ECO-ITS: Intelligent Transportation System Applications to Improve Environmental Performance

FINAL REPORT

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16. Abstract
This report describes recent research supported by the US DOT's AERIS program, building upon existing work through developing and improving data collection methods, developing new data fusion techniques to improve estimates, and applying appropriate models for ITS environmental/energy assessments. In addition, the report includes a synthesis of information gathered on other programs in ITS environmental research, as well as a set of technical recommendations on how to proceed with Tracks 1 – 3 of the AERIS program.

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1 Introduction

Many Intelligent Transportation System (ITS) applications have been developed over the last decade to improve safety and reduce congestion, on the whole making surface transportation more efficient. In addition, many ITS programs also likely have an environmental and energy benefit, which is now well recognized and addressed as part of the US DOT's ITS-JPO Applications for the Environment: Real-Time Information Synthesis (AERIS) program.

One of the major challenges for environmentally-focused ITS applications is to properly quantify their potential environmental and energy impacts, due to a lack of data. Better data collection methods with appropriate models need to be developed and implemented to improve the quantification of these ITS applications. The AERIS program has recognized this dearth of data and has focused many of the objectives on data, namely: 1) capturing environmental data from vehicles; 2) integrating these data with transportation management and performance improvements; and, 3) creating specific applications for transportation management and travelers that use ITS environmental data.

Over the last several years, researchers at the University of California-Riverside's Center for Environmental Research and Technology (CERT) have been actively researching and working towards performing energy/environmental assessments for various ITS programs. Indeed, UCR's CERT established its own eco-friendly intelligent transportation system (ECO-ITS) technology research program in 2006 and it continues to grow. This ECO-ITS research program is aimed at developing and evaluating innovative applications, based on the use of advanced technologies, targeted at reducing energy and environmental impacts of vehicles and transportation systems. As part of this program, UCR researchers have developed new energy and emission modeling methodologies, applied these methods to analyze different ITS scenarios, and have also developed several ITS applications that are specifically targeted to reduce traffic energy consumption and emissions. Each of these applications has been shown to potentially reduce fuel consumption and emissions from vehicles on the order of 5-20%. Examples include eco-routing navigation systems, freeway-based dynamic eco-driving system, arterial-based dynamic eco-driving system, advanced driver alert system, among others.

This report describes recent research that has been supported by the AERIS award DTFH61-10-P-00168. This work builds upon existing work through developing and improving data collection methods, developing new data fusion techniques to improve estimates, and applying appropriate models for ITS environmental/energy assessments. In addition, the report includes a synthesis of information gathered on other programs in ITS environmental research, as well as a set of technical recommendations on how to proceed with Tracks 1 – 3 of the AERIS program plan.

2 Data Collection and Modeling Methodologies

In 1995, the U.S. DOT and other agencies realized that the using standard *macroscale* transportation and emission models for estimating transportation-based energy and air quality impacts were not well suited for intelligent transportation system projects that affect traffic system operations. As a result, an NCHRP program (25-11) was initiated to create a methodology and a suite of emissions models that could be used for this type of *microscale* evaluation [NRC, 2000]. The University of California-Riverside carried out this NCHRP research project from 1996 through 2000, which resulted in the Comprehensive Modal Emissions Model (CMEM), a microscale emissions model capable of predicting second-by-second fuel consumption and tailpipe emissions of carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x) based on different modal operations from an in-use vehicle fleet [Barth et al., 2000]. The model was further developed with the support from the U.S. Environmental Protection Agency (EPA). In the modeling approach of CMEM, the entire fuel consumption and emissions process is broken down into components that correspond to physical phenomena associated with vehicle operation and emissions production. Each component of CMEM is modeled as an analytical representation consisting of various parameters that are characteristic of the process. These parameters vary according to vehicle type, engine, emission control technology, and level of deterioration. The initial versions of CMEM contain a model database for 23 light-duty vehicle/technology categories. With the constant addition of new vehicle/technology categories into the model database, the current version of CMEM includes 28 light-duty vehicle/technology categories and three heavy-duty vehicle/technology categories. It should be noted that CMEM is based on over thousand vehicles that have been tested over the years, both on a variety of dynamometer tests as well as through on-board testing (using portable emissions measurement systems). Further details on CMEM are documented in several references including [Barth et al., 1996; An et al., 1997; Barth et al., 1997; An et al., 1998; An et al., 1999; Barth et al., 1999; Barth et al., 2000; Barth et al., 2001a; Barth et al., 2004; Barth et al., 2006].

Much of the CMEM methodology has been adopted as part of the U.S. EPA’s new MOVES model (see [http://www.epa.gov/otaq/models/moves/index.htm]) emissions generator component called PERE. As a result, CMEM and MOVES are consistent, collaborative models.

CMEM has been developed primarily for evaluating transportation projects where second-by-second vehicle trajectories (location, velocity, acceleration) are measurable (e.g., through GPS technology). These vehicle trajectories can be applied directly to CMEM, resulting in both individual and aggregate vehicle energy/emissions estimates. As a result, it is possible to measure traffic prior to an ITS project implementation and then measure traffic after the implementation to determine the net environmental benefit of the project.

Using CMEM directly typically works well when microscale vehicle trajectories (or a representative subset of trajectories) are readily available; however, when vehicle trajectories are not available, then other mesoscale methods must be applied. These mesoscale methods are typically used when other traffic performance parameters, such as average speed, density, and flow are available.

Beginning in 2006, UCR CERT initiated research to develop a new mesoscale modeling methodology using a large database of vehicle activity data in conjunction with MOVES and/or CMEM to produce emission factors at the roadway link level [Barth & Boriboonsomsin, 2008]. These mesoscale energy and emission factors were designed to be indexed by a number of link attributes, including traffic speed, density, etc. An example is illustrated in Figure 2.1, which shows the relationship between vehicle fuel consumption and average traffic speed. This type of curve seen in the graph can be created for multiple vehicle categories in either MOVES or CMEM, after which it can then be used to assign energy and emission factors to each link in the roadway network based on their historical or real-time traffic performance. The result is the quantification of energy/emission benefits of traffic operation strategies that improve traffic performance.

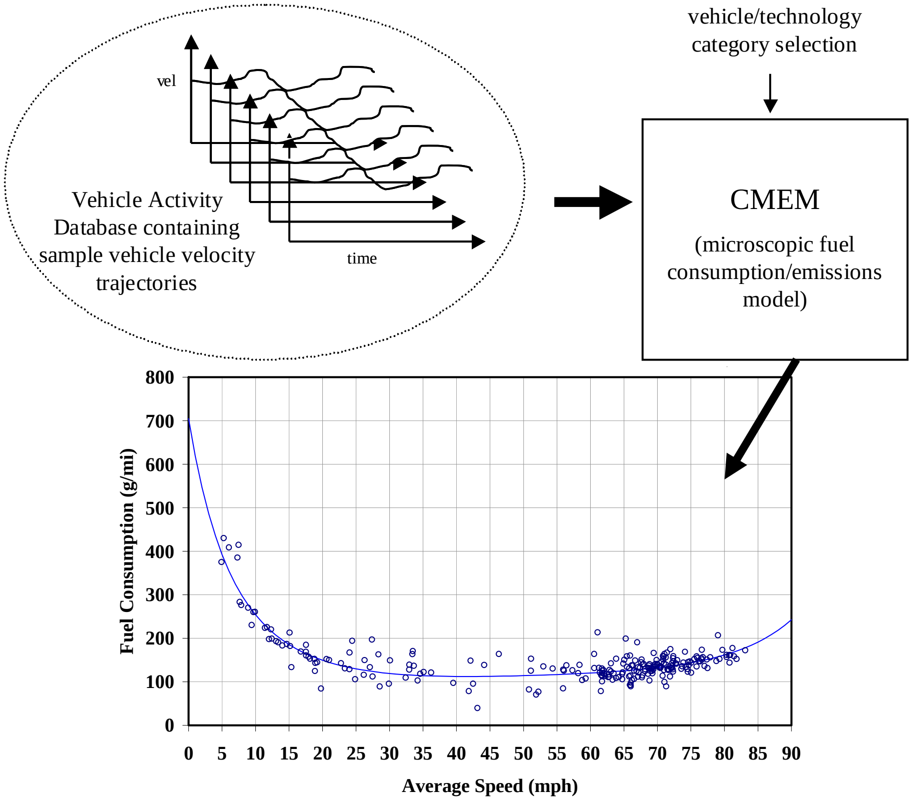


Figure 2.1. Link-level fuel consumption modeling methodology

Thus far, this methodology has been well developed for freeway traffic; however, research on other roadway types, such as surface streets with traffic signals, is still needed. Further, newer vehicle types such as hybrids and electric-drivetrain vehicles need to be considered as part of the vehicle mix.

As part of this AERIS project (and other co-funding from other sources), we have explored and developed a new method to estimate energy and emissions impacts from arterial roadways with traffic signals. This research is addressed in Section 2.1 below. In addition, we have begun to develop new mesoscale speed-emissions curves for different hybrid electric vehicles, described in detail in Section 2.2.

2.1. Arterial Roadway Energy/Emissions Estimation using Trajectory Reconstruction

One of the major problems of using the previously described speed-emissions curve for signalized arterials (i.e., roadways with *interrupted* flow) is that they cannot be completely characterized by average traffic speed alone. There are several cases where traffic speed along a corridor can be the same for different scenarios, and yet their energy consumption and emissions can be drastically different, based on various factors such as number of stops/starts and acceleration/deceleration patterns. For example, it was shown that a vehicle cruising at 35 km/h for 40 seconds consumes much less fuel and produces fewer emissions than the same vehicle cruising at 70 km/h for 20 seconds followed by idling at a traffic light for another 20 seconds, even though they have the same average speed [Mandava et al., 2009].

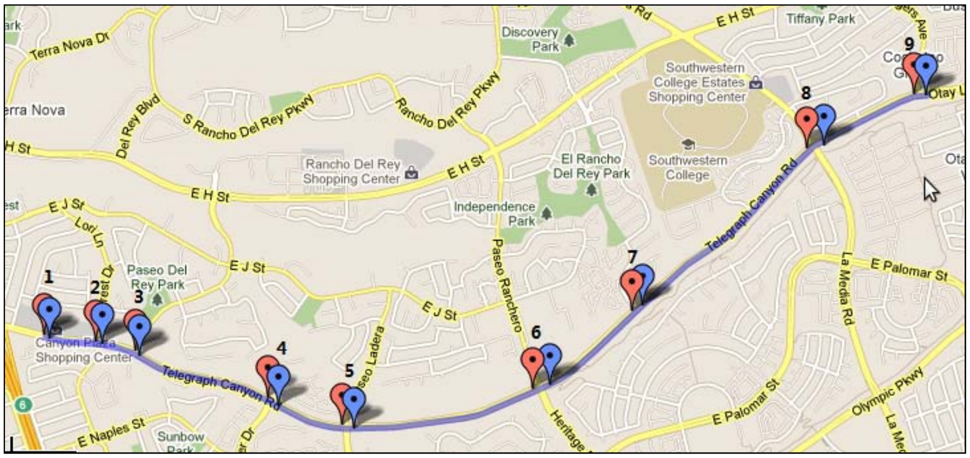
As an alternative method, we have developed a method to estimate energy/emissions on an arterial corridor using state-of-the-art traffic sensors located near traffic signals along the corridor. Using data from these sensors, it is possible to re-create approximate trajectories of the vehicles travelling along the corridor. These approximated trajectories can then be run through a microscale energy/emissions model and then integrated for all vehicles to get an overall energy/emissions estimate for all traffic. Previous approaches developed to reconstruct or generate vehicle trajectories served a variety of applications. In [Mandava et al., 2009] and [Mandava, 2010], the authors generated future vehicle trajectory to assist the driver to pass a signalized corridor without being stuck at the traffic lights. Given an expected travel time and travel distance, motion-based velocity profile was used first in [Mandava et al., 2009] and a sinusoid-based trajectory was further developed in [Mandava, 2010]. Both methods determine the parameters (e.g., acceleration/deceleration rates) of the trajectory by solving an optimization problem which minimizes the power required during the trip. The authors in [Li et al., 2009] calculated the speed and time for different part of the trajectory before the intersection which is defined based on the speed measurement of several sensors along the link in order to estimate the travel time. In contrast to the previous methods, our method first defines a model of vehicle trajectories going through a signalized intersection which consists of different driving modes and then estimates the time length of each mode based only on the traffic measurements of the wireless sensors.

[Note: The details of this research are provided in an academic paper that is published and presented at the IEEE Intelligent Transportation System Conference (ITSC-2011) in Washington D.C., in October 2011 {Yang et al., 2011}.]

