-	-	5	19	-	19	0
Jordan	5	17	5	17	5	19	17	31	28
Ortega	5	17	5	17	5	18	18	31	0
Distel	-	-	17		-	17	7	17	0
Rengstroff	5	18	5	18	5	18	17	30	0
Escuela	17		-	-	17	17	-	17	0
El Monte	-	-	17		-	17	7	17	0
Miramonte	17	17	17	17	7	17	7	17	32
Castro	6	18	6	18	6	17	17	28	60
Calderon	5	17	5	17	5	19	17	31	39
Grant	7	17	7	17	5	17	17	29	4

Table 96: OD Matrix of 3-Intersection Segment of the El Camino Real Network.

Zone	1	2	3	4	5	6	7	Total
1	-	1,695	0	0	44	49	35	1,823
2	691	-	0	0	87	46	28	852
3	0	0	-	0	0	0	0	0
4	0	0	0	-	0	0	0	0
5	11	161	0	0	-	35	0	207
6	34	76	0	0	29	-	0	139
7	49	76	0	0	0	0	-	125
Total	785	2,008	0	0	160	130	63	3,146

Appendix D. Eco-Speed Harmonization for Arterials

It is well known that speed and acceleration have major impacts on a vehicle's fuel economy and tailpipe emissions. With the availability of real-time traffic information or other external conditions (e.g., roadway grade and road weather conditions), speed advice at particular locations and time instances can be dynamically provided to drivers, which allows them to reduce unnecessary stop-and-go maneuvers while meeting specific driving requirements (e.g., travel time). For drivers, it is not realistic to sacrifice travel time to gain marginal environmental benefits. It also cannot be assumed that the reduction in travel time saves energy. It is noted that the speed advice can be disseminated through at least two channels: 1) the TMC provides a speed recommendation to all vehicles to harmonize speed of the entire roadway; or 2) each individual vehicle optimizes its speed based on data (i.e., traffic conditions) collected from infrastructure and data from the vehicle's controller area network. In this report, we assume the latter for information dissemination, as shown in Figure 123.

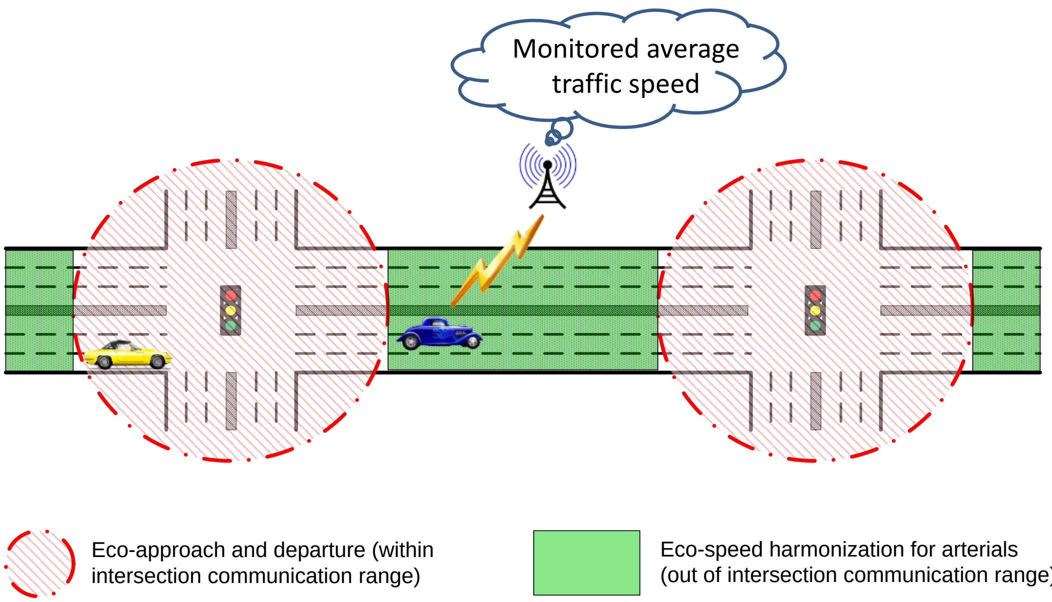


Figure 123: Illustration of Implementation of Eco-Speed Harmonization for Arterial.

This module can be implemented in a variety of ways, depending on how the set speed is determined. In this application, in particular for arterial, the research team developed the set speed determination algorithm based on the average speed of surrounding traffic, which can be directly measured and estimated by using the connected vehicle (CV) technology. For any segment, within time intervalΔT, the average traffic speed is:

$$\bar{V} = \begin{cases} V^{ff}, & \text{no vehicle within } \Delta T \\ \dfrac{\text{Vehicle miles traveled within } \Delta T}{\text{Vehicle hours spent within } \Delta T}, & \text{otherwise} \end{cases}$$

where V^{ff} is the free-flow speed or speed limit of that roadway segment.

With the measured average speed of surrounding traffic, a simple regression model is developed to determine the recommended speed for the subject vehicle, withinΔT,

$$V^{ctrl} = a \cdot \bar{V} + b \qquad (1)$$

It is noted that the values of V^{ctrl} and $\bar{V}$ were determined from the second-by-second vehicle trajectories collected in the field and microscopic simulation. Under different levels of service (LOS) of the traffic network, V^{ctrl} were selected to minimize the trip's fuel consumption without sacrificing too much in travel time. Figure 124 provides an example to illustrate the relationship between V^{ctrl} and $\bar{V}$ (scatter plots), and a candidate set of values that *a*'s and *b*'s can choose. (For more details, please refer to Barth and Boriboonsomsin, 2009).

