AERIS: State-of-the-Practice Scan of Environmental Models

FINAL REPORT

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16. Abstract

This report has been developed under the Track 1 effort of Phase 1 of the AERIS program and presents the findings of the state-of-the-practice scan of environmental models to estimate environmental impacts (emissions, fuel consumption, etc.) due to changes in traveler behavior and trip choices in response to implementation of ITS strategies. Several environmental models were examined to determine the sensitivity and validity of these models in estimating emissions impacts of ITS strategies. The report includes a detailed assessment of the suitability of Motor Vehicle Emission Simulator (MOVES), Comprehensive Modal Emission Model (CMEM) and EMission FACtor (EMFAC) emissions models in evaluating emissions impacts of ITS strategies.

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EXECUTIVE SUMMARY

Purpose of the Project

The primary objective of the *Applications for the Environment: Real-time Information Synthesis (AERIS) State-of-the-Practice Support* project is to establish a foundation for the future research work to be conducted as a part of the Connected Vehicle AERIS program by conducting a state-of-the-practice assessment of travel behavior and activity-based models, environmental models, and tools and technology available to enable environmental data acquisition. Conducting the state-of-the-practice scan will help:

- Assess the capabilities of behavioral and activity-based models to predict changes in travel behaviors in response to implementation of intelligent transportation system (ITS) strategies and evaluate whether the behavior changes predicted by the behavior models can be used to estimate environmental impacts.
- Understand the capabilities of environmental models to estimate environmental impacts (emissions, fuel consumption, etc.) due to traveler behavior and trip choices.
- Identify technologies that will allow the capture of environmental data needed by environmental models and other data needed to measure environmental impacts.

The AERIS program is delineated into three phases (extending over 5 years) namely:

1. *Foundational Analysis (Phase I)*
2. *Candidate Applications Evaluation (Phase II)*
3. *Research Investment Planning (Phase III).*

*Each phase has six major tracks that span a*cross the entire duration of the AERIS program, namely:

1. *Establish Foundation*
2. *Identify Candidate Strategies*
3. *Analyze and Evaluate Candidate Strategies*
4. *Recommend Strategies and Applications*
5. *Policy and Regulatory Research*
6. *Stakeholder Interactions and Technology Transfer.*

This report has been developed under the Track 1 effort of Phase 1 of the AERIS program and presents the findings of the state-of-the-practice scan of environmental models to estimate environmental impacts (emissions, fuel consumption, etc.) due to traveler behavior and trip choices in response to implementation of ITS strategies. Separate reports will be prepared that summarize the state-of-the-practice of behavior and activity based models and data acquisition technologies.

To complete the state-of-the-practice scan of emissions models, the project team:

- Examined the environmental models in order to determine the sensitivity and validity of these models in estimating emissions impacts of ITS strategies

- Reviewed Motor Vehicle Emission Simulator (MOVES), Comprehensive Modal Emission Model (CMEM) and EMission FACtor (EMFAC) emissions models in detail to assess their suitability in evaluating emissions impacts of ITS strategies.
- Identified transportation and non-transportation data needed by environmental models.

Background to the Report

The AERIS program's vision is "Cleaner Air through Smarter Transportation." In order to meet the vision, the AERIS program attempts to generate, capture, and analyze vehicle-to-vehicle and vehicle-to-infrastructure data to create actionable information that allows surface transportation system users and operators to make "green" transportation choices. The U.S. Department of Transportation (USDOT) and its contractors are in the process of identifying applications that have demonstrated environmental benefits through the use of ITS technologies and looking at opportunities for the AERIS program to use these applications. A recent study conducted by Noblis *(AERIS – State-of-the-Practice Assessment of Applications)* has identified a preliminary list of strategies that have demonstrated to yield environmental benefits. The identified applications include:

- **Demand and Access Management** strategies such as electronic toll collection, mileage-based fee, congestion pricing, etc. Demand and access management strategies aim to reduce traffic or travel demand by controlling access to roadways, improving pedestrian and transit options, and encouraging policies that reduce peak-hour congestion
- **Eco-Driving** strategies such as eco-driving assistance, adaptive cruise control (ACC), and eco-routing. These strategies attempt to influence driving behavior and promote driving styles that reduce overall emissions
- **Traffic Management and Control** strategies such as implementation of incident management systems, ramp metering, speed management, adaptive signal control, and signal coordination and optimization. These strategies attempt to dynamically adjust the traffic operations to manage traffic, reduce congestion, and hence reduce the emissions generated
- **Logistics and Fleet Management** strategies such as implementation of automated vehicle location (AVL) systems and idle-off, stop-start systems. These strategies attempt to reduce emissions by optimizing vehicle maintenance, telematics, speed, and fuel management
- **Freight Management** strategies such as delivery management, platooning, and eco-driving
- **Transit** improvement strategies such as implementing bus rapid transit (BRT) to improve the mode share or reducing transit emissions by implementing transit signal priority (TSP).

Some common traveler behavior changes associated with the above strategies can be broadly classified as behavior changes that reduce the overall VMT (and directly reduce the emissions generated) or behavior changes that do not result in an overall reduction in VMT, but still succeed in emissions reduction. Examples of behavior changes include the following:

Behavior changes that directly result in VMT reduction

- Change in routes (targeted at minimizing travel distance)

- Change in mode of travel (take transit, carpool, non-motorized travel such as walking, biking, etc.)
- Change in number of trips
- Change in trip chaining patterns

Behavior changes that do not directly result in VMT reduction but those that can have a positive impact on the environment

- Change in time of travel (for instance, peak spreading, or changing the time of departure to avoid congestion and/or toll)
- Compliance with variable speed limits that improves the smoothness of travel
- Change in driving behavior (eco-driving)
- Improved freight planning and operations
- Eco-routing (note that eco-routing sometime can also lead to reduced VMT)
- Change in Fuel choices.

Change in traveler behavior in one or more of the ways listed above is likely to have a direct impact on the environment. For example, if the traveler reduces the amount of auto travel, changes the time of day of travel, or changes the driving style or behavior, then these changes may result in reduced VMT and/or fuel consumption (due to reduction in VMT or improvement in driving style) and hence result in reduced emissions.

Note that freight management techniques also can yield environmental benefits. *Freight Transport Management* includes various strategies of increasing the efficiency of freight and commercial transport. *Logistics* is a technical term for efficient freight management, including shipping practices (e.g., vehicle type, shipment size and frequency) and related activities. Logistics usually focuses on minimizing shipper costs, with little consideration of social costs such as congestion or pollution impacts.

Summary and Findings

In order to quantify the emissions impacts of ITS strategies, it is necessary to adopt a modeling approach that integrates travel demand models with traffic simulation models and feeds the results from traffic simulation models to emissions models. The graphic below shows the sequencing of steps to estimate emissions impacts of ITS strategies.

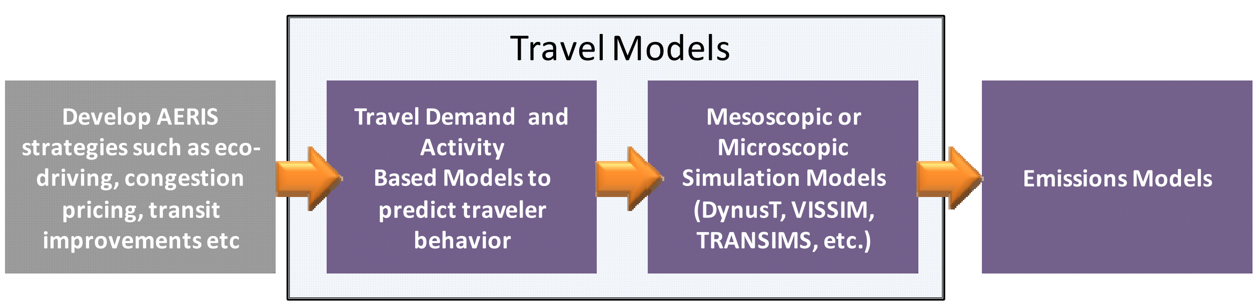

Figure E-1: Emissions Modeling Steps for ITS Evaluation

In recent years, it has been well documented that the aggregate network performance data created by traditional static assignment models is not suitable for estimating emissions accurately. Microscopic simulation models are best suited to capture the network performance change in response to implementation of ITS strategies. Without using microsimulation models, it is not possible to perform detailed "project-level" or micro analysis with advanced emissions models such as MOVES. The state-of-the-practice of behavior and activity-based models and the suitability of these models for use to evaluate ITS strategies are discussed in the "State- of-Practice Scan of Behavior and Activity-Based Models Report" developed as a part of this project.

Activity-based models are best suited to predict traveler behavior changes and microsimulation models are best suited to estimate the transportation system efficiency changes. The key inputs to emissions models are "speed" and "vehicle activity data" (if advanced emission models such as CMEM and MOVES are used). Vehicle activity data typically includes vehicle data such as distribution of vehicle miles traveled by vehicle class, vehicle miles of travel (VMT) distribution by hour, starts per day distribution by vehicle class and vehicle age, engine starts per day and their distribution by hour of the day, average trip length distribution, and engine start soak time distribution by hour (cold soak distribution). Once detailed speed data and vehicle data are generated, establishing the linkage between traffic simulation models and emissions models is relatively straightforward.

Transportation emission models can be grouped into four classification categories:

- Emission factor models
- Physical power demand models
- Acceleration and speed based models
- Dispersion models.

Provided below is a brief description of these emissions model types:

- **Emissions Factor Models:** An emissions factor is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., kilograms of particulate emitted per megagram of coal burned). Such factors facilitate estimation of emissions from various sources of air pollution[1]. Emissions factor is derived from the average value of repeated measurements of total emissions per driving cycle. One commonly used U.S. transport emissions models is EMFAC. These models provide a convenient way to model area-wide vehicle emissions levels because they require less detailed information on traffic flow and operation pattern than the other three types of models (Bai, 2008). Note that models can also include emissions factors for non-criteria pollutants (i.e. carbon dioxide and other greenhouse gases).

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[1] *Emissions Factors & AP 42, Compilation of Air Pollutant Emission Factors* (http://www.epa.gov/ttnchie1/ap42/ - accessed on May 12, 2011).

- **Physical power demand models:** The second category of transportation emission models comprises the physical power-demand models. These models can predict second-by-second tailpipe emissions for different driving conditions and vehicle types. CMEM is a widely used physical power-demand model that determines vehicle emissions rate as a function of vehicle operation characteristics, such as engine power, engine speed, air / fuel ratio, fuel use, engine-out emissions, and catalyst pass fraction (Rakha, 2003 and Yin, 2011). This modeling approach provides a more accurate estimate of vehicle emissions levels by incorporating the effects of vehicle operation and driving environment into the emissions model. Additionally, these models are sensitive to changes in vehicle acceleration behavior and thus can be used for the evaluation of operational-level transportation projects such as re-timing signals, modeling toll plazas, and modeling highway sections and other ITS strategies (Rahka, 2003). However, detailed data on operational characteristics at varying speeds and acceleration rates for multiple vehicle types is usually difficult to obtain, impeding the application of these models (Yin, 2011).
- **Acceleration and speed based models:** Acceleration and speed-based models comprise the third category. These models estimate emissions as a function of vehicle type, instantaneous speed, and acceleration. U.S. Environmental Protection Agency's (EPA) MOVES model is an example of acceleration and speed-based model. Early versions of these models derived the average emissions rate based on estimates of 14 typical driving moduli (Yin, 2011 referencing Joumard, 1995). Emission rates are then denoted as a function of a combination of linear, quadratic, and cubic transforms of the instantaneous speed and acceleration, which can readily be derived from data on the average speed and number of stops of the specified driving modulus (Yin, 2011 referencing Ahn, 1999, Ahn, 2002, and Rakha, 2004). This modeling approach is promising for evaluating ITS strategies, as less detailed engine operation and driving environment information is required (compared with the physical power-demand models) and the influence of vehicle movement is controlled compared to the absence of that factor in emissions factor models (Yin, 2011). The detailed engine operation and driving environment information necessary for these models will be available in a Connected Vehicle environment and this information can be directly collected from the vehicle.
- **Dispersion Models:** Dispersion models use mathematical formulations to estimate the concentration of pollutants at specified ground-level receptors surrounding an emissions source.[2] These types of models may not readily accept input from travel demand models and hence are not suitable to estimate emissions related to ITS strategies.

Emissions models need both transportation and non-transportation data to estimate emissions. The key data needed to conduct a detailed emissions analysis include the following:

- **Travel Data:** Driving Schedule, Vehicle Operating modes, Link characteristics (such as grade) and vehicle fleet characteristics
- **Non Transportation Data:** Meteorological data (such as humidity, temperature, pressure etc.), fuel supply data and Inspection and Maintenance Program data.

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[2] *Atmospheric Dispersion Models Description in Wikipedia* (http://en.wikipedia.org/wiki/List_of_atmospheric_dispersion_models - last accessed June 27, 2011)

While some data can be easily collected or generated, some data needed by advanced emissions models, such as MOVES or CMEM, is not readily available. In order to run the "project-level analysis," the most detailed level of emissions analysis supported by MOVES, advanced traffic simulation models such as Paramics, VISSIM, etc. should be used to produce the operating mode distribution of the vehicles or the second-by-second drive cycles. Emissions models in general require a number of input data values and parameters to estimate emissions. For example, MOVES has default VMT distributions by month, day of week, and hour of day. Before applying the model, the user should update these data values so that the values reflect the "local" conditions of the region being modeled. Also, as the emissions generated from the vehicles are very sensitive to the speed, it is very important that the vehicle speeds are captured accurately from traffic simulation models to predict the emissions impacts of ITS strategies. Using aggregates of average speed values is likely to produce wrong estimates of emissions. Emissions rates are also very sensitive to the vehicle type (such as passenger truck, light duty vehicle, transit bus, combination long-haul truck) and specifying the correct vehicle type proportions is very critical. Non-transportation data such as temperature and humidity also have impacts on the emissions results and these values should be adjusted to meet the "local" conditions. It must be noted that significant data processing is needed to use simulation model outputs as inputs to emissions model and the results are highly sensitive to the data processing methods used. This is especially true while using MOVES for project level analysis. Caution should be used while aggregating transportation data needed as inputs to MOVES.

MOVES and CMEM have been used recently as a part of research studies to evaluate ITS strategies. Sample applications of using advanced emissions models to evaluate ITS strategies are as follows:

- Using TRANSIMS, the University of Buffalo is evaluating the likely environmental benefits of lowest fuel consumption route guidance in the Buffalo-Niagara metropolitan region. This study will conduct an assessment of the likely environmental benefits of a new application for an environmentally optimized route guidance system for a medium-sized metropolitan area. Activities in this project include developing an integrated simulation modeling framework capable of calculating time-dependent fuel consumption factors; using TRANSIMS-MOVES modeling to estimate environmental benefits to be expected from implementing low fuel consumption routing; assessing the impact of market penetration on the likely benefits of the strategy; assessing additional benefits to be expected from taking into account real-time information about traffic disturbances; and assessing modal benefits
- Sample vehicle trajectory files generated by VISSIM and Paramics were processed and interfaced with MOVES software to demonstrate the use of traffic simulation model outputs for MOVES project level analysis[3]
- An ongoing "Impact of Operational Improvements on Induced Demand and Emissions" is looking at using the MOVES model to quantify the emissions impacts of Operational Improvements[4]

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[3] Robert Chamberlin, Ben Swanson, Eric Talbot, Jeff Dumont, Steve Pesci, *Utilizing MOVES' Link Drive Schedule for Estimating Project- Level Emissions*, TRB Workshop on Integrating MOVES with Transportation Microsimulation Models, 2011 (http://trbairquality.org/wp-content/uploads/2011/02/Chamberlin-Presentation.pdf - accessed on May 14, 2011).