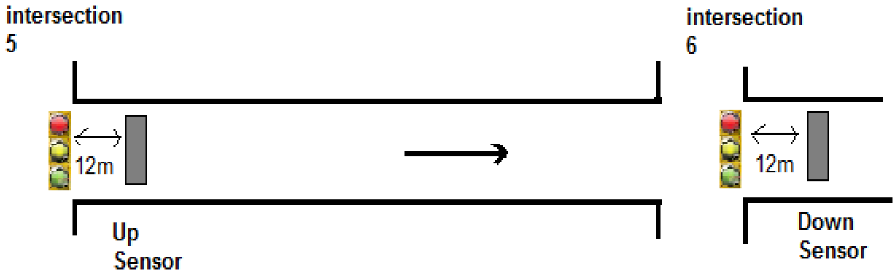
2.1.1 Data Collection

New wireless vehicle detection systems are being deployed in a variety of roadways around the world (e.g., see [Sensys Networks, 2011]). These sensors are not only able to measure lane occupancy, flow, and speed, but can also match “vehicle signatures” between different sensors (i.e., vehicle re-identification) to provide overall travel time estimates of individual vehicles [Sensys Networks, 2011]. With these travel-time data, it is possible to further extract the information on platoon patterns of the vehicles.

For our research experiments, we have used a wireless traffic sensor network that is installed along a primary arterial corridor in Chula Vista, California (Telegraph Canyon Road; see Figure 2.2a). This network consists of 18 sensors in both directions located at the 9 signalized intersections, spaced approximately 500 meters apart, along the corridor. Again, the upstream magnetic signature of a vehicle passing over a sensor can be matched to a downstream signature (see Figure 2.2b), allowing for vehicle re-identification and a good estimate of travel time.



(a). Chula Vista Sensor Network



(b). sensor matching along a single link in the network.

Figure 2.2. Chula Vista Wireless Sensor Network

Approximately 70 percent of the total vehicles traveling over consecutive intersections in the lane(s) that have the sensors installed can be re-identified, providing an accurate travel time and also an absolute time stamp. A 100% match rate is not possible due to lane changing and vehicle ingress/egress patterns along the corridor. The lane occupancy when vehicle crosses over each sensor can also be measured for use in estimating a spot speed for each vehicle, which can be aggregated to result in average traffic speed. Example travel time data are shown in Figure 2.3, where the x-axis corresponds to different time stamps, and the y-axis corresponds to the travel time. The green vertical lines represent the re-identified vehicles with their corresponding travel times (height); yellow lines correspond to detected but unmatched vehicles.

Another important piece of information that can be extracted from this travel time data is the whereabouts of each vehicle within a "platoon" of vehicles traveling down the corridor. For an example in Figure 2.3, platoons of vehicles are easily identified by their clusters within the travel time plots. If a platoon of vehicles gets stopped by a red light, then the first car in the platoon usually has the longest travel time, and the vehicle at the end typically has the lowest travel time between sensors. Once these platoons are identified, it is then possible to extract the position of any vehicles within their particular platoon.

Over a period of time, it is possible to create a travel time histogram of traffic between signalized intersections, as shown in Figure 2.4a. It is apparent that there is a wide range of travel times between two neighboring intersections (in this example, intersections 5 and 6 along the study corridor). This wide range of travel times is due to a variety of factors, including traffic signal phase and timing (i.e., whether the vehicles are stopped by a red light) and driver behavior.

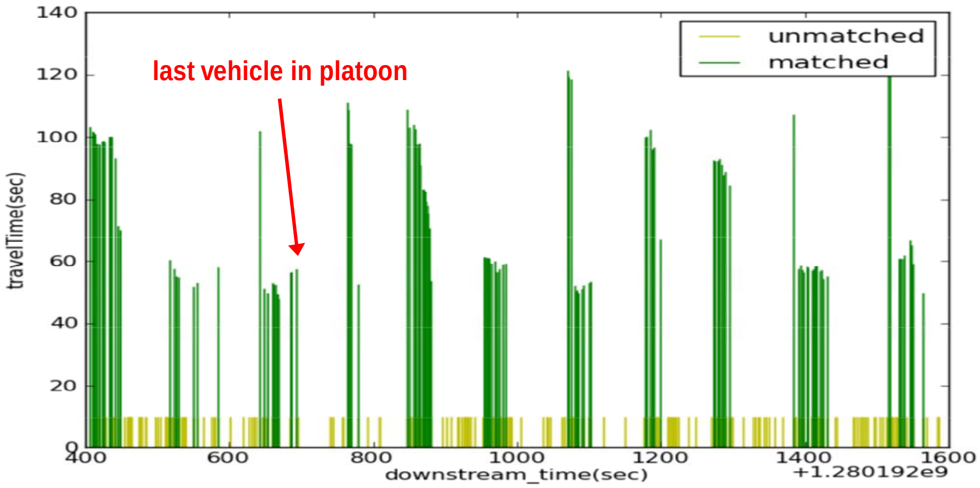


Figure 2.3. Travel time plot between two intersections

In order to determine actual vehicle movements along with traffic signal phase and timing information, a large-scale ground truth study was carried out using video cameras placed along the study corridor. Video imagery of the vehicle movements was captured simultaneously with traffic data from the wireless sensors for a wide range of traffic conditions. Given these time-synchronized data sets, traffic scenes in each traffic light cycle as well as the travel time data of each vehicle could be extracted. Vehicles traveling together in one cycle were grouped as one platoon. Meanwhile, whether a vehicle was stopped or significantly delayed by traffic lights was manually checked from the videos across different levels of traffic congestion. It was then possible to validate a variety of details associated with the wireless traffic sensor dataset. For example, the travel time histogram shown in Figure 2.4a can now be segmented in to different groups, as shown in Figure 2.4b. Green bins represent travel times of non-stop vehicles, while the blue bins belong to the stopped vehicles. Group 1 (green bins) vehicles were confirmed that passed through the intersection without stopping at the red light, Group 2 (blue bins) corresponds to the vehicles that were stopped for one red cycle, and Group 3 (red bins) corresponds to the vehicles that were stopped for two red cycles.

Using a thresholding technique, it is possible to assign a probability for each intersection pair on how many stops a vehicle typically makes, based on their travel time. Furthermore, the location of each vehicle in its platoon can be identified through the instantaneous travel time data. These data are critical in reconstructing an approximate vehicle trajectory.

Using the ground truth derived data shown in Figure 2.5, several observations can be made. For the Group 1 vehicles that are able to travel through the intersection without stopping, their travel times are simply a function of their average speed which can be modeled as a Gaussian distribution. For the Group 2 vehicles, their travel times depend highly on the delay due to getting stopped by the red light and by the queue dispersion. The travel time is less dependent on the free flow speed prior to decelerating due to a red light; what is more important is the arrival time of the vehicle during the red cycle time. As expected, the vehicles at the head of the queue (which arrive at the intersection earlier) would wait for the green cycle longer than the vehicles arriving later in the cycle.

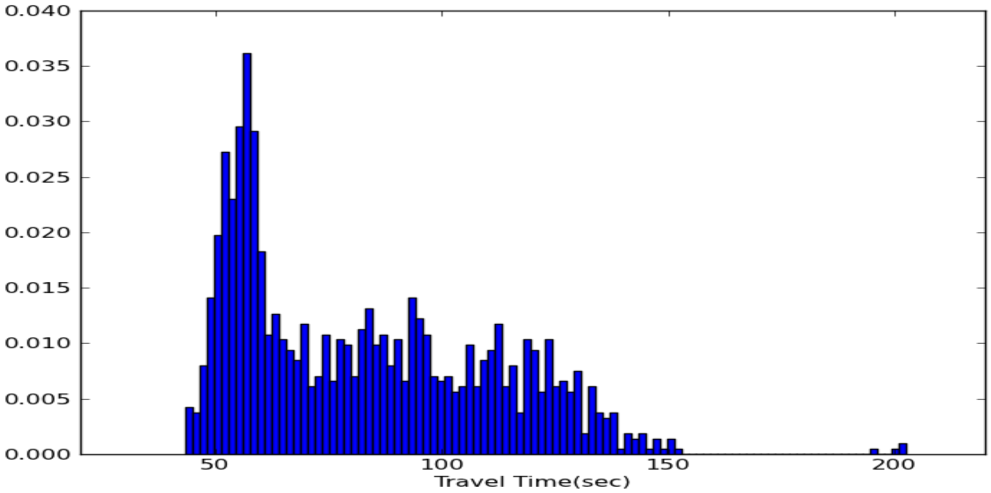


Figure 2.4a. Travel Time Histogram along a link in the study corridor

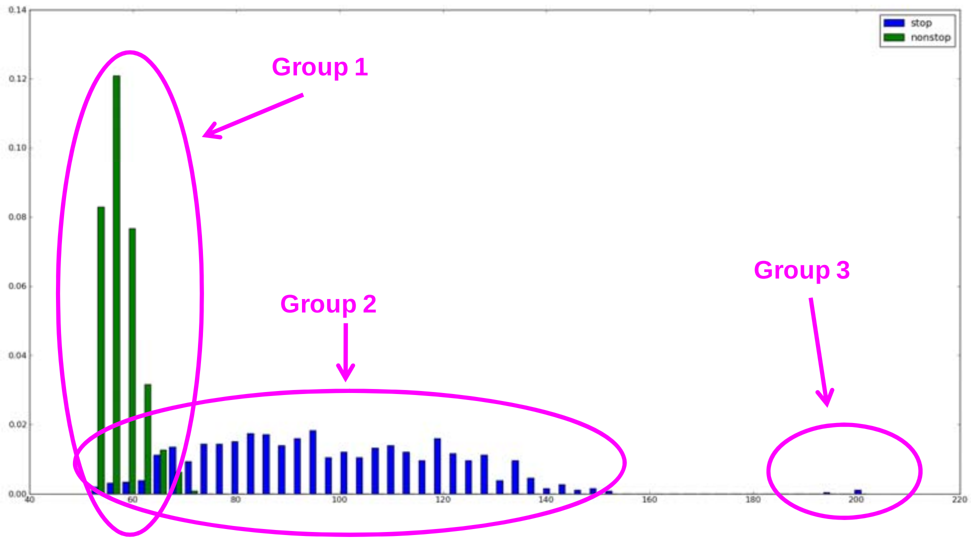


Figure 2.4b. Different groups of vehicle movements identified from video data

A thresholding technique is used to separate the Group 1 and Group 2 vehicles, which can be calibrated for each intersection pair. The travel times of Group 1 vehicles are then modeled as a Gaussian distribution, where the peak of the data is used as the mean μ; the left side of the distribution then determines the standard deviation σ. All the vehicles with travel times smaller than $\mu + 3\sigma$ (corresponding to the 99% percentile) are classified as Group 1 vehicles. The Group 1 vehicle trajectories are determined only by their average speed to estimate emission and fuel consumption. Vehicles with travel times greater than $\mu + 3\sigma$ are considered as Group 2, whose trajectories are estimated based on a more complicated modal reconstruction method, described in detail in [Yang et al., 2011]. Since in our data set, group-3 only contains a small number of vehicles and can be easily identified by a large travel time threshold.

To calculate vehicle fuel consumption and emissions, we use the CMEM microscale emissions model [Barth et al., 1996; An et al., 1997; Barth et al., 1997; An et al., 1998; An et al., 1999; Barth et al., 1999; Barth et al., 2000; Barth et al., 2001a; Barth et al., 2004; Barth et al., 2006] which requires second-by-second velocity as input. For a group-1 (non-stopped) vehicle, a smooth velocity trajectory is used centered around its average speed. For the group-2 vehicles (i.e., vehicles that are stopped by the traffic light), the velocity trajectory is constructed using the particular modes described in the previous section. Given the wireless traffic sensor-based travel time, instant speed, and vehicle count within the platoon, as well as using calibrated constants for average free flow speed, acceleration, and deceleration, the scenario type and time length of each mode is estimated as described in [Schulz, 2000]. This approximated second-by-second velocity trajectory is then run through the microscopic emissions model to determine fuel consumption and emissions.

2.1.2 Experimental Results

To verify the performance of the proposed methodology, a variety of experiments have been carried out from field testing in Chula Vista California. In order to test the validity of the fuel consumption/emissions estimation process, a probe vehicle was used extensively on two separate days on Telegraph Rd. in Chula Vista California (July 27th and Oct 19th, 2010). The probe vehicle reports second-by-second velocity trajectories along with position information. Given time and location information, the probe vehicle profiles were matched to the wireless traffic sensor data. A total of 58 second-by-second velocity trajectories of the vehicle were used in this analysis. Based on the 58 trajectories, the average free flow speed was set to be 50 mph, typical acceleration is at 2mph/sec, and deceleration is approximately 3mph/sec. The distance of the link 5→6 is 0.78 miles and the effective queuing vehicle length is set to be 5 meters.

An example trajectory of a group-1 unstopped trajectory is illustrated in Figure 2.5. Figure 2.5a shows the actual vehicle trajectory in green, and the red line illustrates the corresponding trajectory estimate. Figure 2.5b (typical passenger vehicle) and 5c (typical sports utility vehicle) show the fuel consumption and CO_2 emissions for three cases: 1) the estimation using the standard speed-based emission factor approach; 2) the estimation using the modal decomposition method; and 3) the ground truth energy/emissions based on the actual second-by-second vehicle trajectory. For this example freeflow trajectory, it can be seen that case 1) and 2) are the same, and slightly underestimate actual energy/emissions due to not capturing small acceleration/deceleration perturbations around the average speed.