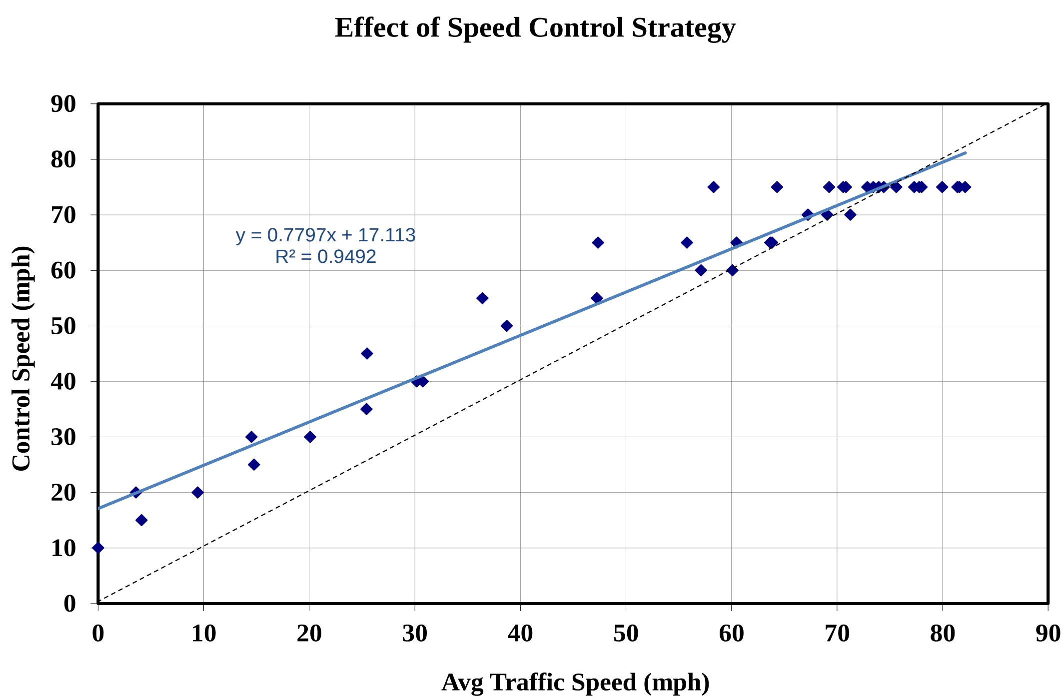
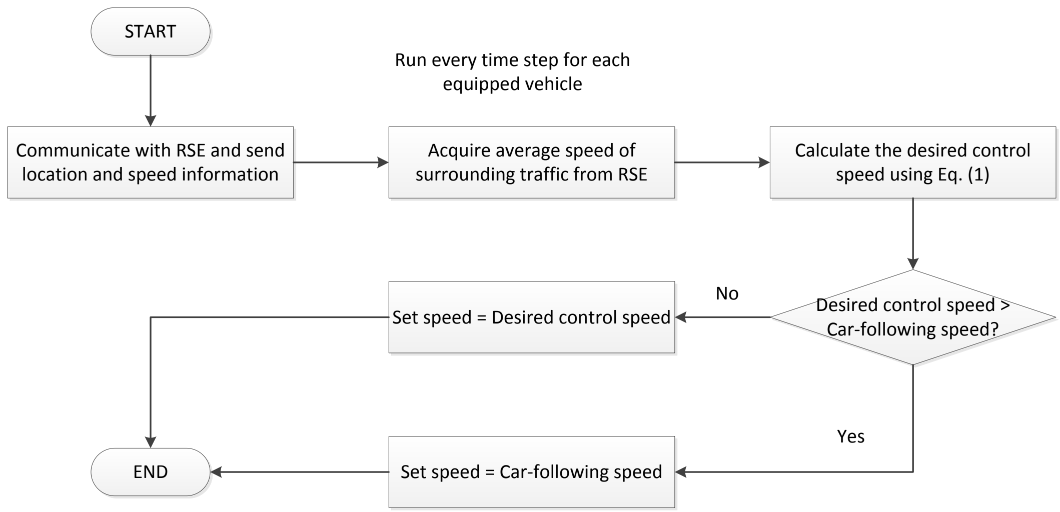


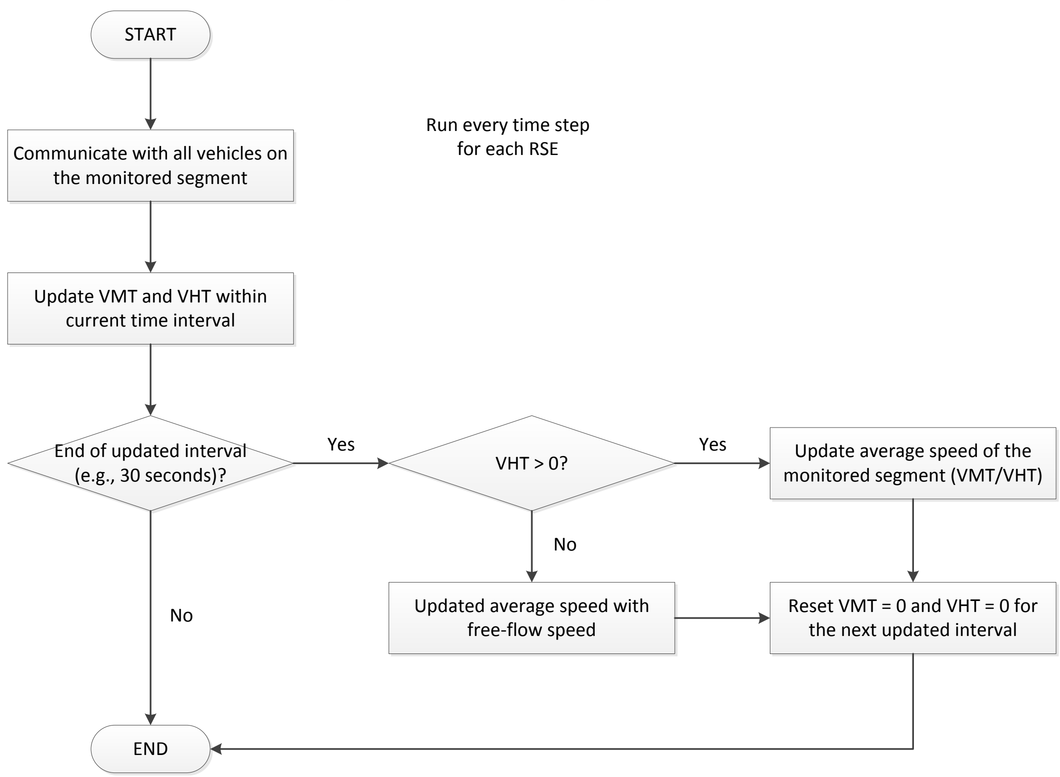
Figure 124: A Candidate Strategy for Control Speed Determination.