- A recent study demonstrated through a case study, an integrated, automated modeling framework of MOVES and simulation-based dynamic traffic assignment (SBDTA) model, i.e., DynusT, especially for project level emission analyses. This project demonstrates integration of MOVES with a dynamic traffic assignment model in order to perform project level estimation in MOVES and investigate the differences in using MOVES default drive schedule (i.e., specifying only link average speed) versus using local specific operating mode distribution input[5]

- As a part of the "Optimizing Traffic Control to Reduce Fuel Consumption and Vehicular Emissions" study being carried out by Florida Atlantic University, CMEM is used to model field fuel consumption using an integrated approach with VISSIM, CMEM, and VISGAOST (a stochastic optimization program)

- El Paso Comprehensive Modal Emissions Model (CMEM) Case Study: This project looked at methodologies and data requirements for running the comprehensive modal emissions model (CMEM) and documents the results of a case study conducted in the El Paso, Texas, area. The main purpose of the model was to estimate vehicle tailpipe emissions for various categories of vehicles, with consideration given to the length of time the vehicle is operating and vehicle operations such as accelerating, decelerating, idling, and cruising[6]

- ECO-ITS Study: This project is being carried out by University of California – Riverside (UCR) under the Research on ITS Applications to Improve Environmental Performance Broad Agency Announcement (BAA) contract. Previous UCR research developed a microscopic emissions CMEM model capable of predicting second-by-second fuel consumption and tailpipe emissions. This study will build upon previous research to synthesize results and recommend the following: data collection methods; environmental analysis methods; integration of simulation and environmental modeling tools; and suggestions for environmental ITS applications and strategies.[7]

The state-of-the-practice scan of emissions models indicate that MOVES and CMEM microscopic emissions models allow fine level emissions analyses and calculate emissions impacts of ITS strategies. However, the project team makes the following recommendations on how to improve these models:

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[4] Richard Margiotta, *Impact of Operational Improvements on Induced Demand and Emissions*, Preliminary findings presented at TRB Workshop on Integrating MOVES with Transportation Microsimulation Models, 2011.

[5] Jane Lin, Yi-Chang Chiu, Song Bai, Suriya Vallamsundar, *Integration of MOVES and Dynamic Traffic Assignment Models for Fine-Grained Transportation and Air Quality Analyses*, TRB 90th Annual Meeting.

[6] Stephen P. Farnsworth, *El Paso Comprehensive Modal Emissions Model (CMEM) Case Study*, November 2001 (http://tti.tamu.edu/documents/2107-2.pdf - accessed on May 15, 2011).

[7] *Research on ITS Applications to Improve Environmental Performance Broad Agency Announcement (BAA) project details* published at http://www.its.dot.gov/aeris/baa_factsheet.htm – accessed on May 15, 2011).

- Further research is needed to determine the most effective way to integrate travel demand model outputs with microscopic emissions models to estimate regional emissions impacts more accurately
  - Microscale emissions models typically require extensive data on the system and vehicles included in the study in order to generate accurate emissions estimates. The data needed can be generated only using simulation models and the level of complexity increases dramatically with larger regional networks. In particular, traffic simulation models cannot be used to generate detailed vehicle movement data needed for micro analyses (for example, project level analyses in MOVES) of regional networks

- Further research is needed to determine which essential non-transportation data (such as meteorology, tire pressure, fuel types, and vehicle age distribution) needs to be updated in the emissions models using real-time data (that might be collected using data acquisition technologies) to capture the emissions impacts accurately.

Most emissions models are built based on field data collected through various data collection programs. Where applicable, using the advanced data collection technologies available, the emissions models should be validated. For example, the VSP bin distribution in MOVES needs to be reviewed and validated using field data.

Based on the state-of-the-practice scan, the table below shows the behavior changes associated with different ITS or potential AERIS strategies and the travel demand and emissions models capable of evaluating these strategies.

Table E-1: Capabilities of Models to evaluate ITS/potential AERIS strategies

ITS or Potential AERIS Strategy	Behavior Change Description	Potential Models or Tools for Predicting Behavior Changes	Potential Emissions Models or Tools for Predicting Environmental Impacts*
Behavior Changes that Impact VMT			
Demand and Access Management Strategies, Traffic Management and Control Strategies, Transit Improvement Changes	Change in routes (targeted at minimizing travel distance)	Traditional four-step models, activity based model, Mesoscopic or Microscopic Simulation Models	MOVES, CMEM or EMFAC
	Change in mode of travel (take transit, carpool, non-motorized travel such as walking, biking etc.)	Traditional four-step models or activity based models in combination with mesoscopic simulation models	MOVES, CMEM or EMFAC
	Change in number of trips	Activity based models in combination with	MOVES, CMEM or EMFAC

ITS or Potential AERIS Strategy	Behavior Change Description	Potential Models or Tools for Predicting Behavior Changes	Potential Emissions Models or Tools for Predicting Environmental Impacts*
		mesoscopic models	
	Change in trip chaining patterns	Activity based models in combination with mesoscopic models	MOVES, CMEM or EMFAC
Behavior Changes that do not directly impact VMT			
Speed Harmonization, Eco-Routing	Compliance with variable speed limits that improves the smoothness of travel	Microsimulation models	MOVES or CMEM
	Change in driving behavior (eco-driving)	Microsimulation models	MOVES or CMEM
	Eco-routing (note that eco-routing sometime can also lead to reduced VMT)	Microsimulation models	MOVES or CMEM

*Note that this is not an exhaustive list, but rather an illustrative example of emissions models that can be used.

Table of Contents

1 INTRODUCTION

The primary objective of the Applications for the Environment: Real-time Information Synthesis (AERIS) State-of-the-Practice Support project is to establish a foundation for the future research work to be conducted as a part of the AERIS program by conducting a state-of-the-practice assessment of travel behavioral and activity-based models, environmental models, and tools and technology available to enable environmental data acquisition. The purpose of this report, in particular, is to document the ability of emissions models to quantify emissions impacts of Intelligent Transportation Systems (ITS) strategies. As a separate but related part of this project, the research team has also conducted a detailed analysis of behavioral and activity-based models and a state-of-the-practice scan of technologies for use in capturing environmental data and data needed to measure environmental impacts.

While this report describes the state-of-the-practice assessment of emissions models to support AERIS program, the project team has prepared, as a part of this project, two additional reports that summarize the state-of-the-practice of behavioral and activity-based models and state-of-the-practice of technology to enable environmental data acquisition.

1.1 Research Objectives

The AERIS program vision is to generate, capture, and analyze vehicle-to-vehicle and vehicle-to-infrastructure data to create actionable information that allows surface transportation system users and operators to make “green” transportation choices. The U.S. Department of Transportation (USDOT) and its contractors are in the process of identifying applications that have demonstrated environmental benefits through the use of ITS technologies and looking at opportunities for the AERIS program to use these applications. The preliminary list of strategies that have demonstrated to yield environmental benefits includes:

- **Demand and Access Management** or **Transportation Demand Management** (TDM) strategies such as electronic toll collection, mileage-based fee, congestion pricing, en-route or pre-trip traveler information, etc. Demand and access management strategies aim to reduce traffic or travel demand by controlling access to roadways, improving pedestrian and transit options, and encouraging policies that reduce peak-hour congestion
- **Eco-Driving** strategies such as eco-driving assistance, adaptive cruise control (ACC), and eco-routing. These strategies attempt to influence driving behavior and promote driving styles that reduce overall emissions
- **Traffic Management and Control** strategies such as implementation of incident management systems, ramp metering, speed management, adaptive signal control, and signal coordination and optimization. These strategies attempt to dynamically adjust the traffic operations to manage traffic, reduce congestion, and hence reduce the emissions generated
- **Logistics and Fleet Management** strategies such as implementation of Automatic Vehicle Location (AVL) systems and idle-off stop-start systems. These strategies attempt to reduce emissions by optimizing vehicle maintenance, telematics, speed, and fuel management
- **Freight Management** strategies such as delivery management, platooning, and eco-driving

- **Transit** improvement strategies such as implementing BRT to improve the mode share or reducing transit emissions by implementing TSP.

Some common traveler behavior changes associated with the above strategies can be broadly classified as behavior changes that reduce the overall VMT (and directly reduce the emissions generated) or behavior changes that do not result in an overall reduction in VMT, but still succeed in emissions reduction. Examples of behavior changes include the following:

Behavior changes that directly result in VMT reduction

- Change in routes (targeted at minimizing travel distance)
- Change in mode of travel (take transit, carpool, non-motorized travel such as walking, biking, etc.)
- Change in number of trips
- Change in trip chaining patterns

Behavior changes that do not directly result in VMT reduction but those that can have a positive impact on the environment

- Change in time of travel (for instance, peak spreading or changing the time of departure to avoid congestion and/or toll)
- Compliance with variable speed limits that improves the smoothness of travel
- Change in driving behavior (eco-driving)
- Improved freight planning and operations
- Eco-routing (note that eco-routing sometime can also lead to reduced VMT)
- Change in Fuel choices.

Change in traveler behavior in one or more of the ways listed above is likely to have a direct impact on the environment. For example, if the traveler reduces the amount of auto travel, changes the time of day of travel, or changes the driving style or behavior, then these changes may result in reduced VMT and/or fuel consumption (due to reduction in VMT or improvement in driving style) and hence result in reduced emissions.

Freight management techniques also can yield environmental benefits. *Freight Transport Management* includes various strategies of increasing the efficiency of freight and commercial transport. *Logistics* is a technical term for efficient freight management, including shipping practices (e.g., vehicle type, shipment size and frequency) and related activities. Logistics usually focuses on minimizing shipper costs, with little consideration of social costs such as congestion or pollution impacts. Below are examples of Freight Transport Management activities[8]:

- Encourage shippers to use modes with lower social costs, such as rail and water transport rather than truck for longer-distance shipping. Trucking uses much more

[8] *Freight Transport Management, Increasing Commercial Vehicle Transport Efficiency,* Victoria Transport Policy Institute, May 2011 (http://www.vtpi.org/tdm/tdm16.htm, last accessed June 2011)

energy per unit of transport than rail or water (ten times as much in many situations), although only certain types of goods and deliveries are suitable for such shifting.

- Improve rail and marine transportation infrastructure and services to make these modes more competitive with trucking. (Note that by reducing shipping costs this may increase total freight traffic volumes, resulting in little or no reduction in energy consumption, emissions or other externalities.)

- Improve scheduling and routing to reduce freight vehicle mileage and increase load factors (e.g., avoiding empty backhauls). This can be accomplished through increased computerization and coordination among distributors.

- Organize regional delivery systems so fewer vehicle trips are needed to distribute goods (e.g., using common carriers that consolidate loads, rather than company fleets).

- Reduce total freight transport by reducing product volumes and unnecessary packaging, relying on more local products, and siting manufacturing and assembly processes closer to their destination markets.

- Use smaller vehicles and human powered transport, particularly for distribution in urban areas.

- Implement fleet management programs that reduce vehicle mileage, use optimal sized vehicles for each trip, and insure that fleet vehicles are maintained and operated in ways that reduce external costs (congestion, pollution, crash risk, etc.).

- Encourage businesses to consider shipping costs and externalities in product design, production and marketing, for example by minimizing excessive packaging and unnecessary delivery frequency, and relying on more local suppliers.

- Change freight delivery times to reduce congestion.

- Increase land use Accessibility by Clustering common destinations together, which reduces the amount of travel required for goods distribution.

- Pricing and tax policies to encourage efficient freight transport.

- Increase freight vehicle fuel efficiency and reduce emissions through design improvements and new technologies. These include increased aerodynamics, weight reductions, reduced engine friction, improved engine and transmission designs, more efficient tires, and more efficient accessories.

- Improve vehicle operator training to encourage more efficient driving.

A variety of models are available to support freight planning and modeling activities. Detailed information of the freight modeling tools and methods can be found at (http://onlinepubs.trb.org/onlinepubs/ncfrp/ncfrp_rpt_008.pdf - last accessed on June 17, 2011).

To support AERIS and other research programs, it is essential to have modeling tools that are capable of evaluating the benefits of different ITS scenarios or deployment strategies to help agencies determine the best application or bundles of applications that can be deployed. Some of the ITS strategies such as the demand management and access strategies tend to influence traveler behavior more directly than other strategies such as eco-driving. For strategies that do not influence the traveler behavior greatly, microsimulation tools such as TRansportation ANalysis Simulation System (TRANSIMS), VISSIM, Paramics, AIMSUN, etc. have been successfully used to generate transportation data that can be fed to emissions models to estimate emissions.

1.2 Modeling Needs to Support the AERIS Program

The primary objectives of AERIS are to accomplish the following:

1. Generate/capture environmentally relevant real-time transportation data (from vehicles and the system)
2. Use this environmental data to create actionable information that can be used by system users and operators to support and facilitate "green" transportation choices for all modes
3. Assess whether doing these things yields a good enough environmental benefit to justify further investment by the USDOT.

As traveler choices impact the VMT or distance traveled, speed, smoothness of travel, and / or driving characteristics, traveler choices have a direct impact on emissions. To quantify the environmental benefits of implementing ITS strategies, it is necessary to:

1. Model traveler response to ITS strategies at a fine level of detail;
2. Interface the outputs from travel demand models with traffic assignment models to predict network performance such as speed, volume, delays, vehicle mix, etc., and
3. Feed the speed, volume, and vehicle movement data to emissions models to quantify the air quality and fuel consumption impacts of traveler choices.

Typically, outputs from travel demand models (such as speed, volume, fleet mix, etc.) are provided as an input to emissions models to quantify vehicle emissions and fuel consumption. For several years now, transportation planning agencies have input speed estimates from traffic assignment procedures in traditional four-step models (and recently from simulation-based models) to the Mobile6 Emissions model to perform air quality analysis. Mobile6 is a macroscopic emissions model and does not allow much flexibility to change the input parameters and assumptions. However, there have been some recent improvements to emissions models, and the Environmental Protection Agency (EPA) recently released Motor Vehicles Emissions Simulator (MOVES), a next-generation, simulation-based emissions model. The MOVES model is capable of receiving travel demand data inputs at a finer level of detail when compared to Mobile6 (e.g., it can read driving cycles or operating mode distribution of vehicles).

1.2.1 Sequencing of Steps to Evaluate Emissions Impacts

Predicting and representing traveler behavior in response to ITS strategies is important to determine the impacts of ITS strategies on the environment. Behavioral or demand models such as the four-step demand models or activity-based models are used to predict the changes in mode choice, time-of-day choice, route choice, etc., and typically, the behavior changes result in changes in traffic volumes or travel during congested times. The outputs of the demand models are the Origin-Destination matrices of trips by mode, time of day, etc.

To quantify the emissions impacts of ITS strategies, it is not sufficient to predict the behavior changes or the updated Origin-Destination (OD) matrices in response to ITS strategies; it is also necessary to estimate the change in network performance (speeds, congestion, volumes, delays, etc.) as a result of change in behavior. For example, the output of behavioral models cannot predict the environmental impact of change in driver characteristics (smooth driving). Traffic assignment procedures or microsimulation tools (mesosocopic and microscopic) are used to model network performance changes resulting from the behavior changes (both pre-trip and while driving). "State-of-the-Practice Scan of behavioral and activity based models Report" presents the findings of ability of behavioral and activity based models to predict behavior changes in response to ITS strategies and the suitability to use the behavior changes to estimate emissions impacts.