Another example trajectory is shown in Figure 2.6, where the trajectory includes a stop. Using the same cases as before, it can be seen that the modal decomposition approach is approximately 93% of the ground truth, compared to the 68% estimate using the standard speed-emissions approach.

It is possible to compute and compare the total sum of all trajectories; this provides a general sense on how well the method performs. Figure 2.7 illustrates these overall results, indicating that the modal decomposition method is approximately 8% less than the true energy/emissions whereas the standard speed-emissions approach underestimate the energy/emissions by nearly 40%.

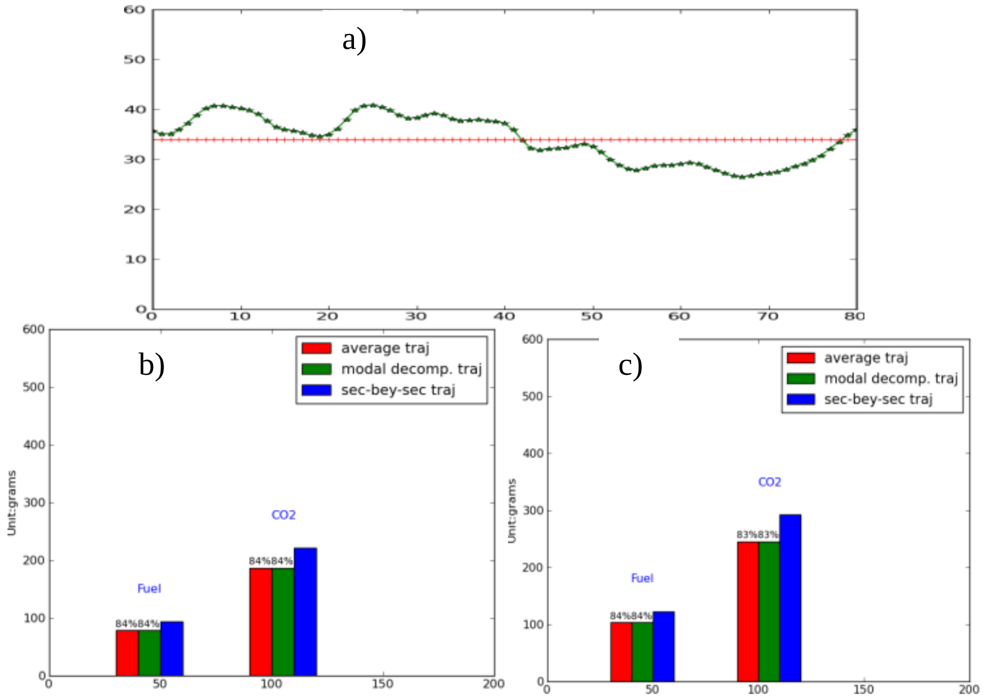


Figure 2.5. Example freeflow vehicle trajectory; a) actual trajectory (green) and estimate (red); b) energy/emissions for passenger vehicle; c) energy/emissions for sports utility vehicle

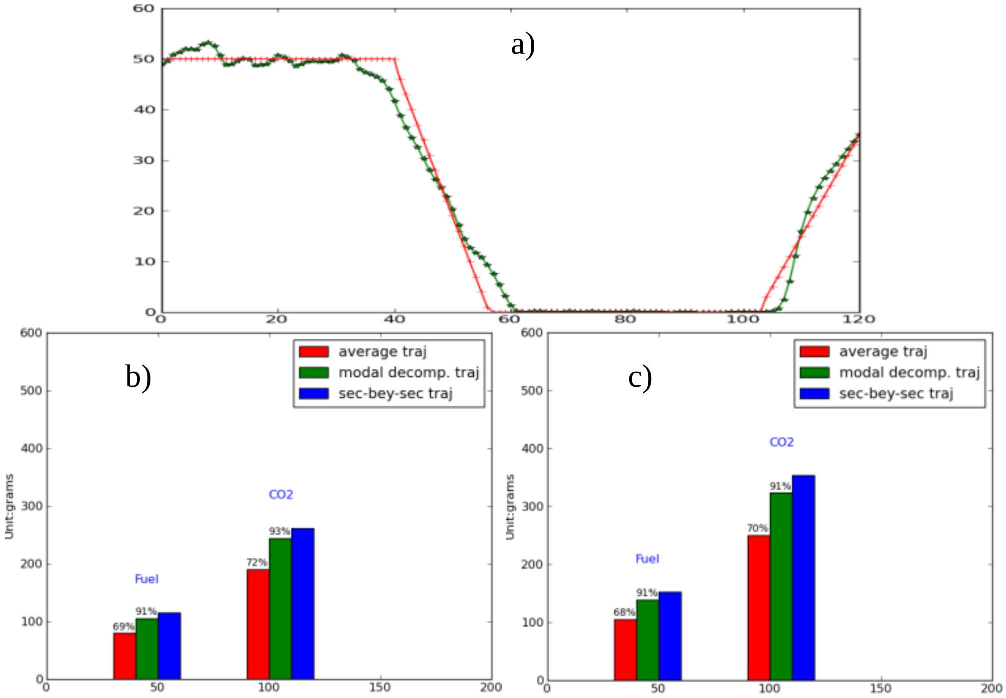


Figure 2.6. Example stopped vehicle trajectory; a) actual trajectory (green) and estimate (red); b) energy/emissions for passenger vehicle; c) energy/emissions for sports utility vehicle

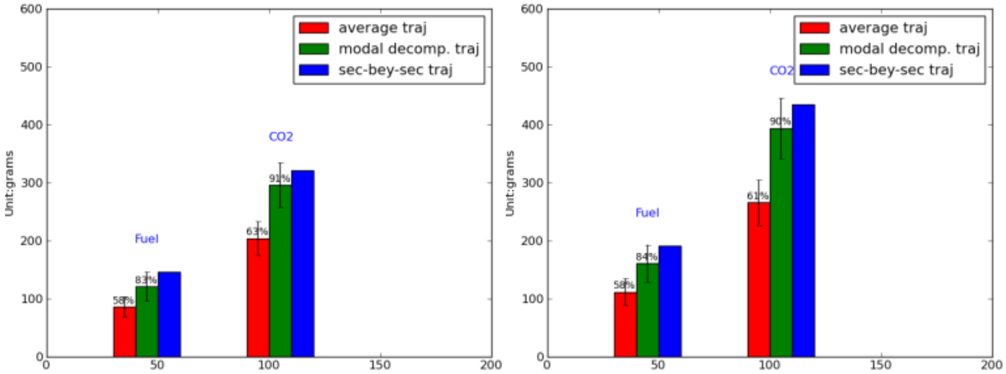


Figure 2.7. Total energy/emissions estimates for all trajectories; a) energy/emissions for passenger vehicle; b) energy/emissions for sports utility vehicle

2.1.3 Summary and Conclusions

Accurately estimating fuel consumption and tailpipe emissions from vehicles traveling on arterial corridors is difficult since the standard methods typically do not take into account differences between when a vehicle flows through the corridor without stopping at traffic lights, and when the vehicle is stopped at one or more red lights. In order to better estimate energy/emissions in these cases, we have developed a technique that takes advantage of new wireless traffic sensors that not only measure traffic speed, density, and flow, but also can perform vehicle re-identification to get an accurate link-to-link travel times. Furthermore, the sensor data also provide information on vehicle platoons, such as platoon length and where a particular vehicle is within a platoon. All of this information can be used in estimating an approximate vehicle trajectory that is more realistic than a simple average speed-based estimate. The acceleration and deceleration behavior and idle duration during one stop can be estimated, thereby better estimating energy and emissions associated with the corridor. Results show that this new method is typically within 10% of the true values, compared to the standard approach which falls within 40% of the actual values. Future work includes improving the acceleration and deceleration properties of the reconstructed trajectory and extending this method to multi-stop trajectories.

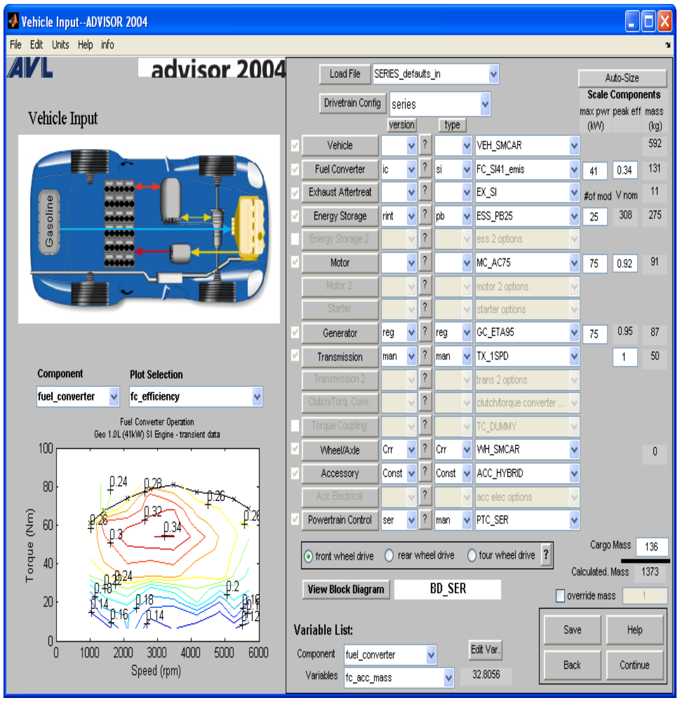
2.2 Estimating Energy/Emission Curves for Hybrid Electric Vehicles

Thus far, the mesoscale emissions modeling approach using speed-emissions curves have been developed for conventional light- and heavy-duty vehicles. However, for estimating energy and emissions for future vehicle fleets, it is highly likely that the percentage of electric drive-train vehicles (battery-electric vehicles (BEV), hybrid electric vehicles (HEV), and plug-in hybrid electric vehicles (PHEV)) will increase. As a result, we have begun to develop mesoscale speed-emission curves for these vehicle types.

As an initial approach, we consider one of the more popular hybrid electric vehicles, the Toyota Prius. The Toyota Prius currently has the largest market share of HEVs, and has achieved benefits of low emissions and high energy efficiencies while meeting the performance characteristics that consumers have come to expect.

One of the critical considerations of any HEV development is the design of the energy management strategy, which determines how energy in a hybrid powertrain should be produced and utilized as a function of various vehicle parameters (e.g., power demand, battery state-of-charge, auxiliary power level, etc.). Characteristics of each major component will provide the limits within which the strategy will operate. Various static energy management strategies are in use today, allowing the vehicle to make use of battery energy storage, while maintaining the health of the batteries for extended life.

To develop typical speed emissions curves as outlined in Figure 2.1, we used the model Advisor, which is Advanced Vehicle Simulator software created by AVL [US DOE, 2011]. This software uses a set model, data and script text files for use with Matlab and Simulink to simulate the performance of advanced drivetrain vehicles. The model is designed and used for rapid analysis of the performance and fuel economy of conventional, electric and hybrid vehicles. An example screenshot of the Advisor model is shown in Figure 2.8.



Component: fuel_converter
Plot Selection: fc_efficiency

Load File: SERIES_defaults_in
Drivetrain Config: series

		version		type		max pwr (kW)	peak eff	mass (kg)
☑	Vehicle		?		VEH_SMCAR			592
☑	Fuel Converter	ic	?	si	FC_SI41_emis	41	0.34	131
☑	Exhaust Aftertreat		?		EX_SI	#of mod	V nom	11
☑	Energy Storage	rint	?	pb	ESS_PB25	25	308	275
☐	Energy Storage 2		?		ess 2 options			
☑	Motor		?		MC_AC75	75	0.92	91
	Motor 2		?		motor 2 options			
	Starter		?		starter options			
☑	Generator	reg	?	reg	GC_ETA95	75	0.95	87
☑	Transmission	man	?	man	TX_1SPD		1	50
	Transmission 2		?		trans 2 options			
	Clutch/Torq. Conv.		?		clutch/torque converter ...			
☐	Torque Coupling		?		TC_DUMMY			
☑	Wheel/Axle	Crr	?	Crr	WH_SMCAR			0
☑	Accessory	Const	?	Const	ACC_HYBRID			
	Acc Electrical		?		acc elec options			
☑	Powertrain Control	ser	?	man	PTC_SER			

● front wheel drive ○ rear wheel drive ○ four wheel drive ?

Cargo Mass 136
Calculated. Mass 1373
☐ override mass 1

View Block Diagram: BD_SER

Variable List:
Component: fuel_converter
Variables: fc_acc_mass 32.8056

Figure 2.8. Example screenshot of the Advisor model

In developing speed emission curves, a similar methodology was used as described in [Barth and Boriboonsomsin, 2008]. A large vehicle activity database representing typical trips in Southern California was applied to the Advisor model to estimate typical fuel economy and emission values. This database contains numerous GPS-based vehicle velocity trip patterns collected as a post-census travel survey in 2001 by the Southern California Association of Governments (SCAG). This data set represents approximately 467 households with 626 vehicles. The total miles driven in this data set is approximately 28,000. These representative trips were then applied to Advisor, calibrated for various HEV models.