An application programming interface (API) has been coded in Paramics to implement the arterial eco-speed harmonization algorithm. Figure 125 presents the flow chart of this module.

As can be seen from the figure, at each time step, each individual equipped vehicle communicates with the associated road-side equipment (RSE) whose communication range covers the segment on which the vehicle is travelling. Then the RSE calculates the average traffic speed (the ratio of vehicle-mile-traveled and vehicle-hour-traveled of that segment) and provides this information to the involved vehicle. Based on the average speed of surrounding traffic, the vehicle can determine its desired control speed. Due to the car-following constraint (i.e., maintaining safe headway with preceding vehicles), the set speed has to be the minimum of desired control speed and car-following speed. It is also noted that the average speed information is updated at certain frequency.



(a) For individual equipped vehicle



(b) For each RSE

Figure 125: Flow Chart of Eco-Speed Harmonization (for Arterial) Module.

Preliminary Results

Table 97 summarizes the benefits from the Eco-Speed Harmonization (for arterial) module over different V/C. Compared with the modules in Connected Eco-Driving (i.e., Generalized Eco-Driving Principles and Eco-Approach/Departure), the Eco-Speed Harmonization (for arterial) module, despite its simplicity, outperforms any of them in terms of energy savings or emission reduction. A hypothesis is that the proposed Eco-Speed Harmonization module works better than those modules in terms of regulating the entire traffic flow.

Table 97: Changes (Percentage) in Measures of Effectiveness (MoEs) Due to the Eco-Speed Harmonization Along 27-Intersection El Camino Real Corridor Over Different V/C Ratios (100 Percent Penetration Rate).

V/C	Energy (KJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi	PM-2.5 (g/mi)	VHT (s/veh)	VMT (mi/veh)
0.20	18.90	18.92	46.47	18.21	23.09	37.60	-8.96	-0.31
0.50	17.83	17.86	44.21	17.72	23.15	38.66	-8.88	-0.62
0.83	14.27	14.37	40.56	14.60	19.23	34.78	-8.47	-0.23
1.00	12.64	12.66	36.75	11.34	18.83	33.80	-7.35	-0.40

In addition, the research team also investigated potential interactions between Eco-Speed Harmonization and any of the major modules in Connected Eco-Driving Application. The results under the baseline traffic demand (V/C = 0.83) are presented in Table 98. As can be observed from the table, the benefit from the Eco-Speed Harmonization module will be boosted by combining it with Generalized Eco-Driving Principles module, but will be greatly reduced by combining it with the Eco-Approach/Departure module. It must be pointed out that the results are site specific. The effectiveness of the Eco-Speed Harmonization module needs to be further verified in other roadway networks.

Table 98: Changes (Percentage) in MoEs Under Different Module Combinations (Morning Peak, Baseline Traffic Demand, where V/C is 0.83) Along 27-Intersection El Camino Real Corridor (100 Percent Penetration Rate).

Module Comb.	Energy (KJ/mi)	CO_2 (g/mi)	CO (g/mi)	HC (g/mi)	NOx (g/mi	PM-2.5 (g/mi)	VHT (s/veh)	VMT (mi/veh)
H	12.64	12.66	36.75	11.34	18.83	33.80	-7.35	-0.40
A+H	-0.25	-0.15	15.57	0.28	3.60	12.80	-32.00	-0.72
P+H	13.97	14.07	42.57	14.47	19.82	38.03	-10.93	-0.70
A+P+H	-0.35	-0.26	26.52	3.03	2.17	18.01	-34.95	0.23

A: Eco-approach/departure; P: Eco-driving principles; H: Eco-speed harmonization

Preliminary Results for the Combined Modeling

The initial testing of the Eco-Speed Harmonization component of Connected Eco-Driving shows great potential in the reduction of fuel use and resultant emissions, but was not included in the combined analysis for the same reasons as stated in Chapter 7. When the combined modeling was performed on the 27-intersection model of the El Camino Real, it was obvious that the Eco-Approach and Departure application was not providing emissions results that were as good as in the theoretical models with larger distance between the intersections. This seemed to indicate that the application was not as effective in closely spaced, urban corridors. The results of the Eco-Speed Harmonization module, however, showed much more promise on the closely spaced intersections of the El Camino Real. So with the idea that we may be able to substitute some of the Eco-Signal Operations applications depending on the proper configuration for a given roadway, preliminary sensitivity analyses were carried out on the combined applications using the Eco-Speed Harmonization module with the Eco-Approach and Departure module, as well as without.

The first sensitivity analysis was used simply to test the three configurations of the modules with the other four applications (Eco-Traffic Signal Timing, Eco-Transit Signal Priority, Eco-Freight Signal Priority, and Connected Eco-Driving): Eco-Approach Alone, Eco-Speed Harmonization Alone, and the two combined. The sensitivity analysis was conducted on the same El Camino Real corridor, using the baseline signal timings, demand, freight percentages, and transit headways. In Figure 126 below, the resultant impact on the different pollutant types can be seen, for all vehicles in the network, for the three configurations.