After predicting the behavior changes and determining the change in network performance in response to ITS strategies, finally, to quantify the emissions impacts due to the behavior changes, the network performance data (detailed speeds, volumes, etc.) generated by the traffic simulation tools is fed to emissions models such as MOVES or Comprehensive Modal Emission Model (CMEM). **Figure 1** shows the modeling capability needed to predict the air quality impacts of ITS strategies.

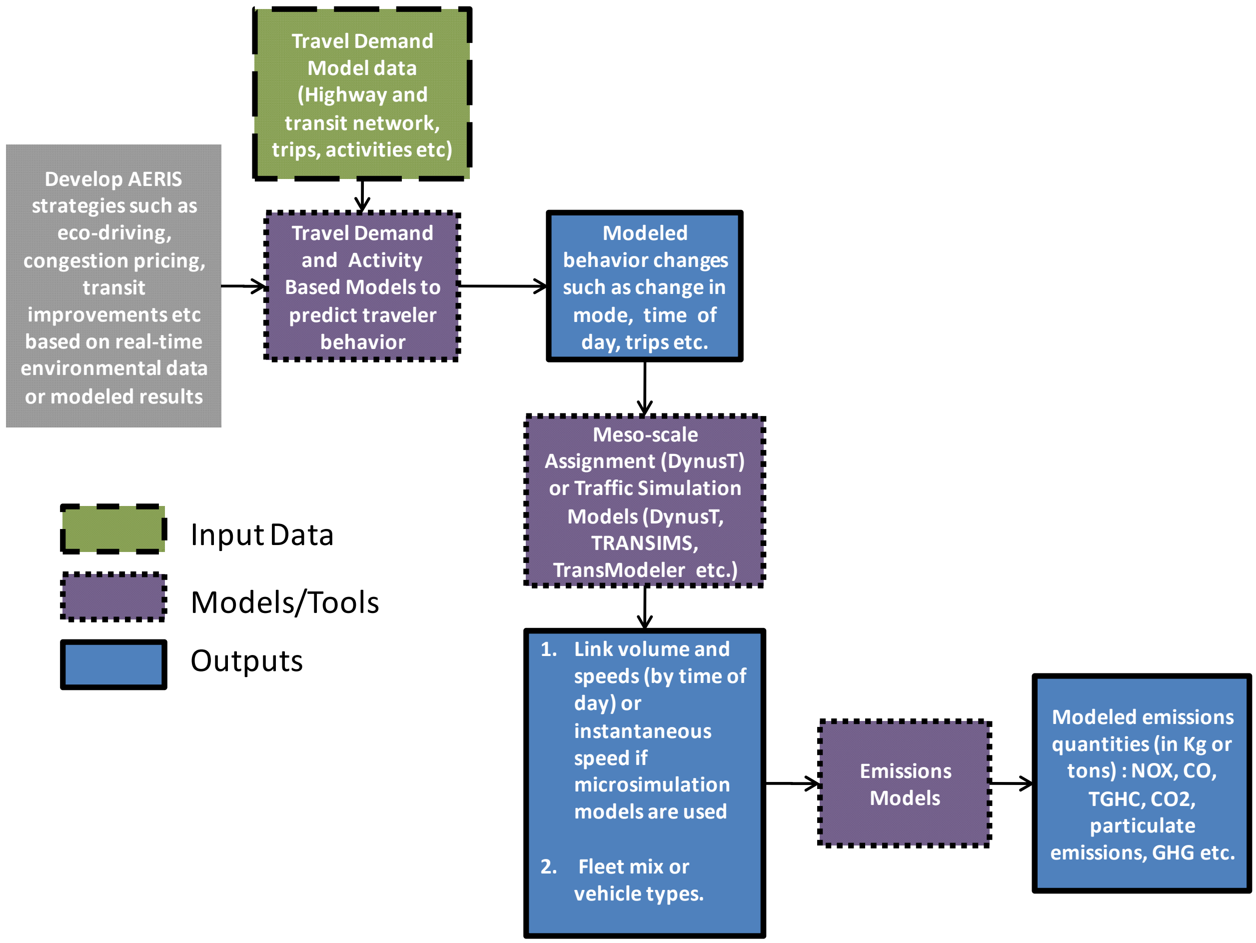

Figure 1: Sequencing of Steps to Evaluate Emissions Impacts of ITS Strategies

Several transportation agencies are implementing TDM techniques and other ITS strategies to influence travel behavior and, hence, reduce emissions. Emission quantities generated from a car depends on the amount of travel (i.e., VMT) and speed with which the travel occurs. Cars and trucks emit significantly higher emissions at lower travel speeds as compared to higher travel speeds (note that certain emissions increase marginally at significantly higher speeds). Also, trucks and other heavy-duty vehicles emit more emissions than cars. Sharp acceleration and deceleration rates also increase the amount of emissions generated by vehicles. As a result, improvement in travel speeds and/or reduction in overall travel volume will help in reducing emissions. Also, smoothing the travel flow and reducing the acceleration and deceleration rates help reduce the emissions.

The purpose of this report is to document the state-of-the-practice of environmental models in general and to conduct detailed reviews of the MOVES, Comprehensive Model Emissions Model (CMEM) and Emissions Factors (EMFAC) models and assess their suitability in evaluating ITS strategies.

1.3 Overview of Environmental or Emission Models

The traffic assignment module in travel demand models generates estimate of the speeds, volumes, and fleet mix. These outputs are typically used as inputs to emissions models to estimate GHG and criteria pollutant emissions. Several air quality analysis tools are available to quantify emissions from the speed and volume estimates generated by travel demand models.

Transportation emission models can be grouped into four classification categories:

- Emission factor models
- Physical power demand models
- Acceleration and speed based models
- Dispersion models.

Emissions Factor Models: For emission factor models, an emissions factor is derived from the average value of repeated measurements of total emissions per driving cycle. One commonly used U.S. transport emissions models is EMission FACtor (EMFAC), where baseline emissions rates are derived from a standard U.S. laboratory test procedure, the Federal Test Procedure (FTP). Correction factors are established to incorporate the influence of factors such as vehicular speed, temperature, fuel type, and vehicle age on the baseline emissions rates (Yin, 2011). These models provide a convenient way to model area-wide vehicle emissions levels because they require less detailed information on traffic flow and operation pattern than the other three types of models (Bai, 2008). However, this modeling approach is unable to account for the effects of vehicle operation states and driving environment on emissions rates and will have limited value in evaluating ITS strategies.

Physical power demand models: The second category of transportation emission models comprises the physical power-demand models. These models can predict second-by-second tailpipe emissions for different driving conditions and vehicle types. CMEM is a widely used physical power-demand model that determines vehicle emissions rate as a function of vehicle operation characteristics, such as engine power, engine speed, air/fuel ratio, fuel use, engine-out emissions, and catalyst pass fraction (Rakha, 2003 and Yin, 2011). This modeling approach provides a more accurate estimate of vehicle emissions levels by incorporating the effects of vehicle operation and driving environment into the emissions model. Additionally, these models are sensitive to changes in vehicle acceleration behavior and thus can be utilized for the evaluation of operational-level transportation projects such as re-timing signals, modeling toll plazas, and modeling highway sections and other ITS strategies (Rahka, 2003). However, detailed data on operational characteristics at varying speeds and acceleration rates for multiple vehicle types is usually difficult to obtain, impeding the application of these models (Yin, 2011).

Acceleration and speed based models: Acceleration and speed-based models comprise the third category. These models estimate emissions as a function of vehicle type, instantaneous speed, and acceleration. U.S. EPA's MOVES model is an example of an "acceleration and speed- based" model. Early versions of these models derived the average emissions rate based on estimates of 14 typical driving moduli (Yin, 2011 referencing Joumard, 1995). Emission rates are then denoted as a function of a combination of linear, quadratic, and cubic transforms of the instantaneous speed and acceleration, which can readily be derived from data on the average speed and number of stops of the specified driving modulus (Yin, 2011 referencing Ahn, 1999, Ahn, 2002, and Rakha, 2004). This modeling approach is promising for evaluating ITS strategies, as less detailed engine operation and driving environment information is required (compared with the physical power-demand models) and the influence of vehicle movement is considered, which it is not in the emissions factor models (Yin, 2011).

Acceleration and speed-based models may also allow for air quality analysis that has generally been done by dispersion models. EPA has proposed that MOVES be used to complete PM and CO hot-spot analysis (EPA, 2010). In addition, MOVES will likely be used to complete NEPA analysis of transportation projects (ibid.). Furthermore, the MOVES model allows users to represent intersection traffic activity with a higher degree of sophistication compared to previous models and to account for speed and temperature variations, linked to emissions factors and processes obtained from extensive in-vehicle data collection (Chamberlin, 2011). The improved functionality of MOVES makes it a good candidate tool for conducting air quality assessments of ITS strategies.

Dispersion models: Dispersion models use mathematical formulations to estimate the concentration of pollutants at specified ground-level receptors surrounding an emissions source. These models use meteorological data to predict concentrations of emissions at selected downwind receptor locations and can be used to determine compliance with National Ambient Air Quality Standards as well as other regulatory requirements. These models are used to assess the emissions from stationary sources such as smoke stacks and wildfires and are not used for transportation purposes. These types of models may not readily accept input from travel demand models. Because of lack of applicability to estimate emissions related to ITS strategies, this report will not address dispersion models beyond the summary information provided in Section 3.1.

2 STATE OF PRACTICE

2.1 Summary of Environmental or Emission Models

2.1.1 Overview

As described in **Section 1.3,** transportation emission models can be grouped into four classification categories:

- Emission factor models
- Physical power demand models
- Acceleration and speed based models
- Dispersion models.

Table 1 below shows the list of commonly used environmental or emissions models used to quantify air quality impacts of traffic operational improvements under each of the above four categories.

Table 1: Summary of Environmental Models

Model	Developer	Model Description	Current Status
Emission Models - Emission Factor Models			
Consolidated Community Emissions Processing Tool (CONCEPT)	Lake Michigan Air Director's Consortium/Mid-west Regional Planning Organization	The CONCEPT model includes modules for the major emissions source categories: area source, point source, on-road motor vehicles, non-road motor vehicles (used MOBILE 6 factors) and biogenic emissions, as well as a number of supporting modules, including spatial allocation factor development, speciation profile development, growth and control for point and area sources, and Continuous Emissions Monitoring (CEM) point source emissions handling. Modules under development include graphical tools, and an interface to the traffic demand models for on-road motor vehicle emissions estimation	Currently available as open source
Emission Factors (EMFAC)	California Air Resources Board	EMFAC is an on-road, integrated mobile source emission model where local-specific emission rates and vehicle activity are combined internally to generate hourly or daily total emissions for various geographic areas in California	Used in California

Model	Developer	Model Description	Current Status
MOBILE	EPA	MOBILE is a mobile source emission model where local-specific emission rates and vehicle activity are combined internally to generate hourly or daily total emissions for various geographic areas	Replaced by MOVES in Dec. 2009
TREMOVE	K.U.Leuven and DRI, then updated by Transport & Mobility Leuven	TREMOVE is a policy assessment model to study the effects of different transport and environment policies on the emissions of the transport sector. It includes passenger and freight transport in 31 countries and covers the period 1995-2030	Used in Europe; In 2009 began developing a U.S. model at Duke University of North Carolina
Emission Models - Physical Power Demand Models			
Comprehensive Modal Emissions Model (CMEM)	University of California, Riverside	CMEM is a microscopic emissions model that is capable of predicting second-by-second fuel consumption and tailpipe emissions of CO2, carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NOx) based on different modal operations from an in-use vehicle fleet	Used across the U.S.
Versit and Versit+micro	TNO in the Netherlands	VERSIT+micro calculates PM10, CO2, and NOx emissions on a detailed level for specific vehicle types and technologies (e.g., fuels, drive trains, injection technologies)	Used in Europe
Assessment System for Urban & Regional Evaluation (MEASURE)	Georgia Institute of Technology / EPA	Mobile Emissions Assessment System for Urban and Regional Evaluation (MEASURE) focuses on estimating emissions for ozone precursor pollutants (volatile organic compounds, nitrogen oxides, carbon monoxide) and has limited emission estimation capabilities for other pollutants. In the future, better characterization of particulate matter and hazardous air pollutant (air toxic) emissions is planned	A working research model for Atlanta, GA, developed by Georgia Tech

Model	Developer	Model Description	Current Status
Passenger car and Heavy-duty Emission Model (PHEM)	Graz University of Technology	PHEM was developed to simulate a full fleet of heavy-duty vehicles, passenger cars, and light commercial vehicles. The supporting data-set includes gasoline and diesel vehicles from EURO 0 to EURO 6. PHEM calculates vehicle fuel consumption and emissions, using speed trajectories as model input. PHEM calculates the engine power in 1 Hz (cycles per second) based on the given courses of vehicle speed (the "driving cycle") and road gradient, the driving resistances and the losses in the transmission system. The 1 Hz course of engine speed is simulated based on the transmission ratios and a gear shift model. The model results then are the 1 Hz courses of engine power, engine speed, fuel consumption and emissions of CO, CO2, HC, NOx, NO, particle mass (PM) and particle number (PN). Theoretically, PHEM can be used to take data instantaneously from a traffic microscopic flow model and translate this into emissions	Used in Europe
MODEM	Consortium of three European laboratories (in France, Germany, and UK)	The MODEM microscopic emission database was developed as a part of the European Commission's DRIVE II research program. It is a microscopic modal emissions database based on the results of chassis dynamometer driving cycle measurements. Fourteen different cycles were used in the development of the MODEM emissions database based upon a large-scale survey of the operating characteristics of vehicles used in urban areas across Europe with the aim of representing real-world driving conditions	Used in Europe

Model	Developer	Model Description	Current Status
Emission Models - Acceleration and Speed Based Models			
Motor Vehicle Emission Simulator (MOVES)	EPA	Modal emission model that derives emissions estimates based on second-by-second vehicle performance characteristics for various driving modes and geographic areas ranging from the nation down to link	Used across the U.S.
Microscale Emission Factor (MicroFac)	Dr. R. Singh (University of Waterloo)/EPA	The Microscale Emission Factor (MicroFac) is a micro scale emission factor model for predicting gaseous and particulate matter motor vehicle emissions and fuel consumption. The algorithm used to calculate emission factors in MicroFac is disaggregated based on the on-road vehicle fleet, and calculates emission rates from a real-time site-specific fleet. MicroFac starts with geographically resolved data, for example modeling traffic fleet on an individual length of road. Emissions factors are calculated for site-specific on-road traffic fleet, e.g. CO emissions in g/VKT. Total emissions for a geographical area of interest can then be obtained by summing contributions from individual road segments. The model requires vehicle fleet characterization, speed, and ambient temperature. MicroFac is primarily designed to be used with dispersion models and to support remote sensing studies in converting emission concentrations to g/km units	MicroFacPM is designed to estimate emission factors for the U.S. motor vehicle fleet and is suitable for estimating real-time emission factors in microenvironments of human exposure near roadways

