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

Techniques for Evaluating the Environmental Impacts of ITS Deployment

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16. Abstract

The goal of this report is to present an overview of the state of the practice for techniques that could be used to evaluate the environmental impacts of ITS deployments enabled by real-time communications.   Commercial freight and public transit applications are considered as well as applications affecting private passenger vehicles. This report will be used along with other AERIS Track 1 projects to help evaluate potential applications and strategies for future development and testing.

The paper discusses the state of the practice in three general methods of evaluation: direct measurement of vehicle emissions, infrastructure-based air quality measurements, and modeling. The paper then reviews 41 recent papers that exemplify how these evaluation techniques have been used to measure or predict environmental impacts. For each paper the review presents purpose, background, description, results, and potential applicability to future AERIS study.

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Executive Summary

The U. S. Department of Transportation (USDOT) Research and Innovative Technology Administration (RITA) and the Intelligent Transportation Systems (ITS) Joint Program Office (JPO) are engaged in connected vehicle research to enable safe, interoperable networked wireless communications among vehicles, the infrastructure, and passengers' personal communications devices.[1] The three major goals of connected vehicle research are to increase safety on U.S. roadways, improve system productivity and individual mobility, and reduce the negative environmental impacts of the surface transportation system.

Applications for the Environment: Real-time Information Synthesis (AERIS) is a major component of this program. The AERIS program focuses on the capture, synthesis, and delivery of real-time, vehicle- and infrastructure-based, environmentally relevant information to support system management that advances environmental improvements and "green" choices within the transportation system.

The goal of the AERIS program is to find and promote transformational applications and strategies that can affect a significant decrease in emissions and fuel consumption, in addition to applications and strategies that bring incremental improvements to existing capabilities. To achieve this goal, it is necessary to estimate the amount and percent of emissions (pollutants and greenhouse gases) and fossil fuel consumption that can be reduced or avoided through the use of real-time AERIS applications and strategies.

This report is produced as part of Track 1 of the AERIS program: "Establish Foundation." The goal of the report is to present an overview of the state of the practice for techniques that could be used to evaluate the environmental impacts of ITS deployments enabled by real-time communications. Commercial freight and public transit applications are considered as well as applications affecting private passenger vehicles. This report will be used along with other Track 1 projects to help evaluate potential applications and strategies for future development and testing.

The report presents three categories of evaluation techniques. An overview of each category and a summary of its uses for evaluation are presented below.

Direct Measurements of Vehicle Emissions and Fuel Use

Emissions and fuel consumption can be measured on individual vehicles with appropriate instrumentation such as Portable Emissions Measurement Systems (PEMS) or On-Board Diagnostic (OBD-II) devices. OBD-II provides access to numerous data from the engine control unit (ECU) and offers a valuable source of information when troubleshooting problems inside a vehicle. Such measurements can be used for evaluation in two ways:

- The measurements can be used as input when constructing emissions models, adding more detail by vehicle type and age and driving conditions.

- Driving trials can be designed, either in a laboratory or in a field test environment, to drive vehicles in conditions representing before and after deployment of a real-time AERIS application. Results from such trials can be extrapolated to a larger vehicle population, taking into account the following factors:

    - The extent to which the actual mix of vehicles is represented by the instrumented vehicle type(s) in terms of engine type, engine maintenance state, and fuel type.
    - The extent to which actual driving conditions reflect the conditions present in the driving trials.

Studies have frequently installed and used instrumentation on small numbers of vehicles. This technology is well understood, and the results are regarded as accurate. However, no study has been encountered that places instrumentation on a large number of vehicles. Thus any estimates of corridor or regional environmental benefits are extrapolations from a small number of vehicles, or the result of emissions models.

Measurements of emissions from instrumented vehicles will likely play a role in evaluations of AERIS applications. Applications such as eco-driving, transit and freight fleet management, and signal priority for privileged vehicles where benefits accrue to a relatively small number of instrumented vehicles are candidates for direct evaluation with the sensors. This approach is less likely to be used to measure the benefit of infrastructure-based applications like signal control or ramp metering where the benefit accrues in small amounts at specific places for many vehicles.

Infrastructure-Based Air Quality Measurements

The most straightforward way to quantify the impact of an ITS deployment is take air quality measurements before and after deployment.

Infrastructure sensors for air quality monitoring are widespread, but there are few real-time decision making systems that are tied to air quality readings from sensors. Ambient air quality measurements are most likely to be useful for evaluation of AERIS applications where the benefit of reduced emissions is localized, such as a restricted access zone, an intersection with advanced signal control or ramp metering, or a location with recurrent congestion that may be mitigated. In these cases, the application is infrastructure based, so that large numbers of vehicles are affected, each saving a small amount of emissions near the location with the air quality sensor.

When making a comparison between air quality measurements taken before and after deployment of an ITS application, and looking for the difference attributable to the deployment, one must be careful that all other factors are unchanged as much as possible. Some of these confounding factors include:

- Time of day and day of week
- Changes in traffic control, including lanes and signalization
- Unusual traffic conditions, such as caused by a special event, an incident, or a holiday
- Atmospheric conditions, including temperature, precipitation status, and wind speed

Data from infrastructure air quality sensors are also used to calibrate emissions and atmospheric dispersion models. These models may then be used to extrapolate the effects of emissions to larger vehicle populations and larger areas. These larger areas may be more appropriate levels than the

project or corridor level to assess the potential environmental value of proposed connected vehicle technologies.

Finally, air quality sensors may be integral parts of decision support systems that assist traffic managers decide when or whether to impose traffic restrictions or take other measures when air quality is bad or is likely to become bad.

Modeling the Effects of Connected Vehicle Deployment

Three types of models were examined, including policy, mesoscale, and microscale models. Mesoscale and microscale emissions models use data describing vehicle movements as inputs. Actual vehicle movement data collected from vehicles or from stationary sensors may be used as input. Alternatively, the output of traffic models may be used as input to emissions models; microscale emissions models typically require so much detailed input that outputs from microscale traffic models are required. In general, microscopic traffic models and emissions models are required to quantify the impact of traffic smoothing and improved traffic operations, whereas mesoscopic models are more suited if the effect of the ITS application is a reduction in vehicle miles traveled across one or more classes of vehicles, such as the result of traveler information. Policy models do not involve simulation, but use simpler correlation models to derive regional or national comparative figures to aid policy decision making. The models may use nomographs or spreadsheets to estimate emissions given policy decisions such as driving restrictions or mandated fuel efficiency changes. They may or may not require traffic models to provide input data.

The advantages of models include:

- External factors can be controlled to permit a meaningful comparison between before and after results.

- Modeling can be used to study applications that are not advanced enough or widespread enough to be tested in the field.

- Modeling may be less expensive than field tests, especially if large numbers of vehicles and/or sensors are involved.

- No fuel is consumed or pollutants are emitted during the trials.

- Incidents and unsafe conditions may be modeled without risk of human injury or property damage or creation of congestion.

Models are typically used to estimate the impacts of applications that:

- Involve a large number of vehicles where instrumentation would be impractical, such as optimization of a large traffic signal network or estimating the effect of large scale eco-driving.

- Involve analysis of proposed future facilities or future policies, such as new lanes, new HOV restrictions, new signal timing, new variable speed limits.

- Involve an event such as an incident that cannot be predicted and is not feasible to create.

A wide number of traffic and emissions are being used in the U.S. and internationally to evaluate emissions from light duty vehicles, transit vehicles, and medium and heavy duty trucks. Traffic simulation models that have been used to study the traffic impacts of ITS applications and to produce detailed vehicle movement data as input into emissions models include TRANSIMS, CORSIM, AIMSUN, VISSIM, TransModeler, and Paramics. Emissions models that were used in the studies summarized in this report include MOVES, CMEM, PHEM, and VERSIT+.

Future Work

There appears to be a gap between estimates of environmental impact at a corridor or intersection level, and the impacts at a regional or national level. No studies were encountered that presented a rigorous approach for extrapolating project or corridor-level results to a larger scale. Approaches such as Regional Science, pioneered by Walter Isard, may provide a way to perform this extrapolation. Policy models described in Section 4.4 of the report can operate at a national level, but do not include the detail necessary to capture the effects of traffic smoothing.

For many ITS applications involving pre-trip or en route traveler information, additional work will be required to quantify human responses to the information before the results of the applications can be accurately captured in a detailed traffic model.

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[1] http://www.its.dot.gov/connected_vehicle/connected_vehicle.htm

1 Introduction

1.1 Background of the AERIS Program

The U. S. Department of Transportation (USDOT) Research and Innovative Technology Administration (RITA) and the Intelligent Transportation Systems (ITS) Joint Program Office (JPO) are engaged in connected vehicle research to enable safe, interoperable networked wireless communications among vehicles, the infrastructure, and passengers' personal communications devices.[2] The three major goals of connected vehicle research are to increase safety on U.S. roadways, improve system productivity and individual mobility, and reduce the negative environmental impacts of the surface transportation system.

Applications for the Environment: Real-time Information Synthesis (AERIS) is a major component of the connected vehicle research program. The AERIS program focuses on the capture, synthesis, and delivery of real-time, vehicle- and infrastructure-based, environmentally relevant information to support system management that advances environmental improvements within the transportation system. The vision for AERIS research is to generate, capture, and analyze data to create actionable information that allows systems users and operators to make "green" transportation choices.[3]

Several components of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications can work toward providing environmental benefits. Providing travelers, transit managers, and commercial freight dispatchers with real-time information about traffic congestion and other travel conditions can help them make more informed decisions that can reduce the environmental impact of trips. Informed travelers may decide to avoid congestion by taking alternate routes or by taking public transit, or by rescheduling their trips – all of which can make their trips potentially more fuel-efficient and eco-friendly. The ability for vehicles to "talk to" the infrastructure can provide information to the traffic signal infrastructure and the vehicle operator so that he or she can drive through a network of traffic signals at optimum speeds to reduce stopping and unnecessary speed changes. Many transportation management activities that enhance mobility can also reduce emissions and fuel consumption by reducing vehicle idling due to traffic congestion. The AERIS program will better define how these and other ITS applications might contribute to mitigating some of the negative environmental impacts of surface transportation.

The USDOT is collaborating with International organizations, including the European Union's Directorate-General for Information Society (DG INFSO) and the Ministry of Economy, Trade and Industry (METI) in Japan to study and implement ITS applications and strategies to benefit the environment and improve sustainability. The European and Japanese agencies have also produced reports investigating the capability of ITS technologies to help the environment. "Methodologies for Assessing the Impact of ITS Applications on CO_2 Emissions" [1] provides a wide-ranging analysis of environmental evaluation techniques available in Europe.

1.2 Purpose and Organization of the Report

This report is produced as part of Track 1 of the AERIS program: "Establish Foundation." The goal of the report is to present an overview of the state of the practice for techniques that could be used to evaluate the environmental impacts of deploying AERIS applications and strategies enabled by connected vehicle technologies. Commercial freight and public transit applications are considered as well as applications affecting private passenger vehicles. This report will be used along with other Track 1 projects to help evaluate potential applications and strategies for future development and testing.

Section 2 of the report describes negative ways in which surface transportation might affect the environment and ways in which AERIS applications and strategies may reduce some of the negative impacts. Section 3 presents an overview of methods for evaluating these benefits. Section 4 presents examples of applications of those methods or techniques, gathered from a review of recent literature. Section 5 presents a summary of findings and conclusions.

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[2] http://www.its.dot.gov/connected_vehicle/connected_vehicle.htm

[3] http://www.its.dot.gov/aeris/index.htm

2 Environmental Impacts and How Connected Vehicle Technologies Can Help

2.1 Environmental Impacts of the Surface Transportation System

The major goal of the AERIS program is to reduce the environmental impact of transportation. Before considering how such reduction may be achieved, the following paragraphs outline major ways in which surface transportation affects the environment. Following sections discuss ways in which these impacts may be mitigated using ITS deployments enabled by connected vehicle technologies, and ways in which the extent of mitigation can be measured, modeled, or otherwise estimated.

The focus of the AERIS program is on improving air quality, reducing greenhouse gas (GHG) and regulated emissions, and reducing fuel consumption, but the negative environmental impacts of the surface transportation system are more widespread:

- Emissions from internal combustion engines: Internal combustion engines in vehicles produce emissions, including pollutants and greenhouse gases. Chief among the pollutants are nitrous oxides (NOx), Sulfur oxides (SOx), Carbon monoxide (CO), and particulate matter (PM). Particulate matter is sub-categorized into coarse (PM-10) and fine (PM-2.5). Greenhouse gases are not as directly harmful to plant and animal life as pollutants, but contribute significantly to climate change. Chief among the greenhouse gases is carbon dioxide (CO_2); others are water vapor (H_2O), methane (CH_4), and nitrous oxide (N_2O). Reduction of pollutants and GHGs produced by surface transportation is a major goal of the AERIS program.

- Emissions from fossil fuel power plants: Since electric vehicles do not burn fossil fuels in internal combustion engines, they can provide relief from combustion engine pollutants and may be of significant value to a community trying to minimize its environmental impacts. However, electricity must be generated to charge and recharge those vehicles' batteries. Electricity may be generated by a variety of methods including nuclear power, solar cells, geothermal energy, and wind turbines. Electricity generated by renewable sources greatly offsets fossil-generated energy for transportation, but the primary source of power for electricity generation in the U.S. is fossil fuels (coal, oil, and natural gas)[4]. Electric power plants burning fossil fuels emit pollutants and greenhouse gases, so electric vehicles are also responsible for emissions. Thus miles driven by electric vehicles and their drive cycles should also be considered in environmental applications.

- Impact on natural ecosystems of recovery and processing of fossil fuels: The recovery of fossil fuel (crude oil, natural gas, and coal) from the earth and their subsequent processing have significant environmental impacts, ranging from disturbance of natural

areas and by-products and wastes from production, to the risk and occasional occurrence of large-scale environmental disturbances such as oil spills. Thus any reduction in the demand for fossil fuels for combustion in vehicles or for power generation is helpful to the environment. The economic and political impacts of fossil fuel acquisition are enormous, but are outside the scope of the AERIS program.

- Transportation of fossil fuels: Transportation of fossil fuels results in the risk and occurrence of events that directly damage the environment, including pipeline leaks, natural gas explosions, and spills of hazardous materials (hazmat). In addition, these events often in turn have serious negative impacts on transportation, causing delays or blocking roads altogether, with attendant decreases in safety and mobility. These negative impacts are assumed to be reduced in proportion to reductions in the demand for fossil fuels, but are not discussed further in this report.

- Production and disposal of vehicles and components: The production and eventual disposal of vehicles and components, including steel, rubber, glass, and trace materials, often has a negative impact on the environment. Reductions in vehicle miles traveled may reduce the number of vehicles produced and ultimately discarded. This environmental impact is included for completeness, but is not discussed further in this report.

- Noise pollution: The noise created by motor vehicles is often considered to be a form of pollution. Although connected vehicle applications to reduce vehicle miles traveled and/or to reduce vehicle accelerations and decelerations are also likely to reduce noise, these effects are not discussed further in this report.

- Urban sprawl: Ease and travel time of personal and commercial transportation are factors that contribute to decisions of where to locate residential, commercial, and industrial facilities. Connected vehicle applications and strategies that affect travel times or reliability may have secondary positive or negative effects on growth and development patterns, but these effects are beyond the scope of this report.

2.2 Ways Connected Vehicle Technologies Can Reduce the Environmental Impacts of Transportation

The USDOT connected vehicle research program envisions a wide range of applications and strategies that have the potential to increase safety, improve mobility, and benefit the environment. Often an application or strategy has the potential to support two or all three of these goals at the same time.

The following three subsections list ways in which these connected vehicle applications or strategies can benefit the environment. Some applications or strategies are incremental improvements to traditional approaches to traveler information and traffic management. Others are more transformational, creating new paradigms of operations. Both types are enabled by ubiquitous V2V and V2I communications.

2.2.1 Modify Demand Type

Some connected vehicle technologies enable the modification of demand so that fewer vehicle miles are traveled; travelers are encouraged to make use of low-polluting vehicles or modes; and commercial fleets and public transit systems are operated more efficiently. Specific examples of such applications and strategies are cited below:

- Congestion pricing and advanced traveler information can result in decisions not to make a trip, or to combine trips, thus eliminating trips. The majority of eliminated trips are likely to be private vehicle trips.

- Congestion pricing and advanced traveler information can result in mode shifts to public transit, carpooling/ride-sharing, or bicycle or pedestrian trips. Each trip shifted to one of these modes eliminates a private vehicle trip without eliminating the trip itself. Highly reliable and accessible transit systems will attract more riders to transit systems.

- More efficient transit management systems and greater reliability might enable transit operators to satisfy demand for public transit more efficiently using fewer vehicle trips. To the extent that efforts to move trips from private vehicles to public transit are successful, the potential energy and emissions savings from this strategy are reduced.

- Freight management (e.g., drayage optimization, dynamic route guidance for freight, etc.) enables commercial fleets to operate more efficiently, requiring fewer trips or shorter trips for commercial vehicles. A particular goal is to reduce the proportion of trips made by empty trucks. Multi-modal coordination may enable freight to be carried more efficiently by rail than by truck.

In general, reduction in the number of vehicle miles traveled reduces the amount of emissions caused by internal combustion or electricity generation, and reduces the amount of fuel consumed. Reduction in fuel consumption reduces dependence on foreign fuels, and the environmental impact of domestic fuel production. The number of vehicles miles traveled can be reduced either by eliminating entire trips or by shortening trips.