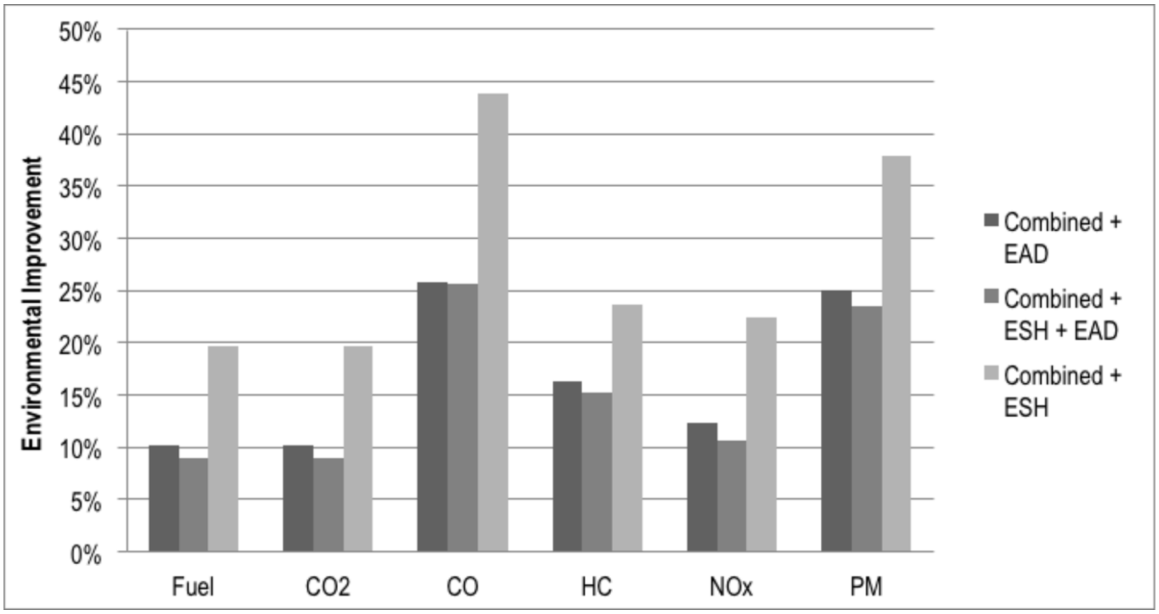


Figure 126: Environmental Impact of the Combined Modeling of Applications against the Baseline, for Each of the Three Module Combinations.

In the figure above, it can be seen that adding the Eco-Speed Harmonization module on top of the other combined applications does not improve emissions; rather, there is a small loss in improvements when it is added. This is likely due to the differences in speed advice when crossing between the harmonization and approach zones, especially in tightly spaced corridors, resulting in queues and spillbacks that prevent greater improvements by the applications. On the other hand, it can be seen that when the Eco-Approach and Departure is taken out and the Eco-Speed Harmonization is used, there is a significant improvement of the combined applications over the baseline model in all pollutants that were analyzed. All of these findings help to support the hypothesis that there are appropriate times to use some applications and not others, depending on the roadway configuration in question.

Another sensitivity analysis was performed for increasing levels of connected vehicle OBE penetration rate for the combined applications. For this analysis, the Eco-Approach and Departure and Eco-Speed Harmonization were examined exclusively, since the last analysis showed that their combination was not useful. Using the same baseline model as described above, the fuel consumption improvements were collected for increasing levels of on-board equipment (OBE) penetration rate against the baseline. Figure 127 shows the results for the two combinations, for all vehicles.

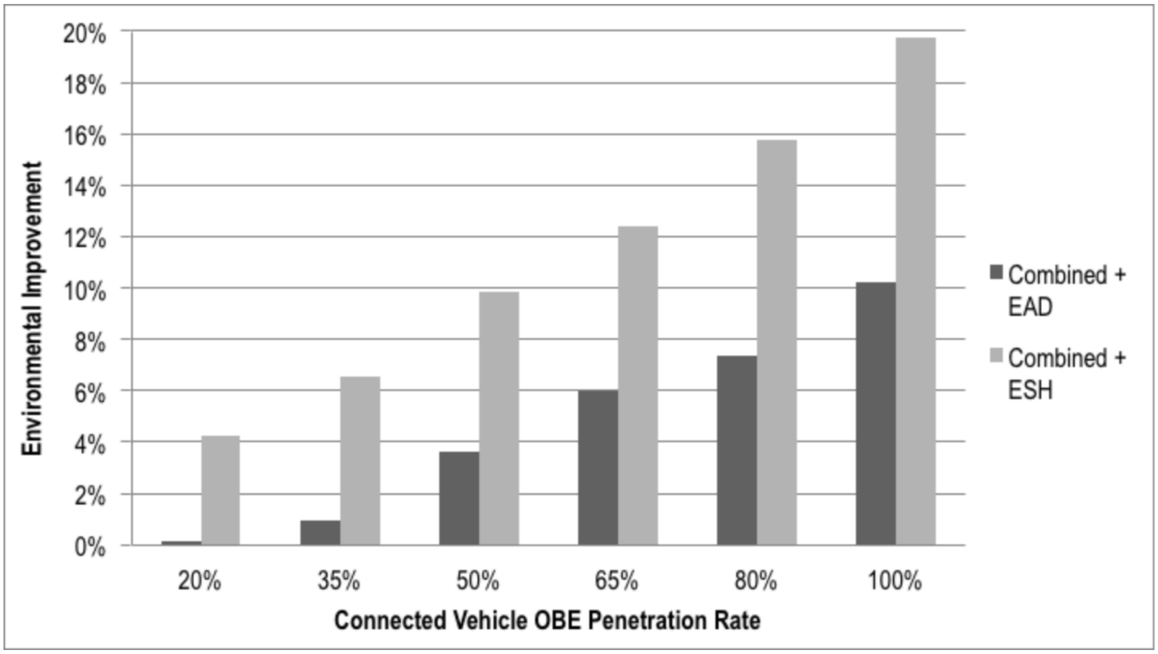


Figure 127: Environmental Impact of the Combined Modeling of Applications Against the Baseline, for Increasing Levels of Connected vehicle OBE Penetration Rate.

The results in the figure above illustrate that both configurations that were analyzed show increasing environmental benefits with increasing connected vehicle penetration rate. The Eco-Speed Harmonization, as before, has at least twice the fuel savings benefits in all levels of OBE penetration rate. The interesting takeaway from this analysis, however, is the applications in the lowest levels of OBE penetration (20-35 percent). At these lower levels, the benefits of the combined applications while using the Eco-Approach and Departure module are relatively small and insignificant, while the combination with the Eco-Speed Harmonization shows 4 percent to 7 percent benefits in fuel consumption. This proves that the applications are able to work better at lower levels of OBE penetration with this configuration, especially because the non-connected vehicles would also benefit from the speed adjustments. This analysis also shows that if the right combination of applications is chosen, significant benefits can be obtained even at very low levels of penetration.

The final preliminary sensitivity analysis that was conducted compared the use of Eco-Approach and Departure versus Eco-Speed Harmonization with the combined modeling for the different levels of congestion ratio along the El Camino Real (0.38, 0.77, and 1.00). The results of this analysis are shown in Figure 128, for all vehicles in the network.