The initial results of this are shown in Figure 2.9. It can be seen that most of the differences of these HEV models is at the lower (congestion) speeds. In general, hybrid have lower emissions at this lower end, where some hybrid designs perform better than others.

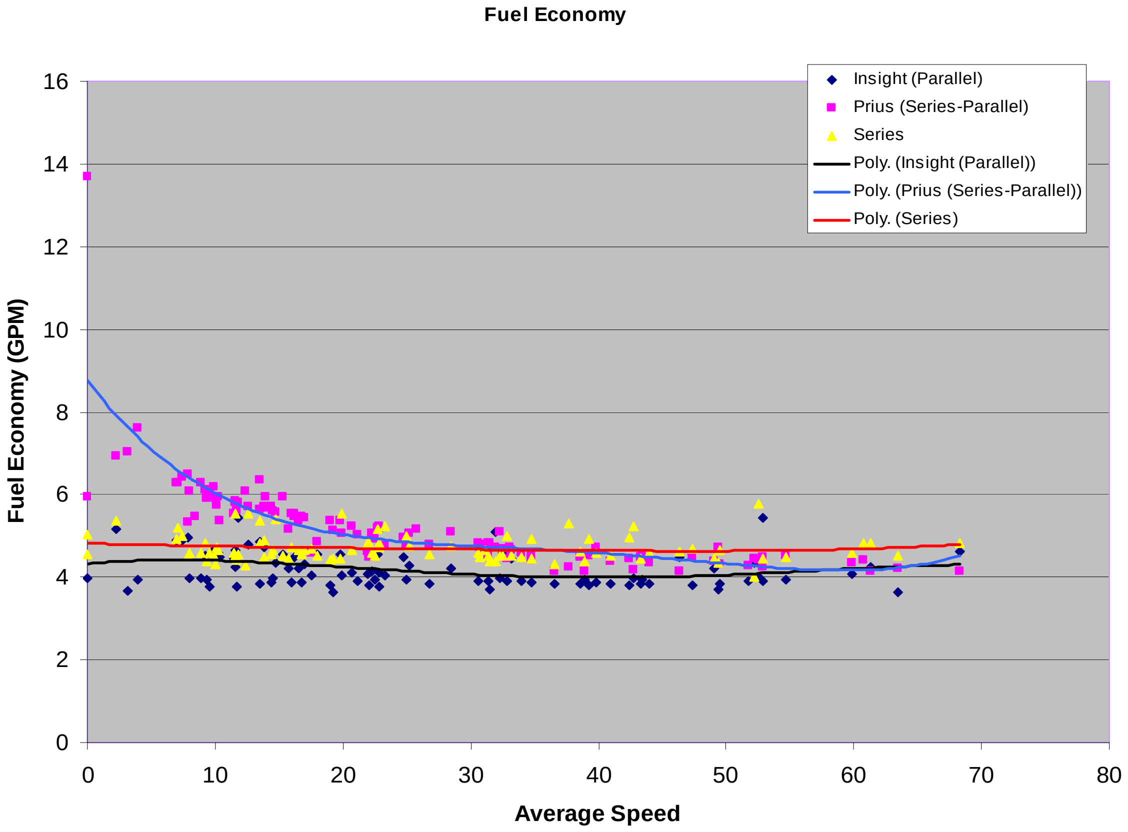


Figure 2.9. Speed-Energy curves of different hybrid vehicle designs

We have also compared these example HEV results to a typical light duty internal combustion vehicle, with the results shown in Figure 2.10. Again, the key result is that the differences are at the tails of the curve. At high speeds, the HEVs tend to be a bit more aerodynamic, and therefore don't have a sharp increase in fuel economy at the higher speeds. Even more pronounced is the tail at the low-end speeds, where the internal combustion engine vehicle operating in stop and go traffic has much higher grams-per-mile fuel consumption. This is because most of the HEVs take advantage of battery power at low speeds, and during idle, most engines shut off, whereas the typical ICE vehicle idles with the engine on.

We are continuing to look at other HEV models and other vehicle activity databases to build up the speed-emission curve database for mesoscale ITS modeling.

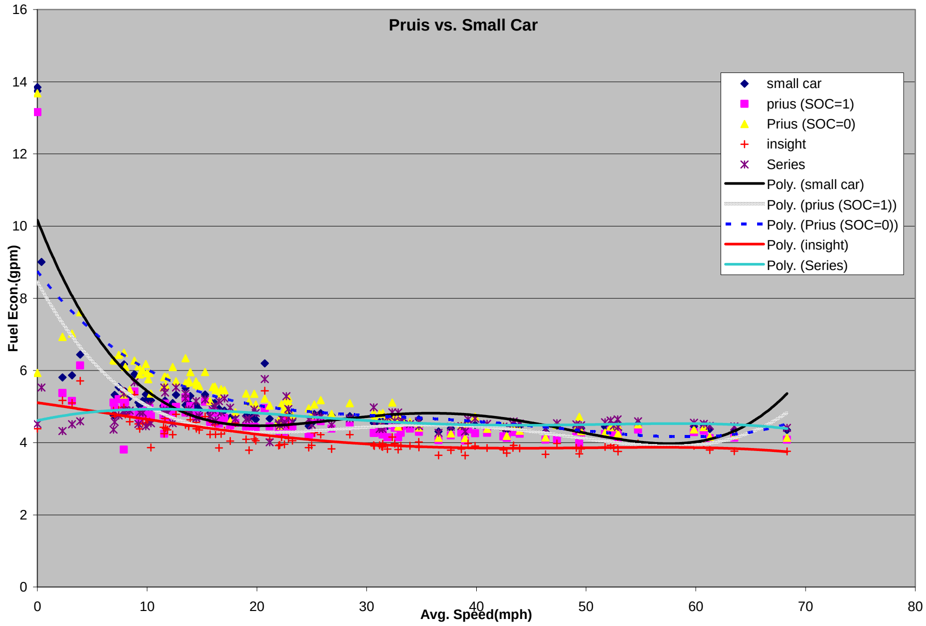


Figure 2.10. Speed-fuel consumption comparison between HEVs and typical internal combustion vehicles

3 Integrated Traffic Simulation and Environmental Modeling Tools and Analysis

There will be many cases when it is difficult or impossible to measure and collect vehicle activity data for a particular ITS scenario, in particular for a large scale projects that are targeted well into the future. In this situation, transportation engineers often utilize traffic simulation modeling tools that can produce evaluation results under numerous conditions. Transportation modeling tools typically have good measures of traffic performance, however many do not have sophisticated energy or emissions measures. As a result, there has been a good deal of activity over the last decade to tightly integrate transportation modeling tools with appropriate energy and emission models.

Similar to the methodology outlined in the previous section, vehicle activity information in the form of vehicle trajectories (location, velocity, acceleration) can be acquired from traffic simulation models by post-processing, and then applied to an energy/emissions model like CMEM or MOVES. However, to run many scenario evaluations, it is useful to embed the energy/emissions model directly into the traffic simulation model. UCR has done extensive work in the past on developing Application Programming Interfaces (APIs) for CMEM that work directly with the most popular traffic simulators such as CORSIM, PARAMICS [Barth et al., 2001b], VISSIM, and TransModeler. The general method for interfacing CMEM with transportation models is described in Section 3.1.

For the MOVES model, there has been recent activity on this transportation/emissions modeling interface, including a workshop at the Annual Meeting of the Transportation Research Board (TRB) in January 2011 entitled “Integrating the U.S. Environmental Protection Agency MOVES Model with Transportation Microsimulation Models”. A general description of interfacing MOVES with transportation models is described in Section 3.2.

As part of this AERIS project (and co-funding from other sources), we have used our integrated transportation/emissions modeling tools to examine specific infrastructure-to-vehicle (I2V) signal control strategies, i.e., using Signal Phase and Timing or SPaT. This work has been co-funded with funding from FHWA’s EAR project in Advanced Traffic Signalization [Skabardonis et al., 2011], and is described in two recent academic papers. This work is summarized in Section 3.3.

[Note: This research is described in detail in two academic paper: one that has been published and presented at the IEEE Forum for Integrated Sustainable Transportation Systems (FISTS-2011) in Vienna Austria in June 2011 [Barth et al., 2011]; and one that is published and presented at the IEEE Intelligent Transportation System Conference (ITSC-2011) in Washington D.C., in October 2011 {Xia et al., 2011}.]

Finally, we have explored the energy/emissions modeling interface with a relatively new microscale traffic simulation tool that was developed specifically for ITS applications that rely on wireless communications such as DSRC and cellular communications. This modeling tool is called SUMO, and is described further in Section 3.4.

3.1 CMEM’s Interface with Transportation Models

The transportation and emission modeling process involves the interfaces among travel demand model, traffic simulation model, and emissions model at different levels of details, as shown in Figure 3.1. At the macro/mesoscopic level, the regional travel demand model estimates number of zone-to-zone trips in the area based on land use and socioeconomic factors. After determining mode split, it assigns zonal vehicle trips onto the roadway network based on the minimization of trip travel time between pairs of zones. This loaded network is used to calculate traffic performance measures and relevant statistics on a link-by-link basis, which can then be applied to the corresponding emission factors from the mescoscopic CMEM to result in emission estimates for each roadway link. Finally, these link-level emissions can be aggregated up, resulting in total emission estimates for the area.

Alternatively, the loaded network in the travel demand model can be used to extract a sub-area network of interest and its vehicle origin-destination (OD) tables for conducting microscopic traffic simulation. In addition to the network and travel demand, the traffic simulation model also takes the inputs of vehicle fleet composition and model configuration parameters. After being properly calibrated for an existing condition, the model can be used to simulate other what-if scenarios. The simulated results include traffic performance measures and relevant statistics. The simulation model also produces an animation of vehicle movement in the network. In addition, the microscopic CMEM that interfaces with the traffic simulation model calculates emissions of each individual vehicle being simulated. The emissions results are then aggregated and reported.

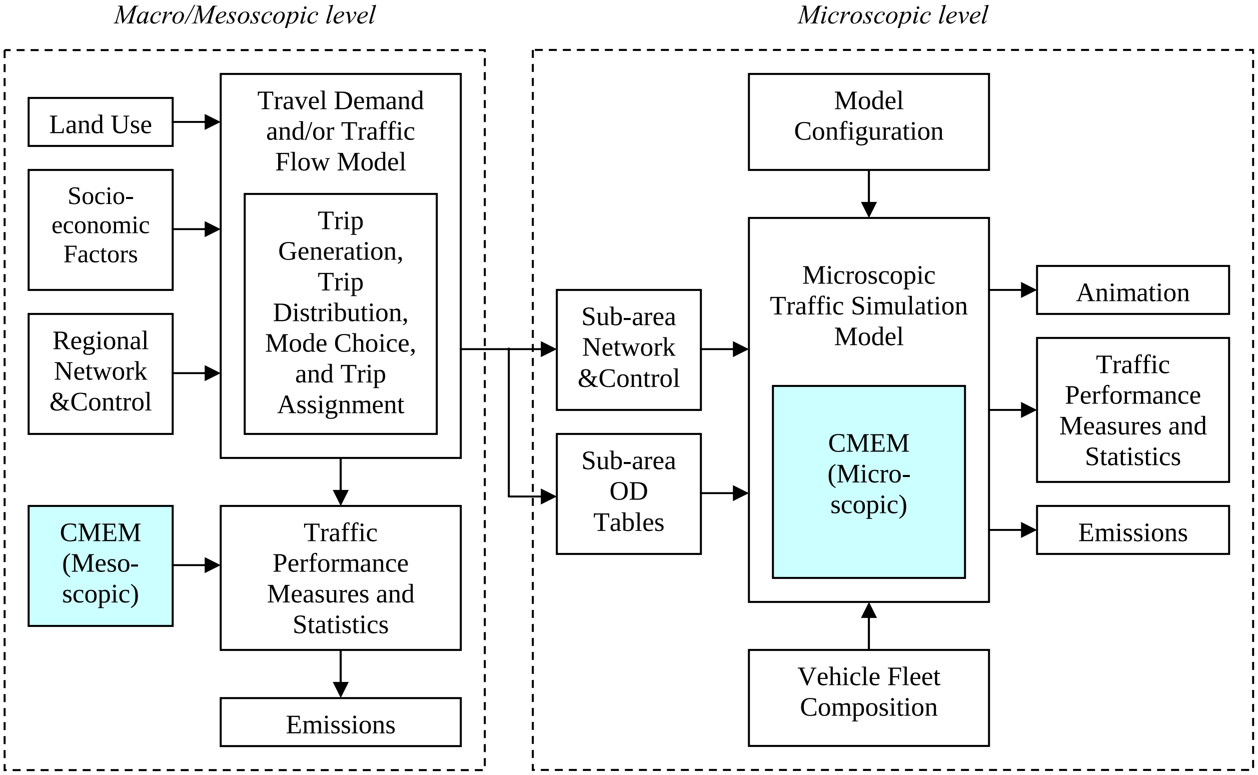


Figure 3.1. CMEM's interface with transportation models

It should be noted that CMEM was designed so that it can interface with a wide variety of transportation models and/or transportation data sets in order to perform detailed fuel consumption analyses and to produce a localized emissions inventory. CMEM has been developed primarily for microscopic traffic simulation models that typically produce second-by-second vehicle trajectories (location, speed, and acceleration). These vehicle trajectories can be applied directly to the model, resulting in both individual and aggregate energy/emissions estimates.