Model	Developer	Model Description	Current Status
Virginia Tech Microscopic Energy and Emission Model (VT-Micro Model)	Dr. Hesham Rakha (Virginia Tech Transportation Institute)	VT-Micro models were developed for application within a microscopic simulation model or using field instantaneous speed measurements using Global Positioning Systems. The original VT-Micro model was developed using chassis dynamometer data on nine light duty vehicles. The VT-Micro model was then expanded by including data from 60 light duty vehicles and trucks. Statistical clustering techniques are applied to group vehicles into homogenous categories. Specifically, Classification and Regression Tree algorithms are utilized to classify the 60 vehicles into 5 LDV and 2 LDT categories. In addition, the model k accounts for temporal lags between vehicle operational variables and measured vehicle emissions	Used across the U.S.
Vehicle Transient Emissions simulation Software (VeTESS)	Developed within the EU 5th framework project DECADE	VeTESS is a single, vehicle-based emissions model. VeTESS is a vehicle level simulation based emissions modeling tool developed for the simulation of fuel consumption and emissions of vehicles in real traffic and transient operation conditions. VeTESS, calculates emissions and fuel consumption made by a single vehicle during a defined drive-cycle. The drive cycle is a representation of the route to be driven by the vehicle. It contains details of the speed of the vehicle and the road gradient over a complete route. The drive-cycle could be from a recorded journey, calculated from traffic flow models, or produced from knowledge of typical journeys. Starting with a given driving cycle, VeTESS uses simple mathematical calculations involving gear ratios and their efficiencies to determine the engine's operating conditions from the force on the vehicle	Used in Europe

Model	Developer	Model Description	Current Status
Dispersion Models			
AMS/EPA Regulatory Model (AERMOD)	EPA	AERMOD model is a steady-state plume model that incorporates air dispersion based on planetary boundary layer turbulence structure and scaling concepts, including treatment of both surface and elevated sources, and both simple and complex terrain. There are two input data processors that are regulatory components of the AERMOD modeling system: AERMET, a meteorological data preprocessor that incorporates air dispersion based on planetary boundary layer turbulence structure and scaling concepts, and AERMAP, a terrain data preprocessor that incorporates complex terrain using USGS Digital Elevation Data	Used across the U.S.
California Line Source Dispersion Model (CALINE-4)	California Department of Transportation	CALINE-4 is a Carbon monoxide (CO) hot spot analysis model. The model uses traffic emissions, site geometry, and meteorology to predict air pollutant concentrations near roadways. Predictions can be made for carbon monoxide, nitrogen dioxide, and suspended particles. Options for modeling near intersections, parking lots, elevated or depressed freeways, and within canyons are available in this model	Used in California

Model	Developer	Model Description	Current Status
California Puff Model (CALPUFF)	Sigma Research Corporation / TRC Environmental Corporation	CALPUFF is an advanced, integrated Gaussian puff modeling system for the simulation of atmospheric pollution dispersion distributed by the Atmospheric Studies Group at TRC Solutions. It is maintained by the model developers and distributed by TRC. The integrated modeling system consists of three main components and a set of pre-processing and post-processing programs. The main components of the modeling system are CALMET (a diagnostic 3-dimensional meteorological model), CALPUFF (an air quality dispersion model), and CALPOST (a post-processing package)	Used in California
Canyon Plume Box Model, version 3.6a (CPB3)	Federal Highway Administration	CPB3 is designed to simulate mobile source impacts within an urban street canyon and narrow highway cut sections (where the surrounding topography is above the level of the roadway) for complex site geometries. The model was developed by FHWA	Used for estimating canyon impacts
Contaminants in the Air from a Road-Finnish Meteorological Institute (CAR-FMI)	Finnish Meteorological Institute	CAR-FMI models an open-road network of finite line-source emissions for inert and reactive (NOx and ozone [O3]) gases, as well as fine particulates (PM2.s) from vehicle exhaust. Dry deposition is included for particulates. There is limited chemistry using the discrete parcel method for CO, NO, NO2, NOX, O3, and PM2.5	Used in Europe

Model	Developer	Model Description	Current Status
Hybrid Roadway Model (HYROAD)	SAI / ICF	HYROAD integrates three historically individual modules that simulate the effects of traffic, emissions, and dispersion. The traffic module is a microscale transportation model that simulates individual vehicle movement. The emission module uses speed distributions from the traffic module to determine composite emission factors; spatial and temporal distribution of emissions is based on the vehicle operation simulations. HYROAD is designed to determine hourly concentrations of CO or other gas-phase pollutants, PM, and air toxics from vehicle emissions at receptor locations that occur within 500 m of the roadway intersections	HYROAD is primarily an intersection model, but can simulate a highway link by creating a very long link between intersections (on and off ramps)
Point, Area, Line (PAL)	EPA	PAL is a multisource steady-state Gaussian plume model for nonreactive gaseous and suspended particulate pollutants. Developed in the 1980s, its application is primarily at the urban microscale environment (up to several hundred meters) and is included here for historical perspective. Six source types can be modeled with PAL: point, area, two types of line sources (line and slant line), and two types of curved path sources (curved and special path	Used by EPA
Quick Urban & Industrial Complex (QUIC)	Los Alamos National Laboratory	The Quick Urban & Industrial Complex (QUIC) Dispersion Modeling System is a fast response urban dispersion model that runs on a laptop. QUIC is comprised of a 3D wind field model called QUIC-URB, a transport and dispersion model called QUIC-PLUME, a pressure solver, QUIC-PRESSURE, and graphical user interface called QUIC-GUI	Used as a dispersion model

Model	Developer	Model Description	Current Status
Atmospheric Dispersion Modeling System (ADMS)-ROADS	Cambridge Environmental Research Consultants (CERC)	ADMS-Roads models the full range of sources that may be important in calculating air quality around small networks of roads: more than 7000 road links (150 road sources each with up to 50 vertices), and up to 3 point, 3 line, 4 area, and 25 volume industrial sources	Use for small networks
Operational Street Pollution Model (OSPM)	National Environmental Research Institute of Denmark	The Operational Street Pollution Model (OSPM) is an atmospheric dispersion model for simulating the dispersion of air pollutants in so-called street canyons. It was developed by the National Environmental Research Institute of Denmark, Department of Atmospheric Environment. For about 20 years, OSPM has been used in many countries for studying traffic pollution, performing analyses of field campaign measurements, studying efficiency of pollution abatement strategies, carrying out exposure assessments, and as reference in comparisons to other models. OSPM is generally considered as state-of-the-art in practical street pollution modeling	Used in Demark
PROKAS	Lohmeyer Consulting Engineers, Inc.	PROKAS_V is a model based on the German guideline VDI 3782/1 "Gaussian Dispersion Model for Air Quality Management". It models up to 5000 line sources (reproduced by sets of point sources) of a network of streets is possible. The influence of traffic induced turbulence, the influence of the course of streets on dams and the influence of noise protection devices for each street are included	Used in Germany
Micro-Calgrid Model (MCG)	R. Stern and R. Yamartino	MCG is an urban-canopy-scale photochemical model designed to be used in specific European cities	Used in Europe
ROADWAY-2	NOAA Air Resources Laboratory	Roadway-2 is a finite difference model that predicts pollutant concentration near a roadway	Used by NOAA

Model	Developer	Model Description	Current Status
PUFFER	University of Nottingham (UK)	The PUFFER model was developed as part of a doctoral dissertation at the University of Nottingham (UK) to model vehicular pollutants in an urban street canyon. The dispersion is based on Gaussian puff methods but with an extended range of applicability. The model includes the explicit effects of individual vehicles as sources of pollution and turbulence over multiple lanes of traffic. Each vehicle emits a puff at the start of a time step, and each puff maintains its independence of all other puffs (i.e., no consideration for puffs crossing paths)	Used in UK
TRAQSIM	University of Central Florida	The TRAQSIM model was developed by the University of Central Florida in support of a doctoral dissertation. TRAQSIM is a puff model for flat terrain (i.e., topography is not addressed) that tracks vehicular exhaust released as individual puffs using modal emissions factors from CM EM that were incorporated into a lookup table for TRAQSIM. TRAQSIM combines traffic, emissions, and dispersion components into an integrated, graphical framework. TRAQSIM is applicable for emissions of CO and other nonreactive pollutants	Used fir air emissions studies
UCD 2001	University of California, Davis	The UCD 2001 dispersion model was developed by the University of California, Davis, and is designed to estimate pollutant concentrations near at-grade roadways	Used for at-grade roadways

2.1.2 Data Considerations

As explained in **Figure 1**, traffic simulation models are used to predict change in network performance (speed and volume by vehicle type) resulting from implementation of AERIS or other ITS strategies. In order to quantify the emissions impacts of these strategies, the output from the travel simulation models are fed as input to emissions models.

Traffic simulation models are broadly classified as Macroscopic, Mesoscopic, and Microscopic simulation models.

- **Macroscopic Simulation Models:** Macroscopic simulation models use deterministic relationships of the flow, speed, and density of the traffic stream to determine system performance. The macroscopic models simulate traffic on a section-by-section basis, rather than by tracking individual vehicles, and have higher fidelity than traditional traffic assignment procedures in travel demand models. Macroscopic models have considerably fewer demanding computer requirements than microscopic models; however, they do not have the ability to analyze transportation improvements in as much detail as the microscopic models. These models are not capable of evaluating the environmental impacts of ITS strategies as they do not model network performance at the desired level of detail. Examples of Macroscopic simulation models include FREQ, TRANSYT-7F, SATURN, and VISTA.

- **Mesoscopic Simulation Models:** Mesoscopic simulation models combine the properties of both microscopic and macroscopic simulation models. As in microscopic models, the mesoscopic models' unit of traffic flow is the individual vehicle. Their movement, however, follows the approach of the macroscopic models and is governed by the average speed on the travel link. Mesoscopic model travel simulation takes place on an aggregate level and does not consider dynamic speed/volume relationships. As such, mesoscopic models provide less fidelity than the microsimulation tools, but are superior to the typical planning analysis techniques. Mesoscopic simulation models (also referred to as dynamic simulation models) are well suited to support evaluation of the environmental benefits of ITS strategies as they can model large regions of transportation network at relatively high levels of fidelity for much less computer resources as compared to microsimulation tools. Examples of mesoscopic simulation tools include CONTRAM, DYNAMIT, DYNASMART-P, DYNU.S.T, VISUM, and AIMSUN.

- **Microscopic Simulation Models:** Microscopic models simulate the movement of individual vehicles based on car-following and lane-changing theories. Typically, vehicles enter a transportation network using a statistical distribution of arrivals (a stochastic process) and are tracked through the network over small time intervals (e.g., 1 second or a fraction of a second). Typically, upon entry, each vehicle is assigned a destination, a vehicle type, and a driver type. Computer time and storage requirements for microscopic models are large, usually limiting the network size and the number of simulation runs that can be completed. These tools develop detailed vehicle movement data that can be directly fed to simulation-based emissions models such as MOVES and CMEM to quantify the air quality impacts of implementing ITS strategies. Examples of microscopic simulation tools include AIMSUN2, CORSIM, INTEGRATION, VISSIM, Paramics, TRANSIMS, and TransModeler.

Microscopic simulation models are best suited for producing the speed data required by advanced physical power demand emissions models (such as CMEM) or acceleration and speed-based models (such as MOVES). Irrespective of the emissions model used, emissions are estimated based on vehicle speed and acceleration characteristics. In order to quantify the emissions impacts of ITS strategies, good quality data needs to be generated from traffic simulation models.

In order to build and run the traffic simulation models to generate the necessary data for emissions models, a significant amount of effort generally is required to learn to use traffic simulation models, including setting up the appropriate inputs and parameters. A significant amount of effort may also be required to obtain traffic and network data to conduct the analysis and to calibrate the model to local conditions. Especially the parameters in the traffic microsimulation models should be calibrated carefully so that the lane changing and other driving characteristics are similar to what is observed in "real" world. Also, different traffic simulation models produce the output data in different formats and / or granularity and post processing is generally necessary to interface traffic simulation model outputs with emissions models.

Inputs necessary to run the traffic simulation models include:

- Transportation data such as
    - Traffic volumes by link and intersection turning movement
    - Link travel times
    - Percent heavy vehicles and buses

- Network data such as
    - Lanes
    - Turning lanes
    - Speed limits
    - Lane widths
    - Intersection control (e.g., signal phasing, timing plan).

Typical outputs generated by traffic simulation models include data such as average speeds, travel time, delay, etc. Advanced traffic simulation models such as VISSIM, Paramics, etc., produce second-by-second speed profiles of vehicles.

2.2 Review of MOVES Model

2.2.1 Overview

EPA's Office of Transportation and Air Quality (OTAQ) recently developed the MOVES. MOVES is a next generation air quality analysis tool that estimates emissions from mobile sources for a broad range of pollutants such as Total Gaseous Hydrocarbons (TGH), Non-Methane Hydrocarbons, Volatile Organic Compounds, Carbon Monoxide, Particulate emissions such as Organic Carbon, Sulphate Particulates, Carbon dioxide, Methane, Nitrous Oxide etc. MOVES2010, the latest version of MOVES software, is a state-of-the-art EPA modeling tool capable of estimating emissions from cars, trucks, motorcycles, and buses, based on EPA's analysis of millions of emission test results.

Mobile6 was used as the EPA-approved emissions modeling tool to be used by transportation planning agencies for State Implementation Plans (SIP) development, conformity submissions, and National Environmental Policy Act (NEPA) analysis. The Clean Air Act (CAA) requires EPA to regularly update its mobile source emission models. EPA continuously collects data and measures vehicle emissions to make sure the Agency has the best possible understanding of mobile source emissions. Mobile6 was difficult to maintain by EPA and update, as it was developed using FORTRAN and all the parameters and data inputs were hard-coded in the code. In order to advance emissions modeling practice, EPA developed MOVES model, which is a database based application and easy to maintain and update.

EPA recently approved and announced the availability of the MOVES Software for official use outside of California and approved the use of MOVES2010 (MOVES) in official State Implementation air quality Plan (SIP) submissions to EPA and for certain transportation conformity analyses outside of California. This authorization started a 2-year grace period before the MOVES emission model is required to be used in all new regional emissions analyses for transportation conformity determinations outside of California.

With this approval, MOVES has become EPA's approved motor vehicle emissions factor model for estimating volatile organic compounds (VOCs), nitrogen oxides (NOx), carbon monoxide (CO), direct particulate matter (PM10 and PM2.5) and other precursors from cars, trucks, buses, and motorcycles by state and local agencies for SIP and transportation conformity purposes outside of California.[9] EPA has also announced that MOVES2010 is EPA's best tool for estimating air toxic and greenhouse gas emissions from on-road mobile sources.

MOVES2010 is EPA's latest on-road mobile source emissions model and adopts an advanced modeling approach to mobile source emission modeling based upon recommendations made to the agency by the National Academy of Sciences (NAS).

2.2.2 Model Description

MOVES support three levels of analysis namely National Level, County or Region Level, and Project Level analysis:

- **National Level** analysis uses a default national database with state and local allocation factors. While the National level analysis can be used to estimate rough magnitude of emissions, the use of this approach is not prescribed for air quality assessments.

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[9] *Policy Guidance on the Use of MOVES2010 for State Implementation Plan Development, Transportation Conformity, and Other Purposes* (http://www.epa.gov/otaq/models/moves/420b09046.pdf - accessed on May 12, 2011).

- **County Level** analysis in MOVES is used for SIP and regional conformity analysis and requires the user to provide county-specific data.

- **Project Level** analysis in MOVES is used for estimating emissions resulting from highway, transit and freight projects at a network link level. This level of analysis requires detailed transportation data input at link level (volumes, speeds, gradient, etc.) and some non- transportation data at county level (meteorology data, vehicle inspection data, etc.). Data needed for this analysis is only generated by traffic simulation models and not traditional or static assignment models.