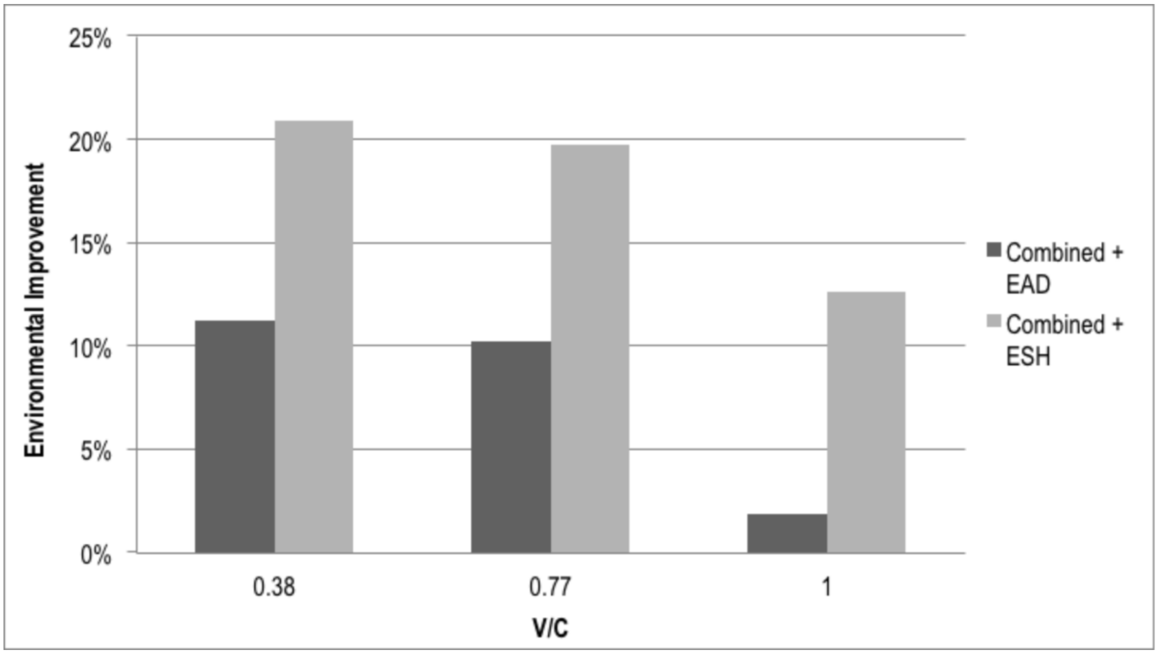


Figure 128: Environmental Impact of the Combined Modeling of Applications Against the Baseline, for Different Levels of Congestion Ratio.

While the patterns are similar between the two configurations over the different congestions levels, it can clearly be seen that the Eco-Speed Harmonization module, combined with the other four Eco-Signal Operations applications, provides significantly more fuel savings than the other way around. The most interesting takeaway from this analysis is the performance of the combined applications in the saturated conditions. The fuel savings for the configuration using the Eco-Approach and Departure module become nearly nil during this condition; however, the other configuration containing the Eco-Speed Harmonization still shows significant improvements.

The preliminary results of using the Eco-Speed Harmonization for Arterials module, combined with the other Eco-Signal Operations applications, shows great promise of gaining even more improvements with the implementation of this operational concept. This application was not originally part of the applications that were to be considered as part of the concept, but these results are proof that it should be considered in future research in to signal operations connected vehicle technology applications.

Appendix E. Benefit-Cost Analysis

The purpose of the Benefit-Cost Analysis (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 over the 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-Signal Operations Operational Scenario. Prior to 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. The overall approach of the BCA is illustrated in Figure 129. Many of the following steps required substantial input from the AERIS team, including stakeholders (e.g., FTA) and connected vehicle experts (e.g., connected vehicle 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 to the model, which extrapolated results to the entire nation and provided results for each year in the analysis.

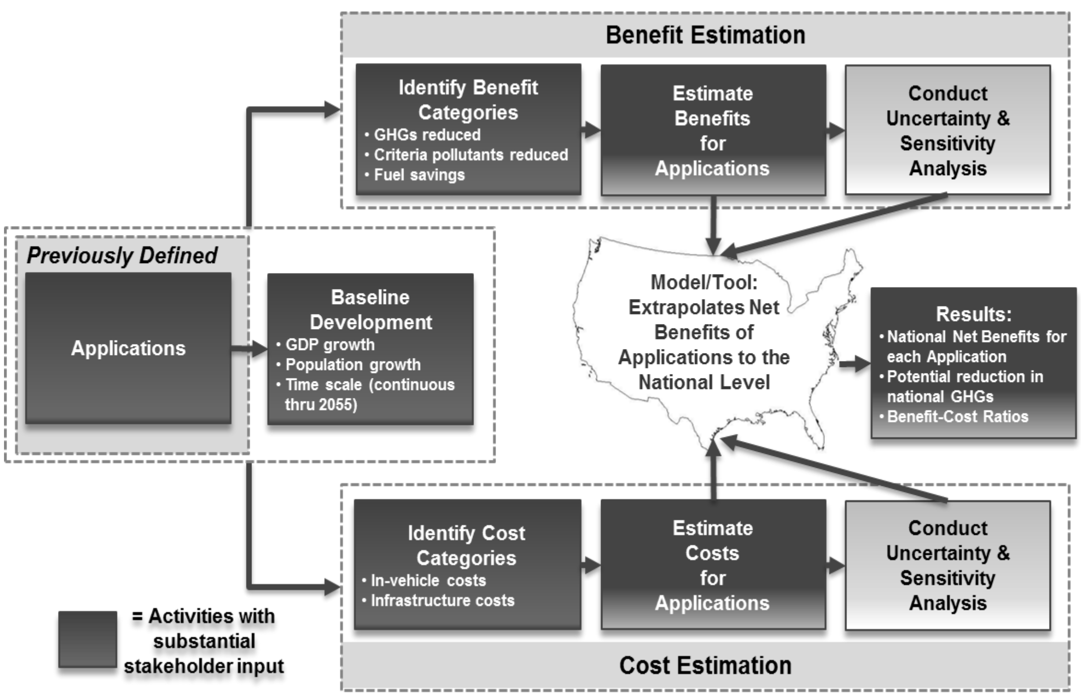


Figure 129: BCA Approach.