If entire vehicle trips are eliminated, vehicle miles traveled as well as cold starts is reduced. Thus, if entire vehicle trips are eliminated, fuel consumption and emissions are directly proportional to the percent reduction in miles traveled for that vehicle type.[5] However, if vehicle miles traveled are reduced by shortening trips rather than by eliminating them, more detailed analysis is required to evaluate the fuel and emissions savings on a regional or national basis.

2.2.2 Improve Efficiency of the Transportation System

A second method by which connected vehicle technologies might be able to minimize emissions and fuel consumption is through improved efficiency of the transportation system, resulting in reduced congestion or optimum speed for energy efficiency.

Any reduction in vehicle miles traveled as described in the previous section helps to reduce congestion by removing vehicles from the road or shortening their trips. Congestion can also be reduced by making more efficient use of network capacity. Reduction in congestion can have other

complementary benefits such as increased travel time reliability, which can result in savings to shipping operations and personal time, and reduced commute stress.

Additionally, with connected vehicle technologies it is possible to promote travel at energy-efficient speeds or smooth traffic by minimizing spatial and temporal variations in speed within and upstream of a bottleneck. Traffic smoothing implies that individual vehicles have less variation in speed, and that there is less variation in speed among neighboring vehicles on the road. Reducing speed variations of individual vehicles saves fuel and emissions through reductions in accelerations. Reducing speed variations among neighboring vehicles increases safety by reducing sudden decelerations or lane changes.

Some examples of congestion reduction by means of increasing individual mobility include:

- Advanced traveler information results in shifts of departure time to a time with less congestion.

- Advanced traveler information results in taking routes with less congestion, thus spreading traffic around to make more efficient use of roadway capacity.

Some examples of congestion reduction by means of efficient traffic management include:

- More efficient traffic signal operations result in fewer slowdowns, less time idling while stopped at intersections, and fewer accelerations from stops at intersections. In addition, signal operations may provide priority travel to transit and emergency response vehicles, e.g., signal priority and/or dedicated right-of-way.

- More efficient freeway traffic management measures such as ramp meters or variable speed limits result in smoother traffic flow and less delay.

- More efficient incident management results in reduced delay to other vehicles in the vicinity of the incident.

- Integrated corridor management (ICM) improves efficiency and productivity of a corridor through multi-modal management of the transportation infrastructure.

- More efficient management of work zones results in reduced delay to other vehicles in the vicinity of the work zones as well as increased safety for the workers.

- Highway, arterial, and intersection ITS safety applications result in fewer incidents, resulting in less delay to other vehicles and fewer incidents of hazmat spills, fires, and other dangers to the environment.

2.2.3 Eco-Driving

A third method by which connected vehicle technologies can result in environmental improvement even without fewer trips or congestion reduction, is the area of "eco-driving." Using information from other vehicles and the infrastructure, including traffic signals, vehicles can operate more efficiently with respect to emissions and fuel consumption. Eco-driving may refer either to:

- Applications that provide real-time situation-responsive suggestions to drivers on how to drive so as to minimize fuel consumption and/or emissions, or

- Applications that directly control the engine, brakes, or other vehicle components to achieve the same ends without requiring driver intervention.

Examples of situations where eco-driving could be employed effectively include:

- Responding to trajectory changes by nearby vehicles,

- Anticipating upcoming terrain features and intersections,

- Anticipating the traffic signal state of an upcoming signalized intersection using signal phase and timing (SPAT) messages,

- Responding to hazardous road conditions caused by an incident or by weather (such as fog or slippery road surface), and

- Platooning with other vehicles at a speed that provides the greatest environmental benefit.

ITS applications may also enable transit vehicles to travel in electrified, dedicated right-of-ways to minimize fuel consumption and/or emissions. Smoother and faster travel by transit vehicles will provide an additional incentive for mode change from private single-occupancy-vehicles to transit.

These eco-driving applications will be enabled by connected vehicle V2V and V2I communications.

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[4] The U.S. Energy Information Administration at http://www.eia.doe.gov/cneaf/electricity/epm/table1_1.html lists the following percentages for the 12 months ending June 2010: coal 45%, petroleum 1%, natural gas 23%, nuclear 20%, hydro 6%, and renewable sources 4%

[5] For example, page 75 of Reference 1 says about the PAYD (Pay As You Drive) option: "PAYD will reduce fuel consumption by the same proportion that it reduces driving. Based on results from different sources it was estimated that PAYD would decline driving in USA by 8% nationwide. This driving reduction would reduce carbon dioxide emissions by 8 percent."

3 Quantifying the Environmental Impacts of Connected Vehicle Applications

Many studies have been performed to evaluate and quantify the *mobility* benefits of connected vehicle applications and strategies. These benefits include: increased throughput; reduced delay, stops, and queues; and increased travel time reliability. These results are appropriate for evaluating enhanced mobility, but must be carried an additional step to evaluate *environmental* impacts. The next step is typically the use of emissions models.[6] The use of emissions models as an evaluation technique is discussed later in this section.

The ultimate measure of the environmental impacts of surface transportation would entail analyses of climate change and health effects of pollution and greenhouse gases[7] and the environmental impact of fossil fuel production. However, such complex analyses are beyond the scope of this report and the initial stages of the AERIS program. An appropriate goal for analysis is to estimate the amount and percent of emissions (pollutants and greenhouse gases) and fossil fuel consumption that can be avoided through the use of connected vehicle applications and strategies. The goal of the AERIS program is to find and promote transformational applications and strategies that can affect a significant decrease in the emissions and fuel consumption, in addition to applications and strategies that bring incremental improvements to existing capabilities.

One excellent guide for evaluating the environmental impact of ITS deployments is "An Environmental Evaluation Guidebook for ITS Deployments and Field Tests" [2]. Since this guidebook was written in 1995, it does not address greenhouse gases and is not focused on connected vehicle applications. However, its recommended evaluation framework for emissions and fuel consumption are still applicable. The current report does not supplant this guidebook. Rather it supplements and updates the guidebook by reviewing more recent studies that have been performed around the world, and provides a focus on connected vehicle applications and strategies.

This section discusses approaches currently being used to quantify and evaluate the impacts of connected vehicle applications and strategies, relating to the categories introduced in the preceding section. Section 4 presents specific examples of the application of these approaches.

3.1 Direct Measurements of Vehicle Emissions and Fuel Use

The first step in the ability to evaluate environmental impacts of connected vehicle applications and strategies is the ability to measure actual emissions and fuel consumption accurately. "Before" and "After" measurement of emissions may apply to transit and freight vehicles as well as private vehicles.

3.1.1 Portable Emissions Measurement Systems

Emissions and fuel consumption can be measured on individual vehicles with appropriate instrumentation such as Portable Emissions Measurement Systems (PEMS). Such measurements can be used for evaluation in two ways:

- The measurements can be used as input when constructing emissions models, adding more detail by vehicle type and age and driving conditions.

- Driving trials can be designed, either in a laboratory or in a field test environment, to drive vehicles in conditions representing before and after deployment of a connected vehicle application. Results from such trials can be extrapolated to a larger vehicle population, taking into account the following factors:

  - The extent to which the actual mix of vehicles is represented by the instrumented vehicle type(s) in terms of engine type, engine maintenance state, and fuel type.
  - The extent to which actual driving conditions reflect the conditions present in the driving trials.
  - The extent to which engine performance is based on actual or projected load capacities.

Section 4.1 presents reviews of papers that discuss the State of the Practice for vehicle emissions measurement with PEMS.

3.1.2 On-Board Diagnostics

A second source of vehicle data is the On-Board Diagnostics Unit (OBD), a computer-based system designed to monitor the performance of some of an engine's major components including those responsible for controlling emissions. The first generation of On-Board Diagnostic requirements was developed by the California Air Resources Board (ARB) and implemented in 1988. As technology and the desire to expand On-Board Diagnostic capability increased, a second-generation of On-Board Diagnostics (OBD II) requirements was developed. The Clean Air Act Amendments of 1990 mandated that, beginning with the 1996 model year, all light-duty vehicle and trucks must also be equipped with OBD-II. In addition, EPA [Environmental Protection Agency] also requires that medium duty vehicles up to 14,000 pounds must also be equipped with OBD-II systems beginning in the 2004 model year[8]. Recently (effective on April 27, 2009) EPA has finalized regulations requiring OBD systems on 2010 and later heavy-duty engines used in highway vehicles over 14,000 pounds and revisions to OBD requirements for diesel highway heavy-duty vehicles under 14,000 pounds[9].

OBD-II provides access to numerous data from the engine control unit (ECU) and offers a valuable source of information when troubleshooting problems inside a vehicle. The SAE J1979 standard defines a method for requesting various diagnostic data and a list of standard parameters that might be available from the ECU. The various parameters that are available are addressed by "parameter identification numbers" or PIDs which are defined in J1979. Manufacturers are not required to implement all PIDs listed in J1979 and they are allowed to include proprietary PIDs that are not listed.

The following systems related to emissions are monitored by the OBD II:

- **Misfire:** This monitor looks for any engine misfires.

- **Fuel System:** This monitor constantly checks the amount of fuel that is used by the engine.

- **Comprehensive Component:** This monitor is looking at all of the various switches and sensors that are involved with engine management.

- **Catalyst:** This monitor uses the readings from oxygen sensors located before and after the catalytic converter

- **Heated Catalyst:** Some vehicles may have an electrically heated catalyst. This monitor will check to make sure that the catalyst heater is working.

- **Evaporative System:** This monitor works to ensure that the Evaporative System is kept in a condition to minimize the release of gasoline vapors.

- **Secondary Air System:** Some vehicles are equipped with a secondary air system, or air injection system. This monitor checks the components, switches, and solenoids that are part of the air injection system.

- **A/C (Air Conditioning) System:** In some older vehicles, this monitor was intended to monitor the vehicle's air conditioning system if it had the older "R-12" style of refrigerant. This monitor will show up as "Unsupported" on most newer vehicles.

- **O2 (Oxygen) Sensor:** The O2 Sensor Monitor watches for the performance of the vehicle's oxygen sensors.

- **Heated O2 (Oxygen) Sensor:** Some oxygen sensors include an electric heater to help them warm up quicker and to begin operating faster. This monitor ensures that the heater circuit of the oxygen sensor is working properly. Since not all vehicles have a heated oxygen sensor, some vehicles will show this monitor as "Unsupported."

- **EGR (Exhaust Gas Recirculation) System:** Many vehicles are equipped with an EGR system. This monitor checks the components of the EGR system to ensure that it is working properly and that there is sufficient flow of exhaust gas through the system.

One study[10] tested various technologies that could be used as bus fleet screening tools for the emissions inspection and maintenance (I/M) program of the Massachusetts Bay Transportation Authority (MBTA), and concluded that the use of the OBD with heavy-duty engines was not advanced as it is with light-duty engines and was not ready for the emissions testing of heavy duty diesel vehicles. The test also pointed out that OBD-II emission testing does not measure emissions directly, but rather infer vehicle emissions performance based on review of related information.

3.2 Infrastructure-Based Air Quality Measurements

The most straightforward way to quantify the environmental impact of a connected vehicle application or strategy deployment is take air quality measurements before and after deployment. Measurements would have to be taken at a project level at locations where a particular deployment has made a noticeable change on congestion levels or manner of driving. Examples of such places might include:

- A highway on-ramp where a ramp meter was installed,

- An arterial intersection where improved signal management enabled by V2I communications was used, and

- A spot on a highway where traffic management enabled by connected vehicle technology has improved recurrent congestion.

When making a comparison between air quality measurements taken before and after deployment of a connected vehicle application, and looking for the difference attributable to the deployment, one must be careful that all other factors are unchanged as much as possible. Some of these confounding factors include:

- Time of day and day of week

- Changes in traffic control, including lanes and signalization

- Unusual traffic conditions, such as caused by a special event, an incident, or a holiday

- Atmospheric conditions, including temperature, precipitation status, and wind speed

The following factors may be changed as a result of the connected vehicle application or strategy deployment. If so, the comparison of the before and after states could be valid. However, if one or both of these factors are different, but not as a result of the connected vehicle application deployment, a direct before and after comparison could be invalid.

- Traffic volume

- Composition of traffic by vehicle type

If the time difference between the "before" and "after" comparison is longer than a year, even if the previously-mentioned variables are the same before and after, variables such as the average efficiency of the engines and average composition of the fuels that have changed between the "before" and "after" measurements can complicate the attribution of differences to connected vehicle application deployment.

Measurement of air quality at selected locations cannot quantify reduction in fuel consumption attributable to deployment of a connected vehicle application. Measurements of differences in fuel consumption can only be done in individual vehicles, or inferred from differences in regional or metropolitan fuel sales over an extended period, after taking into account changes in fuel efficiency.

If an improvement in air quality is found that can be attributed to deployment of a connected vehicle application or strategy, the problem remains how to extrapolate from the location(s) monitored to larger areas, such as a regional, state, or national level. These larger areas may be more appropriate levels than the project or corridor level to assess the potential value of a proposed connected vehicle application.[11]

Measurements from infrastructure air quality sensors may also be used:

- To build and calibrate emissions models.

- To trigger changes in traffic management policies, such as the imposition of travel restrictions on days with bad air quality or days when air quality is projected to be bad.

Section 4.2 presents reviews of papers that discuss the State of the Practice for the use of stationary air quality sensors for these purposes.

The use of air quality sensors may become less important when market penetration of connected vehicle technology increases to a point when a large percentage of vehicles are able to measure and report emissions and fuel consumption directly.

3.3 Modeling the Effects of Deploying Connected Vehicle Technology

The difficulties mentioned in the previous sections lead to the common approach of modeling to quantify the environmental impacts of deployment of connected vehicle technologies. The advantages of models include:

- External factors can be controlled to permit a meaningful comparison between before and after results.

- Modeling can be used to study applications that are not advanced enough or widespread enough to be tested in the field.

- Modeling may be less expensive than field tests, especially if large numbers of vehicles and/or sensors are involved.

- No fuel is consumed or pollutants are emitted during the trials.

- Incidents and unsafe conditions may be modeled without risk of human injury or property damage or creation of congestion.

Of course, there are limitations to the use of models, including:

- Emissions or fuel consumption mechanisms for a particular engine type or situation may not be understood in sufficient detail to model correctly.

- Atmospheric dispersion of emissions is an additional factor that is difficult for most emissions models to incorporate.

- The traffic model may not accurately represent traveler behavior in response to the connected vehicle application or strategy. Additional studies of traveler behavior may be required before attempting to represent the behavior in a traffic model.

- The necessary input data for model development or calibration and validation may be not be available or may be incorrectly gathered.

- Some decision makers may regard results derived from models to be not as reliable or actionable as results derived from actual measurements.

Despite these limitations, the state of the practice for estimating the environmental impacts of connected vehicle technology deployment relies heavily on modeling. It is expected that models will be used in the assessment of environmental effects of connected vehicle applications and strategies in Track 3 of the AERIS program.

The following sections present an overview of the type of models used to estimate emissions and fuel consumption. All models require input specifying the time period to be modeled, vehicle miles traveled

(VMT), and some indication of vehicle type. The more detailed the model of emissions and fuel consumption, the more detailed the input must be.

Mesoscale and microscale emissions models use data describing vehicle movements as inputs. Actual vehicle movement data collected from vehicles or from stationary sensors may be used as input. Alternatively, the output of traffic models may be used as input to emissions models; microscale emissions models typically require so much detailed input that outputs from microscale traffic models are required. For emissions models to reflect the impact of connected vehicle applications, it is necessary for the traffic models to be able to reflect the changes in vehicle movement resulting from the application.

Reference 1 contains descriptions of these basic model types and reviews of traffic and emissions models used in Europe.

3.3.1 Policy Models

Policy models do not involve simulation, but use simpler correlation models to derive regional or national comparative figures to aid policy decision making. The models may use nomographs or spreadsheets to estimate emissions given policy decisions such as driving restrictions or mandated fuel efficiency changes. They may or may not require traffic models to provide input data. Section 4.6 presents reviews of papers that discuss the State of the Practice for models of this type.

3.3.2 Mesoscale Models

A mesoscale emissions model such as the Mobile Source Emissions Factor (MOBILE) series of models used by the EPA, typically computes the emissions produced by each type of vehicle, given the average speed, by looking up the emissions for that average speed, computing emissions per mile based on the average speed, and multiplying by the total number of miles traveled.

Mesoscale models require less detailed input and less computer power to run than microscale models. However, since they use average speeds, they are often not appropriate for estimating the impact of connected vehicle applications, since the speed variability may be affected more significantly than the average speed.

3.3.3 Microscale Models

Microscale emissions models are more detailed than mesoscale models. Rather than using an average speed for each vehicle type, they use as input second-by-second trajectory profiles. They may also use second-by-second engine cycle data if available, or may process second-by-second speed and road grade data to derive engine cycle data. These detailed representations of engine behavior enable the models to compute fuel consumption and emissions generation at a higher level of fidelity than mesoscale models. For example, microscale models predict higher emissions when vehicles are accelerating than when they are cruising.

Advanced emissions models may also represent atmospheric dispersion of emissions, given input for temperature, air pressure, and wind speed. Plume dispersion models take into account these variables as well as the configuration of buildings and geographical features surrounding the road.

Microscale models typically have significant computer run time, memory, and storage requirements. However, the speed, memory, and storage capabilities of modern computers have largely mitigated these issues. The larger amount of human time to gather data and build, calibrate, and validate these detailed models remains the largest significant factor.