Over the past several years, CMEM has been integrated with various traffic simulation models (e.g., CORSIM, TRANSIMS, PARAMICS, etc.). At the latest, CMEM was integrated with PARAMICS, which has an opened architecture for integrating plug-in modules to perform specific simulation functions. Integrating CMEM within PARAMICS was accomplished by creating a plug-in through the use of PARAMICS *Programmer*, which allows the user to access and override many of PARAMICS' variables as well as add new features as the simulation takes place. The integrated PARAMICS/CMEM tool can be used to evaluate emissions benefits of project-level or corridor-specific transportation control measures (e.g. HOV lanes), ITS implementations (e.g. electronic toll collection), and traffic flow improvements (e.g. traffic signal coordination). Research efforts have been continued to expand the CMEM integration with other traffic simulation models such as VISSIM and TransModeler.

3.2 MOVES' Interface with Transportation Models

As mentioned earlier, there has been recent interest and activity on the interface between MOVES and transportation models, ranging from regional travel demand models to microscopic traffic simulation models. This topic was discussed in the workshop at the Annual Meeting of the Transportation Research Board (TRB) in January 2011 entitled "Integrating the U.S. Environmental Protection Agency MOVES Model with Transportation Microsimulation Models". The research efforts to date have been focused on the post processing of transportation model outputs to prepare necessary inputs for MOVES. In general, there are three approaches for linking transportation models with MOVES [Dresser, 2011; Claggett, 2011]:

1. *Through link average speeds*: In this approach, the transportation model will output the average speed for each roadway link in the network, which will be used as an input for MOVES (e.g., [Wang et al, 2011]). Then, MOVES will supply the emission factors corresponding to the default vehicle operating mode distribution that are based on typical driving cycles for that average speed. The default vehicle operating mode distributions are different for different roadway types in MOVES (see Figure 3.2 for examples); therefore, the emission factors for the same average speed but different roadway types are different.

2. *Through link driving cycles*: In this approach, transportation models—especially microscopic traffic simulation models—will output the driving cycles of vehicles on roadway links. These driving cycles can be entered into MOVES directly or can be aggregated into a set of representative driving cycles first before entering into MOVES (e.g., [Chamberlin et al., 2011]). Then, MOVES will calculate the vehicle operating mode distribution base on the supplied driving cycles and subsequently determine the corresponding emission factors.

3. *Through link-specific vehicle operating mode distribution*: In this approach, the vehicle operating mode distribution will first be created from the driving cycles of vehicles on roadway links before being used as an input for MOVES (e.g. [Lin et al., 2011]). Then, MOVES will supply the emission factors corresponding to the supplied vehicle operating mode distribution.

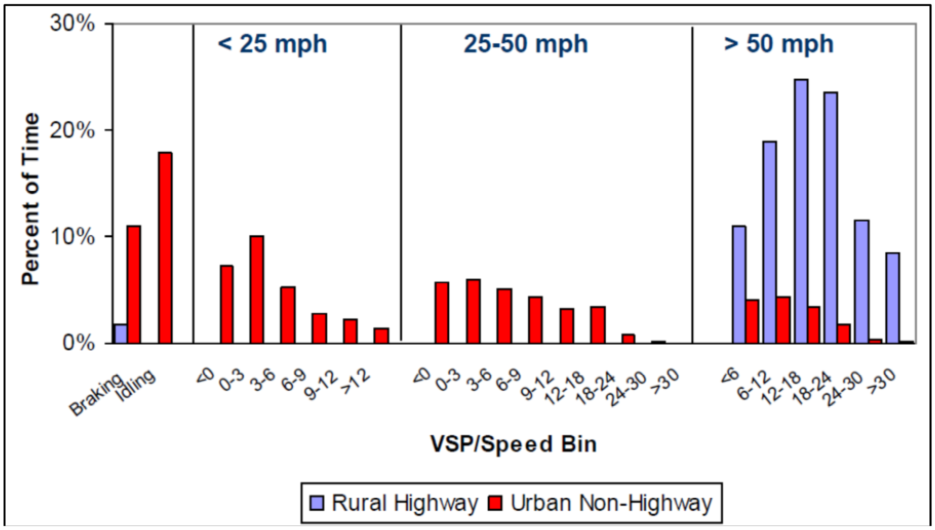


Figure 3.2. Examples of default vehicle operating mode distibution in MOVES

Out of the three approaches, the first approach is the most straightforward and is commonly applicable as link average speed is a standard output of transportation models at all scales from regional (macroscopic) travel demand models to microscopic traffic simulation models. However, it is not appropriate for the analysis where the vehicle operating mode distribution is expected to be different from the default one in MOVES such as when analyzing the impact of ITS technology implementations that minimize vehicle stops and idling (e.g., traffic signal coordination). The second and the third approaches have higher fidelity and are more appropriate for such project-level analysis. However, they are limited to be used with meso- and microscopic transportation models that can generate second-by-second vehicle speed profiles as an output.

3.3 Dynamic ECO-Driving on Signalized Corridors

For roadway segments that have traffic control infrastructure (e.g., traffic lights), traffic suffers from significant delays due to idling at the traffic signals on red and increased fuel consumption and emissions due to inherent accelerations/decelerations required at the signals. Many empirical studies have shown a positive relationship between vehicle emissions and fuel consumption with the delays at traffic signals [Pierre et al., 2008; Myhrberg, 2008; Li et al., 2009]. To minimize delays (and therefore lowering fuel consumption and emissions), most of the research has been focused on infrastructure control, such as developing better traffic signal control algorithms that are both dynamic and adaptive, using information such as vehicle queue lengths (see, e.g., [Stevanovic et al., 2009; Nishuichi and Yoshii, 2005; Li et al., 2004]).

However, with the recent advances in intelligent transportation system technology, it is now possible to put more of the control burden on the vehicles themselves with arterial eco-driving strategies. For example, a traffic controller's Signal Phase and Timing (SPaT) information can now be communicated directly to individual vehicles so that vehicles can adjust their speed as they travel through a signalized corridor, with the goal of minimizing idle time and acceleration events. Several researchers have developed and studied variable speed algorithms for arterial traffic (see, e.g., [Pierre et al., 2008; Myhrberg, 2008, Morsing et al., 2007; Jimenez et al., 2007; Spyropoulou and Karlaftis, 2008]). However, the majority are oriented towards providing optimal speed advice to the driver in order to improve *safety* by taking into consideration the current weather conditions, road grade, etc. Very few of these speed advice algorithms directly deal with minimizing emissions and fuel consumption while maintaining safety.

As part of our research, we have developed a dynamic eco-driving system for signalized corridors that consists of an arterial velocity planning algorithm that attempts to minimize vehicle fuel consumption and emissions. As previously mentioned, the full details of this research is provided in [Barth et al., 2011; [Xia et al., 2011]. In this section, we briefly provide a summary of the arterial velocity planning algorithm, along with some initial results.

3.3.1 Vehicle Trajectory Planning

It is important to first consider the scenario of a single traffic light and its corresponding time-distance diagram as shown in Figure 3.3. In this figure, the traffic light is at a fixed location and changes its phase with time, as shown with the green, yellow, and red lines. Also shown in this figure are several vehicle velocity trajectories that all have the initial velocity of $v_i(t)$ at point $d(t)$. At time t, signal phase and time information is received by the vehicle. We then consider the following cases:

Case 1: in this case, the vehicle increases its speed and manages to make it through the green light with no slowing or idling;

Case 2: in this case, the vehicle continues to drive at speed $v_i(t)$, and when the traffic light turn yellow then red, the vehicle slows down quickly and stops rather suddenly;

Case 3: in this case, the driver of the vehicle takes their foot off of the gas pedal and coasts to a stop at the intersection;

Case 4: in this case, the vehicle actively slows down (i.e., braking) and then travels at a lower speed until the traffic light turns green, after which the vehicle increases its speed, all without stopping.

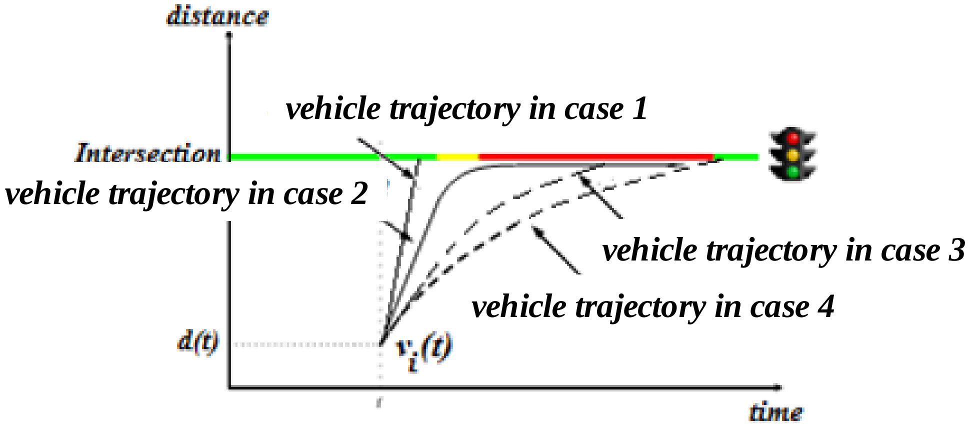


Figure 3.3. Time-space diagram representing different vehicle trajectories approaching an intersection

For these different trajectory cases, fuel consumption and emissions vary greatly. For case 1, even though the vehicle did not have to idle at the red light, the fuel consumption and emissions are high since the vehicle had to accelerate to make the green light. For case 2, fuel/emissions are also high due the fact that the vehicle had to hold the original velocity for a certain amount of time, and then had a long idle period. For case 3, the fuel/emissions are less, since very low fuel is being consumed as the vehicle coasts up to the intersection (case 2 and case 3 have been extensively compared in [Li et al., 2009] with differences around 15%). Finally, case 4 has the lowest fuel consumption and emissions, due to the fact that its acceleration from the red light isn't from a dead stop, but rather from a moving velocity, therefore the energy required to accelerate back up to speed is significantly less.

Therefore, as a vehicle travels down a signalized corridor, it is best to travel at a mid-range speed when possible. As it approaches a signal, it is possible to dynamically adjust its velocity to minimize fuel consumption and emissions. The overall functional requirements of the vehicle are to: 1) try and maintain a steady state speed around the speed limit; 2) maintain safe headway distance to vehicles in front; 2) never cross the intersection on red; 3) minimize the idling time at the traffic signals; and 4) avoid sharp accelerations. An overall vehicle planning algorithm that takes all of these into account is described in the next section.

3.3.2 Velocity Planning Algorithm

The overall block diagram of the arterial velocity planning algorithm is shown in Figure 3.4. The control logic for the velocity planner requires several input parameters:

v_h	the target maximum speed on the roadway link that is dictated by the link speed limit and/or the car following logic, which typically has other input parameters such as headway distance (d_s), headway time (t_h), and current vehicle velocity (v_c);
d_{int}	the distance from the vehicle to the intersection;

v_c the current vehicle velocity;

t_r, t_g the signal phase and timing information from the signal, where t_r is the time until the light changes to red, and t_g is the time until the light changes to green.

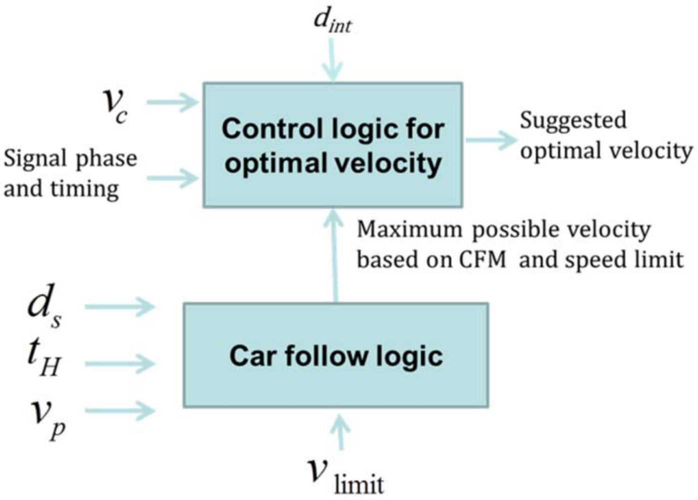


Figure 3.4. Block Diagram of the Arterial Velocity Planning Algorithm

The control logic for the optimal velocity tries to minimize the 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}. In order 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:

$$t \in \begin{cases} [0,t_r) \cup [t_g,t_{r1}) & if\ s = G \\ [t_g,t_r) & if\ s = R \end{cases}$$

Therefore, given the distance to the intersection d_{int}, the possible velocities of the vehicle fall into a range given by $v_{lo} = d_{int} / t_h$ and $v_{ho} = d_{int} / t_l$, where t_l and t_h are the low and high values respectively from the equation above. Figure 3.5 then represents the overall velocity selection algorithm. The acceleration and deceleration trajectory planning are described below.