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

1. Only incremental costs attributable to AERIS were considered, so the connected vehicle infrastructure was assumed to already be in place.
2. Only the following environmental benefits were considered: GHG reductions, criteria pollutant reductions, and fuel savings.
3. Mobility (i.e., travel time savings) and safety benefits were not investigated.
4. Cost data were derived from the ITS Cost-Benefit Database.
5. The benefits were estimated using the modeling results.
6. 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. These are:

- On-Board Equipment (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.
- Roadside Equipment (RSE) Deployment Rate: Traffic signal- based applications require RSEs at signals to receive and transmit data; they 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/or 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 that 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 or not 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 travelled (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 dis-benefits 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., grams per VMT or grams per intersection signal crossing as appropriate). 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 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 connected vehicle 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., connected vehicle RSE).

Figure 130 provides the baseline cost elements that were not accounted for in the BCA, for reasons described above. 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	These costs are not included in BCA; as it is assumed that connected vehicle infrastructure exist
Infrastructure	Closed Circuit Television Cameras Road Signs Environmental Sensors Ramp Meters	These costs are attributed to AERIS applications; Only *incremental* costs to install and operate AERIS applications above and beyond those costs in the baseline
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)	

Figure 130: 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 131 illustrates the key differentiators of the six representative areas.

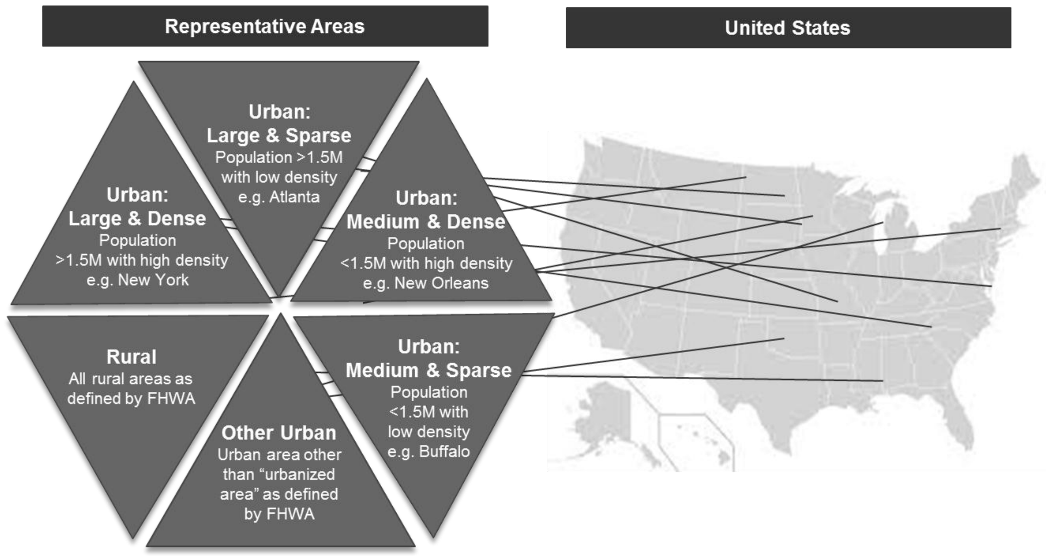


Figure 131: Extrapolation Approach.

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 131 is a representation of the model. The unit values for each application are inputs; and the deployment rate for the application, connected vehicle infrastructure, and compliance rates determine 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 132 shows the overall model functionality.

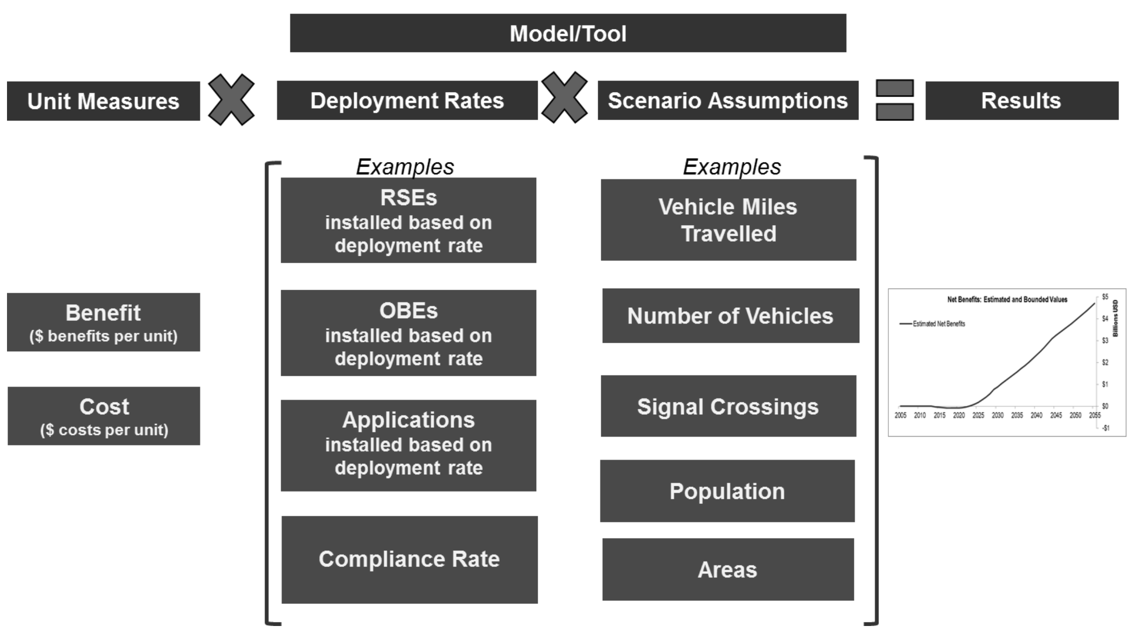


Figure 132: Extrapolation Tool.