Chapter 3 of Reference [1] provides reviews of microscale traffic and emissions models. Examples of traffic models that have been used in the U.S. are AIMSUN[12], Paramics[13], and VISSIM[14]. TRANSIMS[15] is an American microscale traffic model. Examples of emissions models are MOVES[16], VERSIT+[17], PHEM, and CMEM[18].

Several major traffic microsimulation models have emissions models built into them (e.g., AIMSUN, TRANSIMS, VISSIM, and CORSIM). However, it is becoming more common to feed trajectories from traffic microsimulations into detailed emissions models. Some examples of this are the link from Paramics and VISSIM to CMEM, and a link from TRANSIMS to MOVES. Examples of both types of model used in recent studies are presented in Section 4.

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[6] AERIS Performance Measures, M. Savonis, October 2010, draft.

[7] Ibid.

[8] http://www.epa.gov/otaq/regs/im/obd/basic.htm

[9] http://www.epa.gov/otaq/regs/im/obd/regtech/heavy.htm

[10] D. Lowell and A. Herzenberg, "MBTA Bus Fleet Emissions Screening Using Remote Sensing Technology", June 2006, M. J. Bradley & Associates, http://www.mjbradley.com/APTAPaperRSDFINAL5-2-05.pdf

[11] Op. cit. Savonis.

[12] http://www.aimsun.com/site/content/category/1/4/8/

[13] http://www.paramics-online.com/

[14] http://www.vissim.com/

[15] http://code.google.com/p/transims/

[16] "*Considerations in using MOVES for Regional and Project Level Emissions Analysis*", delivered by David Roden at the 2010 TRB Conference, discusses how input from traffic models may be input to MOVES.

[17] http://www.tno.nl/downloads/lowres_TNO_VERSIT8.pdf

[18] http://www.cert.ucr.edu/cmem/

4 Current Techniques for Evaluating Environmental Impacts

This section presents the results of a literature scan for current techniques for evaluating environmental impacts and benefits. Wherever possible, the reviews note whether the evaluation techniques address pollutants, greenhouses, fuel consumption, or a combination of these. Where applicable, the reviews present results from the studies, including percent reductions in emissions and/or fuel consumption.

4.1 Direct Measurement of Vehicle Emissions

This section describes studies that concern direct measurement of emissions from vehicles. These measurements are frequently used as input to emissions models, rather than being used directly to estimate benefits of connected vehicle technology deployment. The second and fourth papers discuss the correlation between emissions and Vehicle Specific Power (VSP), a concept used by the microscopic emissions models.

4.1.1 Emissions Measurements for Light Duty Vehicles

4.1.1.1 Using Portable Emission Measurement Systems for Transportation Emissions Studies: Comparison with Laboratory Methods [3]

Purpose: This study evaluated how well Portable Emissions Measurement Systems (PEMS) perform and how accurate they are compared to the type of testing that occurs in laboratory conditions. This study also discussed whether PEMS can be evaluated as a tool for either emissions inventory development or in-use compliance. Since PEMS data can be used to test real-world emissions in a target area, such as a toll area, a high occupancy vehicle lane, or an arterial signal area, this data can be used for the purposes of compliance, regulation, or decision-making.

Background: The study was performed by the University of California at Riverside College of Engineering at the Center for Environmental Research and Technology and the International Sustainable Systems Research Center.

Description: Three PEMS were carefully evaluated for both gasoline and diesel light-duty vehicles in a dynamometer test facility. Both cumulative mass emissions and modal emissions were measured for three gasoline and three diesel vehicles on three widely varying driving cycles. More than 6000 data points from each vehicle were compared to corresponding laboratory modal analyzer data.

Results: All of the PEMS systems (including emissions analyzer and flow meters) proved to be both reasonably accurate and precise. The CO_2 emissions measured by the PEMS were in excellent agreement (within 98%) with the measurements from the laboratory system. The results show that PEMS have quick and precise response to most pollutants for most driving cycles. The PEMS equipment showed good capacity to be used for capturing emission changes in micro traffic research. There was a strong linear relationship to the laboratory modal system for all pollutants on both response time and value.

Possible applications for AERIS: This type of research fits into the AERIS foundational analysis goal to identify data that will facilitate the development of research to support "green choices". Eventually, this data might be a component that supports applications in areas such as demand management (carbon credit, restricted access zones) or traffic management schemes that incorporate emissions into decisions on how to manage traffic flow.

4.1.1.2   A Field Evaluation of CO2 Emissions at High Speeds [4]

Purpose: This study measured vehicle emissions at speeds up to 95 mph under real-world driving conditions. It also investigated the cycle-based CO_2 emissions rates for a broad range of average cycle speeds. The study evaluated the use of measured emissions data to develop a series of instantaneous emission models, in a format consistent with MOBILE6.2 outputs, which provide estimates of emissions for specific speeds and acceleration rates. The models were applied to a series of representative drive cycles to provide distance based average CO_2 emission rates (g/mi). The intention of the research study was to investigate the trend and variability of fuel economy rates.

Background: The study was performed at the Pecos Research and Testing Center by researchers from the Texas Transportation Institute and the University of Akron.

Description: The study investigated actual CO_2 emissions data for a sample of light-duty gasoline vehicles (LDGV) and class 2b heavy-duty diesel trucks (HDDV-2b) using a PEMS. The PEMS unit was mounted on vehicles that were driven through a series of pre-determined drive patterns on a high speed test track. The Vehicle Specific Power (VSP) approach, as used in EPA's MOVES model, was used in this study to relate instantaneous speed and acceleration data to emission rate measurements. There were four different driving patterns developed for each of the two vehicle classes to cover all the achievable combinations of instantaneous speed, acceleration, deceleration, idling, and cruising.

Results: The results from cruise-speed testing demonstrated that CO_2 emissions of LDGVs increase as cruise speed increases from 40 mph to 70 mph. A different trend was observed for speeds higher than 70 mph. The CO_2 emissions rates remained approximately flat between 70 and 80 mph then increased between 80 and 95 mph. The HDDV-2b vehicles appeared to show that CO_2 emissions are the lowest when the average speed approached 55 mph.

Possible applications for AERIS: The analysis conducted in this paper is helpful for further refinement of vehicle emissions models, particularly at higher speeds where dynamometer testing is not practical. This technique is worth further evaluation for efforts in understanding data collection methods and refining emissions models.

4.1.1.3   The University of Vermont TOTEMS Instrumentation Package for Real-World, On-Board Tailpipe Emissions Monitoring of Conventional and Hybrid Light-Duty Vehicles [5]

Purpose: This study evaluated the results of tailpipe emissions measurements from a 1999 Toyota Sienna minivan with a specific interest in evaluating differences in the emissions due to

the relatively cold climate and hilly terrain of Vermont. This study was performed as part of a proof-of-concept study and will soon be further evaluated as part of a year-long testing of two Toyota Camry study vehicles: one hybrid and one conventional. This research had three main objectives: (1) quantify second-by-second emissions of regulated and unregulated exhaust gases and particles; (2) understand the relationships between tailpipe emissions and major factors such as road grade, engine load, traffic/driving conditions and ambient environmental conditions (temperature and humidity); and (3) quantify the relationships between various exhaust emission species, especially between regulated and unregulated pollutants for mobile source emissions modeling purposes.

Background: The study was conducted in 2009 using a 1999 Toyota Sienna minivan on a 41-mile loop within Chittenden County, Vermont by the University of Vermont School of Engineering Transportation Research Center.

Description: The study consisted of assembling an instrumentation package and performing four trial runs to verify that the data could be collected reliably in real time. "Total On-Board Tailpipe Emissions Measurement System" (TOTEMS) is an assembly of 20 instruments chosen for their ability to quantify a suite of parameters associated with tailpipe emissions for improved real-world measurement and modal emissions modeling of light-duty vehicles. While the vehicle is traveling, TOTEMS collects particle emissions using a particle spectrometer instrument that was not available previously and quantifies mobile source air toxic (MSAT) gaseous emissions in addition to criteria pollutant (CO, NOx, HC) and greenhouse gases (CO_2, N_2O) using a high-speed Fourier Transform Infrared (FTIR) instrument specifically designed for on board vehicle exhaust testing.

Results: The authors felt the data from TOTEMS instruments demonstrated the capability of obtaining high-resolution data for modal modeling purposes. The TOTEMS package enables simultaneous collection of tailpipe emissions for greenhouse gases, particle number distributions and MSATs in addition to vehicle operating parameters and air temperature and humidity. However, when measuring exhaust particle size, for the smallest particles, the device appears to be unable to accurately quantify particle number concentrations less than ~100 particles per cubic centimeter and this minimum detectable concentration decreases with increasing particle size. It should be noted, however, that only during vehicle idle conditions are particle counts below the detection limit.

Possible applications for AERIS: As the project progresses, the real-time emissions monitoring scheme being studied and the measurement package that is being tested may be useful in providing data for models that will feed into AERIS applications such as "Carbon credit" schemes, Restricted traffic zones, "Green" enhanced navigation services, and Eco-driving with on-board assistance. The results of this study can also be used to enhance emissions models to better represent emissions production from real-world driving conditions.

4.1.1.4   *Improved VSP-Bins for Light-Duty Vehicles for Estimating CO2 Emissions in Beijing [6]*

Purpose: This study developed emission-specific VSP bins for estimating CO_2 emissions using an alternative binning approach. PEMS instruments were used in light-duty vehicles to collect data.

Background: The study was conducted in 2009 in Beijing, China by the Laboratory for Urban Transportation Complex Systems Theory, Beijing Jiatong University, in collaboration with Texas Southern University.

Description: A total of 16 light duty gasoline vehicles (LDGVs) were tested in Beijing, including general cars and taxies. 24 VSP bins were defined based on the emission data collected. VSP bins are used in microscopic emissions such as MOVES.

Results: The results indicated that the estimation errors from this alternative proposed binning method were less than those from MOVES and International Vehicle Emissions Model (IVE) models, especially in estimating CO_2 emissions during the peak hour in Beijing. The proposed method can be applied to define emission-specific VSP bins for other emission species such as HC, NOx, CO, or PM when necessary data are available.

Possible applications for AERIS: This paper takes a reasonable approach to developing CO_2 emissions by VSP bins for a specific locality, using second-by-second data collected on selected routes by PEMS. The validation procedure and results were good. AERIS could study the proposed methodology for customizing VSP bins to localities when using the MOVES model. The results could be more accurate emissions forecasts for MOVES. However, as the paper itself says, the values of emissions by VSP are best if computed and validated with local data. Thus, data developed for Beijing is not directly useful for U.S. cities. Furthermore, the paper notes that "almost all the data collected in Beijing are on the flat roads," so the methodology does not capture factors related to road grade.

4.1.2 Emissions Measurements for Medium and Heavy-Duty Trucks

4.1.2.1 Testing and Modeling of Truck Emissions While Idling [7]

Purpose: This study characterizes emissions produced by trucks on both cold and hot short-period idling. Trucks have different pollutant emissions and fuel consumption characteristics during idling that depends on how long the engine has been idling and the type of driving conditions that occurred between idling intervals. This study aims to understand and measure the effects on idling emissions from varying driving conditions.

Background: The measurements were conducted in Houston, Texas by Texas Southern University in 2004-2005.

Description: The monitor interfaces to the On-Board Diagnostics (OBD) port in the truck to get engine operating data, and measures emissions from the tail pipe using an advanced PEMS, On-Board Emission Monitoring system OEM-2100[TM]. Three different scenarios were used: cold start, idling before driving the truck, and idling after driving the truck. The test vehicle was a 2004 International truck with a 7200-cc engine displacement and with almost 1000 miles mileage. Tests were carried on during six days in March 2004 in Houston, Texas. Each day, the test process was as follows: (i) equipping the test vehicle with the OEM-2100 system, (ii) starting and idling the truck for about 30 minutes, (iii) driving the truck to different roadway facilities for at least 45 minutes, (iv) idling the vehicle for about 20 to 30 minutes after driving the truck, and (v) repeating the last two steps. In addition, the measured idling emissions are compared with emissions estimated by the emission factor model MOBILE6 for the particular tested truck.

Results: Results for comparing cold and hot short-period idling demonstrate the test truck produces higher emissions during the temporal cold start engine and tends to be stabilized through time as the engine reaches its hot stabilized state, which is approximately 600 seconds. Comparison between idling tests before and after driving showed that NOx pollutant values before driving were always lower, while HC and CO values were always higher than those after driving the truck. As for fuel consumption and CO_2, it was found when the truck was driven on freeways; the values of these variables were lower in idling after driving than those before driving

the truck. However, when the truck was driven on non-freeway facilities, the results were reversed. It was found that by increasing the driving distance and duration, NOx and CO_2 emission production and fuel consumption decrease, while CO and HC emission production increase during the post-driving idling test. Additionally, emissions tested by OEM-2100 have higher values in comparison with the emissions estimated by MOBILE6.2. MOBILE6.2 estimates are based on the average laboratory tests' results; therefore, in this research (testing one type of vehicle), emissions tested by OEM-2100 should reflect more real-world situations of emissions in idling. Further tests and comparisons should be conducted before more general conclusions can be reached. However, this study concludes emissions estimated by currently understood emission factor models (MOBILE6) are inconsistent with OEM-2100 that is EPA-validated as more accurate, and the current idling emission models could be inaccurate for measuring real-world impacts.

Possible applications for AERIS: This study was used to generate empirical data for trucks that can be used for developing and refining emissions models, which is an important step for implementing emissions modeling within connected vehicle applications. Relationships between emissions and freeway versus non-freeway driving were established.

4.1.2.2   *Emissions and Fuel Consumption Testing for PowerMaxx Combustion Catalyst [8]*

Purpose: The overall goal of this study was to test the possible fuel consumption and emissions benefits for using PowerMaxx combustion catalyst in the diesel fuel of a heavy duty diesel truck. The study used PEMS equipment in performing the analysis of a baseline scenario (without PowerMaxx applied) followed by three more tests during which PowerMaxx was applied.

Background: The study was performed by Texas Transportation Institute (TTI). The test route was a 190-mile loop that stretched from Texas A&M University's Riverside Campus in Bryan, TX to Austin, TX and back to the Campus.

Description: The test vehicle was a 1999 Freightliner truck with a 14-liter diesel engine. The load was simulated by using 21 water-filled median barriers (approximately 36,860 pounds) inserted into a 53-foot trailer. Emissions and fuel consumption data was collected on a second-by-second basis using two types of PEMS equipment (the OEM-2100 "Montana", which was used to measure only PM, and the SEMTECH-DS that collects the other pollutants as well as fuel consumption). Data from the three runs were compared to that of the base case, and the comparisons are divided into the following two categories:

- Not-to-Exceed (NTE) events – NTE events produce an important basis for emissions comparisons because they represent instances where the engine is working the hardest and emissions typically are the greatest.

- Comparable data points – data that when compared were similar spatially (similar location), vehicle speed, acceleration rate, deceleration rate, and throttle position.

Vehicle speed, engine speed in revloutions per minute (RPM), torque, and fuel flow were measured with the vehicle engine control module. The route, elevation, and ground speed of the vehicle on a second-by-second basis were measured by a Global Positioning System (GPS) receiver. The truck followed a pre-determined route from Texas A&M University's Riverside Campus, to Austin, and then back to the Campus. PowerMaxx was added under supervision of TTI staff at the Riverside Campus, and the same procedure for monitoring results in the baseline scenario was performed.

Results: It was found that all tests with the application of PowerMaxx resulted in a reduction in fuel consumption. Reductions of between 6 and 14 % were observed for the various tests. Nearly

all results showed decreases in NOx emissions of between 7 and 20%. A possible explanation for the different NOx result could be attributed to considerably lower levels of relative humidity and the temperature observed on the particular day. In the case of PM, a 23% reduction was observed for the comparable data points based on a gram per second (g/s) emissions rate, and the reduction in PM is 17% if a gram per mile (g/mi) rate is used. The reason for comparison between g/s and g/mi parameters demonstrates that Powermaxx is effective under idling situations since no miles are accumulated during idling. Looking at comparable data points allows identifying particular conditions where Powermaxx provides greater benefits than standard vehicle technology.

Possible applications for AERIS: This study described an approach for evaluating the impacts associated with freight truck operations and the benefits when applying a vehicle technology strategy. This method can be applied for evaluating the benefits from implementing a variety of vehicle technology strategies by comparing results before and after implementation.

4.1.2.3   *Mexican Truck Idling Emissions at the El Paso – Ciudad Juarez Border Location [9]*

Purpose: The overall goal of the study was to develop and apply a methodology to estimate emissions produced by trucks from Mexico crossing the El Paso-Ciudad Juarez border locations. The specific objectives of the study are to develop: 1) a border crossing fleet profile that includes the make, model, and year of trucks crossing the two main border bridges; 2) a border crossing travel profile that includes profiles of the drive cycles (acceleration, deceleration, cruising, idling, and creep idling) of trucks crossing the two main border bridges; and 3) a border crossing emissions profile that provides estimates of idling emissions and driving emissions of trucks crossing the two main border bridges.

Background: This study was co-sponsored by the Southwest University Transportation Center and Region 6 of the U. S. Environmental Protection Agency.

Description: The northbound movements of trucks importing goods into the U.S. create long waiting times in the border locations due to several security and safety inspections that occur during the process. The El Paso-Ciudad Juarez region is served by two major truck ports of entry: the Bridge of the Americas (BOTA) and the Zaragoza border crossing. This experiment used a combination of on-board and external systems in order to collect composite data on truck emissions information relative to duration and distance of travel. GPS technology was used to collect drive-cycle information at both the BOTA and Zaragoza bridges. The drive-cycle information included travel times, idle, creep idle, acceleration, and deceleration data.