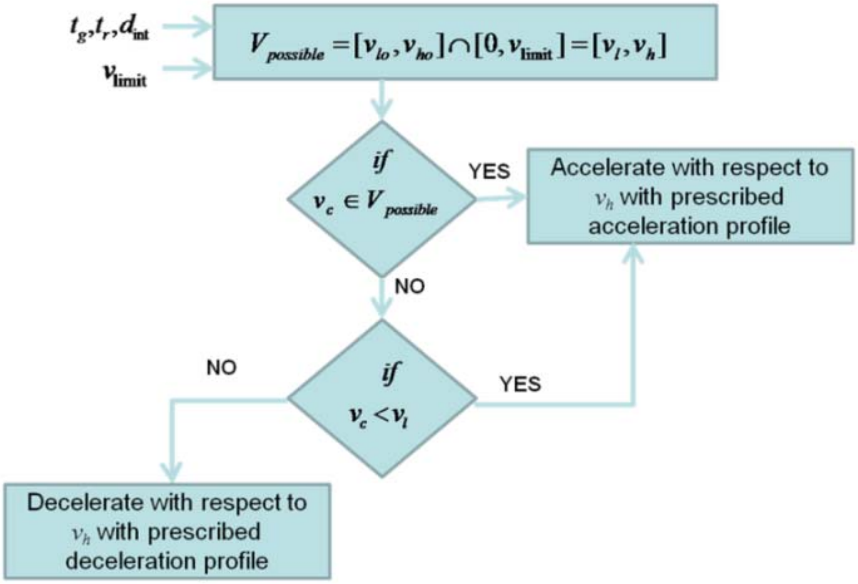


Figure 3.5. Block Diagram of the Arterial Velocity Planning Algorithm

Acceleration Profile Design

In order 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 will need the ability to accelerate at specific times, as indicated in Figure 3.5. There are an infinite number of ways to accelerate from one speed to another speed; several trajectory planning algorithms have been suggested in the literature including constant acceleration, linear-acceleration, and constant-throttle acceleration. However, we want to choose an acceleration profile that minimizes fuel consumption/emissions and is still comfortable to the passengers (i.e., low jerk). As shown in Figure 3.6, we consider an acceleration from current vehicle velocity (v_c) to a velocity that will ensure that we are able to reach a point at a specific time. All possible trajectories need to reach a point (e.g., the intersection), therefore the area of region A must be equal to the area of regions B_1 and B_2 as shown in Figure 3.6.

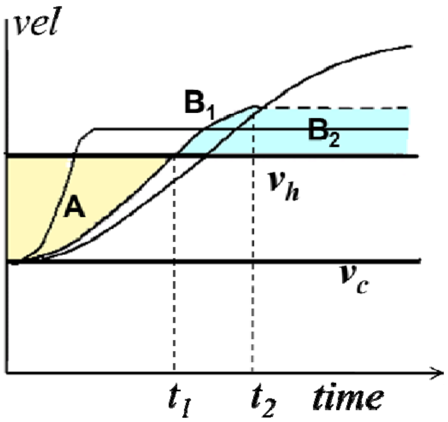


Figure 3.6. Different acceleration profiles for reaching a specific location at a specific time

In order to ensure a smooth trajectory, we have chosen a family of velocity profiles with a trigonometric increase in velocity given by:

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

where d is the target distance, v_h is the higher limit of the velocity range, and v_d is the difference between the current velocity of the vehicle and the higher limit of the velocity range (i.e., $v_d = v_h - v_c$). The parameters s and a define the family of velocity profiles. Different values of (s,a) correspond to different acceleration and jerk profiles. Parameter s controls the rate of change of acceleration in region A and parameter a controls the rate of change of acceleration in region B of Figure 5. Given a value of s, the choice of a will depend on the requirement that the vehicle has to reach the target point at a specific time. Among the family of velocity profiles for different values of (s,a), we choose the velocity profile that has minimum tractive power requirements, in order to minimize fuel consumption, as described in [Barth et al., 2011].

Deceleration Profile Design

The approach to designing a fuel efficient deceleration profile is carried out in a very similar fashion to the acceleration profile design. When a vehicle has to decelerate to a known speed at a known point (e.g., stopping at an intersection), there are an infinite number of ways of performing this deceleration as shown in Figure 3.7.

We again choose a trigonometric family of curves given by:

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

where d is the distance to a specific location such as the traffic intersection. v_h is the upper limit of the possible uniform velocity range required to reach the target location at a specific time. v_d is the difference between the current velocity of the vehicle and the upper limit of the possible velocity range ($v_d = v_c - v_h$).

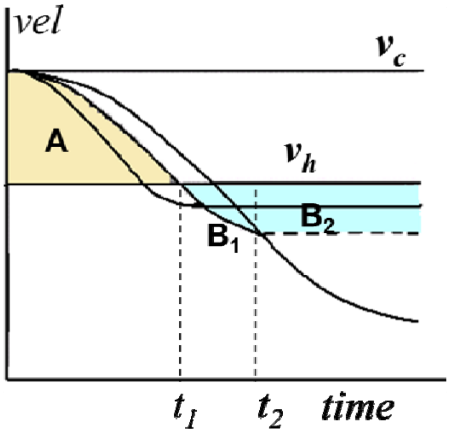


Figure 3.7. Different deceleration profiles for reaching a specific location at a specific time

As before, the parameters *s* and *a* define the family of deceleration profiles. Different values of *(s,a)* correspond to different deceleration and jerk profiles. Parameter *s* controls the rate of change of deceleration in region A and parameter *a* controls the rate of change of deceleration in region B in Figure 3.7. Given a value of *s*, the choice of *a* will depend on the requirement that the vehicle has to reach the target point at a specific time. For the case of deceleration where a vehicle needs to slow down in order to reach a signalized intersection, then speed up when the signal is green, we can see that the choice of *(s,a)* play an important role. A profile with an initial sharper deceleration will have a greater final velocity when it reaches the intersection. This is important, since the energy requirement for the vehicle to accelerate back to the link speed/free flow speed after clearing the intersection will be less than for other profiles. Therefore, the cumulative fuel consumption to decelerate until the intersection and then accelerate back to link speed/free flow speed after clearing the intersection will occur with the largest value of *s*. Similar to the derivations for the acceleration profile, *a* can be determined to minimize cumulative tractive power once *s* has been chosen.

3.3.3 Simulation

Using the dynamic eco-driving velocity planning algorithm for arterial roadways described above, we have applied this to a hypothetical 10-signalized intersection corridor. We did this in a stochastic fashion in order to capture the variability of infrastructure-related parameters and the randomness of traffic-related parameters. For the corridor, the link lengths between intersections ranged between 500m and 600m (selected from a uniform distribution), the speed limit was set to 70 kph, and advanced information on signal phase and timing was set randomly between 200m and 300m prior to the intersection. For the signal timing, we simply used a two-phase signal at all intersections. We chose an actuated signal strategy with the total green period (i.e., minimum green time + extension green time) to be modeled as a uniform distribution, $t_g \sim U(\alpha, \beta)$, where α is 40 s and β is 50 s. Similarly, we assume the same distribution of the total green time for the cross street traffic. Thus, the total red time on the main arterial corridor is also modeled as $t_r \sim U(\alpha, \beta)$.

The simulation was performed for a typical mid-sized sedan car. As described earlier, the engine power of the vehicle is used to determine the maximum acceleration at different speeds, given that road grade of all the links in the simulated corridor is assumed to be zero. The fuel consumption and emissions were determined for this single vehicle type using CMEM.

The velocity planning algorithm was run over 30 times for a vehicle traversing the corridor with various link lengths and random signal phase and timing as dictated by the actuated signal control. For each run, the vehicle velocity profile was extracted across the entire corridor. An example of the velocity profile is shown in Figure 3.8. Also shown in Figure 3.8 is the distance-time diagram of the vehicle as well as the signal phase and timing at each intersection for that simulation run.

For each simulation run, we also created the vehicle velocity profile for a baseline case (i.e. for vehicles that do not have the eco-driving velocity planning algorithm) for comparison purposes. For this baseline comparison, we assumed that the typical driving behavior along a signalized corridor is where the drivers attempts to cruise at or around the speed limit until they are visually aware of the traffic signal ahead (assumed to be at 75 m before the intersection). If the signal is green, the driver simply maintains the cruise speed while crossing the intersection. If the signal is red, the driver slows down, stops, and then waits until the light turns green. Once the signal turns green, the driver accelerates 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-driving speed planning algorithm) are also calculated for the same vehicle type. Table 3.1 shows the energy and emissions comparison results between the vehicles without and with velocity planning for the vehicles. The results for both cases are given in terms of the average value and the standard deviation of the sample set of 30 velocity profiles. According to Table 3.1, the vehicles with velocity planning consume about 12% less fuel and CO_2 emission. Further, the travel time (TT) on an average is approximately 2% shorter for the vehicles with velocity planning as compared to the vehicles without velocity planning.

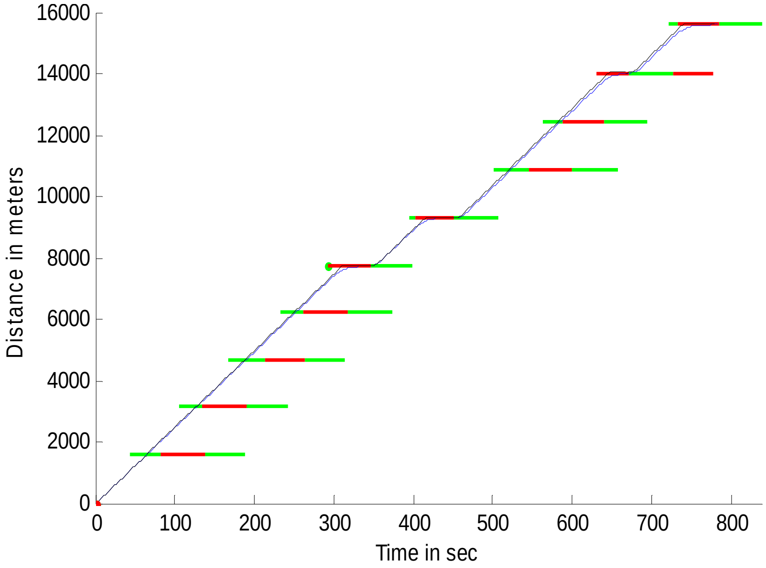


Figure 3.8. Example velocity profile using the dynamic eco-driving velocity planning algorithm

Table 3.1. Energy and Emissions Comparison

passenger car	**Without**		**With**		**% Diff. in Avg.**	***p*-value of *t*-test**
	Avg.	*S.D.*	*Avg.*	*S.D.*		
Fuel (g/mi)	118.3	13.2	103.8	9.3	-12.3	8.7E-06
CO_2 (g/mi)	371.0	41.2	318.8	25.3	-14.1	3.2E-07
TT (sec)	456.7	60.7	451.9	56.9	-1.06	0.635

3.3.4 Conclusions

Fuel consumption and emissions are directly related to the acceleration/deceleration patterns of the vehicles traveling on the arterial and the idling at traffic signals. Unlike freeways, traffic on the signalized corridors suffers from inherent acceleration/ deceleration maneuvers at the traffic signals and idling when they are waiting for the lights to change. By taking advantage of the recent developments in communication between vehicles and road infrastructure, it should be possible to obtain the signal phase and timing information. Using this real-time signal information, we have developed a dynamic eco-driving velocity planning algorithm that attempts to get through an arterial corridor using a minimum amount of fuel.

Based on this research, there are several key findings that are counter-intuitive when compared to typical eco-driving advice. When traveling on a roadway where there are specific points where traffic is controlled (traffic lights), specific constraints emerge in time and space; as a result, it has been found that hard accelerations that quickly get a vehicle up to a target speed and then have a steady cruise to reach a specific location at a specific time are less fuel consuming compared to a velocity profile that takes a longer period of time of acceleration to reach the same point and time. Similarly, it is beneficial to decelerate quickly, and then hold a steady state cruise speed when reaching a traffic signal just as it is turning green. At that point, it takes less energy to accelerate back up to typical speed traversing the corridor, compared to starting from a stop.

Preliminary results of our velocity planning algorithms show approximately a 10% to15% fuel economy improvement over a standard baseline case without the velocity planning. Thus far this has been evaluated under low density traffic conditions. In subsequent work, it is planned to expand this research by evaluating under heavier traffic conditions and also incorporating additional information along the corridor (e.g., traffic speed, density, and flow, as well as other vehicle travel parameters).

3.4 Transportation/Emissions Modeling Interface with the SUMO Model

As previously described, we have worked with both CMEM and MOVES integrated with a variety of traffic simulation modeling tools to determine environmental impacts of ITS applications. For example, the dynamic eco-driving strategy for arterial roadways described in the previous section was evaluated using a combination of CMEM and the PARAMICS traffic simulator [Quadstone, 2011].