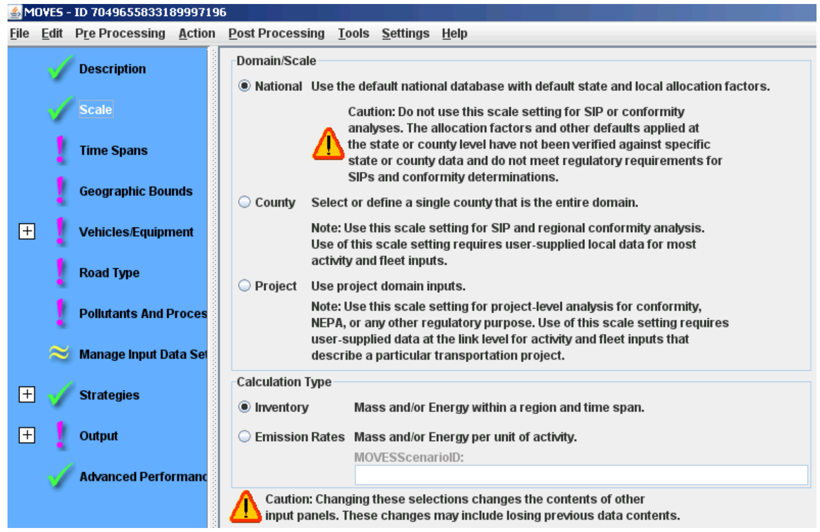

Figure 2: MOVES Interface

MOVES can be interfaced with a variety of transportation models and data sets in order to allow a user to perform detailed fuel consumption analyses as well as produce a localized emissions inventory. In particular, there are two ways by which MOVES can be used to estimate emissions: (1) Emissions Inventory Option, and (2) Lookup Rate option.

The MOVES Inventory option produces emissions quantity in units of mass such as kilograms or tonnes for a specific time period. The MOVES software internally multiplies the emissions rates with vehicle activity to generate total emissions. In the Lookup Rate option, the user can generate an emissions rate lookup table similar to Mobile6 software. Prior to generating the look up rate table, the user can specify or adjust the default MOVES parameters so that the emissions rates (in grams / mile) are reflective of the region being modeled. Provided below is a description of interfacing transportation model outputs with MOVES software to estimate emissions.

MOVES Emissions Inventory Option:

1. The user has to convert transportation model output such as speeds and volumes to a format that can be read by MOVES data importers
2. Then using the Importers, transportation data can be imported into the MOVES database
3. The user can populate other MOVES non-transportation data such as meteorology, fuel type mix, vehicle inspection program assumptions, etc.
4. Run MOVES model with the updated data
5. Summarize the output tables generated by MOVES software.

MOVES Look-up Rate Option:

1. The user has to adjust the default MOVES parameters such as fuel assumptions; meteorology, and vehicle type mix so that the data matches local conditions

2. Run the MOVES model in Emissions look-up rate mode and generate an emissions rate lookup table
3. Use a custom made program to apply the emissions rates table to transportation data such as VMT, speeds, vehicle type mix, etc., classified by facility types (freeways, arterials, etc.) and area types (urban and rural).

Note that the MOVES Inventory Emissions estimates are likely to be more accurate than the Lookup rate option as in this case MOVES emissions calculations are internal and will be subject to less rounding errors.

2.2.3 Model Approach and Underlining Theory

MOVES uses a detailed approach to modeling that incorporates large amounts of in-use data from a wide variety of sources, such as data from vehicle inspection and maintenance (I / M) programs, remote sensing device (RSD) testing, certification testing, portable emission measurement systems (PEMS), etc. This approach also allows users to incorporate a variety of activity data to better estimate emission differences such as those resulting from changes to vehicle speed and acceleration patterns. For example, MOVES can be used to estimate project-level PM2.5 and PM10 emissions. MOVES uses a modeling concept where total vehicle emissions are the product of vehicle activities, base emission rates, and a series of adjustment factors. The MOVES model is more complex than MOBILE6 or EMFAC in how vehicle activities are quantified, how emission rates are measured, and how vehicle activities and emission rates are paired spatially and temporally (Bia, 2008).

Documents released by the EPA summarize the modeling approach and underlying theory used by MOVES (http://www.epa.gov/otaq/models/moves/420r10026.pdf - *accessed May 12, 2011*). MOVES is a new modeling tool for estimating emissions produced by on-road (cars, trucks, motorcycles, etc.) and, eventually, non-road (backhoes, lawnmowers, etc) mobile sources. MOVES estimates greenhouse gases (GHG), criteria pollutants, and selected air toxics from highway vehicles.

The MOVES model calculates emissions for running exhaust, start exhaust, a number of evaporative processes, and several other emission processes. In general, MOVES calculates these emissions by multiplying emission rates by emission activity and applying correction factors as needed. The emission rates and activity in MOVES are distinguished at a much finer level than in MOBILE6. For example, most running emissions are categorized into one of 25 operating modes, depending on vehicle speed and vehicle specific power (VSP). Start emissions are distinguished based on the time a vehicle has been idle prior to start, and evaporative emissions modes are defined based on whether the vehicle is operating or has recently been operating. Vehicles are categorized into narrow subtypes or "source bins" with similar fuels, engine sizes, and other emission-related characteristics.

The MOVES model calculates emissions by calculating a weighted average of emissions by operating mode. For running exhaust emissions, the operating modes are defined by Vehicle Specific Power (VSP) or the related concept, Scaled Tractive Power (STP). Both VSP and STP are calculated based on a vehicle's speed and acceleration. They differ in how they are scaled. The VSP equation is used for light duty vehicles and the STP equation is used for heavy-duty vehicles. MOVES use the coefficients below to calculate VSP and STP for each source type according to the equation:

$$VSP = \left(A/M\right)*v + \left(B/M\right)*v^2 + \left(C/M\right)*v^3 + \left(a + g*\sin\theta\right)*v$$

where A, B, and C are the road load coefficients in units of (kilowatt second)/(meter), (kilowatt second^2)/(meter^2) , and (kilowatt second^3)/(meter^3) respectively. The denominator term, M is the fixed mass factor for the source type in metric tons, g is the acceleration due to gravity (9.8 meter/ second^2), v is the vehicle speed in meter/second, a is the vehicle acceleration in meter/ second^2, and sinθ is the (fractional) road grade.

2.2.4 Data Inputs, Outputs, and Gaps

MOVES is a database application that uses a default MOVES database as the input data. The default database includes emission relevant information for the entire United States. MOVES uses numerous data input parameters to generate emissions estimates. *"MOVES2010 Highway Vehicle – Population and Activity Data"* Technical Report published by EPA provides a clear description of the MOVES input data fields. The data for MOVES default database comes from many sources including EPA research studies, Census Bureau vehicle surveys, FHWA travel data, and other federal, state, local, industry, and academic sources. The MOVES team continually works to improve this database, but, for many uses, up-to-date local inputs will be more appropriate, especially for analyses supporting SIPs and conformity determinations.

MOVES users may update the database selectively to match the "local" conditions of the modeling region. The table below shows the key input data used in MOVES model and the commonly available data sources to update MOVES default values.

Table 2: MOVES Input Data Needs

MOVES Input Data	Description	Source of Data to Update Defaults
avgSpeedFraction	Distribution of time among average speed bins	Travel demand models and preferably Traffic Simulation Models
dayVMTFraction	Distribution of VMT between weekdays and weekend days	Counts from Automatic Traffic Recording (ATR) stations
averageSpeed	Average speed of each drive schedule	Traffic Simulation Models

MOVES Input Data	Description	Source of Data to Update Defaults
sourceTypeID, roadTypeID, DriveScheduleID, isRamp	Mapping of which drive schedules are used for each combination of sourcetype and roadtype	Traffic Simulation Models
speed	Speed for each second of each drive schedule	Traffic Simulation Models
fuelEngFraction	Joint distribution of vehicles with a given fuel type and engine technology. Sums to one for each sourcetype and model year	Data is not available easily
hourVMTFraction	Distribution of VMT among hours of the day	Counts from Automatic Traffic Recording (ATR) stations
HPMSBaseYearVMT, baseYearOffNetVMT, VMTGrowthFactor	Base Year VMT by HPMS vehicle types and annual VMT growth factors	Counts from Automatic Traffic Recording (ATR) stations
AC Activity Terms (A, B & C)	Coefficients to calculate air conditioning demand as a function of heat index	Data is not available easily
monthVMTFraction	Distribution of annual VMT among months	Counts from Automatic Traffic Recording (ATR) stations
modelYearGroupID	Assigns model years to appropriate model year groups. These vary with pollutant/process	Data is not available easily
regClassFraction	Fraction of vehicles in a given "Regulatory Class." Sums to one for each sourceType, modelYear and fuel/engtech combination	Data is not available easily
roadTypeVMTFraction	Distribution of VMT among roadtypes	Travel Demand Models
dayID, SourceTypeID	Identifies vehicles in SampleVehicleTrip	Data is not available easily

MOVES Input Data	Description	Source of Data to Update Defaults
stmyFuelEngFraction, stmyFraction	Incorporates the fractions found in the FuelEngFraction, RegClassFraction, SizeWeightFraction and SCCVTypeDistribution tables, but also expected fractions for vehicles that do not exist in the existing fleet. The expected values are used with the Alternative Vehicle Fuel & Technology Strategy inputs to generate alternate future vehicle fleet source bins	Data is not available easily
priorTripID, keyontime, keyOffTime	Trip start and end times; used to determine vehicle start and soak times	Data is not available easily
SCCVTypeFraction	Distribution of sourcetypes to EPA Source Classification Codes	Data is not available easily
sizeWeightFraction	Joint distribution of engine size and weight. Sums to one for each sourceType, modelYear and fuel/engtech combination	Data is not available easily
sourceBinActivityFraction	Distribution of population among different vehicle sub-types (sourcebins)	Data is not available easily
survivalRate, relativeMAR, functioningACFraction	Rate of survival to subsequent age; relative mileage accumulation rates and fraction of air conditioning equipment that is functioning	Data is not available easily
ageFraction	Fraction of vehicle population at each age	DMV Records
idleSHOFactor	Prevalence of air conditioning equipment	Data is not available easily
ACPenetrationFraction	Ratio of extended idle time to driving time, by hour	Data is not available easily
isSizeWeightReqd, isRegClassReqd, isMYGroupReqd	Indicates which pollutant-processes the source bin distributions may be applied to and indicates which discriminators are relevant for each source type and pollutant/process	Data is not available easily
sourceTypePopulation, salesGrowthFactor, migrationRate	Vehicle counts and growth factors	Counts from Automatic Traffic Recording (ATR) stations

MOVES Input Data	Description	Source of Data to Update Defaults
rollingTerm, rotatingTerm, dragTerm, sourceMass	Road load coefficients for each SourceType, used to calculate Vehicle Specific Power	Data is not available easily
idleAllocFactor, startAllocFactor, SHPAllocFactor	Allocation of activity to zone (county)	Travel Demand Models
SHOAllocFactor	Allocation of driving time to zone (county) and roadtype	Travel Demand Models

As the table above indicates, MOVES uses several input data tables and values. Specifically, key data needed to run MOVES micro level or project level analysis include the following:

- **Travel Data:** Driving Schedule, Vehicle Operating modes, Link characteristics (such as grade), and vehicle fleet characteristics

- **Non Transportation Data:** Meteorological data (such as humidity, temperature and pressure), fuel supply data and Inspection and Maintenance Program data.

While some data can be easily collected or generated, some data needed by MOVES is not easily available. In order to quantify the emissions impacts of implementing ITS strategies, outputs generated by static or simulation based traffic assignment models have to be post processed and applied to MOVES . Static travel models generate average weekday volumes by 3 or 4 auto occupancy levels (HOV2, HOV3 etc.) and 1 or 2 truck types (Light Duty Trucks, Heavy Duty Trucks etc) by 2 or 3 time periods (AM peak, PM peak, Off peak, etc.) on each link. Simulation models on the other hand are capable of producing vehicle movement data every second. In order to run the "project-level analysis," the most detailed level of emissions analysis supported by MOVES, advanced traffic simulation models such as Paramics, VISSIM, etc. should be used to produce the operating mode distribution of the vehicles or the second-by-second drive cycles.

The table below shows the list of key transportation and non-transportation data needed by the MOVES model. Note that there is no correlation between the columns in each row.

Table 3: Data Needed by MOVES

Transportation Data	Non-Transportation Data
Total Annual VMT by HPMS	Source type population (number of vehicles in the county/domain)
Vehicle Population	Vehicle Age distribution (vehicle age/technology data)
Vehicle Miles Traveled (VMT) Fraction by Month and Vehicle type	Fuel supply (market share for fuels by year and month)

Transportation Data	Non-Transportation Data
Vehicle Miles Traveled (VMT) Fraction by facility type (restricted and unrestricted) and Vehicle type	Meteorology data (temperature and humidity)
Vehicle Miles Traveled (VMT) Fraction by day of the week, facility type (restricted and unrestricted) and Vehicle type	I/M program specifications
Vehicle Miles Traveled (VMT) Fraction by hour of the day, day of the week, facility type (restricted and unrestricted) and Vehicle type	
Vehicle Miles Traveled (VMT) Fraction by speed, hour of the day, day of the week, facility type (restricted and unrestricted) and Vehicle type	
Link Drive Schedules (second by second speed of vehicles on each link) – Needed for project level analysis	
Operating Mode Distribution (vehicle type. Pollutant process and operating mode fraction) – Can be used for project level analysis instead of link drive schedules described above	

2.2.5 Types of Emissions Addressed

MOVES model is capable of estimating a wide range of pollutants emitted by vehicles. MOVES can also model emissions for a variety of vehicle and fuel types. The table below shows the list of pollutants, vehicle types, and fuel types considered by the MOVES model. Note that there is no correlation between the columns in each row.

Table 4: Emissions, Vehicle Types, and Fuel Type considered by MOVES

Emissions Type	Fuel Types	Vehicle Types
Total Gaseous Hydrocarbons	Gasoline	Passenger Car
Non-Methane Hydrocarbons	Diesel	Passenger Truck
Non-Methane Organic Gases	Compressed Natural Gas (CNG)	Light Commercial Truck
Total Organic Gases	Liquid Propane Gas (LPG)	Refuse Truck
Volatile Organic Compounds	Ethanol (E85 or E95)	Single Unit Short-haul Truck
Carbon Monoxide (CO)	Methanol (M85 or M95)	Single Unit Long-haul Truck
Oxides of Nitrogen	Gaseous Hydrogen	Motor Home
Ammonia (NH3)	Liquid Hydrogen	School Bus
Nitrogen Oxide	Electricity	Transit Bus

Emissions Type	Fuel Types	Vehicle Types
Nitrogen Dioxide		Intercity Bus
Sulfur Dioxide (SO2)		Combination Short-haul Truck
Total Energy Consumption (total, Petroleum, Fossil)		Combination Long-haul Truck
Methane (CH4)		Motorcycle
Nitrous Oxide (N2O)		
Atmospheric CO2		
CO2 Equivalent		
Particulate Matter (PM 10 and PM2.5 for Organic Carbon, Elemental Carbon, Sulfate Particulate, Brake-wear Particulate, Tire-wear Particulate)		

2.2.6 Methodology Used to Calculate Emissions and the Factors Considered

MOVES model uses modal activity to estimate emissions. The MOVES model incorporates input data that includes vehicle fleet composition, traffic activities, fuel information, and meteorology parameters and conducts modal-based emissions calculations using a set of model functions. Based on the resulting modal-based vehicle emission rates, emission inventories or emission factors are then generated for the desired geographic scale (macro, meso, or micro scales) as well as temporal resolution (year, day, and hour). Four major functions constitute the basic framework of MOVES[10]: an activity generator, a source bin distribution generator, an operating mode distribution generator, and an emissions calculator. The graphic below shows the overall model structure of the MOVES Model.