PEMS was used to collect data on NOx, HC, and CO, and the Tapered Element Oscillating Microbalance system was used to collect data on PM. PEMS units within the trucks collected idling information. Some trucks drove through the FAST lane at the commercial border crossing, which is similar to express toll lanes and aims to reduce idling emissions. In these lanes, a wireless radio frequency identification (RFID) reader reads a unique identification displayed on the windshield, allowing the truck to pass through as pre-approved. This methodology is used to estimate truck idling emissions at an individual border location, and this can be seen as a first step in developing a comprehensive Border Crossing Emissions Measurement Model (BCEMM). The model would have wide applications in determining and forecasting commercial vehicle emissions at land border crossings. A detailed database of the truck fleets, a comprehensive set of drive cycles, and a comprehensive sample of emissions rates under different driving modes should be used as building blocks for developing the BCEMM.

Results: The study presented a method for identifying and evaluating the emission impacts associated with high-traffic border crossing and congestion points. It was found that approximately 24 tons on NOx and 0.3 tons of PM are produced on an annual basis by trucks

idling at the BOTA and Zaragoza bridges. These emissions are not particularly high as compared with the total on-road mobile source emissions for the El Paso region (less than 1%). However, it should be noted that these emissions are generated in a very small geographic area (two border bridges) resulting in high concentrations of pollutant emissions in these areas. The results demonstrate that overall reduced emissions and fuel consumption are gained from using FAST lanes. The study team found that it was possible to collect emissions from a truck during actual crossings through the U.S.-Mexico border. However, due to the extensive coordination effort and the extremely sensitive nature of the fairly new FAST lane technology, numerous challenges were encountered, and it is recommended to collect the emissions on either the U.S. or Mexico side by having the trucks travel according to pre-determined drive cycles while being equipped with PEMS units.

Possible applications for AERIS: This study presented a feasible technique for evaluating emission impacts associated with border crossing. The study recognized the sensitivity challenges with actual implementation at the U.S.-Mexican border, but the method can be used for other areas of congestion caused by inspections or permitting/collection systems (e.g., toll booths). Transportation agencies or international organizations can consider methods to speed up border crossings to reduce idling time or organize border crossing schedules to reduce congestion.

Note: Evaluation 4.1.1.2, listed under light duty vehicles, also includes measurements for heavy duty vehicles.

4.1.3 Emissions Measurement for Transit Vehicles

Note: Papers 4.3.7.3.1 and 4.3.7.3.2 in Section 4.3.7.3 on eco-driving also use onboard sensors to measure emissions for transit vehicles.

4.1.3.1   Collection and Analysis of School Bus Emissions and Activity Data Using PEMS Equipment and GPS Units [10]

Purpose: This study compared average exhaust emission rates of diesel school buses developed from second-by-second in-use emissions data acquired from PEMS and corresponding MOBILE6 estimations.

Background: This study took place on the Riverside Campus of the Texas A&M University in 2006 by TTI.

Description: A select group of representative school buses were equipped with state-of-the-art SEMTECH D/S PEMS units to measure emissions and GPS units to track location data. NOx, HC, and CO emissions measurements were collected for the comparison to MOBILE6 estimates. PEMS tests were performed during July 2006 for a select set of five buses representing the typical diesel-fueled Texas school bus fleet under typical operation between the hours of 8:00 AM and 4:00 PM. Data from the units were collected over several days during actual operations on the real-world school bus routes and at a test track. Each bus was loaded with 56 50-lb. sand bags (2,800 lbs.) to replicate an average loading situation (approximately equal to 30 children). Test data evaluated in the study include engine parameters such as engine speed, throttle position, and engine load for data quality checking; second-by-second vehicle speed from the GPS; and emission rates. The data were utilized to characterize school bus drive cycles and emissions profiles.

Results: The study showed that the MOBILE6 emission rates estimated for the Texas diesel school bus fleet are all significantly higher than the emission rates produced by the sample fleet

as measured with the PEMS. The paper discusses the various reasons for the differences observed between PEMS measurement and MOBILE6 estimates. The factors that contribute to these differences are the effects of start emissions, variability of drive cycles, conversions from engine data to vehicle emissions, vehicle/engine data aggregations, and fuel parameters.

Possible applications for AERIS: The analysis conducted in this paper exemplifies the importance of collecting scenario-specific data to generate accurate emissions estimates. This technique can be adopted for efforts in understanding data collection methods and refining emissions models.

4.2 Infrastructure-Based Air Quality Measurements

This section describes studies that concern techniques for measuring air quality in the field. This type of measurement could be used either for input to emissions models, or to real-time decision tools, such as strategies to impose travel restriction when air quality reaches or is projected to reach specific levels.

4.2.1 Integrated Air Quality & Congestion Management Tool [11]

Purpose: The study entailed the development of an integrated air quality and traffic management platform to implement a new tool (TRACE [**TR**ansportation **A**ir quality & **C**ongestion **E**valuation]) for measuring, monitoring and improving traffic condition and air quality of different traffic networks. The tool also evaluates and forecasts performance and benefits of the deployed ITS technologies.

Background: The study was conducted as a small scale prototype on US-19 in Pinellas County, Florida by Telvent, Inc.

Description: The TRACE tool uses real-time data measurement using air quality sensors (CO, NO, NO_2, NOx, PM10 or PM2.5), traffic detectors (e.g., volume, speed and vehicle types) and (if available) weather monitoring systems (wind speed and direction, ambient temperature, and cloud cover). Weather data is also collected from various meteorological data providers through websites. The TRACE tool utilizes real-time traffic data as well as air quality and meteorological measurements to inform traffic managers of conditions and suggested appropriate response strategies to mitigate environmental impacts through increased transportation efficiency.

Results: No results from testing were included in the paper since testing is ongoing. The anticipated outcome of a pilot scale deployment at US-19 in Pinellas County, Florida will establish a benchmark for evaluation of various scenarios and response plans to manage prevailing traffic and air quality conditions. Future work will include integration of TRACE with EPA's MOVES 2009 modeling software as well as addition of new tools to estimate carbon dioxide and other greenhouse gas emissions.

Possible applications for AERIS: Use of the TRACE tool uses real-time traffic data as well as air quality and meteorological measurements to inform traffic managers of conditions and suggested appropriate response strategies to mitigate environmental impacts through increased transportation efficiency. This application is relevant to AERIS goals by using measurable data to calculate congestion and air quality impacts to a transportation system and implementing strategies using a variety of connected vehicle applications to mitigate the impacts. The tool consistently evaluates conditions of the system as strategies are implemented, allowing dynamic optimization. It also supports providing information to the public to allow better transportation

choices. Encouraging increased use of public transit including buses and light rail will likely be one of the "appropriate response strategies."

4.2.2 Modeling Environmental Impacts of Traffic using a New Generation of Pervasive Sensors [12]

Purpose: This study featured an array of fixed and mobile sensors to monitor traffic occupancy, location, temperature, humidity, noise, carbon monoxide and nitrogen dioxide as well as mobile environmental sensors.

Background: This study was conducted in 2009 at Gateshead and Leicester, England by Newcastle University.

Description: The fixed and mobile sensors have a data logger and a wireless mesh networking standard to communicate data through a gateway to a remote central server. The raw data is calibrated, using the manufacturer's specifications and subsequently quality assured and cleaned. Air quality data collected by these sensors was combined with an AIMSUN model to model emissions. A micro-simulation model was built for the Gateshead town centre area, using both the AIMSUN and the VISSIM software.

Results: In general, a good match was achieved between the data derived from micro-simulation and from existing legacy systems. Through the pervasive sensors it was possible to validate the OSPM dispersion applied to two different emissions models (SCOOT-based and micro simulation). An important observation for CO is the systematic drop in levels at the time of the peak hour when, because of idling emissions the levels are expected to be higher. A possible explanation for this is that these emissions estimates are based on average flow and speed emissions factors and ignore congested related emissions. The reduction in CO is consistent with low (or even zero) flow when the traffic is congested.

Possible applications for AERIS: The collection of air quality data by mobile and fixed sensors and the integration of the data into microsimulations is a good pattern to follow for evaluating the impact of connected vehicle applications, if before and after measurements can be achieved.

4.2.3 Control of Pollutant Emissions by ITS on the Austrian High Level [13]

Purpose: This paper describes the operation of a data-driven traffic management system in Vienna, Austria.

Background: The study was conducted in 2007-2008 for a highway section in Tyrol, Austria by ASFINAG, an Austrian motorways and expressways finance company.

Description: Traffic sensors measure the number of vehicles and vehicle speeds. Coupled with meteorological measurements (e.g. wind), air quality emissions are estimated using a quadratic function regression curve based on empirical data. The frequency of sampling depends on the specific local conditions (wind, terrain, etc.). Within the speed range specified in the regression curve (80-140 km/h), emission factors (measured in g PM10 or NOx/km) can be estimated using the measured speed in the quadratic functions. The algorithm calculates the contribution of light vehicles to air pollution every half-hour according to the regression curve equation. The algorithm is corrected by a prediction module concerning traffic and on a dynamic factor based upon past experiences. Video cameras complement and provide visual evidence for the information from the sensors. For the Tyrol case, if the estimated air pollution contribution is over a threshold

value, a maximum speed of 100 km/h is set ("speed 100"); otherwise the speed is set at 130 km/h. Threshold values are determined by retrospective analysis – the actual contributions of light vehicles to air pollution are calculated every half hour during the past year. The threshold value is stipulated by the government, but it can vary from year to year due to different meteorological conditions.

Results: A first year of experience with "speed 100" was performed until the end of 2008, for a highway section in Tyrol, Austria, with a length of about 80 km. In the first case study in Tyrol, Austria, during an entire year, temporary speed restrictions were in effect about 30% of the time, achieving an air pollution reduction of about 60% of the reduction that would have been achieved with a permanent speed reduction. During occasions when the air pollution was at the 95% percentile, the air pollution reduction effect of the reduced speed limit was about 75% of the reduction that would be achieved with a permanent speed reduction.

Possible applications for AERIS: This application has a similarity to proposed AERIS applications, using real-time measurements (in this case traffic volume and speeds) and emissions modeling to make a traffic control decision that reduces emissions. Insight into the modeling capabilities and algorithms the system uses for optimizing environmental impacts and traffic flow could be worth further evaluation.

4.3 Use of Models to Evaluate Environmental Impacts

This section discusses the use of models to evaluate the environmental impacts of ITS applications. Section 4.3.1 addresses traveler information, Section 4.3.2 addresses traffic signal control, Section 4.3.3 addresses transit operations, Section 4.3.4 addresses freight operations, Section 4.3.5 addresses Integrated Corridor Management, Section 4.3.6 addresses demand management, Section 4.3.7 addresses eco-driving, and Section 4.3.8 addresses model sensitivity.

4.3.1 Traveler Information

This section describes papers that concern evaluating the potential environmental benefits of traveler information. These studies use models to compare fuel consumption and emissions before and after the modeled implementation of a traveler information application.

4.3.1.1   *Fuel Saving Potential of Car Navigation Systems [14]*

Purpose: A fuel estimation model was developed within the project ECO2Nav to evaluate the impact if a car navigation system were to calculate a fuel efficient route in addition to the conventional shortest route or fastest route.

Background: The study was performed between Salzgitter and Braunschweig and between Salzgitter and Hamburg, Germany by the University of Applied Sciences, Institute of Traffic Management, Salzgitter, Germany, and reported in 2009.

Description: The paper shows results from driving tests carried out by the Institute of Traffic Management and presents a fuel calculation model for use in future navigation systems. A mathematical equation (model) for calculating the fuel consumption, based on the fundamental equation of vehicle dynamics, was developed.

Results: Driving tests showed that route choice, maximum speeds selected and the driving behavior have a strong influence on fuel burn leading to fuel savings of up to 43% with only 15%

increase in driving time (comparison of short route/fuel economic with fast route/standard). The fuel calculation model was compared with driving test results on various routes, and for two driving behaviors the average error of the model is less than 5%. The model shows a very good correlation with the standard driving behavior of with an error less than 2%.

Possible applications for AERIS: This technique (when fully developed) can be used to test "green enhanced navigation services" and possibly "Eco Driving". This paper describes research in methods to enable navigation devices to factor fuel consumption into the potential routes a driver can take.

4.3.1.2   *An Energy and Emissions Impact Evaluation of Intelligent Speed Adaptation [15]*

Purpose: The purpose of this paper is to evaluate the energy and emissions impact of advisory, active support, or mandatory Intelligent Speed Adaptation (ISA) systems to set speeds for fuel efficiency.

Background: The study was conducted in 2006 at University of California, Riverside. *Description:* "An Intelligent Speed Adaptation (ISA) system monitors the location and speed of the vehicle, compares it to a defined set speed, and takes corrective action such as advising the driver and/or governing the top speed of the vehicle… In addition to safety improvements, ISA has the potential to mitigate congestion by smoothing traffic flow during congested conditions, which may also lead to lower fuel consumption and pollutant emissions." This study used the Paramics traffic simulation to model freeway traffic scenarios from level of service (LOS) A (free-flow) through F (totally congested). The outputs from the Paramics models were used as input to the CMEM emissions model.

*Results: "*As expected, little benefit was seen at LOS A–C since very little congestion occurs during these conditions. On the other hand, the energy/emissions benefits of ISA are much more significant for congested freeways, i.e., at LOS conditions D-F. Implementing ISA to limit the vehicles speed at LOS D, where traffic approaches unstable flow, has the greatest impact on emissions (CO: 93%, HC: 90%, NOx: 86% reduction) and fuel savings (70%). This is because the normal acceleration/deceleration events associated with stop-and-go maneuvers of the vehicle velocity trajectory is damped out considerably. Interestingly, it was found that ISA also helps decrease travel time by up to 15% during congested freeway conditions (LOS D-F)."

Possible applications for AERIS: Intelligent Speed Adaptation is a possible connected vehicle application that could be evaluated by AERIS. AERIS evaluation might entail extending this model on a larger scale, using data from actual representative freeways taken under various congestion conditions. Emissions from transit vehicles should be considered as well as emissions from private and freight vehicles. The AERIS study would extrapolate these data to estimate the extent of LOS A through F congestion on total freeway mileage and to discuss how the results of the study would scale to a regional level. ISA could be classified as a traffic control application if the speed restrictions are implemented as automatic controls to the vehicle rather than as advisories to the drivers.

4.3.2 Traffic Signal Control

This subsection describes papers that concern evaluating the potential environmental benefits of improved traffic signal control operations. These studies use models to compare fuel consumption and emissions before and after the modeled implementation of a traffic signal control application.

4.3.2.1 Evaluation of an Adaptive Traffic Signal Control System: Route 291 in Lee's Summit, Missouri [16]

Purpose: This study evaluated the effectiveness of new traffic signal control deployment. Before and after real-world data were collected and compared.

Background: This report was developed at the Midwest Research Institute in March 2010 to evaluate a newly installed adaptive control system along Route 291 corridor between I-470 and US 50 in Lee's Summit in Kansas City, Missouri.

Description: The measures evaluated included fuel consumption and emissions along with travel time and delay. A new adaptive system was installed in the spring of 2009. The study data included travel times, speed and acceleration (peaks and off-peaks) during the study period by running 4 vehicles equipped with PC-Travel Software linked to Global Positioning System (GPS) receivers. GPS locations were reported on a second by second basis from which travel time and average speed and acceleration were calculated. Average fuel consumption in gallons for a passenger car was estimated by the PC-Travel software based on travel time and average speed. Average emissions of volatile organic compounds (VOC), carbon monoxide (CO), and oxides of nitrogen (NOx), each measured in grams, were derived from speed and acceleration by the PC-Travel software.

Results: Adaptive type control strategy was more effective in reducing fuel consumptions and vehicle emission (HC, CO, and NOx) during non-peak hours. The reduction level is more closely associated with the number of stops. When the number stops are effectively reduced, the fuel consumption and vehicle emission will be reduced in general. From the data tested, following was observed.

- Fuel consumption was reduced from 0% to 21.4%, except AM peak (increased 4.5%)

- HC was reduced from 8.9% to 42.6%, except that in AM peak (increased 6.2%)

- CO was reduced from 4.9% to 28.9%, except that in AM peak (increased 4.3%)

- NOx was reduced from 8.1% to 50%, except that in AM peak (increased 8.8%)

Possible applications for AERIS: Using GPS equipped vehicles to collect individual vehicle speed and acceleration data to calculate fuel consumption and vehicle emission is a feasible approach because of its simplicity and low cost. It can be used to evaluate any technologies or even improvement in roadway infrastructure.

4.3.2.2 Optimizing Traffic Control to Reduce Fuel Consumption and Vehicular Emissions: Integrated Approach with VISSIM, CMEM, and VISGAOST [17]

Purpose: The purpose of the study is to improve methods of measuring the savings in fuel consumption and emissions that can be realized by optimization of signal timing.

Background: This study was a joint collaboration between the University of Utah and the University of Michigan. It was presented at the 2010 TRB conference.

Description: The team linked the microscopic traffic simulation model VISSIM, the emissions model CMEM, and the signal timing model VISAGAOST[19] to optimize signal timings and minimize fuel consumption and CO_2 emissions for a 14-intersection network in Park City, Utah. Given an initial estimate of traffic flow, VISAGAOST produced a synchronized signal timing plan. VISSIM was run with the timing plan to produce second-by-second trajectories, and those trajectories were fed into CMEM to produce estimates of CO, HC, NOx, and CO_2 emissions. Then the cycle

was repeated with the new traffic volumes until equilibrium was reached. Signal timings were optimized for seven optimization objective functions to find the lowest fuel consumption and emissions.