Unfortunately, many of these traffic simulation models do not necessarily have all the critical components required for simulating advanced ITS applications. Therefore, often is the case where the user has to develop specific functionalities using “Application Program Interfaces” within the models themselves. This can become quite complicated as the sophistication of the application increases. As part of our research, we have recently started using a new set of open source models developed in Europe that have better ITS capabilities. Specifically, these models lend themselves well to overlaying wireless communications (e.g., DSRC and cellular communications) on top of the traffic simulations. These models are described briefly below.

3.4.1 Simulation of Urban Mobility (SUMO)

The Simulation of Urban Mobility (SUMO) is an open source highly portable road traffic simulation package that supports handling large road networks (see [SUMO, 2012]). It is developed at the Institute of Transportation Systems at the German Aerospace Center (DLR). Being open source, it is GPL licensed. SUMO is supported in Windows, Linux, and MAC.

SUMO provides several methods of constructing road networks. They can be defined using an XML structure, or converting from any number of existing network tools including VISUM, Vissim, ArcView, TIGER, and OpenStreetMap. SUMO also provides creating network patterns, or random networks for simple validation purposes. Modeling is implemented using O/D Matrices, random routes, and most importantly for ITS applications, dynamic updating online interaction. SUMO allows a user to connect to it to redirect vehicles to take specific routes using the Traffic Control Interface (TraCI).

[Note: Much of this material was summarized from http://sumo.sourceforge.net/.]

3.4.2 Traffic Control Interface (TraCI)

TraCI is an open source protocol to provide access to running a road traffic simulation and uses a TCP based client server architecture to provide access to SUMO. TraCI supports many API for control of SUMO including mobility related commands, subscription-related commands, environment-related commands, and also traffic light commands. The mobility related commands include:

- Setting Max vehicle Speed
- Stopping a Vehicle
- Slowing down a Vehicle
- Forcing a lane change
- Setting new routes
- Setting new destination edge

Subscription commands provide retrieval of an object's value, such as:

- Induction Loop Value Retrieval retrieve information about induction loops
- Multi-Entry/Multi-Exit Detectors Value Retrieval retrieve information about multi-entry/multi-exit detectors
- Traffic Lights Value Retrieval retrieve information about traffic lights
- Lane Value Retrieval retrieve information about lanes
- Vehicle Value Retrieval retrieve information about vehicles
- Vehicle Type Value Retrieval retrieve information about vehicle types
- Route Value Retrieval retrieve information about routes
- PoI Value Retrieval retrieve information about points-of-interest
- Polygon Value Retrieval retrieve information about polygons
- Junction Value Retrieval retrieve information about junctions
- Edge Value Retrieval retrieve information about edges
- Simulation Value Retrieval retrieve information about the simulation

Additionally – State information about the vehicle is also able to be manipulated such as:

- Change Lane State change a lane's state
- Change Traffic Lights State change a traffic lights' state
- Change Vehicle State change a vehicle's state
- Change PoI State change a point-of-interest's state (or add/remove one)
- Change Polygon State change a polygon's state (or add/remove one)
- Change Edge State change an edge's state

Finally using TraCI, vehicles can be added and removed dynamically from the simulation. Furthermore, not only is the SUMO interaction of the vehicles able to be manipulated, the *network communication* between the vehicles is able to be modeled using OMNET++, NS2, Shawn, or JiST. We are currently investigating OMNET++ for network communications. As an example, the Veins project (http://veins.car2x.org/) provides an implementation of SUMO coupled with OMNeT++.

3.4.3 OMNeT++

OMNeT++ is a discrete event simulation environment supported in Windows, Linux, and MAC. Its primary application area is the simulation of communication networks, but because of its generic and flexible architecture, is successfully used in other areas like the simulation of complex IT systems, queuing networks or hardware architectures as well. It provides component architecture for models. Components *(modules)* are programmed in C++, and then assembled into larger components and models using a high-level language *(NED)*. Reusability of models comes for free. OMNeT++ has extensive GUI support, and due to its modular architecture, the simulation kernel (and models) can be embedded easily into your applications. The components of OMNET++ include:

- simulation kernel library
- compiler for the NED topology description language
- OMNeT++ IDE based on the Eclipse platform
- GUI for simulation execution, links into simulation executable (Tkenv)
- command-line user interface for simulation execution (Cmdenv)
- utilities (makefile creation tool, etc.)
- documentation, sample simulations, etc.

Using SUMO, TraCI, and OMNET++ provides an established framework to develop the behaviors for each vehicle. Using this platform, we are now exploring new energy/emissions reducing strategies at signalized intersections using not just I2V communications, but also V2I and V2V.

4 Real-Time Vehicle Environmental Information Research

One prominent objective within the AERIS program is the capturing of real-time environmental data from vehicles and using the data as feedback to different ITS applications. As a new innovative approach, it is possible to embed energy/emission models directly on-board a vehicle and transmit these fuel consumption and emission values to the transportation infrastructure. Several ITS applications can take advantage of this real-time broadcast of fuel consumption/emissions by utilizing system operation optimization such as ramp metering, traffic signal phase and timing control, and variable speed limits.

As part of this AERIS research project, we investigated the interface between a vehicle's on-board diagnostic bus (OBD-II for light-duty vehicles) data stream and an on-board energy/emissions model in order to estimate fuel consumption and emissions in real-time. Based on the original CMEM model, we have developed an application on several platforms such as an iPhone smartphone, and iPad, and an android smartphone. The goal of the research is to compute energy and emissions on a second-by-second basis for any type of vehicle, following a straightforward calibration process. This concept is called Mobile Energy/Emissions Telematic System (MEETS), and illustrated in Figure 4.1.

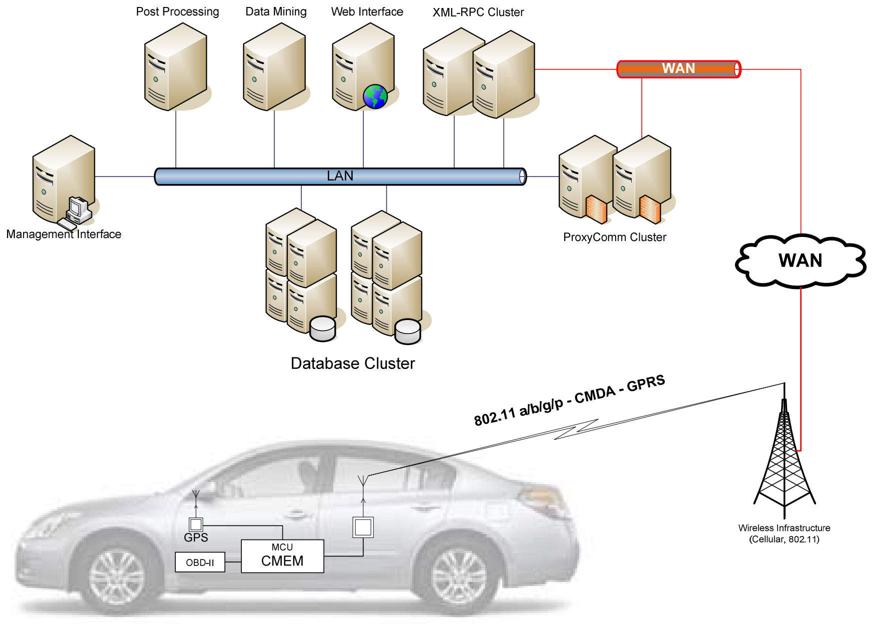


Figure 4.1. Concept of Mobile Energy/Emissions Telematic System (MEETS)

In this concept, the on-board hardware (i.e., smartphone) is connected to the vehicle's on-board data bus and collects pertinent information on the engine and vehicle performance (e.g., speed, RPM, fuel pulse width, etc.); a modified CMEM model is then used to estimate real-time energy consumption and emissions. This model requires calibration, where the calibration parameters can be acquired through an external vehicle database accessed telematically. Once calibrated, the vehicle can send in environmental performance data (instantaneous and/or averaged fuel economy, pollutant emissions, and greenhouse gas emissions) in any form. It is important to note that the established wireless infrastructure is used to both calibrate and to receive data, and can be cellular-based, DSRC, or any other method.

To date, we have developed MEETS on an on-board computer of UCR's ECO-ITS testbed vehicle (see Figure 4.2). Example screenshots of MEETS on the testbed vehicle are shown in Figure 4.3.

On-board computer interfaces with the vehicle CAN bus, navigation system, and wireless communications system

GPS-based location system and wireless communication capability

Programmable navigation system with touch-screen capability available to driver and passengers

Figure 4.2. UC Riverside ECO-Friendly Intelligent Transportation System (ECO-ITS) Testbed Vehicle

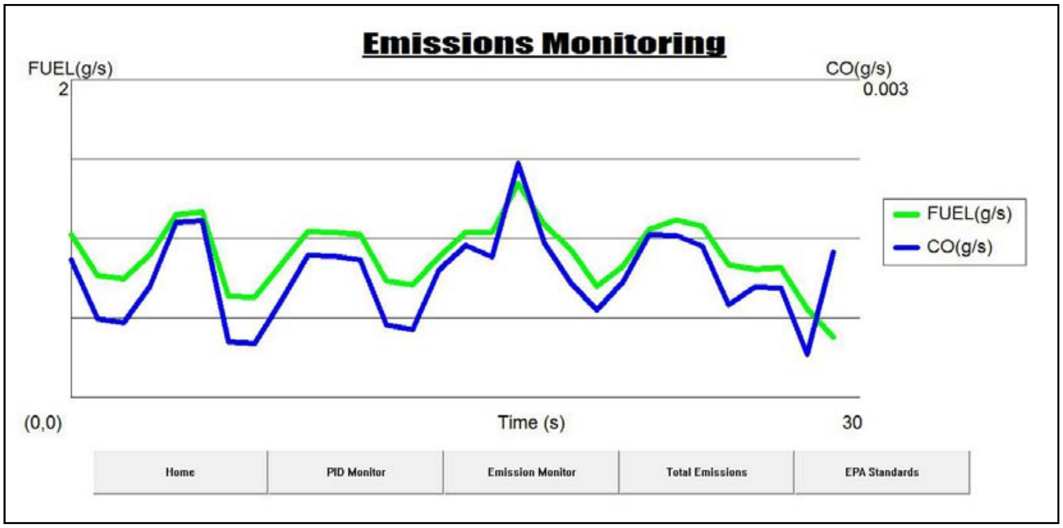
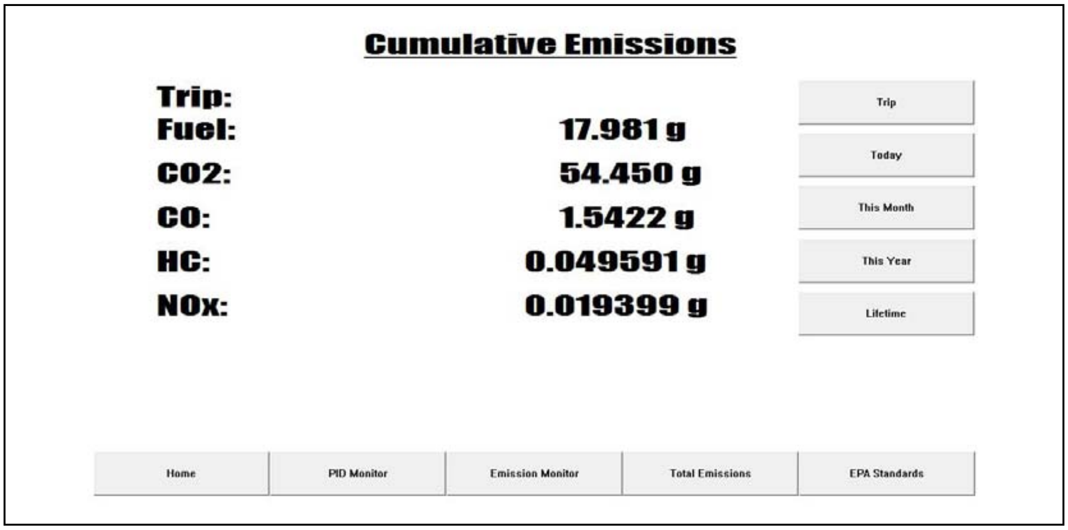


Figure 4.3a. Example screenshot of MEETS application, illustrating real-time second-by-second prediction of fuel and CO while driving



Cumulative Emissions

Trip:
Fuel: 17.981 g
CO2: 54.450 g
CO: 1.5422 g
HC: 0.049591 g
NOx: 0.019399 g

Figure 4.3b. Example screenshot of MEETS application, illustrating cumulative estimation of fuel and pollutants at the end of a trip