10 U.S. EPA. *Motor Vehicle Emission Simulator Highway Vehicle Implementation (MOVES-HVI) Demonstration Version: Software Design and Reference Manual Draft.* Publication EPA420- P-07-001, Office of Transportation and Air Quality, U.S. Environmental Protection Agency, 2007.

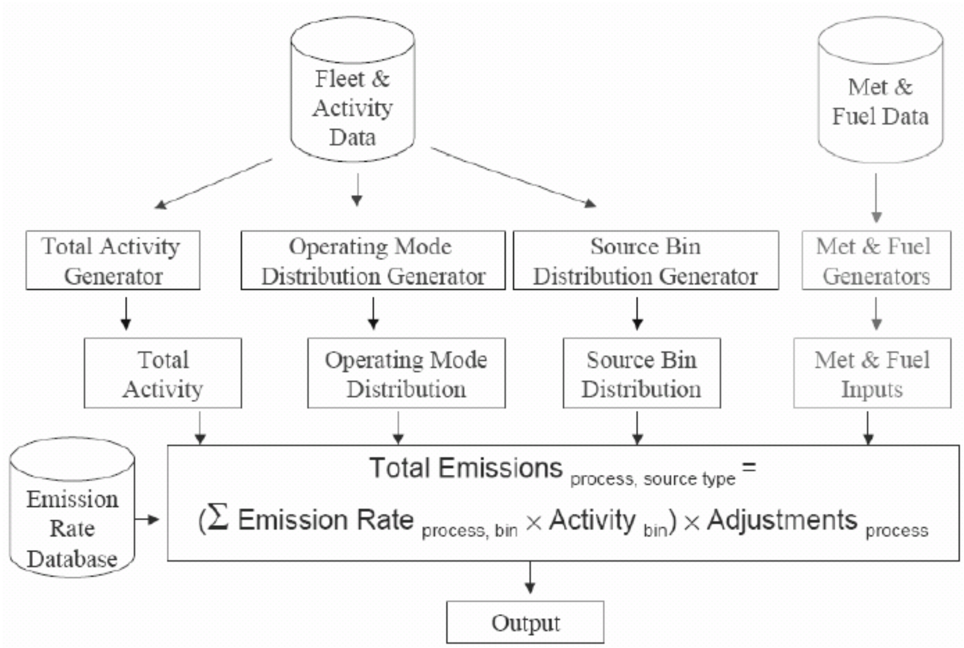

Figure 3: MOVES Model Structure[11]

2.2.7 Omissions and Limitations

MOVES model includes advanced features and functions than traditional emission models. MOVES modal-based approach allows analyses to be completed at various spatial scales that range from national level, region level, or link level. Thus, MOVES provides a great flexibility to model emissions for a wide range of needs. MOVES uses VSP to estimate emissions and since VSP has been shown to be more closely correlated with on-road emissions than speed, use of MOVES-generated emissions factors should represent a more accurate characterization of on-road vehicle emissions than emission factors generated using MOBILE or EMFAC. However, the emissions models accuracy greatly depends on the quantity and quality of the default VSP data available in MOVES and it is unclear as to which portions of the MOVES VSP dataset are most robust, and which require supplemental data to augment the creation of reasonable emission factors. EPA has specified that the medium- and heavy-duty truck portions of the MOVES dataset are less populated than those applicable to the light-duty fleet.

Also, in order in perform project level or link level analysis in MOVES, the user has to generate driving cycle profiles for vehicles on the link or generate the operating mode distribution models. Traffic simulation models are needed to generate this data. Also, "There are limits to the number of Link Drive Schedules that can be input into MOVES. A complicated network with dozens of intersections may challenge the processing capability of the software while also requiring substantial sophistication from the modeler." (Chamberlin, 2010). So the current usage of project level analysis in MOVES is cumbersome.

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[11] Beardsley, M. *MOVES Fleet and Activity Inputs: 1999 Base Year.* Presented at the CRC Onroad Emissions Workshop, San Diego, California, 2004.

While MOVES is the most advanced tool available to model GHG emissions, the current version of MOVES has some limitations related to energy/GHG analysis that will be addressed in future versions For example, Energy/GHG effects of biofuels (E85, biodiesel) are not fully accounted for and some vehicle types (hybrid, fuel cell) are present in the model but not active.[12]

2.2.8 Sensitivity of the Model

As described in **Section 2.2.4** MOVES requires a number of input data values and parameters to estimate emissions. For example, MOVES has default VMT distributions by month, day of week, and hour of day. Before applying the model, the user should update these data values so that the values reflect the "local" conditions of the region being modeled. Also, as the emissions generated from the vehicles are very sensitive to the speed, it is very important that the vehicle speeds are captured accurately from traffic simulation models to predict the emissions impacts of ITS strategies. Using aggregates of average speed values is likely to produce wrong estimates of emissions. Emissions rates are also very sensitive to the vehicle type (such as passenger truck, light duty vehicle, transit bus and combination long-haul truck) and specifying the correct vehicle type proportions is very critical. Non-transportation data such as temperature and humidity also have impacts on the emissions results and these values should be adjusted to meet the "local" conditions.

It must be noted that significant data processing is needed to use simulation model outputs as inputs to MOVES model and the results are highly sensitive to the data processing methods used. This is especially true while using MOVES for project level analysis. Caution should be used while aggregating transportation data needed as inputs to MOVES.

2.2.9 Applicability to ITS Strategies

MOVES uses operating mode distribution or the percentage time spent in each speed bin to estimate emissions. This approach estimates emissions that are sensitive to speed. As fuel consumption or fuel economy varies with speed, ITS strategies that increase or decrease the speed (changing the fuel economy) impact emissions even if the total travel or VMT remains the same. While ITS strategies such as demand and access management strategies (such as electronic toll collection, mileage-based fees, congestion pricing) change the trip behavior and hence VMT, a number of other ITS strategies (such as variable message signs, adaptive cruise control, speed management, adaptive signal control, and signal coordination and optimization) are likely to have a more direct impact on speed and lesser impact on the VMT. As such, it is important to use emissions models that can predict emissions impacts based on detailed estimates of speeds and acceleration and deceleration rates.

The graphic below demonstrates that fuel economy changes with variation in speed. Change in fuel economy changes the fuel consumption and hence the emissions.

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[12] Jeff Houk, FHWA Resource Center, 19th International Emission Inventory Conference, *Greenhouse Gas Emissions Analysis of Regional Transportation Plans with EPA's MOVES Model*, September 2010 (http://www.epa.gov/ttnchie1/conference/ei19/session6/houk_pres.pdf - accessed May 13, 2011).

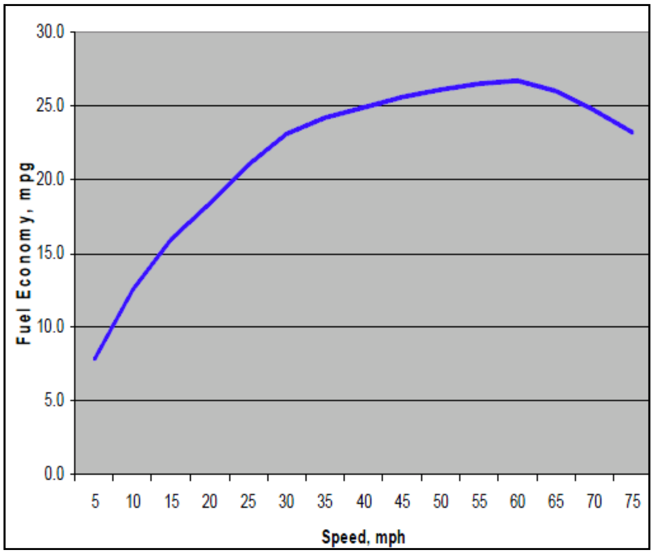

Figure 4: Variation of Fuel Economy with Speed[4]

As demonstrated by the above figure, travel speed has a significant impact on emissions. While most macroscopic models do use speed to estimate emissions, they use average travel speed as the key input variable. Research, however, has demonstrated that the use of average speed as the input is insufficient in estimating vehicle emissions accurately. For the same average speed, one can observe widely different instantaneous speed and acceleration profiles, each resulting in very different fuel consumption and emission levels (Rakha and Ahn). Hence, in order to estimate emissions accurately, it is desirable to have second-by-second speed profiles. Project-level analysis option in MOVES is well suited to estimate emissions based on detailed speed profiles.

The "Using MOVES in Project-Level Carbon Monoxide Analyses" report published by EPA (http://www.epa.gov/otaq/stateresources/transconf/policy/420b10041.pdf - accessed May 12 2011) describes the steps involved in using MOVES project level analysis for detailed emissions modeling. One of the key inputs for modeling emissions is the link drive schedule that includes speed data and grade as a function of time (seconds) on a particular roadway link. Most advanced traffic simulation models are capable of producing this data either at link level or vehicle level. The time domain is entered in units of seconds, the speed variable is miles-per-hour, and the grade variable in percent grade (vertical distance / lateral distance, 100% grade equals a 45-degree slope). MOVES builds Operating Mode Distribution from the Link Drive Schedule and uses it to calculate link running emissions. In order to quantify emissions from field data, link drive schedules could be based on observations using methods such as chase (floating) cars on similar types of links, or on expected vehicle activity based an analysis of link geometry. Link drive schedules will only represent average vehicle activity, not the full range of activity that will occur on the link. This limitation may be overcome by defining multiple links for the same portion of the project (links that "overlap") with separate source distributions and drive schedules to model individual vehicles."

Instead of using drive cycle data, the operating mode fraction data for source types, hour/day combinations, roadway links, and pollutant/process combinations can be used. Operating mode distributions may be obtained from traffic simulation models or field data.

MOVES is well suited for ITS strategies and has been successfully interfaced with traffic simulation models such as TRANSIMS, VISSIM, Paramics, etc., to estimate emissions. For example:

- Using TRANSIMS, the University of Buffalo is evaluating the likely environmental benefits of lowest fuel consumption route guidance in the Buffalo-Niagara metropolitan region. This study will conduct an assessment of the likely environmental benefits of a new application for an environmentally optimized route guidance system for a medium-sized metropolitan area. Activities in this project include developing an integrated simulation modeling framework capable of calculating time-dependent fuel consumption factors; using TRANSIMS-MOVES modeling to estimate environmental benefits to be expected from implementing low fuel consumption routing; assessing the impact of market penetration on the likely benefits of the strategy; assessing additional benefits to be expected from taking into account real-time information about traffic disturbances; and assessing modal benefits
- In 2008, the Georgia Regional Transportation Authority (GRTA) in partnership with the Atlanta Regional Council (ARC) and the Georgia Environmental Protection Division (EPD) implemented TRANSIMS in the Atlanta area. The primary objective of this study included quantifying the potential congestion and emissions impacts of planned transportation projects and integration with the MOVES model[13]
- Sample vehicle trajectory files generated by VISSIM and Paramics were processed and interfaced with MOVES software to demonstrate the use of traffic simulation model outputs for MOVES project level analysis[14]
- An ongoing "Impact of Operational Improvements on Induced Demand and Emissions" is looking at using the MOVES model to quantify the emissions impacts of Operational Improvements[15]
- A recent study demonstrated through a case study, an integrated, automated modeling framework of MOVES and simulation-based dynamic traffic assignment (SBDTA) model, i.e., DynusT, especially for project level emission analyses. This project demonstrates integration of MOVES with a dynamic traffic assignment model in order to perform project level estimation in MOVES and investigate the differences in using MOVES default drive

13 *The TRANSIMS Wiki Page provides details of the recently concluded and ongoing TRANSIMS Case Studies* (http://code.google.com/p/transims/wiki/CaseStudies - accessed on May 14, 2011).

14 Robert Chamberlin, Ben Swanson, Eric Talbot, Jeff Dumont, Steve Pesci, *Utilizing MOVES' Link Drive Schedule for Estimating Project-Level Emissions,* TRB Workshop on Integrating MOVES with Transportation Microsimulation Models, 2011 (http://trbairquality.org/wp-content/uploads/2011/02/Chamberlin-Presentation.pdf - accessed on May 14, 2011).

15 Richard Margiotta, *Impact of Operational Improvements on Induced Demand and Emissions,* Preliminary findings presented at TRB Workshop on Integrating MOVES with Transportation Microsimulation Models, 2011.

schedule (i.e., specifying only link average speed) versus using local specific operating mode distribution input.[16]

2.3 In-Depth Review of CMEM Model

2.3.1 Overview

CMEM is a microscopic emissions model developed at the University of California, Riverside (UCR) with support from the National Cooperative Highway Research Program (NCHRP) and EPA. The model is capable of predicting second-by-second fuel consumption and tailpipe emissions of carbon dioxide (CO2), carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NOx) based on different modal operations from an in-use vehicle fleet. This section presents an in depth review of the model including a discussion of the approach/methodology used by the model, inputs and outputs, sensitivity of the model, and limitations identified by users.

2.3.2 Model Description

The College of Engineering-Center for Environmental Research and Technology (CECERT) at the University of California-Riverside along with researchers from the University of Michigan and Lawrence Berkeley National Laboratory began developing CMEM in 1995. The objective of the effort was to develop a microscale analysis model that accurately characterizes Light-Duty Vehicle (LDV) emissions generated across a vehicle's operating modes. Researchers collected second-by-second tailpipe and engine-out emissions data from a sample of vehicles (approximately 340) to characterize emissions and fuel consumption across a variety of operating parameters and vehicles types. These data were then used to develop algorithms for predicting fuel consumption and emissions, which take into consideration parameters such as vehicle type / technology, vehicle mass, aerodynamic drag coefficient, fuel delivery system, emissions control, vehicle age, and maintenance condition.

CMEM was designed to interface with a variety of transportation models and data sets in order to allow a user to perform detailed fuel consumption analyses as well as produce a localized emissions inventory. The initial version of the model contained 23 LDV categories and accounts for various characteristics including emission control technology, mileage, and power-to-weight ratio. Additional vehicle/technologies categories have since been added to include ultra-low emitting vehicles, super ultra-low emitting vehicles and partial zero emission vehicles. Three heavy-duty vehicle/technology categories have also been added (UCR, 2011).

2.3.3 Model Approach and Underling Theory

In developing CMEM, researchers at UCR attempted to address limitations of previous modal emission models. Earlier models characterized vehicle operating modes at various levels of acceleration and deceleration to derive a speed/acceleration matrix. Emissions can then be measured for each operating mode to generate a matrix of emissions. Multiplying the emissions matrix by a matrix of vehicle activity yields total emissions for each specific vehicle activity.

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16 Jane Lin, Yi-Chang Chiu, Song Bai, Suriya Vallamsundar, *Integration of MOVES and Dynamic Traffic Assignment Models for Fine-Grained Transportation and Air Quality Analyses,* TRB 90th Annual Meeting Sunday Workshop #137, Washington DC, January 23, 2011 (http://trbairquality.org/wp-content/uploads/2011/02/Lin-Presentation.pdf - accessed on May 15, 2011).