Results: When CMEM-estimated fuel consumption is used as an objective function, estimated fuel savings are around 1.5%, a statistically significant decrease. Optimization to minimize fuel consumption resulted in significantly lower fuel consumption than optimization to minimize stops and delay. The study also concluded that the fuel consumption estimates produced by VISSIM itself overstate the fuel consumption compared to CMEM. The only emission modeled was CO_2. The results presented for fuel consumption were not extended to CO_2 emission, but in the table of results for various oprimizations, the level of CO_2 emission does correlate with the level of fuel consumption.

Possible applications for AERIS: This study is an excellent model for the integration of microscale traffic, emissions, and signal timing models. It carefully describes how the models were integrated and how several objective functions were chosen and evaluated in an iterative fashion. However, the paper did not model any emissions other than CO_2, and lacked a discussion of whether the results might be directly applicable to other signalized corridors, and how the results might be generalized to a regional basis.

4.3.2.3   Emission Modeling at Signalised Intersections Using Microscopic Models [18]

Purpose: This project studied traffic simulation models and data at a signalized intersection and compared them to the real world data. The purpose of this paper was to reveal potential deficiencies in traffic simulation when modeling real traffic. Traffic emission measures were used to compare the discrepancies between using real data and using simulated data.

Background: The study was conducted using data from an intersection in Rotterdam, Netherlands.

Description: VERSIT+ is a statistical traffic emission model that is used to estimate vehicle emissions given vehicle speeds and accelerations as inputs. It has built-in models to compute emissions for four vehicle types: cars, heavy duty medium, heavy duty heavy, and buses. The researchers used the VERSIT+ emission model to study traffic emissions by comparing real-world traffic measurements (speeds and accelerations) and those simulated measurements (speeds and accelerations) using VISSIM and AIMSUN.

Results: This article concluded that when vehicles are travelling under non-congested traffic conditions, the simulated data (VISSIM and AIMSUN) more likely to overestimate vehicle emission; whereas they generally under estimate emissions in stop and go traffic conditions.

Possible applications for AERIS: VERSIT is a tool that can be used for evaluating AERIS applications. According to the literature, it requires only speed and acceleration to estimate the traffic emissions for up to four vehicle types. This research provides insights in using evaluation tools such as VISSIM, AIMSUN and VERSIT that are all applicable to AERIS project evaluation. The research revealed the causes of discrepancies in traffic emission estimates between using measured data (speed and acceleration) and the simulated counterparts. The results are also generic so that they are applicable to any use of VISSIM and AIMSUN to evaluate AERIS applications. The research did not mention whether or not the authors had calibrated the VISSIM and AIMSUN models before making the conclusions.

4.3.2.4   Improved Signal Control: Socio-Economic Benefits [19]

Purpose: This study used a microscopic traffic simulation approach (VISSIM) to assess the impacts of signal improvements on three types of signal controls (coordinated, actuated, and isolated fixed-time).

Background: This study examined all 2800 traffic signals in Denmark. It was carried out in 2008 by the Danish Road Directorate Office for Traffic Management and ITS.

Description: The study analyzed impacts of faulty detectors, where applicable, and traffic signal re-timing via signal optimization. Simulated data are used to assess benefits.

Results: The report estimated that a reduction in fuel consumption by use of more efficient traffic signals would reduce the national Danish CO_2 emission from road transportation by 0.5-1.0%.

Possible applications for AERIS: This study took a truly national approach, examining all 2800 traffic signals in Denmark. Attempts to derive a national number for the U.S. might consider this approach. However, the low level of benefits (0.5 – 1%) concluded by this study do not look promising.

4.3.2.5   Real-Time Monitoring of Emissions with Traffic Data, Simulation and Air Quality Measurements [20]

Purpose: This study models the decision when to apply a dynamic traffic management measure to improve air quality and reduce CO_2 emissions.

Background: The study was performed in 2008 and 2009 for the Kruithuisweg intersection, in Delft, Netherlands as part of the Transition Sustainable Mobility (TRAMSUMO) project, Advanced Traffic Monitoring.

Description: The AIMSUN traffic simulation model was used in combination with the VERSIT+ emission model. Video observations were collected from the intersection traffic on a few days in November and December 2008, together with air quality measurements of CO_2, NOx and PM concentrations. Furthermore, traffic data were gathered from loop detectors in the road. For the air quality measurements, a flexible tube was used. The video images were used to derive vehicle trajectories and speeds.

Results: High emissions correspond to vehicles that had to stop at the traffic light. Vehicles that did not have to slow down at all had the lowest emissions, and the middle emissions correspond to vehicles that had to slow down for the traffic light, but did not need to come to a complete stop. The difference in CO_2 emissions between those regimes is very large (a factor of about 3.5). The number of vehicles that had to stop is much larger than the vehicles that did not have to stop. These observations indicate that much can be gained (both for throughput and emissions) by optimizing the traffic signal control.

Possible applications for AERIS: It seems achievable to estimate vehicle emissions at an intersection with reasonable accuracy, if it is known how many vehicles have to stop. It is possible to estimate this with loop detections, combined with information on signal status and queue-length estimation algorithms. A combination of monitoring and modeling is needed for reliable air quality estimations, and current traffic and emission models are often unsuitable for high resolution situations.

4.3.3 Transit Operations

4.3.3.1 Assessing the Net Effect on Emissions of the Implementation of a BRT System in São Paulo, Brazil: a Case Study and some Hypothetical Scenarios [21]

Purpose: This study uses the IVE model (www.issrc.org/ive) to estimate emissions as a function of vehicle type and characteristics, driving cycles and other variables describing local conditions.

Background: The study was performed using traffic data collected in Sao Paolo, Brazil in 2006 ("before") and 2009 ("after") by the Polytechnic School of the University of São Paulo, and BMC Engenharia, an engineering firm.

Description: The model is used to estimate emissions (CO_2 and the following pollutants: CO, VOC (Volatile Organic Compounds), NOx and PM_{10}) using bus and auto volume and speed data collected before and after a Bus Rapid Transit (BRT) project. The paper discusses side-effects of the BRT project, including the diversion of auto traffic to other routes because the capacity for autos was reduced.

Results: The paper presents results for CO_2 and each pollutant in table form, comparing before/after BRT project emissions. The results are not a unilateral reduction of emissions, because emissions from the assumed displaced vehicles are also included. "When the contribution of autos taking alternative routes after the implementation of the BRT system is taken into account in the estimates of total emissions, important change in results can occur; emissions of CO, VOC and CO_2 actually increased and only pollutants more directly related to bus operations, such as particulate material and NOx, decreased."

Possible applications for AERIS: This paper has high relevance to AERIS. Dedicated right-of-ways for transit vehicles could be part of an AERIS strategy. The IVE model is similar to the MOVES model, and the use of the model is similar to the way would be used in an AERIS study to estimate the emissions effect of a connected vehicle application. The paper is clear about pointing out limitations and assumptions in carrying out the study; the same considerations are likely to be relevant in an AERIS study. The concept of balancing volume reductions by increasing volumes in another location or category is good, and should be emulated in AERIS modeling.

4.3.4 Freight Management

4.3.4.1 Environmental Impacts of a Major Freight Corridor: A study of the I-710 in California [21]

Purpose: This paper explores an approach to estimating vehicle emission impacts of freight corridor operations related to the San Pedro Bay Ports (SPBP) area, particularly those associated with heavy duty diesel trucks. The approach involves use of a microscopic traffic simulation model to capture detailed vehicle trajectories and congestion effects, emissions modeling, and modeling the spatial dispersion of pollutants in the corridor. Several emission-reduction scenarios are examined that include the simulation of ITS strategies.

Background: This study was carried out by the University of California Transportation Studies Institute and focuses on operation of the I-710 freeway in the Alameda Corridor, leading from the SPBP area for about 20 miles toward Los Angeles.

Description: The SPBP of Los Angeles and Long Beach is one of the largest container port complexes in the world. A microscopic traffic simulation model (TransModeler), an emissions

model for various pollutants (CMEM), and a dispersion model (CALPUFF View) were used to evaluate the environmental impacts of various scenarios. Three scenarios are considered: 1) a baseline scenario based on 2005 data; 2) a truck replacement scenario; and 3) a shift in freight transportation from trucks to trains. The following strategies were evaluated and compared with the 2005 baseline scenario:

- Replacement of the current fleet of port heavy duty diesel trucks with zero emission trucks (25% [Scenario 1A], 50% [Scenario 1B], and 100% [Scenario 1C] of port trucks)

- Elimination of port heavy duty diesel truck trips (25% [Scenario 2A], 50% [Scenario 2B], and 100% [Scenario 2C] reductions) that would correspond to shifting more containers to other modes such as rail

- Implementation of a truck restricted-lane on I-710 preventing trucks from using the two left most lanes (Scenario 3)

For traffic simulation, traffic origin and destination demand inputs were obtained and validated from the 2000 Southern California Association of Governments traffic study, which is the most comprehensive study available for Southern California. Traffic flow on the I-710 freeway was measured from loop detectors through the Performance Measurement System (PEMS). Coordinates for the basic freeway layout were extracted from a GIS layer provided by Caltrans. Data from the morning peak hour (7:00 AM to 8:00 AM) of Wednesday, March 9, 2005 was selected to represent the baseline scenario. The TransModeler model provided second-by-second information about each vehicle's ID, coordinates, instantaneous speed and acceleration. Vehicle emissions were evaluated by post-processing using CMEM. Meteorological and land-use data from 2005 were used in CALPUFF View along with the emissions results from CMEM to model dispersion.

Results: Implementation of the modeling framework explored in this paper is demonstrated to be feasible. The specific modeling results show that CO in all of Scenario 1, HC in all of Scenario 2, and CO_2, HC, and PM in Scenario 3 are not significantly changed from the base scenario. Scenario 1C shows the largest reduction of emission rates among all scenarios: CO by 1.7%, HC by 8.8%, NOx by 64.1%, and PM by 60%. CO and HC in Scenario 2 and 3 are relatively higher compared to the base scenario because traffic conditions of those scenarios are dominated by light-duty vehicles resulting from truck volume reduction and truck-restricted lanes. The smallest NOx concentration among all scenarios is Scenario 1C, and the smallest concentration of PM is Scenario 2C, even though PM emissions in Scenario 2C are slightly worse than in Scenario 1C. The dispersion model shows that PM concentrations of the base scenario, 1A, 2A, 2B, and 3 indicate unhealthy levels for a sensitive group, and only Scenario 1C indicates good air quality levels. Results show that fleet replacement with cleaner (zero emission) trucks yields the most emission reductions both quantitatively and spatially. Impacts from rail or alternative modes resulting in Scenario 3 are not considered in the study but is something being evaluated in a parallel effort.

Possible applications for AERIS: The technique of using simulation models provides a suitable approach for evaluating environmental and health impacts under various transportation scenarios. This study provides a framework for data collection and processing from various transportation systems and demonstrates the applicability of using existing data sources to generate meaningful results.

4.3.4.2   *A406 VISSIM Study [23]*

Purpose: The study examined the effects of removing Heavy Goods Vehicles (HGVs) with 3 or more axles and weighing over 7.5 tons from the A406, a major highway in England, in terms of how many years of traffic growth would be released (i.e. how many years of traffic growth at 0.7% per year could occur before traffic and emissions levels would return to current levels). A VISSIM model, with its internal emissions model, was used for the study.

Background: This study was performed in2004 for Transport for London by the consulting firm Faber Maunsell.

Description: The base VISSIM model represented one hour of traffic on the A406 (7:70 – 8:30 a.m.) and intersecting roads (Finchley Road and Regents Park Road) with attention to the ratio of passenger cars to HGVs. The VISSIM model calculated the degree of saturation, vehicular throughput, queue lengths, and hours of vehicle delay for scenarios corresponding to removal of 25%, 50%, 75%, and 100% of the HGVs. VISSIM then used simple emissions calculations to estimate carbon monoxide and NOx emissions for cars, HGVs, and buses.

Results: "For 100% removal of HGVs, the levels of Carbon monoxide reduce by approximately 30% whilst Nitrous Oxides reduces by 27%. The future year assessment … has been derived by iterative tests. From the network emissions statistics the total carbon monoxide value is the first key characteristic that reaches the same level as the base 2004 model." "Based on key network performance characteristics of vehicle emissions and network delay, the assessment indicates that approximately 16 years worth of traffic growth could be released or a 12% increase in traffic if 100% of the HGV were to be removed. This value was determined when the first of the characteristics reached the same level as the base 2004 case assuming 0.7% traffic growth per annum. …Removing 75% of the HGV resulted in a growth factor of 9%, which is equivalent to 12 years traffic growth at the average traffic increase of 0.7% per annum. Scenarios 5 and 6, removal of 50% of the HGV's, assumes a growth factor of 5%, which is equivalent to 7 years traffic growth. The results indicated that the removal of 25% of the HGV does not provide any benefit to the operational performance of the network with results being comparable to that of the base year model without any factoring being applied."

Possible applications for AERIS: This study uses the built-in emissions estimation capability of VISSIM, which does not include GHGs or regulated emissions other than CO and NOx. The report states "The UK version of VISSIM provides simple emissions calculations for the network as a whole … It is understood that these parameters are non-UK based, but would provide a basis for comparison." The results were a reasonable estimation of avoided CO and NOx emissions.

4.3.4.3 Modeling Reduced Traffic Emissions in Urban Areas: the Impact of Demand Control, Banning Heavy Duty Vehicles, Speed Restriction, and Adaptive Cruise Control [24]

Purpose: This study uses the VISSIM traffic simulation and the EnViVer emissions model to model four approaches for emissions reduction:

- Reducing traffic volume,

- Reducing the number of heavy vehicles,

- Avoiding acceleration and deceleration with Adaptive Cruise Control (ACC), and

- Obtaining optimal speed.

Background: The study was conducted in 2008 by the Centre for Transport Studies at the University of Twente in the Netherlands. It was sited and calibrated at a single heavy volume intersection in Rotterdam, Netherlands.

Description: VISSIM was used to simulate the base case and four alternate scenarios. Individual second-by-second vehicle trajectories were output. The emissions model used was EnViVer, an offshoot of the VERSIT+ model, focusing on emissions from a stream of vehicle data from a microscopic simulation. Simplifications from VERSIT+ to EnViVer included: modeling only four vehicle types, and rather than multiple drive cycles, only average speed and a "dynamic variable" (a + .014v) were used.

Results: For 20% traffic reduction, total emissions were reduced about 23% for all pollutants. The reduction is more than 20% because of the reduction in congestion. The reduction is slightly higher (27%) for heavy vehicles. For the case where heavy vehicles were banned, CO_2 was reduced 26%, NOx was reduced 50% and PM10 was reduced 31%, even with some increase in emissions from light vehicles. For the speed reduction case, CO_2 decreased 8%, but NOx and PM10 increased. The paper does not have a convincing explanation for the significant increase in PM10. For the ACC case, CO_2 and NOx were reduced 3% but PM10 increased 3%. In EnViVer, PM10 emission is not sensitive to vehicle dynamics.

Possible applications for AERIS: The way speed restrictions and ACC were modeled could be studied and adapted for U.S. use. It appears that the results were driven as much by how these restrictions were implemented in VISSIM as how emissions were modeled.

4.3.5 Integrated Corridor Management

This section includes studies related to the USDOT's Integrated Corridor Management (ICM) program, the Metropolitan Model Deployment Initiative (MMDI).program, and other corridor-related studies. Evaluations conducted for the traffic impact of these corridor applications have also included assessments of environmental impacts.

4.3.5.1 Analysis, Modeling, and Simulation for the I-15 Corridor in San Diego, California [25]

Purpose: This report documents the analysis of Integrated Corridor Management (ICM) strategies as applied to I-15 corridor north of San Diego, California. "The corridor study area consists of the freeway including managed high-occupancy/toll (HOT) lanes and general purpose lanes, frontage roads, Bus Rapid Transit, park-and-ride lots, and regional arterial streets. The analysis investigated various operating conditions on the I-15 corridor including high, medium, and low travel demand, daily operations, and freeway and arterial incidents. ICM strategies analyzed include pre-trip and en-route traveler information, mode shift to transit, freeway ramp metering, signal coordination on arterials with freeway ramp metering, physical bus priority, and congestion pricing on managed lanes."

Background: This report was conducted in 2010 by Cambridge Systematics, with support from San Diego Association of Governments and the I-15 San Diego ICM Team. Evaluation of the future ICM deployment along this corridor is currently being planned by Battelle.

Description: The researchers used TransModeler to build and calibrate a microsimulation of traffic movement, supporting the evaluation of traffic control aspects of ICM strategies, including freeway ramp metering and arterial traffic signal coordination, as well as managed-lane operations. The analysis included multiple scenarios representing high and low demand, extreme weather, and minor and major incidents. The simulation period was the morning peak period from 6:00 AM to 11:00 AM. "Estimation of emissions and fuel consumption … utilizes the IDAS [ITS Deployment Analysis System] methodology that incorporates reference values to identify the emissions and fuel consumption rates based on variables such as facility type, vehicle mix, and travel speed. The emissions and fuel consumption rates were based on currently available sources such as California Air Resources Board EMFAC 2007 and the EPA's MOBILE6." Battelle's evaluation of the air quality benefits of ICM applications is planned to use the EMFAC model, as appropriate for California.