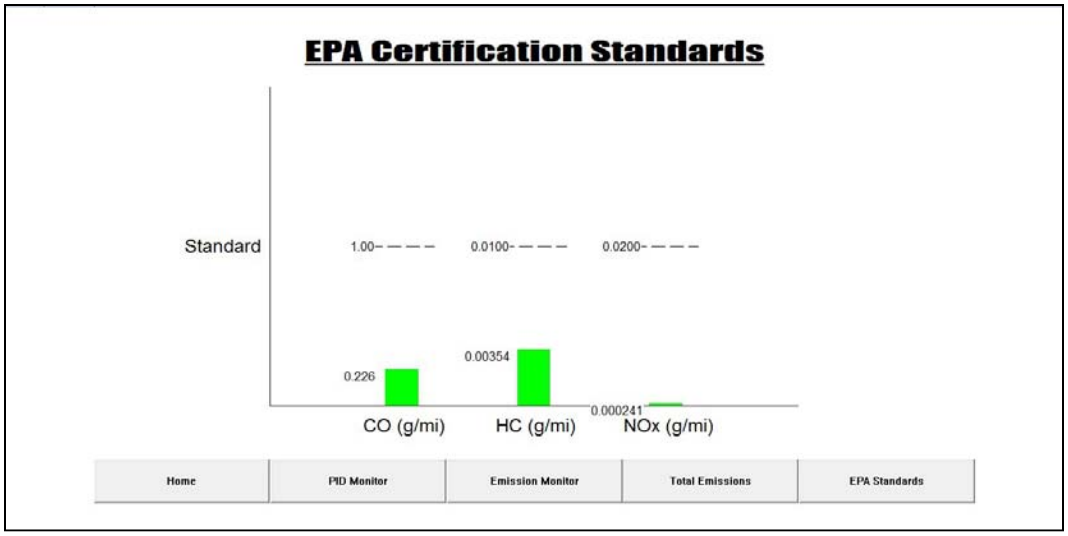


Figure 4.3c. Example screenshot of MEETS application, illustrating estimation pollutants with respect to the EPA certification standards for the vehicle

In order to validate MEETS, vehicle emissions from the testbed vehicle were carefully measured for a wide range of driving conditions on a certified laboratory dynamometer, while simultaneously running the on-board MEETS application. This type of validation is critical for any type of fuel and emissions model prediction. Figure 4.4 shows a regression comparison between the estimated emissions from MEETS versus measured emissions (from dynamometer testing) for the 2007 Nissan Altima testbed for CO_2, CO, HC, and NOx. It is observed that the CO_2 emission estimates are very accurate, having a high correlation value with the measured values. For other pollutants, the correlation values are lower but still reasonably high. Table D summarizes the total estimated and measured emissions. The comparison results for CO_2, CO, and HC are very satisfactory, having the differences of 1.5%, 2.8%, and -5.9%, respectively. For NOx, the difference is 14.6%.

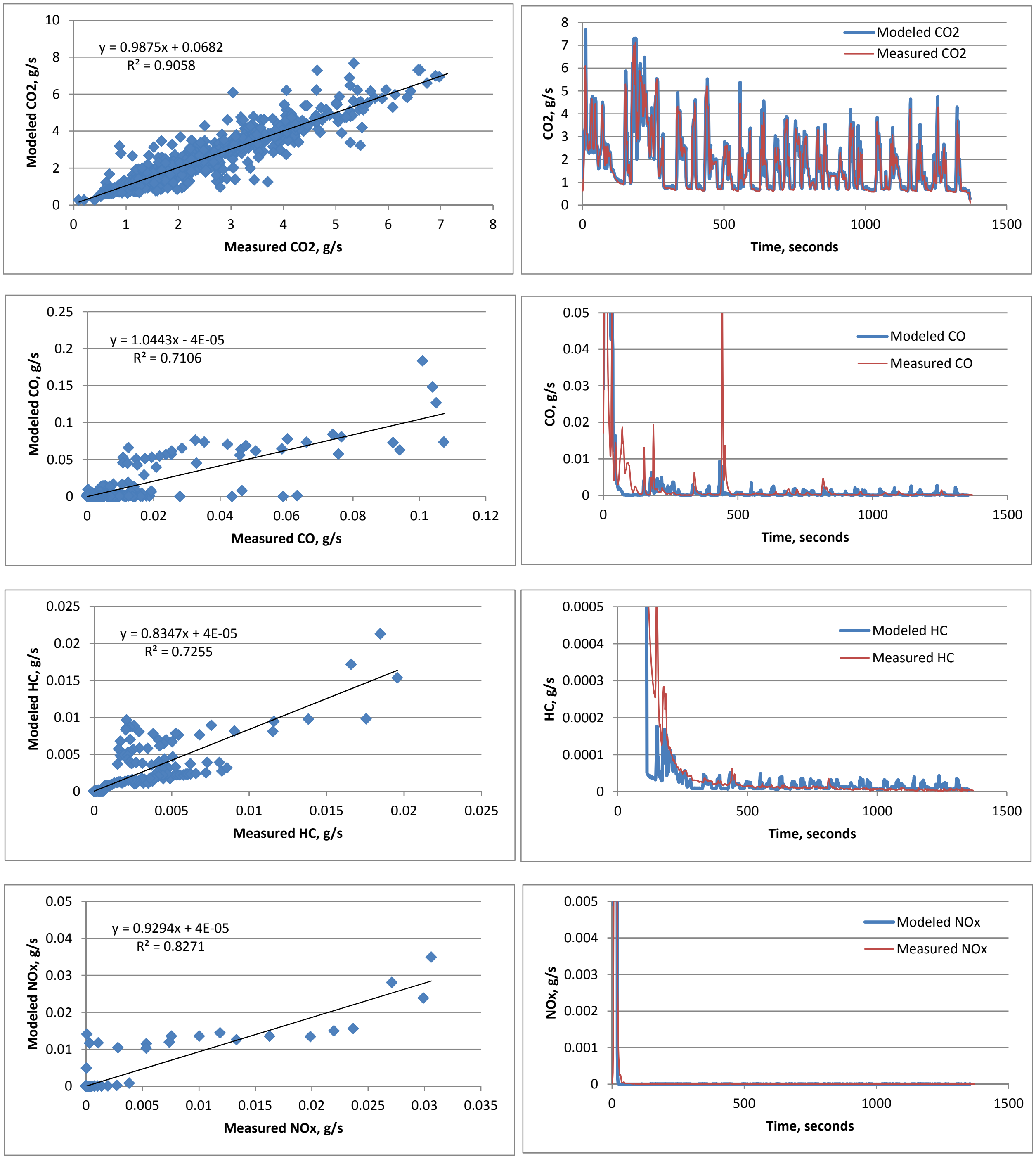


Figure 4.4. Comparison between second-by-second modeled (by MEETS) and measured emissions

Table 4.1. Comparison between total modeled (by MEETS) and measured emissions

	CO2 (g/s)	CO (g/s)	HC (g/s)	NOx (g/s)
Measured	2398.656	3.295	0.514	0.250
Modeled	2434.401	3.388	0.483	0.287
% Difference	1.5	2.8	-5.9	14.6

Not only is this concept valuable for examining the overall performance of different vehicles in traffic, in terms of quantification, but it is also useful if the infrastructure could change its operations based on real-time feedback. For example, traffic signal controllers could use the information to change signal phase and timing, ramp meters for freeway metering, changeable message signs for re-routing, and variable speed limit systems for energy/emissions minimization.

5 Environmentally-Beneficial ITS Application Identification

As previously described, the primary goals of intelligent transportation system applications have generally been focused on improving safety, relieving congestion (i.e., increasing traffic efficiency), while increasing driving comfort and convenience. Only recently has there been a growing emphasis internationally in serving the goal of increased energy efficiency and reducing vehicle emissions (both greenhouse gases and pollutants).

In general, it is difficult to quantify the environmental and energy benefits of different ITS applications. By nature, when improving overall traffic efficiency, you are usually reducing the impacts on the environment. However, it is possible to specifically design ITS applications that have an intended environmental benefit. This is already being seen in Japan with their Energy ITS program (see, e.g., [NEDO, 2011]) and in Europe with their ECOMOVE program (see, e.g., [Vreeswijk et al., 2010]).

In general, it is possible to categorize environmentally-beneficial ITS applications into three broad categories: 1) improvements at the *vehicle* level (i.e., Advanced Vehicle Control and Safety Systems); 2) improvements at the *system* level (i.e., Advanced Traffic Management Systems); and 3) improvements at the *behavioral* level (i.e., Advanced Traveler Information Systems).

Advanced Vehicle Control and Safety Systems (AVCSS)

Examples of AVCSS include anything that smoothes how a vehicle is driven, reducing the number of accelerations and decelerations, as well as minimizing stops. The primary focus application areas here are all the different flavors of automated cruise control (ACC) and cooperative automated cruise control (CACC). Other similar applications include Intelligent Speed Adaptation (ISA) and their variants that go by other terminology: dynamic eco-driving, speed harmonization, and dynamic speed management. These systems can be applied both from non-interrupted flow segments on the road (i.e., freeways) as well as interrupted flow segments (i.e., arterials), which are typically handled very differently. In addition, another key improvement that can be made in this area of AVCSS is the concept of vehicle platooning, where aerodynamic drag reductions are achieved, thereby lowering energy costs and emissions.

Advanced Traffic Management Systems (AVMS)

Examples of ATMS include any strategies that prevent the traffic density on our roadways from becoming so high that traffic flow breaks down, leading to stop-and-go inefficiencies and excess idling of stopped vehicles. Much of this is addressed in [Barth and Boriboonsomsin, 2008]. The tools that ATMS engineers have for freeways include ramp metering and variable speed limits. For arterial roadways, there is much more focus on advanced signalization where signal timing is focused on reducing energy costs and emissions. Another key ATMS component is incident management, which aims to reduce and clear incidents along the roadways that impede traffic flow.

Advanced Traveler Information Systems (ATIS)

ATIS strategies seem to get the least amount of attention; however, they can have a large impact on reducing energy and emissions. These strategies are primarily focused on changing traveler behavior. One of the primary ways of achieving this is to reduce the total number of trips (i.e., VMT reduction) as well as shifting modes of travel. For example, any application that provides better information to travelers, coordinating connections, increasing transit service speed and reliability, reducing delays experienced by transit riders and making the transit ride smoother and more pleasant can encourage more travelers to change modes from the personal automobile to a transit mode.

Another key topic that falls within ATIS is eco-driving, where driver behavior is modified, resulting is smoother vehicle trajectories, thereby improving fuel efficiency. There is now significant interest in eco-driving techniques worldwide. Roadway pricing is another ITS strategy that can influence whether travelers make a trip and how they make trips. There is a large body of literature on this.

Many of these techniques have also been summarized in the foundational report for AERIS, see [Miller et al., 2011]. The overall strategies and applications are summarized in Table 5.1.

Table 5.1. Environmentally-Beneficial ITS strategies and applications reviewed by Miller et al., (2011)

Strategies	**Applications**
Demand and Access Management	• Electronic Toll Collection • Congestion Pricing • Mileage Based Fees
Eco-Driving	• Eco-Driving Information and Eco-Driving Assistance • Adaptive Cruise Control • Eco-Driving Navigation Systems
Logistics and Fleet Management	• Automated Vehicle Location Systems • Commercial Fleet Management Services
Traffic Management and Control	• Incident Management • Integrated Corridor Management • Ramp Metering • Speed Management • Traffic Signal Control, Coordination, and Optimization
Freight Applications	• Wireless Inspections • Parking, Loading, and Delivery Management • Platooning • Eco-Driving for Freight
Transit Applications	• Automated Vehicle Locator and Computer-Aided Dispatch • Automated Demand Responsive Dispatching and Scheduling Systems • Traveler Information Systems • Transit Signal Priority • Operations Management
Others	• Parking Applications

6 Conclusions

UC Riverside's ECO-ITS technology research program continues to be enhanced with funding from a variety of sources, including this initial AERIS project. This summary report highlights many of the current activities that are part of this research program.

Section 2 of this report addressed the challenges to properly quantify their potential environmental and energy impacts of ITS applications, highlighting the lack of pertinent data and suggested better ways of collecting data to support quantitative evaluation. A large part of that involves modeling, and the support from AERIS has gone to improve data curves used in mesoscale modeling. Focus has been placed on developing new data curves for hybrid electric vehicles which will play a major role in future vehicle fleets.

In addition, one of the key challenges has been in estimating ITS impacts on arterial corridors, and a new methodology has been developed allowing for better energy/emission assessments compared to today's standard techniques. This has resulted in an academic paper, showing results that this new method is typically within 10% of the true values, compared to the standard approach which falls within 40% of the actual values.

Section 3 addressed on-going research in the transportation and emissions modeling interface. The UCR team has been working in this area for some time, and has developed a variety of techniques working with the CMEM model as well as MOVES. A summary is provided of the current efforts in this area. In addition, a summary is given of the latest ITS-based transportation models such as SUMO and how a similar energy/emissions estimation process can be applied. Finally, an eco-signal application has been advanced using these tools, showing that specific velocity planning algorithms can result in a 10% to15% fuel economy improvement over a standard baseline case without the velocity planning. This work has also been highlighted in a recent set of academic papers.

In Section 4, an innovative approach has been developed to provide in-situ real-time environmental information estimates from vehicles. This system is called the Mobile Energy/Emissions Telematics System (MEETS) and has the potential to interact directly with the transportation infrastructure (e.g., traffic signals, ramp meters, etc.) for reducing energy and emissions. The system has been validated using UCR ECO-ITS testbed vehicle, showing very promising results.

Lastly, Section 5 outlines several of the general categories of ITS applications that have the potential for energy and emissions reductions.

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