However, this process does not account for other variables that can impact emissions such as road grade or use of accessories. Other previously developed models were based on generating an emissions profile for various engine power and speed combinations. This methodology can account for parameters such as road grade, use of accessories, and acceleration; however, the process of conducting second-by-second emissions testing can be very expensive and time consuming.

CMEM's modeling approach is to first break down the entire fuel consumption and emissions process into components that correspond to physical phenomena associated with vehicle operation and emissions production. Key parameters that characterize vehicle operation and generation of emissions such as vehicle mass, accessory power demand, catalyst aging, and fuel type are identified and factored into the model. Other key parameters related to operation of vehicles and emissions generated are obtained through sampling and testing of vehicle exhaust. This testing, however, is much less intensive than the testing performed for other models which require generating a vehicle's emission profile across a wide range of operating scenarios. Emissions rates are generated by combining the vehicle's physical characteristics and operating parameters. These emissions rates can then be compared to measured emissions data and the modeling components refined to calibrate the model (Scora, 2006).

2.3.4 Data Inputs and Outputs

CMEM uses numerous data input parameters to generate emissions estimates. For each vehicle / technology category, input variables include acceleration or second-by-second speed (which can be used to calculate acceleration), road grade, and accessory use (e.g., air conditioning). In addition to these operating variables, another 55 static parameters have been defined to characterize the vehicle tailpipe emissions for the vehicle/technology categories included in the model (see **Table 5**).

Table 5: CMEM emissions model input parameters

Readily-Available Parameters	Calibrated Parameters	
Specific Vehicle Parameters	***(Insensitive)*** ***Fuel Parameters***	***(Sensitive)*** ***Cold-Start Parameters***
Vehicle mass	Engine friction factor	Cold start catalyst coefficient for CO, HC, and NOx
Engine displacement	Drivetrain efficiency coefficients	Cold F/A equilibrium ratio
Idle speed of engine	Engine-out	Surrogate Temperature to reach stoichiometry
Coastdown power	***Emission Parameters***	Cold EO HC multiplier
Engine speed/vehicle speed	CO enrichment coefficient	Cold EO NO multiplier
Maximum torque	EO CO index coefficient	***Hot Catalyst Parameters***
Engine speed at max torque	EO HC index coefficient	Hot maximum CO, HC, and NOx catalyst efficiencies
Maximum power	EO HC residual value	Hot catalyst CO, HC, and NOx coefficient
Engine speed at max power	NOx stoichiometric index	NOx catalysts tip-in coefficient

Readily-Available Parameters	Calibrated Parameters	
Number of gears	NOx enrich index	***Enrichment Parameters***
Generic Vehicle Parameters	***Enleanment Parameters***	Maximum F/A equilibrium ratio
Indicated efficiency	Maximum HC_{lean} rate	SP threshold factor
Maximum drivetrain efficiency	Transient HC_{lean} rate	
Gear ratio	HC_{lean} threshold value	
Operating Parameters	HC_{lean} release rate	
Road grade	Ratio of O2 to ENC	
Accessory Power	Lean fuel/air equilibrium ratio	
Speed trace	***Soak-Time Parameters***	
Soak time	Soak time engine coefficient for CO, HC, NOx	
Specific humidity	Catalysts coefficient for CO, HC, NOx	

In CMEM, the Readily Available Parameters for each vehicle were obtained from publicly available information from the manufacturer. The Calibrated Parameters were determined using the measured emissions results for each test vehicle by direct measurement, regression equations, or an optimization process. The following parameters were determined directly from dynamometer measurements:

- Maximum hot-stabilized catalyst efficiencies for CO, HC, and NOx emissions
- Maximum fuel/air equivalence ratio
- Maximum lean HC emission rate during long deceleration events
- Maximum lean HC emission rate during transient events
- Minimum fuel/air equivalence ratio during enleanment operation
- Ratio of oxygen and engine-out HC emissions during enleanment operation
- Maximum cold-start fuel/air equivalence ratio.

The output of CMEM is second-by-section tailpipe emissions (i.e., HC, CO, NOx and CO_2), velocity, and fuel consumption.

2.3.5 Types of Emissions Addressed

The default output from the model is second-by-second tailpipe emissions of CO, HC, and NOx. Emissions of CO_2 is an optional output parameter that can also be selected. CMEM does not currently address particulate matter (PM) emissions; however, work on a PM emissions module began in 2005. The concept for this module was to estimate second-by-second PM emissions from vehicles with an emphasis on heavy-duty trucks.

2.3.6 Methodology Used to Calculate Emissions and the Factors Considered

The methodology used by CMEM to estimate emissions involves combining vehicle operating parameters with physical characteristics of the actual vehicles in the fleet being modeled. The following equation illustrates the methodology used to calculate second-by-second vehicle tailpipe emissions:

Tailpipe Emissions = FR * EI_i * CPF

Where:

FR = fuel combustion rate (grams/second)
EI_i = engine-out emission indices for each pollutant in grams of emissions per grams of fuel combusted
CPF = time-dependent catalyst pass fraction (e.g., the ratio of tailpipe to engine-out emissions)

The model contains six distinct modules that individually predict engine power, engine speed, air/fuel ratio, fuel use, engine-out emissions, and catalyst pass fraction (Barth, 2006). For each sub-model, there are a number of vehicle parameters and operating variables factored into the emissions estimate. These include (Scora, 2006):

- Different combinations of engine type (spark ignition, diesel)
- Fuel delivery system (carbureted, fuel injection)
- Emission control system (open-loop, closed-loop technology)
- Catalyst usage (no catalyst, oxidation catalyst, three-way catalyst)
- Readily available (i.e., public domain) static vehicle parameters (e.g., vehicle mass, engine size, etc.)
- Measurable static vehicle parameters (e.g., vehicle accessory power demand, enrichment power threshold, etc.)
- Deterioration parameters (e.g., catalyst aging, etc.)
- Fuel type parameters
- Vehicle operating parameters.

Additional data factored into the model include real world driving information such as:
- Static environmental factors (e.g., ambient temperature and air density)
- Dynamic factors (e.g., commanded acceleration and resultant velocity)
- Road loads (e.g., road grade)
- Use of vehicle accessories (e.g., air conditioning, electric loads).

2.3.7 Omissions and Limitations
While CMEM is a robust model capable of accurately estimating vehicle exhaust emissions at different speeds and accelerations, it is not without limitations. The following exceptions were noted during the literature review conducted for this effort:

- *Inability to estimate Particulate Matter emissions* – Particulate Matter (PM) emissions can cause significant health problems by aggravating asthma, causing difficulty breathing, and decreasing lung function. Vehicles, especially heavy duty vehicles, generate PM from fuel combustion (i.e., tailpipe emissions) as well as from normal brake and tire wear. These PM emissions could be significant when modeling emissions from a large number of vehicles on a macroscale. CMEM currently does not estimate PM emissions; however, a module for PM emissions has been under development for a number of years (Lee, 2009)

- *Vehicle Speed Limitation* – CMEM was developed from emission rates based on speeds up to 80 mph. For situations where speeds on roadways exceed 80 mph (such as the proposed high speed corridor systems in Texas), the model may not accurately estimate emissions (Park, 2010)
- *HDDV emissions after model year 2002* – Heavy-duty vehicles are a significant source of emissions. It is important to accurately estimate emissions from this segment of a vehicle fleet when conducting transportation studies. CMEM does not estimate HDDV emissions for model years after 2002 which has a direct impact on the accuracy of the emission results from this model (Lee, 2009).
- *Microscale vs. Macroscale* – CMEM works well on the microscale level while estimating larger, regional emissions (macroscale) is more complicated and possibly less accurate. Microscale models typically require extensive data on the system and vehicles included in the study in order to generate accurate emissions estimates. The level of complexity increases dramatically with larger networks given the interconnectivity of freeways, intersections, rural highways, and other roadway elements along with the variability of vehicle operation (e.g., varying degrees of congestion in different parts of the network). To overcome this limitation, statistical emission rates can be derived using CMEM from the microscale components as a function of roadway facility type and congestion level and then applied to individual links in a macroscale traffic assignment model (Scora, 2006).

2.3.8 Sensitivity of the Model

As discussed above, numerous input parameters are used in CMEM to develop emission estimates. The input parameters are divided into two main categories: "Readily Available Parameters" and "Calibrated Parameters." The calibrated parameters are further divided into two sub-sets that are referred to as the "insensitive" and "sensitive" data sets. The insensitive data set are known in advance or have a relatively small impact on vehicle emissions. Sensitive set data must be carefully determined as these data can have a significant influence on the accuracy of the emissions generated from the model (Farnsworth, 2001).

2.3.9 Applicability to ITS Strategies

The CMEM software predicts fuel consumption and second-by-second tailpipe emissions of various categories of vehicles operating under different conditions. CMEM allows for comparisons of operating conditions on selected transportation facilities. By comparing selected roadway segments operating in various conditions, an analysis of vehicle fuel consumption and emissions may be conducted. Depending on how the data collection is structured, the user can approximate the effectiveness of implementing emissions reduction strategies. This analysis tool can be used as part of the process of deciding where to make improvements to the transportation system. One of the advantages of the software is that it requires very little in terms of input to run the model. It allows the flexibility of performing a more detailed analysis by modifying the vehicle parameters. These modifications would generate a more specific output for a particular vehicle rather than a class or group of vehicles. The main input to the model is the speed data, and the equipment needed to do this is modest. Another advantage to the equipment is that it is transferable to other vehicles. After assembling

Features of CMEM

- Incorporates numerous vehicle operating parameters
- Applicable to all vehicles and technology types
- Not restricted to steady-state emission rates
- Model is transparent

a package of equipment, the user can transfer the equipment and use it in multiple vehicles. This flexibility is an attractive feature of the system.[17]

CMEM is well suited to support ITS strategies, especially at the microscale level. The model is able to handle all of the factors in the vehicle operating environment that affect emissions (e.g., vehicle technology, operating modes, maintenance, accessory use, road grade) and can be used to predict emissions for a wide variety of vehicles in various states of maintenance across numerous operating scenarios.

Additionally, CMEM is able to easily interface with microscale traffic demand models such as TRAF-NETSIM, FRESIM, and PARAMICS. The output from these models (speeds and volumes of vehicles) are used directly as input to the CMEM to generate emissions profiles for given scenarios (Scora, 2006).

CMEM has been successfully interfaced with advanced traffic simulation models successfully over the past few years. In particular, CMEM has been interfaced frequently with VISSIM for transportation analyses (Nam, E.K., C.A. Gierczak and J.W. Butler. 2003; Stathopoulos, F.G. and Noland, R.B. 2003; Noland, R.B. and Quddus, M.A. 2006; Chen, K. and L. Yu., 2007.) [18]

Sample applications of interfacing CMEM with traffic simulation models to estimate emissions related to implementation of ITS strategies are provided below:

- As a part of the "Optimizing Traffic Control to Reduce Fuel Consumption and Vehicular Emissions" study being carried out by Florida Atlantic University, CMEM is used to model field fuel consumption using an integrated approach with VISSIM, CMEM, and VISGAOST.

- CMEM - Modeling the Effectiveness of HOV Lanes at Improving Air Quality Project: Although improving air quality is one of the main purposes of implementing high occupancy vehicle (HOV) lane system especially in nonattainment areas, it has been pointed out that the air quality benefits/impacts of HOV lanes are unclear. Further, most of the HOV literatures to date use a traditional emissions modeling methodology that is not sensitive to operational effects. Using the state-of-the-art integrated PARAMICS/CMEM. modeling tool, this study models and compares the effectiveness of two different HOV lane configurations, limited access (Southern California) and continuous access (Northern California), in terms of reducing pollutant emissions.[19]

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[17] Stephen P. Farnsworth, *El Paso Comprehensive Modal Emissions Model (CMEM) Case Study*, November 2001.

[18] Jane Lin, Yi-Chang Chiu, Song Bai, Suriya Vallamsundar, *Integration of MOVES and Dynamic Traffic Assignment Models for Fine-Grained Transportation and Air Quality Analyses,* TRB 90th Annual Meeting Sunday Workshop #137, Washington DC, January 23, 2011. (http://trbairquality.org/wp-content/uploads/2011/02/Lin-Presentation.pdf - accessed on May 15, 2011).

[19] *Description of Modeling the Effectiveness of HOV Lanes at Improving Air Quality Project* available at http://www.cert.ucr.edu/cmem/proj_1.html - accessed on May 15, 2011.

- CMEM - Evaluating Air Quality Benefits of Proposed Network Improvements on I-10 in the Coachella Valley Project: The objective of this study is to evaluate air quality benefits of the transportation network improvement projects along the I-10 corridor in the Coachella Valley. Using state-of-the-art integrated PARAMICS/CMEM modeling tool, this study simulates the traffic in the corridor with and without the improvements and quantifies the amount of emissions reduced in future years. With traffic conditions being simulated, the CMEM plug-in for PARAMICS was simultaneously executed to calculate emissions from simulated traffic during a 3-hour morning peak period for each scenario. In addition, with a unique capability of CMEM, the study takes into account the fact that future vehicle models will be cleaner as a result of new stricter emission standards. Thus, the quantified emissions reduction is differentiated between reduction as a result of the new interchanges and reduction as a result of a cleaner fleet. [20]

- I-215/SR-60 Moreno Valley Freeway Expansion Project: The primary objective of this case study was to estimate the relative traffic flow and emission benefits for different lane designation scenarios along the I-215/SR-60 shared section of the Moreno Valley Freeway. Three choices exist for a fourth lane in each direction: 1) a high-occupancy vehicle (HOV) lane; 2) a truck climbing lane going uphill (eastbound); or 3) another mixed-flow lane. For this study, estimates of traffic flow and emission benefits were accomplished by modeling the corridor initially in CORSIM, followed by post-processing vehicle trajectories for determining emissions and fuel consumption. Later, the same analysis was carried out using PARAMICS with the CMEM plug-in module. Both the current and proposed future geometries of the freeway were determined, including grade information measured by CE-CERT's instrumented vehicle. In addition, vehicle classification counts were performed along the freeway section and connecting ramps, which also included vehicle occupancy estimates.[21]

- El Paso Comprehensive Modal Emissions Model (CMEM) Case Study: This project looked at methodologies and data requirements for running the comprehensive modal emissions model (CMEM) and documents the results of a case study conducted in the El Paso, Texas, area. The main purpose of the model was to estimate vehicle tailpipe emissions for various categories of vehicles, with consideration given to the length of time the vehicle is operating and vehicle operations such as accelerating, decelerating, idling, and cruising.[22]

- ECO-ITS Study: This project is being carried out by the University of California – Riverside (UCR) under the Research on ITS Applications to Improve Environmental Performance Broad Agency Announcement (BAA) contract. Previous UCR research developed a microscopic emissions CMEM model capable of predicting second-by-second fuel

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[20] *Description of Evaluating Air Quality Benefits of Proposed Network Improvements on I-10 in the Coachella Valley Project* available at http://www.cert.ucr.edu/cmem/proj_1.html - accessed on May 15, 2011.

[21] *Description of Evaluating Air Quality Benefits of Proposed Network Improvements on I-215/SR-60 in the Moreno Valley Freeway Expansion Project* available at http://www.cert.ucr.edu/cmem/proj_3.html - accessed on May 15, 2011.