*Results: "*The benefits from ICM are attributable to reduced travel times, improved travel time reliability, reduced fuel consumption, and reduced mobile emissions. Expected annual savings include 245,594 hours of vehicle-hours of travel, a reduction of fuel consumption by 322,767 gallons of fuel, and an annual reduction of 3,057 tons of vehicular emissions. Across all operational conditions, most of the ICM benefit is attributed to the travel time, travel time reliability, and fuel savings on the southbound freeway and arterials. With the provision of improved traveler information, more arterial travelers are attracted to the freeway thus improving arterial performance and overall system performance."

Possible applications for AERIS: Many of the applications evaluated for this study are applicable to AERIS, such as pre-trip and en-route traveler information, mode shift to transit, ramp metering, signal coordination, and congestion pricing. However, the study concentrated more on mobility impacts than environmental impacts. The IDAS evaluation methodology using tables from EMFAC and MOBILE 6 does not use the full second-by-second trajectory data available from the microsimulation, but uses average speeds and data aggregated by link. More detailed modeling of emissions for a corridor implementation using microsimulations of emissions may provide a more comprehensive analysis of emissions effects.

4.3.5.2   *Analysis, Modeling, and Simulation for the US-75 Corridor in Dallas, Texas [26]*

Purpose: This report documents the analysis of Integrated Corridor Management (ICM) strategies as applied to US-75 corridor north of Dallas, Texas. The goals and approaches of the project are the same as those for the study of the I-15 corridor north of San Diego, California (reference 25).

Background: This report was conducted in 2010 by Cambridge Systematics, with support from Dallas Area Rapid Transit and the US-75 Dallas ICM Team. Evaluation of the future ICM deployment along this corridor is currently being planned by Battelle.

Description: The researchers simulated the morning peak period along the US-75 corridor from 5:30 AM to 11:00 AM. The mesoscopic modeling tool DIRECT was used to model the corridor, unlike the TransModeler microsimulation used for San Diego. In other respects, the analysis approach, including the variety of scenarios and the analysis of fuel consumption and air quality impacts, was the same as the approach used for San Diego (see Reference 25). Battelle's evaluation of the air quality benefits of ICM applications is planned to use the EPA's MOVES model.

*Results: "*The benefits of ICM are attributable to reduced travel times, improved travel time reliability, reduced fuel consumption, and reduced mobile emissions. Expected annual savings include 740,000 hours of person-hours of travel, a reduction of fuel consumption by 981,000

gallons of fuel, and a reduction of 9,400 tons of vehicular emissions." The analysis of the results follows the same approach as for the San Diego study.

Possible applications for AERIS: Many of the applications evaluated for this study are applicable to AERIS, such as pre-trip and en-route traveler information, incident signal retiming plans for arterials, managed lanes. However, the study concentrated more on mobility impacts than environmental impacts. The IDAS evaluation methodology using tables from MOBILE 6 and using output from a mesoscale simulation does not provide an in-depth study of the drive cycle effects of the mobility applications and the corresponding emissions effects.

4.3.5.3   ITS Impacts Assessment for Seattle MMDI Evaluation: Modeling Methodology and Results [27]

Purpose: This paper reports the results of a study to evaluate the impact of the Seattle model deployment, Smart Trek, in the areas of Advanced Traveler Information Services (ATIS), Advanced Traffic Management Systems (ATMS), and Incident Management Systems (IMS). The paper presents the methodology of the study and details findings for a mixed freeway/arterial corridor model drawn from the roadway network north of downtown Seattle. Impacts are characterized in terms of near-term peak period delay reduction, travel time reliability, changes in regional mode choice, corridor travel throughput, fuel consumption, emission rates, and other measures.

Background: This study was performed in 1999 by Mitretek Systems (now Noblis) for the Metropolitan Model Deployment Initiative (MMDI).

Description: The study used the Process for Regional Understanding and EValuation of Integrated ITS Networks (PRUEVIIN) ITS evaluation methodology, featuring a traditional four-step transportation planning model and a traffic simulation to capture regional and corridor level ITS impacts. EMME/2 was implemented as the transportation planning model and INTEGRATION 1.5 was implemented as the simulation model. The simulation was exercised through a series of 30 scenarios. Each scenario represented a particular combination of weather impacts, and travel demand variation, as well as a pattern of incidents and accidents in the corridor. Link-level speed and stop data were used to drive an energy and emissions post-processor developed for MMDI evaluation at the Virginia Polytechnic Institute and State University. Energy estimates were calculated as total liters of fuel consumed. Total emissions of hydrocarbons (HC), carbon monoxide (CO) and nitrates of oxygen (NOx) were also estimated.

Results: "The energy and emissions impacts from ATMS measures did not fully compensate for the 0.4% increase in subarea travel in the emissions analysis. Overall, small increases were indicated for fuel consumption and the three pollutants, but none of these increases are statistically significant when compared with the inherent randomness in the simulation… The ATIS experiment resulted in a small decrease in subarea travel and a small increase in total vehicle stops. These changes translate into small positive impacts on subarea energy consumption and total emissions using the Virginia Tech postprocessor. Viewed against the inherent randomness in the simulation, however, none of these changes can be shown to be statistically significant… The IMS measures resulted in a 5.5% drop in number of stops, resulting in across-the-board improvements in energy efficiency and emissions reductions. A 3.0% reduction in total CO emissions and total NOx emissions was indicated, primarily the result of a reduction in high-speed stops. A smaller reduction was indicated for HC, while overall fuel consumption dropped by 0.8%."

Applicability for AERIS: This study made effective use of a mesoscale model (Integration 1.5) to separate out the effects of ATIS, ATMS, and IMS measures. Many AERIS applications fall into the same categories. The PRUEVIIN methodology derives benefits across a selection of 30 scenarios, rather than a single scenario. It is recommended for AERIS evaluations to employ a similar evaluation methodology.

4.3.6 Demand Management

This section describes studies relating to modification of demand or demand types or infrastructure improvements relating to demand.

4.3.6.1 Evaluating Air Quality Benefits of Proposed Network Improvements on Interstate 10 in the Coachella Valley [28]

Purpose: The purpose of the study is to evaluate the air quality benefits of several proposed improvements to the I-10 corridor in southern California, using microscopic traffic and emissions models. The changes include intersection improvements and lane expansions on the mainline. About 25 miles of the highway are studied, including 13 interchanges. The models separate out the differences resulting from highway changes from differences resulting from anticipated cleaner fuels mandated by California.

Background: This report was conducted in 2006 by the Center for Environmental Research and Technology, part of the University of California at Riverside.

Description: The study used a PARAMICS model of the I-10 corridor, calibrated for traffic in 2000 and evaluated with morning peak hour traffic projected for 2030 with and without highway improvements. The results from the Paramics model were fed into the CMEM Version 3.0 emissions model. Integrating CMEM within PARAMICS was accomplished by creating a plug-in through the use of PARAMICS *Programmer*, which allows the user to access many of PARAMICS' features and variables as the simulation takes place. The researchers projected the proportions of vehicle types, ages, and engine maintenance. The researchers took into account the phenomenon of induced demand from increased highway capacity as well as normal projected increased demand. In addition to fuel consumption, the following emissions were estimated: CO_2, CO, HC, and NOx.

Results: Comparing scenarios with network improvements vs. the current network given future demand (but not including induced demand) resulted in increased fuel consumption and emission rates of CO_2 and NOx. The authors speculated that this could be caused by the drop in the ratio of hours traveled to miles traveled, (essentially a network speed measure) after the network improvements, as "CO_2 and NOx emissions are known to have an inverse relationship with speed at low speed ranges (< 30 mph)". Requirements for cleaner fuels resulted in improvements for all measures except CO, greater than the setbacks in emissions. When the same comparison was performed for demand including induced demand (approximately 10% additional), "the network improvements consistently reduce pollutant emissions and fuel consumption, as the cleaner fleet does… The absolute reductions in CO_2, CO, HC, and NOx are 22.44, 2.18, 0.22, and 0.10 tons per hour, respectively."

Possible applications for AERIS: Although the changes studied in this paper address intersection and highway lane improvements rather than ITS deployment, the methodology for comparing fuel consumption and emissions while taking into account induced demand and mandated cleaner fuels as well as fleet age and engine efficiency is useful to keep in mind for AERIS studies. The

description of the tie from PARAMICS to CMEM could also be useful. However, if the result of congestion reduction applications is increased emissions and fuel consumption as it was for the first comparison in this study, additional research should be performed to determine the underlying mechanism.

4.3.6.2   *Impacts of Freeway High-Occupancy Vehicle Lane Configuration on Vehicle Emissions [29]*

Purpose: The purpose of this paper is to evaluate the difference between continuous and limited access high-occupancy vehicle (HOV) lanes in California using microscopic traffic simulation and emissions models.

Background: This report was conducted in 2006 by the Center for Environmental Research and Technology, part of the University of California at Riverside.

Description: The study considered a 12-mile stretch of State Route 91 East in Riverside County, California. Detailed data for April 2006 for morning peak period (6 - 9 a.m.) from California Department of Transportation was used for calibrating the model. The freeway was modeled with a limited access HOV lane and a continuous access HOV lane. Vehicle types included single-occupancy vehicles, high-occupancy vehicles, light-duty trucks, medium-duty trucks, and heavy-duty trucks. The final calibrated networks were further equipped with the CMEM plug-in. During the simulation, the plug-in calculated second-by-second tailpipe emissions of CO, HC, NOx, and CO_2 from the simulated vehicles.

*Results: "*Under the same traffic condition the continuous access network produces less emission than the limited access network for every pollutant. The largest emission differences are for CO, followed by HC. The continuous access network produces about 12–17% less CO and 7–13% less HC. For NOx and CO_2, the differences are comparatively lower than CO and HC. It is observed that the trends of emissions differences between the two networks do not change significantly as the overall vehicle demand increases. In the limited access network, HOVs are required to change lane from the HOV lane to the adjacent MF lane, and vice versa, only at designated ingress/egress locations. Therefore, the lane changing activities are highly concentrated over the limited length. With this constraint, they often have to conduct unnatural driving behaviors such as slowing down rapidly to wait for an acceptable gap in the adjacent lane, accelerating aggressively to take the gap ahead of them, or making a forceful merge into the adjacent lane, which may cause the following and surrounding vehicles to brake unexpectedly. These behaviors not only affect the driving pattern of the HOVs themselves but also influence the driving pattern of other vehicles in the mainstream traffic in all lanes. As a result, the frequency and magnitude of acceleration/deceleration (and thus vehicle emissions) on these sections are relatively high. In contrast, HOVs in the continuous access network have less constraint in their driving; i.e. they are given unlimited opportunity to search for an acceptable gap to change lane. The weaving maneuvers in this network are distributed over a longer distance and the unexpected driving behaviors are less likely to occur. Therefore, the levels of acceleration/deceleration and the associated emissions are lower."

Possible applications for AERIS: This study shows how reducing accelerations and decelerations by spreading out the opportunities for lane-changing into and out of the HOV lanes reduces HC, CO, CO_2, and NOx emissions. The goal of many connected vehicle applications such as adaptive signal control and eco-driving is to reduce accelerations and decelerations through traffic smoothing, so the techniques of this modeling approach should be applicable to studies of those applications as well.

4.3.6.3 *CORSIM Application of Alternative Fuels for Transit Buses [30]*

Purpose: This paper uses the CORSIM microsimulation to model service reliability, fuel economy, and environmental effects of the following alternative fuels for transit vehicles: biodiesel, compressed natural gas (CNG), liquefied natural gas (LNG), ethanol, hydrogen, and hybrid electric.

Background: This study was conducted by the University of Delaware, and presented at the 2010 Transport Chicago Conference.

Description: The authors built two CORSIM models of bus operation using data from the National Renewable Energy Laboratory (NREL), the Department of Energy (DOE) case studies, and the Altoona Bus Research Center. "One is a model that is provided with the program (CORSIM City) and the second is a model that has been created to replicate the campus of the University of Delaware. CORSIM City is a much larger network that encompasses both surface and freeway networks. The campus network is on a smaller scale and only utilizes a surface network. Fuel consumption and emission rates can be entered into the software dependent upon the speed and acceleration rates of the vehicle. For a given network, CORSIM produces output of the actual fuel consumption and emissions rate that occurred throughout the network. The assessment of service reliability focused on travel time, delay time, and average speed. The fleet size is then determined from the headway and travel time. The fuel economy of the bus is the number of miles that can be traveled by the bus per gallon of fuel (No. 2 diesel gallon equivalent). Three types of emissions are compared: hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx). These three are selected because they are the only emissions that can be measured within CORSIM. They are expressed in grams per mile."

Results: "The MPG for the diesel bus remains almost identical between surface and freeway travel. The biodiesel and hydrogen buses experience better fuel economy on the freeway network. CNG, LNG, ethanol, methanol, and hybrid each experience better fuel economy on the surface network. Hydrogen experiences the best fuel economy overall, far surpassing biodiesel with the second best overall fuel economy. One trend that is apparent is the fuels with a higher fuel economy, biodiesel and hydrogen, have a higher MPG on the freeway, and fuels with a lower fuel economy have a lower MPG on the freeway." Regarding emissions, "Clearly the hydrogen bus is the best selection in terms of environmental effects because it is a zero emissions vehicle. For the other alternatives, there is little consistency in terms of the amount of pollution that a fuel emits from one pollutant to the next. For example, LNG and hybrid emit a very small amount of HC and CO, however, their NOx emissions are somewhat high. In the CORSIM analysis, it is important to note the relative change in emission rates as a result of changing speeds. On a freeway network, when buses are forced to accelerate to higher speeds, the bus is expected to emit more pollutants as shown in the surface vs. freeway test. Therefore, if a bus is required to use a freeway or travel at higher speeds, a LNG, methanol, or hybrid bus would be a clean option."

Possible applications for AERIS: The paper points out how some of the results were affected by CORSIM features, which may not be present in other simulations. A commendable feature of the study is that modeled speeds and delays affected headways, which in turn affected the fleet size required to provide service, which in turn affected fuel consumption and emissions. A similar study could be conducted for a large metropolitan area.

4.3.7 Eco-Driving Techniques

This subsection describes papers that concern measuring the environmental benefits of eco-driving. Subsection 4.3.7.1 addresses light-duty vehicles, Subsection 4.3.7.2 addresses freight vehicles, and Subsection 4.3.7.3 addresses transit vehicles.

4.3.7.1 Eco-Driving for Light Duty Vehicles

4.3.7.1.1 Development of Ecological Driving Assist System: Model Predictive Approach in Vehicle Control [31]

Purpose: This study examined the development of an ecological driving assist system (EDAS) designed to receive instant road-vehicle-traffic information from connected vehicle sensing and communication technologies, and provide drivers with eco-driving assistance by anticipating possible behavior of leading vehicles and traffic signals ahead.

Background: This study was performed by the Department of Electrical and Electronic Systems Engineering Lab Kyushu University in Japan.

Description: Vehicle performance was measured with and without driver assistance. Baseline data representing performance without assistance were generated using the AIMSUN NG base model (Gipps Method). The EDAS was designed to minimize fuel consumption per unit distance by providing drivers with input that could be used to reduce unnecessary braking and acceleration in various driving situations. For computational simplicity, only the longitudinal motion of a host vehicle, lead vehicle, and a signalized intersection were assessed. The potential impacts of other traffic around the host vehicle or vehicles in front of the lead vehicle were not included in the analysis.

Results: Average results from different vehicles under different conditions indicated the system could reduce fuel consumption by approximately 10 percent.

Possible applications for AERIS: AIMSUN NG is a microscopic transportation simulation model. The model provides a straightforward way to evaluate vehicle performance (fuel consumption) with and without AERIS applications on a simplified transportation network. The model appears to be flexible and used widely in the transportation industry. However, it is unclear from this paper how the fuel consumption benefits are calculated from the model output, and if these data would be compatible with models that estimate emissions reductions from fuel savings. User manuals that describe how to run the model would be useful to determine the value of this model for specific applications.

4.3.7.1.2 Energy and Emissions Impacts of a Freeway-Based Dynamic Eco-Driving System [32]

Purpose: This paper evaluated the potential impacts of an eco-driving system designed to help drivers smooth speed profiles and improve traffic flow by reducing unnecessary acceleration and braking in heavy traffic. The proposed system was designed to be managed at a traffic management center (TMC) and provide dynamic speed recommendations to drivers based on current traffic conditions (e.g., level of service, congestion levels) and other external variables such as weather.

Background: Lab experiments were conducted at the University of California-Riverside. Limited field experimentation included a comparison of eco-driving and non-eco-driving on SR-91 in the PeMS coverage area in Southern California.

Description: The PARAMICS microscopic traffic simulation tool was applied to the Comprehensive Modal Emissions Model (CMEM) to examine performance under a variety of traffic conditions. To determine the effectiveness of the dynamic eco-driving system, speed profiles of eco-driving and non-eco-driving vehicles were compared on a straightforward section of freeway having varied levels of service (LOS) and a penetration rate of 20% for eco-driving vehicles. The model was constructed using traffic data collected from probe passenger vehicles on freeways in Southern California during September 2005, May 2006, and March 2007. The model was calibrated using typical vehicle type population data typical of Southern California. CMEM was used to estimate resulting fuel consumption and carbon dioxide emissions.

Results: The following energy/emission statistics were calculated for an example vehicle traveling "with" and "without" eco-driving assistance on a congested segment of freeway stabilized at an average speed of 40 km/h.