Using the modeling results, the initial AERIS BCA was updated to estimate the benefits of the Eco-Signal Operations applications. The goal of the analysis was to estimate benefits for a study period between years 2019 and 2055. Year 2019 is when the connected vehicle technology deployment is assumed to begin, and Year 2055 is when full penetration of the connected vehicle technology is expected. The approach for this analysis is largely based on the initial BCA carried out prior to 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 connected vehicle technology deployment rates and adoption rates along with numerous other factors. In this analysis, the Eco-Signal Operations applications' modeling results are used as input to the BCA model. The BCA model considers the variation in traffic demands throughout the day, throughout the year, and also 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 CO_2 savings per intersection crossing (e.g., grams of CO_2 saved per intersection crossing while using the Eco-Approach and Departure at Signalized Intersections application as compared to the baseline scenario). The CO_2 savings obtained from the simulation runs are typically presented as *xx* grams/mile. They are normalized by converting grams/mile to grams/intersection-crossing using the total VMT and the total number of intersection crossings for the respective simulation runs.

The total number of intersection crossings in the study network was determined by using the origin-destination (OD) demand matrix and multiplying it by the corresponding number of intersections between any given OD pair. The value was used to estimate the fuel savings benefit per intersection crossing.

The values in the OD matrices are multiplied with the number of intersections vehicles crossed while going from an origin to the destination.

Table 99 shows the unit benefit values obtained for different 0.77 V/C ratio at 100 percent penetration rate on the ECR-27 network. The benefits are presented as benefits per intersection crossing. The BCA analysis takes into account demand variations between different regions and different times of the day while estimating the net benefits across the United States, throughout the analysis period. It also takes into account the variation in number of signals and arterial miles traveled by vehicles in different parts of the United States. In this case, the values of CO_2 savings per intersection crossing are input into the BCA model for extrapolation.

Table 99: Unit Benefits (CO2 Savings in Grams/Intersection Crossing) for Coordinated and Uncoordinated Scenarios With Different V/C Ratios.

Eco-Signal Operations Application	CO_2 (g/mi)	CO2 total	CO2 savings/intersection crossing (g/intersection crossing)
Baseline	785	31095038	
Eco-Freight Signal Priority	759.3	1017581	8.009043
Eco-Transit Signal Priority	764.6	810024.5	6.375435
Eco-Traffic Signal Timing	743.3	1654114	13.01898
Eco-Approach and Departure	764.7	803686.9	6.325554
Connected Eco-Driving	763.9	836167.1	6.581195
Combined Applications	704.7	3182664	25.04969

The unit benefit estimates obtained are plugged into the BCA model to obtain detailed benefit estimates for the whole of the United States between 2019 and 2055 (refer *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 connected vehicle deployment is assumed to begin at 2019; the application deployment rates are shown in Figure 133.

BCA

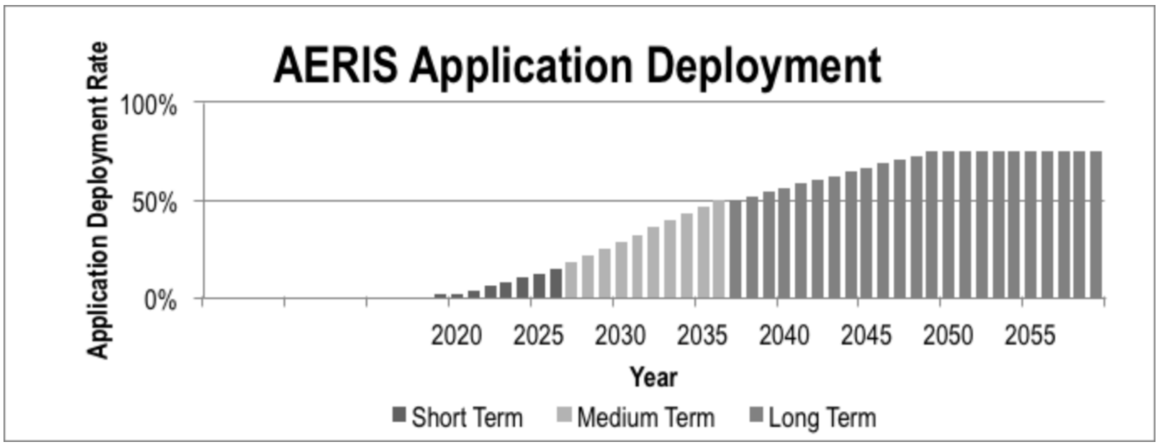


Figure 133: Application Deployment Rates for the Duration of Analysis.

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 ECR-27 network were used for each application. The modeling results that were input into the model to generate the following BCA graphs are presented in Table 99.

Figure 134 presents the net benefits of the Eco-Signal Operations applications when they are all deployed together. 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.

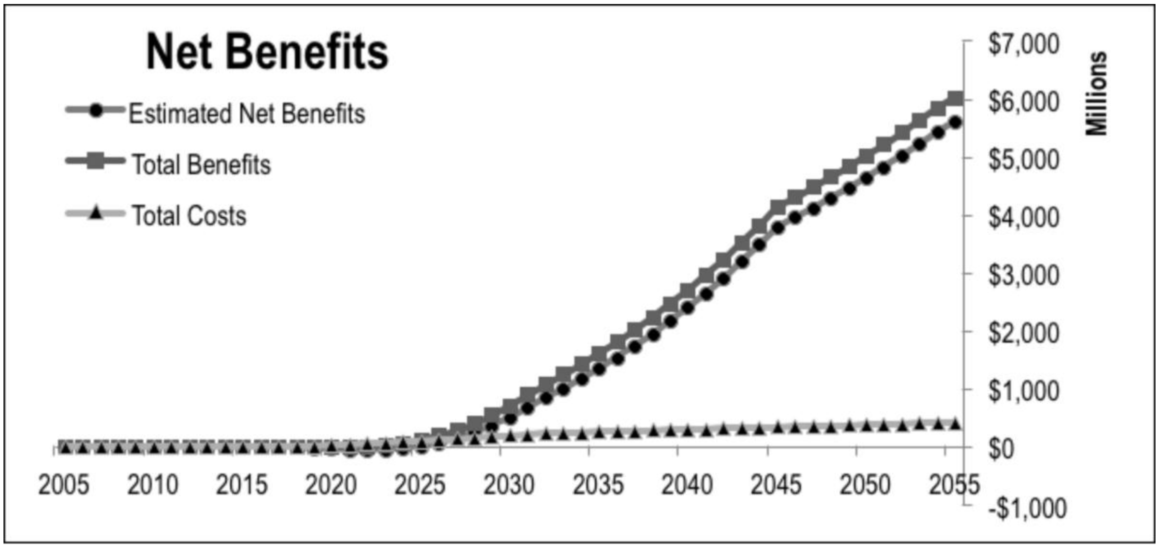


Figure 134: Net Benefits, Total Costs, and Total Benefits of the Combined Applications.