Velocity Trajectory	Non-Eco-Driving	Eco-Driving	Difference
CO_2 (g)	1605.13	1044.81	- 34.9%
Fuel consumption (g)	531.23	333.29	- 37.3%
Travel time (min)	8.9	9.6	7.7%

Possible applications for AERIS: PARAMICS enabled individual vehicles to be modeled in fine detail for the duration of their entire trip, providing good estimates of traffic flow, travel time, and congestion information. The interface between drivers and ITS was able to be modeled. PARAMICS allowed users to easily integrate additional modules through the use of an application programming interface (API). A CMEM API was developed to predict emissions and fuel consumption. Findings from limited real-world vehicle experimentation supported the simulation results.

4.3.7.2 Eco-Driving for Trucks

4.3.7.2.1 Training heavy vehicle drivers to reduce fuel consumption: Results from a pilot Eco-Drive project [33]

Purpose: Research on the potential for an Eco-Driving program to reduce fuel consumption was conducted in Australia to indicate whether the same program techniques used in Europe or North America are transferrable to local Australian conditions. The pilot field trial aimed to quantify the impact of the Eco-Driving training program for heavy vehicle drivers.

Background: The study was developed by the Australian Cement Industry in conjunction with the Commonwealth Government of Australia. The pilot was conducted from one of the cement manufacturer's depot on the northern edge of the Melbourne metropolitan area (population 3.8 million) in Victoria.

Description: Three independent organizations were directly involved in the pilot – a cement manufacturer made available drivers and vehicles, a specialist commercial driver trainer delivered the Eco-Driving training, and the evaluation was conducted by the authors at Monash University. The vehicles used in the field trial were two 25-meter, 68-tonne B-double trucks which were both fully loaded with powdered cement. The trucks had almost identical specifications, aside from a difference in the gearing ratios. Each truck was equipped with a portable GPS device that logged

position as a function of elapsed time while completing the 30-km test circuit. The circuit itself was divided into six separate segments defined on the basis of major intersections. Bordering segments also represent different combinations of traffic density, road type, speed zone, and density of traffic control. The circuit represented the outer suburban nature of the cement company's operations and included a section of freeway as well as outer urban arterial roads, strip shopping areas, and a segment of rural arterial. Three groups of drivers participated:

- Group 1 participated in the complete training program that included pre- and post-classroom on-road assessment and feedback by the driving instructor.

- Group 2 participated in a classroom training session only.

- Group 3 served as a control and received no training.

The training program covered the knowledge areas as identified in literature research of a Switzerland Eco-Driving program that involve skipping gears when changing up, changing gears at lower engine revolutions, and braking less forcefully and less often. Other techniques include using the air conditioner sparingly, maximizing aerodynamic profile, minimizing unnecessary weight, adhering to a regular servicing regiment, and ensuring tires are inflated to their maximum advisory pressures. Four drivers for each group were randomly selected from a group of 30 drivers. Follow-up data was collected six weeks after the training program from all Groups and twelve weeks after training for only Group 1. For Group 1, an assessor travelled with each driver and recorded observational data on, gear changes, over revving the vehicle, brake applications, scanning ahead, and following distance. The two trucks used throughout the trial had their dual fuel tanks filled at the same fueling station at the start of each session and were then topped off at the end of each assessment run to maintain consistency in recording fuel consumption.

Results: Overall, implementation of an Eco-Driving program specific to Australian conditions was demonstrated to be successful. The fully trained group (Group 1) performed better than the other groups indicating a benefit from the training. This may be attributed to driving immediately prior to the course enables better transfer of information to the classroom training, and/or driving immediately after allows the opportunity to immediately practice the Eco-Driving techniques just learned. On average, the fuel consumption of the Group 1 drivers was reduced by about 27%. Additionally, they continued to achieve lower fuel consumption in the follow-up assessments conducted six and twelve weeks after the initial training. For the Group 1 drivers, brake applications were down about 41% following training while gear changes were reduced by about 29%. The reduction in fuel consumption by the drivers who only received the classroom training (Group 2) was similar to the fully trained drivers before the course and also to the control drivers who received no training. This suggests that the classroom session alone was not effective in changing driver behavior.

Possible applications for AERIS: The research reported in this study represents a first step in understanding the role of driver training in reducing fuel consumption. This study also demonstrates that Eco-Driving impacts can be measured and assessed with a combination of limited data collection instruments (i.e. GPS) and human data collection. An expanded study would include more automated data collection of driver behavior, such as with video or a data logger linked to the engine management system.

4.3.7.3   *Eco-Driving for Transit Vehicles*

4.3.7.3.1   Fair and Intelligent EcoDriving Incentive System for HDV Drivers [34]

Purpose: External factors such as road geometry, vehicle type, amount of traffic, and number of passengers have considerable effects on fuel consumption from bus operations. This study

evaluates a method for differentiating these external factors and making a fair comparison among bus drivers' fuel consumption across these factors by using monitoring systems.

Background: This study was developed during 2003–2005 for the Tampere City Transport in Finland by Tampere University of Technology.

Description: The case study evaluated was Tampere City Transport, a local bus company with approximately 150 buses and 400 drivers. Equipment for measuring driver's performance was installed into 12 buses on 2 routes. Buses drove approximately 26,000 km per month on both routes. Information of driver's driving pattern is gathered by a data logger attached to the vehicle. GPS adds information of time and place and information is sent to a database on a server. In the first phase, gathered data was divided into the two routes. The second phase divided the two routes into six directions to evaluate fuel consumption associated with road direction and road type. In the third phase, the data was further divided into groups according to the hour during which each run had started. Data is analyzed automatically on the server and monthly reports for each driver as well as summary reports of drivers, buses, and routes are produced for managers. Each driver receives a unique fuel economy percentage score for comparison that is calculated from measured fuel consumption. Because external factors have a considerable effect on fuel consumption, the study argues that direct comparison of drivers without considering these effects is misleading. This method performs the comparison of runs under similar driving conditions, and dividing data into groups of greater levels of granularity as described allows for more detailed comparison.

Results: Drivers are compared fairly and not based on external factors by using this method, and the economy percentage can be used as a driver performance indicator in an incentive system. On-board equipment can be utilized not only in an incentive system but also in fleet management, route planning, and vehicle maintenance. Fairness as perceived by the drivers is important to engage them in incentive programs.

Possible applications for AERIS: This study uses data collection and evaluation techniques that offer relevant environmental information and presents an effective approach in maintaining an effective fleet management program. This information enables managers to target areas of improvement while providing a fair evaluation system for all drivers. The methods discussed in this study can contribute to other Eco-Driving programs and be used with on-board diagnostics to enhance driver participation.

4.3.7.3.2 Analysis of Driving Behavior and Emission Characteristics for Diesel Transit Buses Using PEMS Measurements [35]

Purpose: The primary objectives of this study are to collect real-world emissions data from heavy-duty diesel buses using PEMS and driving activity data from diesel transit buses using GPS in Beijing; estimate emissions of diesel transit buses by a VSP-bin approach using the collected emissions and driving activity data; analyze the actual driving behaviors of diesel transit buses; and evaluate and compare the emission characteristics of diesel transit buses from the perspectives of different driving conditions, spatial and temporal distributions, and public transit priority policy.

Background: This study was performed by Beijing Jiaotong University and took place within the 5th Ring Road Expressway in downtown Beijing, China.

Description: Emissions data of heavy-duty diesel buses were collected in the real-world network using Montana OEM-2100, a PEMS instrument manufactured by Clean Air Technologies International, Inc. This instrument mainly consists of four components: the dual five-gas analyzer and PM monitor, the engine data obtaining subsystem, GPS, and the on-board computer. NOx,

HC, CO, CO_2 and PM emissions can be obtained from tailpipe exhaust and engine activity parameters, and the corresponding speed, latitude, and longitude data can also be recorded by the GPS system. In this study, four heavy-duty diesel buses were selected, all of which use No. 0 diesel fuel. The vehicles were tested with no load in a pre-designed route separately on July 5, 2007, and April 8, November 5, 2008. Load correction factors were added to the collected emission data. The 42-km testing route includes expressway, principal arterial, minor arterial, and collectors. The data collection time contained three periods: morning rush hour (7:00 AM-9:00 AM), off-peak hours (11:30 AM-12:30 PM), and evening rush hour (5:00 PM-7:00 PM). The collected driving activity data are used to analyze driving behaviors and identify VSP distributions and associated emission rates for diesel transit buses.

Results: Results from the study identify key parameters for evaluating emission impacts under various driving conditions. Emission factors are generated for various road types, speeds, and other operating conditions for diesel transit buses. The emission factors are highest on the minor arterials, lowest on the expressways, and similar for frontage roads and principal arterials. The emission factors of NOx, HC, CO and PM at bus stations are 1.64, 3.33, 2.65 and 1.73 times higher than those on regular road segments, thus improving driving conditions at bus stations is critical. The average emission factors of NOx, HC, CO and PM during morning and evening rush hour are 1.18, 1.23, 1.11, and 1.16 times higher than those during off-peak hours. Additionally, the emissions during evening rush hour are slightly higher than those during morning rush hour. Emission rates identified are shown to gradually decrease from the city center outward. These results allow targeting of the transportation system conditions that contribute most to emission impacts. When evaluating the Bus Rapid Transit strategy, results show that the average travel speed on bus exclusive lanes is about 11.15% higher than on normal lanes, and the corresponding reductions of emissions are all higher than 10% except for PM. Therefore, the public transit priority policy demonstrates improvement in operational efficiency of diesel transit buses and also reduces emissions.

Possible applications for AERIS: This technique demonstrates the ability to collect and evaluate data associated with bus transit systems to identify areas of improvement and benefits of emission-reduction strategies. The study exemplifies the use of location-specific measurements to evaluate location-specific impacts and provides additional data sets for further refinement of emissions estimations. This technique can be used to support real-time data analysis and understanding the effects of specific connected vehicle strategies.

4.3.7.3.3 Training urban bus drivers to promote smart driving: A note on a Greek eco-driving pilot program [36]

Purpose: The objective of the study was to investigate the effects of modifying urban bus driver behavior through training courses on Eco-Driving using in-vehicle monitoring systems.
Background: The Eco-Driving pilot study was conducted in 2007 by the Centre for Renewable Energy Sources of Greece in collaboration with the Organization of Urban Transportation of Athens and the Thermo-Bus Company.

Description: The training courses were designed to increase the knowledge of bus drivers regarding economical driving techniques that reduce fuel consumption, improve road safety, and decrease maintenance costs. The first step was to prepare the pilot action plan. The second phase involved pre-training data collection on fuel consumption, distance traveled, average speed, and other driving parameters to establish a baseline for comparison. Specialized equipment, EDM1404, was installed on the selected vehicles. The monitoring period over which the base data was collected was one and a half months. The third phase developed the training material that constituted a package of instructions concerning driving styles targeted at urban buses with automatic gear boxes. The Eco-Driving courses were then performed in three parts under the guidance of trained personnel. In the first part, three bus drivers traveled a

predetermined 15-km test route using their usual driving style while fuel consumption and driving time were recorded. In part two, the drivers attended an analytical Eco-Driving seminar. The third part applied the Eco-Driving instructions over the same 15 km-route. The changes in fuel consumption along with the driving time were recorded in all runs. Post-training monitoring continued for two months to evaluate the bus drivers' driving performance under actual driving conditions.

Results: Results from the implementation of Eco-Driving practices show that the two drivers managed to decrease their fuel consumption by up to 17.8% and also decreased their driving time confirming that Eco-Driving does not indicate slower driving. The third driver achieved only a small increase of 1.78% in fuel consumption while driving for almost 40% longer than the baseline route. Overall, the average decrease in fuel consumption for all bus drivers was 10.2%. The study generated average fuel consumption per km measurements for the buses before and after Eco-Driving. The benefit of the training was an overall 4.35% reduction in fuel saving per km. This equates to an approximate annual savings of 2,610 liters of diesel fuel saved per bus. Annual savings for each bus is estimated to be €1,697 per year amounting to €2,884,900 per year over the 1,700 bus fleet.

Possible applications for AERIS: The use of on-board monitoring systems is a first step towards allowing better management of driving behavior in real time. Establishing factors for average fuel consumption under both Eco-Driving and baseline scenarios contributes to understanding the effects of Eco-Driving under certain conditions. With greater knowledge of the effects of Eco-Driving techniques, better estimations can be generated from implementing Eco-Driving programs.

4.3.8 Model Sensitivity

4.3.8.1 Mobile Source Air Toxics Emissions: Sensitivity to Traffic Volume, Fleet Composition, and Average Speed [37]

Purpose: This study used an emissions modeling tool, CT-EMFAC, to assess the sensitivity of mobile source air toxics (MSATs) emissions to changes in traffic volumes, speeds, and fleet composition.

Background: The study was performed in 2009 by the Department of Civil and Environmental Engineering, University of California using "a hypothetical freeway case study using real-world southern California activity data (volumes, fleet mix, and speeds)"

Description: "The California-specific CT-EMFAC model estimates emissions for the six priority MSATs identified in EPA's 2001 MSAT rule and FHWA's 2006 MSAT guidance (DPM, formaldehyde, 1,3-butadiene, benzene, acrolein, and acetaldehyde), in addition to other key pollutants (TOG, CO, NOx, SOx, PM10, or PM2.5) and CO_2. CT-EMFAC may be applied at the project level with user inputs of speed-based vehicle miles traveled (VMT)". The project estimated average speeds using a 1960s Bureau of Public Roads equation and a Texas Transportation Institute equation. No traffic simulations were used to generate speeds, and only average speed was used.

Results: "Results show that emissions more than doubled in 2004 and increased by a factor of two to four in 2030 when traffic volumes increased 30% above base-case conditions. The non-linear shift in emissions was a function of decreased travel speeds and increased g/mi emission rates that accompanied increased traffic volumes."

Possible applications for AERIS: The model used in this paper breaks out emissions into six components. This is more details than many other models. It takes care to think about how average speeds are derived from volumes and looks at an interesting future growth scenario. However, the model does not ingest the results of traffic simulations, and uses only average speed. Its results may be limited to California. Because of the model does not use simulation input and uses only average speeds, it is not likely that the model runs described in this paper will be useful for most AERIS purposes. For those, more detailed speeds and drive cycles will be necessary. Since the model uses comparatively simple equations for predicting speeds given volumes, it cannot capture most effects of connected vehicle technology.

4.3.8.2 *Traffic Emission Using Floating Car and Traffic Sensor Data [38]*

Purpose: This paper documents a study performed using the AIMSUN microsimulation to determine the percentage of probe vehicles required to provide a statistically good representation of CO emissions from all vehicles. Different penetration rate of probe vehicles were simulated and the values of carbon monoxide estimated from probe vehicles were compared against the emissions from simulated vehicles. The study looked at the network level and the link level.

Background: This paper was written in 2007 by Emmanuel Bert, Edward Chung, and André-Gilles Dumont at EPFL. The study evaluated evening rush hour traffic in the city center of Lausanne, Switzerland.

Description: "AIMSUN calculates the emission produce by the different vehicle types in the network using a Fuel Consumption Model. The vehicle state (accelerating, decelerating, idling or cruising) and the vehicle speed are used to calculate the emission from each vehicle for each simulation time step."

Results: "Based on the simulation network, for an accuracy of 95 % or higher, at least 2 % of probe vehicle is needed for heavy traffic conditions and 10 % for light conditions, T tests showed that estimates from 2 or more percent of probe vehicles are significant at 95 % confidence interval."

Possible applications for AERIS: The results may be useful if there is a project to outfit a small percent of vehicles in a network as probes. Since CO is the only emission studied, and there is no comparison to actual measurements, there is no way this study could assess the accuracy of emissions estimates produced by AIMSUN itself.

4.4 Policy Models

This section describes papers concerning policy models. These models do not simulate emission and they do not use output from traffic simulation models.

4.4.1 An Introduction to Long range Energy Alternatives Planning System (LEAP) [39]

Purpose: The purpose of the study is to describe an integrated modeling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy and to assess policy analysis and climate change mitigation.

Background: LEAP is a software tool developed by Stockholm Environment Institute (SEI).

Description: LEAP has built-in calculations to handle all of the "non controversial" energy, emissions and cost-benefit accounting calculations. It allows the user to enter spreadsheet-like expressions that can be used to specify time-varying data or to create a wide variety of sophisticated multi-variable models, thus enabling econometric and simulation approaches to be embedded within LEAP's overall accounting framework.

Results: None Reported

Possible applications for AERIS: The tool seems to have great flexibility for generating different models of energy systems. However this paper did not define the methodologies used for quantifying emissions or the data requirements. More research is needed on this tool to identify the methodologies and assumptions used within the tool and to determine whether these methodologies could be used for any of the AERIS applications.

4.4.2 Macroscopic Greenhouse-Gases Emissions Model of Urban Transportation for Municipalities [40]

Purpose: "The MUNTAG (MUNicipal Transportation And Greenhouse) gases model, was developed to help municipalities estimate their current transportation emissions, set future targets, and run forecasting scenarios and response to policies."

Background: This study was conducted by the University of Toronto, using Toronto data from 2004.

Description: "The model contains five strategies: land-use intensification, public transport, active transport, financial policies, and vehicle technology." "It is a macroscopic, highly aggregate model that works at the municipal level and solely considers the movement of people. It is particularly suitable as a screening tool, and more detailed analyses should be pursued to accurately predict the impact of specific projects."

Results: "Results from MUNTAG performed within 17.3% when compared to emissions calculated for the 2004 Toronto GHG Inventory (Table 6), produced by ICF International."

Possible applications for AERIS: For connected vehicle applications and strategies that reduce VMT, the model could compare projected urban emissions with and without that reduction. Likewise, improvements in fuel efficiency can be represented at a high level. However, there is no tie to microscopic traffic simulation; thus using the model to estimate benefits of many connected vehicle applications is not possible. Since there is no link to a traffic simulation model, it is not likely to be a high priority for AERIS research.

4.4.3 The Four Circles: An Integrated Approach to Behavior-Based Greenhouse Gas Reduction [41]

Purpose: This paper introduces the "Four Circle Approach" as an integrated framework that combines and complements previous attempts to reduce greenhouse gas (GHG) emissions.

Background: This paper was written in 2009 at the Institute of Transportation Studies, University of California at Davis.

Description: This approach groups GHG reduction strategies into four categories/circles:

1) *Characteristics of the Built Environment* – Focuses on how characteristics of the built environment influence VMT reduction (e.g. increase transit frequency)

2) *Pricing Policies* - Examines why pricing policies are important for both maximizing GHG reductions and generating revenue for local and regional governments (e.g. increase fuel taxes)

3) *Vehicle Capacity Constraint* - Shifting funding priorities away from VMT growth (added vehicle infrastructure capacity) toward prioritizing a "Fix it First" policy at multiple levels of government (e.g. converting SOV lanes to HOV lanes)

4) *Transport System Efficiency* - Addresses how people actually drive, rather than how to reduce the amount of VMT (e.g. educating the public on how vehicle maintenance and handling of their automobile affects fuel economy).

Rather than just focusing on vehicles technology and fuel carbon intensity, this framework also "focuses on the role that individuals have on GHG emissions from both 'how much they drive' (VMT) and 'how they drive' (transport efficiency)" to be able to achieve greater GHG reductions. According to this paper: an integrated framework such as the Four Circle Approach seeks to ensure implementation and accountability by tying funding directly to supporting GHG reduction strategies and addressing institutional barriers to national climate change and economic objectives and to achieve ambitious federal and state GHG reduction targets.

Results: None reported.

Possible applications for AERIS: This paper claims that the Four Circle approach will help reduce GHG emissions through attempting to decrease VMT, the use of price signals, changes in funding priorities, and public engagement. However, this integrated framework is more valuable and applicable at a federal, state and/or local community development plans and could not be used for the evaluation of a specific connected vehicle application or strategy.

4.5 Other Analyses

4.5.1 Estimating the Impact of Electric Vehicle Charging on Electricity Costs Given an Electricity Sector Carbon Cap [42]

Purpose: This paper estimates the extra electricity that would be required to recharge plug-in hybrid electric vehicles (PHEVs) with varying assumptions about market penetrations (1%, 5% or 10%) and the time of day the recharging occurs (evening, nighttime, or twice a day).

Background: The study was performed at the University of Vermont Transportation Research Center, based on 2009 legislation concerning Cap-and-Trade Legislation for CO_2 emissions for the generation of electricity.

Description: The study estimates the additional average and marginal cost of generating the additional electricity, given the Regional Greenhouse Gas Initiative, a cap-and-trade system currently in effect in New England.

Results: "The results presented here show that PHEV demand would increase CO_2 emissions allowance prices when the electricity sector has a GHG cap but the transportation sector does not. In this case, switching energy consumption from the liquid fuels sector to the electricity

sector, as occurs with PHEV deployment, simultaneously reduces overall CO_2 emissions and drives CO_2 allowance prices up in the electricity sector. In the model described here, a 5% deployment of PHEVs would increase the price of CO_2 allowances from \$3.4/ton to \$8.4/ton, increasing electricity costs for all electricity customers, not merely PHEV owners.

Possible applications for AERIS: Any AERIS study that includes electric vehicles or hybrid vehicles should consider this paper as a guide for making sure that additional CO_2 emissions caused by electricity generations are properly considered.

4.5.2 Evaluation of Methods, Models, and Parameters to Represent Freight in Air Quality and Greenhouse Gas Models [43]

Purpose: This paper evaluates all methods, models, and parameters used to generate emissions information from freight transportation activities in the U.S.

Background: This paper is the summary of a project sponsored by the National Cooperative Freight Research Program. It was carried out in 2009, using data from all the freight networks in the U.S.

Results: The paper acknowledges that MOBILE6 and EMFAC2007 are not detailed enough to model the effects of congestion since they use average speed. It is anticipated that MOVES2009 and CMEM will do a better job. "For those strategies that have an effect on congestion levels (e.g. incident management, congestion pricing), only modal emissions models are able to capture such effects."

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[19] http://www.trafficlab.utah.edu/documents/VISGAOST.pdf

5 Conclusions

This section summarizes the current state of the practice for each evaluation technique as described in this paper.

5.1 Summary of Findings

5.1.1 Evaluation Framework

The evaluation framework recommended in "An Environmental Evaluation Guidebook for ITS Deployments and Field Tests" [2] is a good approach for impact evaluation. A similar framework may be adopted by the AERIS Program for assessing connected vehicle applications for their potential to minimize negative environmental impacts. The recommended framework consists of the following seven steps:

1. Hypotheses of ITS Impacts
2. Evaluation Goals and Objectives
3. Measures of Effectiveness
4. Evaluation Study Design
5. Data Collection and Monitoring
6. Data Analysis
7. Result Interpretation and Presentation

Steps 6 and 7 will frequently include modeling and evaluation of the model results, as discussed in this report.

5.1.2 Direct Measurements of Vehicle Emissions and Fuel Use

Studies have frequently installed and used PEMS instrumentation on small numbers of vehicles. This technology is well understood, and the results are regarded as accurate. Emissions and fuel consumption values from these studies have been used as inputs to emissions models. For example, the MOVES model contains a large database of emissions characteristics for vehicles of various types, manufacture, and age.

No study has been encountered that places instrumentation on a large number of vehicles. Thus any estimates of corridor or regional environmental benefits are extrapolations from a small number of vehicles, or the result of emissions models, such as MOVES.

Since 1996 all light-duty vehicles have OBD units that can provide information on engine performance. The regulations requiring OBD units for heavy duty trucks are more recent (April 2009),

so fewer instrumented heavy duty trucks are available. No studies were encountered that derived fuel consumption and emissions directly from OBD data. Future demonstrations and pilot projects using connected vehicle technologies could potentially test the real-time transmission and processing of data from OBD units.

Measurements of emissions from instrumented vehicles, whether they come from PEMS or OBD devices, will likely play a role in evaluations of AERIS applications. Applications such as eco-driving, transit and freight fleet management, and signal priority for privileged vehicles where benefits accrue to a relatively small number of instrumented vehicle are candidates for direct evaluation with the sensors. This approach is less likely to be used to measure the benefit of infrastructure-based applications like signal control or ramp metering where the benefit accrues in small amounts at specific places for many vehicles. Applications of that type are more likely to be evaluated with models, using emissions input parameters that have been derived from measurements obtained from PEMS or OBD units on a small number of instrumented vehicles.

5.1.3 Infrastructure-Based Air Quality Measurements

Infrastructure sensors for air quality monitoring are widespread, but there are few real-time decision making systems that are tied to air quality readings from sensors. More common are applications to modify the speed limit based on fog or other visibility limitations detected by real-time visibility sensors[20]. These systems could provide a model for driving restrictions based on real-time air quality and for measuring the effectiveness of these restrictions.

Ambient air quality measurements are most likely to be useful for evaluation of AERIS applications where the benefit of reduced emissions is localized, such as a restricted access zone, an intersection with advanced signal control or ramp metering, or a location with recurrent congestion that may be mitigated. In these cases, the application is infrastructure based, so that large numbers of vehicles are affected, each saving a small amount of emissions near the location with the air quality sensor.

Data from infrastructure air quality sensors are also used to calibrate emissions and atmospheric dispersion models. These models may then be used to extrapolate the effects of emissions to larger vehicle populations and larger areas, as described in Section 4.3.

Finally, air quality sensors may be integral parts of decision support systems that assist traffic managers decide when or whether to impose traffic restrictions or take other measures when air quality is bad or is likely to become bad.

5.1.4 Modeling the Effects of Connected Vehicle Technology Deployment

Section 4.3 describes studies that have used models to estimate the environmental impacts of various connected vehicle-related applications. There is a wide variety among the models in terms of which emissions are reported (CO_2 or various pollutants) and whether microscopic (second-by-second speeds and accelerations) or mesoscopic (average speed) aspects of traffic behavior are used as input by the emissions models. In general, microscopic traffic models and emissions models are required to quantify the impact of traffic smoothing and improved traffic operations, whereas mesoscopic models are more suited if the effect of the connected vehicle application is a reduction in VMT across one or more classes of vehicles, such as the result of traveler information.

Models are typically used to estimate the impacts of applications that:

- Involve a large number of vehicles where instrumentation would be impractical, such as optimization of a large traffic signal network or estimating the effect of large scale eco-driving.

- Involve analysis of proposed future facilities or future policies, such as new lanes, new HOV restrictions, new signal timing, new variable speed limits.

- Involve an event such as an incident that cannot be predicted and is not feasible to create.

A wide number of traffic and emissions are being used in the U.S. and internationally to evaluate emissions from light duty vehicles, transit vehicles, and medium and heavy duty trucks. Traffic simulation models that have been used to study the traffic impacts of ITS applications and to produce detailed vehicle movement data as input into emissions models include TRANSIMS, CORSIM, AIMSUN, VISSIM, TransModeler, and Paramics. Emissions models that were used in the studies summarized in this report include MOVES, CMEM, PHEM, and VERSIT+.

In general, advantages of models include the following:

- External factors can be controlled to permit a meaningful comparison between before and after results.
- Modeling can be used to study applications that are not advanced enough or widespread enough to be tested in the field.
- Modeling may be less expensive than field tests, especially if large numbers of vehicles and/or sensors are involved.
- No fuel is consumed or pollutants are emitted during the trials.

Disadvantages to the use of models include:

- Emissions or fuel consumption mechanisms for a particular engine type or situation may not be understood in sufficient detail to model correctly.
- The model may not accurately represent driver behavior in response to the connected vehicle application or strategy.
- The necessary input data for model development or calibration and validation may be not be available or may be incorrectly gathered.

5.2 Future Work

A review of the literature showed that there is a gap in evaluating the environmental impacts on a regional or a national level.

There appears to be a gap between estimates of environmental impact at a corridor or intersection level, and the impacts at a regional or national level. No studies were encountered that presented a rigorous approach for extrapolating project or corridor-level results to a larger scale. Approaches such as Regional Science, pioneered by Walter Isard, may provide a way to perform this extrapolation.

Policy models described in Section 4.4 can operate at a national level, but do not include the detail necessary to capture the effects of traffic smoothing.

For many connected vehicle applications involving pre-trip or en route traveler information, additional work will be required to quantify human responses to the information before the results of the applications can be accurately captured in a detailed traffic model.

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[20] For examples, see http://ops.fhwa.dot.gov/weather/best_practices/casestudies/002.pdf and
http://ops.fhwa.dot.gov/Weather/best_practices/CaseStudies/029.pdf

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APPENDIX A.   List of Acronyms

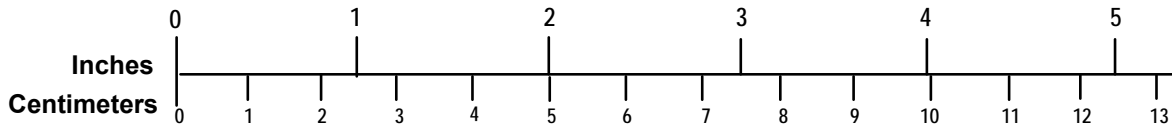|	
ACC	Adaptive Cruise Control
AERIS	Applications for the Environment: Real-time Information Synthesis
API	Application Programming Interface
ARB	Air Resources Board
ATIS	Advanced Traveler Information System
ATMS	Advanced Traffic Management System
BCEMM	Border Crossing Emissions Measurement Model
BOTA	Bridge of the Americas
BRT	Bus Rapid Transit
CH_4	Carbon Tetrahydride (methane)
CMEM	Comprehensive Modal Emissions Model
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DG INFSO	Directorate-General for Information Society
DOE	Department of Energy
ECU	Engine Control Unit
EDAS	Ecological Driving Assist System
EGR	Exhaust Gas Recirculation
EMFAC	Emissions Factors Model
EPA	Environmental Protection Agency
FTIR	Fourier Transform Infrared
GHG	Greenhouse Gases
GPS	Global Positioning System
HC	Hydrocarbons
HDD	Heavy Duty Diesel
HGV	Heavy Goods Vehicle
HOT	High Occuonacy Toll
HOV	High Occupancy Vehicle
H_2O	Hydrogen Dioxide (water)
ICM	Integrated Corridor Management
IDAS	ITS Deployment Analysis System
IMS	Incident Management System
I/M	Inspection/Maintenance
ISA	Intelligent Speed Adaptation
ITS	Intelligent Transportation Systems
IVE	International Vehicle Emissions
JPO	Joint Program Office
LDGV	Light-Duty Gasoline Vehicles
LEAP	Long range Energy Alternatives Planning
LNG	Liquefied Natural Gas
LOS	Level of Service
MBTA	Massachusetts Bay Transportation Authority
METI	Ministry of Economy, Trade and Industry
MMDI	Metropolitan Model Deployment Initiative

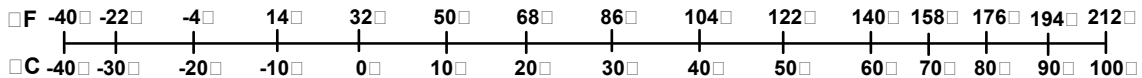|	
MOVES	Motor Vehicle Emissions Simulation
MSAT	Mobile Source Air Toxic
MUNTAG	MUNicipal Transportation And Greenhouse
NOx	Nitric Oxide (NO) and Nitric Dioxide (NO_2)
NREL	National Renewable Energy Laboratory
N_2O	Nitrous Oxide
OBD	On-Board Diagnostics
PAYD	Pay As You Drive
PEMS	Portable Emissions Measurement Systems
PHEV	Plug-In / Hybrid Electric Vehicle
PID	Parameter Identification Number
PM	Particulate Matter
PRUEVIIN	Process for Regional Understanding and EValuation of Integrated ITS Networks
RFID	Radio Frequency IDentification
RITA	Research and Innovative Technology Administration
RPM	Revolutions per Minute
SOx	Sulfur Oxides
SPAT	Signal Phase and Timing
SPBP	San Pedro Bay Ports
TMC	Traffic Management Center
TTI	Texas Transportation Institute
TOTEMS	Total On-Board Tailpipe Emissions Measurement System
TRACE	TRansportation Air quality & Congestion Evaluation
TRB	Transportation Research Board
USDOT	United States Department of Transportation
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compounds
VSP	Vehicle Specific Power
V2I	Vehicle-to-Infrastructure (communications)
V2V	Vehicle-to-Vehicle (communications)

APPENDIX B. Metric/English Conversion Factors

ENGLISH TO METRIC	**METRIC TO ENGLISH**
LENGTH (APPROXIMATE)	**LENGTH (APPROXIMATE)**
1 inch (in) = 2.5 centimeters (cm) 1 foot (ft) = 30 centimeters (cm) 1 yard (yd) = 0.9 meter (m) 1 mile (mi) = 1.6 kilometers (km)	1 millimeter (mm) = 0.04 inch (in) 1 centimeter (cm) = 0.4 inch (in) 1 meter (m) = 3.3 feet (ft) 1 meter (m) = 1.1 yards (yd) 1 kilometer (km) = 0.6 mile (mi)
AREA (APPROXIMATE)	**AREA (APPROXIMATE)**
1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2) 1 square foot (sq ft, ft^2) = 0.09 square meter (m^2) 1 square yard (sq yd, yd^2) = 0.8 square meter (m^2) 1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2) 1 acre = 0.4 hectare (he) = 4,000 square meters (m^2)	1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2) 1 square meter (m^2) = 1.2 square yards (sq yd, yd^2) 1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2) 10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres
MASS - WEIGHT (APPROXIMATE)	**MASS - WEIGHT (APPROXIMATE)**
1 ounce (oz) = 28 grams (gm) 1 pound (lb) = 0.45 kilogram (kg) 1 short ton = 2,000 pounds = 0.9 tonne (t) (lb)	1 gram (gm) = 0.036 ounce (oz) 1 kilogram (kg) = 2.2 pounds (lb) 1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons
VOLUME (APPROXIMATE)	**VOLUME (APPROXIMATE)**
1 teaspoon (tsp) = 5 milliliters (ml) 1 tablespoon (tbsp) = 15 milliliters (ml) 1 fluid ounce (fl oz) = 30 milliliters (ml) 1 cup (c) = 0.24 liter (l) 1 pint (pt) = 0.47 liter (l) 1 quart (qt) = 0.96 liter (l) 1 gallon (gal) = 3.8 liters (l) 1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3) 1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)	1 milliliter (ml) = 0.03 fluid ounce (fl oz) 1 liter (l) = 2.1 pints (pt) 1 liter (l) = 1.06 quarts (qt) 1 liter (l) = 0.26 gallon (gal) 1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3) 1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)
TEMPERATURE (EXACT)	**TEMPERATURE (EXACT)**
$[(x-32)(5/9)]$ °F = y °C	$[(9/5)\, y + 32]$ °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION

	0	1	2	3	4	5
Inches						

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
Centimeters														

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

F	-40	-22	-4	14	32	50	68	86	104	122	140	158	176	194	212
C	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80	90	100

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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