A comparison of the total monetary benefits is presented in Figure 135. The combined benefits are significantly higher than the benefit of each application. The lowest benefits are seen for the Eco-Transit and Eco-Freight Signal Priority applications. The low benefits are due to the relatively low percentage of truck and transit traffic as compared to passenger vehicles. The applications that benefit all the vehicles, like the Connected Eco-Driving, Eco-Traffic Signal Timing and Eco-Approach and Departure at Signalized Intersections, yield higher benefits. It is interesting to note that the slope of the combined application curve is steeper than that of the individual applications. This is due to the sensitivity of the applications to the increasing OBE penetration rate.

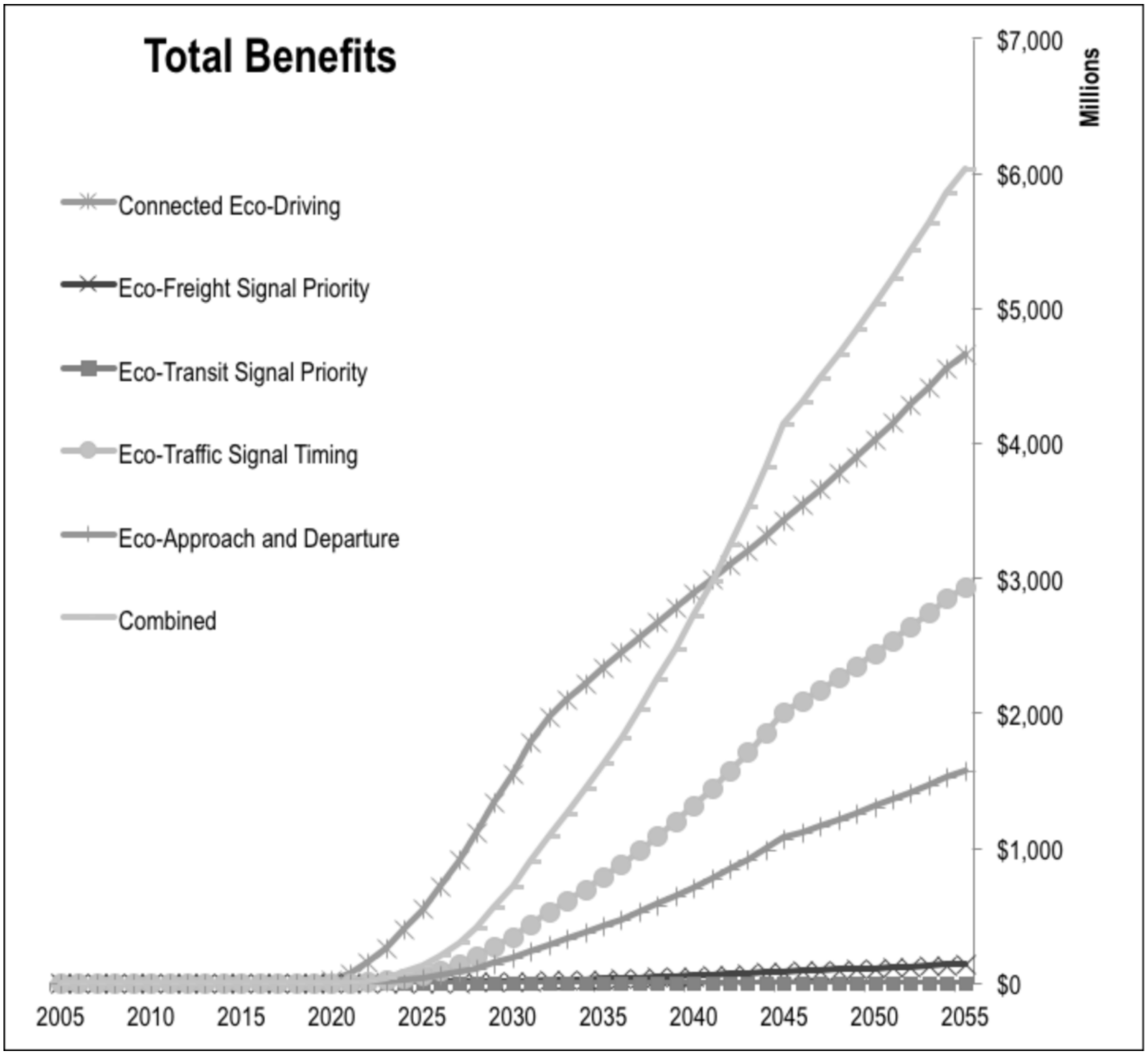


Figure 135: Comparison of Total Benefits of Each Application, Along With the Benefits of All the Applications Combined Together.

Table 100 was generated to summarize the results of the BCA. All the results are presented in Net Present Value assuming a 7 percent discount rate. The most important inference from the table is that the deployment of Eco-Signal Operations applications yields significant benefits. The costs of deploying the applications as a bundle are more beneficial than deploying them individually. Some of the cost elements are common among the applications, which make it beneficial to deploy them all together to achieve higher benefits at lower costs. It is also possible to achieve significant reductions in GHG emissions— on the order of 115 million tons over 35 years. The actual benefits obtained may be higher or lower than the projected values. The benefits are not expected to be uniform across the country. Since the Eco-Signal Operations applications yield maximum benefits in areas with signalized intersections, the benefits of this operational scenario are expected to be significant on the arterials and urban areas.

Table 100: Summary of the Combined BCA Results.

Signposts (Moderate)	2025	2055	Total*
Costs (Billion USD)	$0.11	$0.43	$1.54
Benefits (Billion USD)	$0.13	$6.04	$10.2
Net Benefits (Billion USD)	$0.02	$5.61	$8.7
Benefit-Cost Ratio	1:1	14:1	7:1
GHG Emissions Reduction (Million Tons)	0.2	7.2	115
GHG Emissions Reduction (percentage of baseline)	0.0%	0.4%	0.1%

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

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