[22] Stephen P. Farnsworth, *El Paso Comprehensive Modal Emissions Model (CMEM) Case Study*, November 2001 (http://tti.tamu.edu/documents/2107-2.pdf - accessed on May 15, 2011).

consumption and tailpipe emissions. This study will build upon previous research to synthesize results and recommend the following: data collection methods; environmental analysis methods; integration of simulation and environmental modeling tools; and suggestions for environmental ITS applications and strategies.[23]

2.4 In-Depth Review of EMFAC Model

2.4.1 Overview

The EMission FACtors (EMFAC) model is an emission inventory model developed by the California Environmental Protection Agency - Air Resource Board. It is a mobile source emissions model designed to calculate emission rates from all motor vehicle types operating on all road types in California (CARB, 2006 and CARB EMFAC Users Guide, 2006). The model is capable of producing emission rates and inventories of exhaust and evaporative hydrocarbons, carbon monoxide, oxides of nitrogen and particulate matter associated with exhaust, tire-wear and brake-wear. This section presents an in depth review of the model including a discussion of the approach/methodology used by the model, inputs and outputs, sensitivity of the model and limitations identified by users.

2.4.2 Model Description

The California Environmental Protection Agency - Air Resource Board (ARB) developed, improves upon, and maintains the EMFAC model. They began development of EMFAC in the 1980s as part of California's Motor Vehicle Emission Inventory (MVEI) models that was designed to estimate the state's on-road motor vehicle emission inventory. In the early 2000s, the 2000 series of EMFAC replaced MVEI for calculating emission inventories for motor vehicles operating on roads in California.

ARB staff performed special test programs and research projects to isolate variables to determine their relative effects on emissions. Hundreds of analyses were performed to characterize emissions across a variety of operating parameters and vehicle types. These data where then used to develop algorithms for predicting emissions and fuel consumption that take into consideration parameters such as vehicle type/technology, fuel type, emissions controls, vehicle age, and maintenance condition.

EMFAC was designed to interface with a variety of transportation models and data sets in order to allow a user to show how California motor vehicle emissions have changed over time and are projected to change in the future. The initial version of the model contained 10 different vehicle classes and 3 technology groups to form 19 vehicle/technology groups that estimated emissions for calendar years 1970 through 2020 (Californian Environmental Protection Agency, Air Resource Board, 2000). Additional vehicle type/technology, fuel type, emissions controls, vehicle age, and maintenance condition have been added to reflect the ARB's current understanding of how vehicles travel and how much they pollute. The latest version of the model, EMFAC2007 v2.3, estimates emission rates of 1965 and newer vehicles, powered by

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[23] *Research on ITS Applications to Improve Environmental Performance Broad Agency Announcement (BAA)* project details published at ttp://www.its.dot.gov/aeris/baa_factsheet.htm – accessed on May 15, 2011).

gasoline, diesel or electricity, for more than 100 vehicle/technology groups for calendar years 1970 through 2040 (EMFAC2007 v2.3 User's Guide, 2006).

2.4.3 Model Approach and Underlining Theory

The model approach for EMFAC has three steps. First, vehicle emission rates are specified for different vehicle classes based on dynamometer tests of predefined driving cycles. Second, a set of correction factors are applied to the base emission rates, to account for vehicle deterioration, temperature, humidity and inspection/maintenance programs. Third, emission rates are adjusted and coupled with associated vehicle activities (Bai, 2008).

EMFAC is an integrated mobile source emissions model, in which local-specific emission rates and vehicle activity are combined internally to generate hourly or daily total emissions for various geographic areas in California (Bai, 2008). EMFAC produces activity specific emission rates that are functions of vehicle type and age, average speed, temperature, altitude, vehicle load, air conditioning usage, and vehicle operating mode. These emission rates are multiplied by vehicle activities such as vehicle miles-traveled, number of trips, and vehicle-hours traveled in order to estimate total emission levels (Rahka, 2003).

2.4.4 Data Inputs and Outputs

EMFAC uses numerous data input parameters to generate emission rates and inventories. The input factors for EMFAC include vehicle fleet composition (vehicle population, fleet age distribution, vehicle miles of travel, and technology fractions), traffic activities (speed distribution and mileage accrual rates), fuel Reid vapor pressure (Reid Vapor Pressure is a number expressed in pounds per square inch. It represents the fuel's volatility at its initial boiling point), and meteorology parameters (e.g., ambient temperature, relative humidity, altitude, and smog check requirements) (CARB, unknown date).

In EMFAC, the input factors were obtained from test data, with no preconceived assumption regarding the end result, and vehicle activity data provided by California regional transportation agencies. Emission input factors were determined using the measured emission results by direct measurement, regression equations, or an optimization process. Single factor tests and research programs were conducted to isolate their relative effects on emissions. In addition, multivariate tests were conducted to determine whether interactions exist between factors. ARB staff review and re-evaluate input factors and undertake research and test projects where the latest emission modeling information available was found to be lacking (Californian Environmental Protection Agency, Air Resource Board, 2000). This helps ensure the latest input factor data from new technologies are included in the model.

The model is comprehensive and flexible. Because the model is flexible, it requires basic input data for generating emission rates and inventories. The basic input data required are the following:

- Geographical area – statewide, air basin, air pollution control district, or county
- Calendar year – any calendar year between 1970 and 2040
- Month or season – summer, winter, or annual average
- Model years included in the calculation

- Inspection and maintenance (IM) programs – users can change the default IM programs
- Emission model – Burden: Area Planning Inventory, EMFAC: Area Fleet Average Emissions, or California Motor Vehicle Emissions Factor Model (CALIMFAC): Detailed Vehicle Data.

The output of EMFAC varies by the emission mode selected. The model has three emission modes. Burden mode calculates total emissions in tons per day. EMFAC mode calculates emission factors in grams per activity, and this output data is easily input into travel demand models and air quality models such as Direct Travel Impact Model and URBEMIS (Urban Emissions). CALIMFAC mode calculates basic emission rates for each vehicle class by model years from 1965 to the selected calendar year.

The EMFAC model is commonly used by the California ARB, California regional transportation agencies, transportation exports that need emission rates and inventories for California or regions within the state. The format for the EMFAC output data is flexible. There are multiple types of output formats a user can select that generally be read using a text editor or comma-separated-value compatible software (EMFAC2007 version 2.30 User's guide, 2006). The model also easily generates files for use with air quality models such as DTIM, AIRSHED, CALINE and URBEMIS.

EMFAC produces emission rates and inventories of exhaust and evaporative hydrocarbons, oxides, and particular matter associated with exhaust, tire-wear, and brake-wear. This model is capable of producing regional emission rates or regional emissions factors and emission inventories within California for the following pollutants:

- Hydrocarbons (HC) – expressed as Total Organic Gases (TOG), Volatile organic compounds (VOC), total hydrocarbon (THC) or methane (CH4)
- Carbon monoxide (CO)
- Oxides of Nitrogen (NOx)
- Oxides of Sulfur (SOx)
- Particulate Matter 10 microns or less in diameter (PM10), and Particulate Matter 2.5 microns or less in diameter (PM2.5)
- One greenhouse gas – Carbon Dioxide (CO2)
- Lead (Pb) for calendar years older than 1992
- Fuel consumption – although fuel consumption is not a pollutant, it is calculated based on the emissions of CO, CO2, and THC using a carbon balance equation (Chen, 2011 and EMFAC2007 v2.3 User's Guide, 2006).

EMFAC calculates these emission rates for 45 model years of vehicle class within each calendar year, for 24 hourly periods, for each month of the year, for each district basin, or county and sub-county in California (CARB, Overview of EMFAC Emissions Inventory Model, date unknown, and EMFAC2007 version 2.30 User's guide, 2006).

2.4.5 Methodology Used to Calculate Emissions and the Factors Considered

The methodology used by EMFAC to estimate California statewide or regional emissions involves multiplying emission rates by vehicle activity data provided by the regional transportation agencies. This model provides a convenient way to model area-wide vehicle emissions levels because it requires less detailed information on traffic flow and operation pattern (Bai, 2008).

In EMFAC, baseline emissions rates are derived from a standard U.S. laboratory test procedure, the Federal Test Procedure. An emissions factor is then derived from the average value of repeated measurements of total emissions per driving cycle. Correction factors are established to incorporate the influence of factors such as vehicular speed, temperature, fuel type, and vehicle age on the baseline emissions rates (Yin , 2011). The following equation illustrates the methodology used to calculate regional California on-road vehicle emissions:

Emissions in tons per day = Emission factor x Correction factor x travel activity

The model contains three distinct modes that individual predict total emissions in tons per day, emission factors in grams per activity, or detailed emission rates for each vehicle class by model years from 1965 to the selected calendar year (EMFAC2007 v2.3 User's Guide, 2006). For each mode, there are a number of vehicle parameters and operating variables factored into the emission estimates. These include (Ibid):

- Different combinations of 13 vehicle classes (passenger cars, trucks, buses, motorcycles, and motor homes)
- Fuel type (gasoline, diesel, or electric)
- Vehicle weight
- Vehicle activity
- Fuel delivery system (carbureted, fuel injection)
- Catalyst usage (no catalyst, oxidation catalyst, three-way catalyst)
- Deterioration parameters (e.g., catalyst aging, etc.)
- Inspection and maintenance programs
- Environmental factors (e.g., ambient temperature and air density).

2.4.6 Omissions and Limitations

EMFAC is one of the most comprehensive, powerful, and flexible models of its type; however, it does have limitations. The following limitations were noted during the literature review conducted for this effort:

- *Emission factor models general limitation* – This type of model provides a convenient way to model state and regional vehicle emissions, as less detail on traffic flow and operational patterns are required. However, this modeling approach is unable to account for the effects of vehicle operation states and driving environment on emissions rates (Yin, 2011)

- *Inaccurate emission estimates for extremely low emitting vehicles* – EMFAC does a reasonable job at an order of magnitude emission estimate for overall on-road driving from extremely low emitting vehicles. However, this model does a poor job at predicting component behavior. For example, EMFAC typically significantly overestimates running emissions and underestimates start emissions for the extremely low emitting vehicles (Barth, et al., 2006).

- *Heavy duty truck emissions in year 2005* – the EMFAC2007 model has a known issue with the estimated emissions for heavy duty trucks in year 2005. This occurs in the EMFAC2007 model; other years seem to work properly (Caltrans, ARB).

2.4.7 Sensitivity of the Model

As described in this section, numerous input parameters are used in EMFAC to develop emission rates and inventories. The input parameters include emission factors and correction factors. These parameters are continuously being validated by ARB staff, regional transportation agencies in California, and other transportation experts to ensure they are as accurate as possible. Senate bill 2174 requires these validation efforts be presented every 3 years (CARB, overview of EMFAC Emissions Inventory Model, date unknown). The model then helps minimize these input parameters ability to significantly influence the accuracy of the emissions generated by only requiring basic input data (previously discussed in section 3.4.4). However, the model is flexible by allowing a user to manipulate most of the input parameters. If the default parameters are not used, then one must be careful in determining how the parameters are change as these changes to the input parameters can have a significant influence on the accuracy of the emissions generated.

2.4.8 Applicability to ITS Strategies

EMFAC is suited to support area-wide ITS strategies for the State of California. Area-wide emissions inventories are used as one gauge by which to measure attainment progress, as well as estimate the cost effectiveness of control measures. EMFAC is well suited to provide a convenient way to model area-wide vehicle emissions levels because it requires less detailed information on traffic flow and operation pattern than the other two types of models (Bai, 2008). For ITS strategies that are used for area-wide control measures in the state of California, EMFAC is a good model to use. It can be run at a class specific or hourly specific rate to determine what vehicle classes might contribute exceedingly to the emission inventory thus making them likely candidates for potential ITS strategies.

However, this modeling approach is unable to account for the effects of vehicle operation states and driving environment on emissions rates (Yin, 2011 and Bai, 2008). So for smaller scale analyses such as mesoscale and microscale level analyses, this model will have limited value. Thus, this model will have limited value in evaluating ITS strategies that are not area-wide for California or involve factors in the vehicle operating environment that affect emissions.

Nonetheless, the development of EMFAC provides several good lessons learned for what to include in ITS strategy emission models. The EMFAC bottom-up model development approach (i.e., the model is constructed from test data) is well regarded by EPA, regional transportation agencies, and academia. The model is constantly re-evaluated to ensure the latest emission model information is included in it. It is a comprehensive, powerful, and flexible emission factor mode that can be used to determine area-wide methods for efficient reduction of air pollutants, and making informed decisions based on the data at hand.

3 MODELING FOR ITS STRATEGIES

In order to quantify the emissions impacts of ITS strategies, it is necessary to adopt a modeling approach that integrates travel demand models with traffic simulation models and feed the results from traffic simulation models to emissions models. The graphic below shows the sequencing of steps to support ITS strategies.

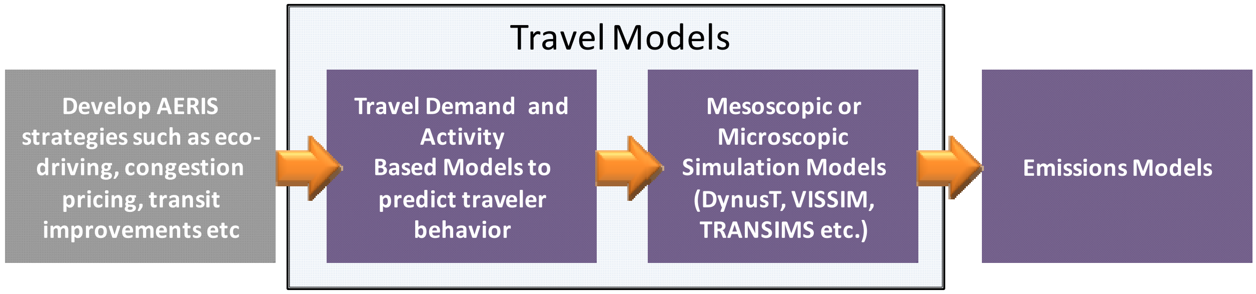

Figure 5: Emissions Modeling Steps for ITS Evaluation

In recent years, it has been well documented that the aggregate network performance data created by traditional static assignment models is not suitable for estimating emissions accurately. Microscopic simulation models are best suited to capture the network performance change in response to implementation of ITS strategies including AERIS strategies. Without using microsimulation models, it is not possible to perform detailed "project-level" or micro analysis with advanced emissions models such as MOVES. The state-of-the-practice of behavior and activity-based models and the suitability of these models for use to evaluate ITS strategies is discussed in the "State-of-the-practice Scan of Behavior and Activity-Based Models Report" developed as a part of this project.

Activity-based models are best suited to predict traveler behavior changes and microsimulation models are best suited to estimate the transportation system efficiency changes. Key inputs to emissions models include the "speed" and "vehicle activity data" (if advanced emission models such as CMEM and MOVES are used). Vehicle activity data typically includes vehicle data such as distribution of vehicle miles traveled by vehicle class, vehicle miles of travel (VMT) distribution by hour, starts per day distribution by vehicle class and vehicle age, engine starts per day and their distribution by hour of the day, average trip length distribution and engine start soak time distribution by hour (cold soak distribution) Once detailed speed data and vehicle data is generated, establishing the linkage between traffic simulation models and emissions models is relatively straightforward.

Interface between different traffic simulation models and emissions models have been successfully created and used to quantify the air quality impacts of traffic operational changes and other ITS improvements. **Table 6** shows the common linkages that have been used.

Table 6: Interface between Simulation and Emissions Models

Microsimulation Tool	Emissions Model
AIMSUN	Versit+micro
Paramics	CMEM
DYNU.S.T	CMEM, MOVES
VISSIM	Versit, PHEM, MODEM, CMEM
TRANSIMS	MOVES

As MOVES is a relatively new emissions modeling tool, MOVES hasn't been integrated with many traffic simulation models yet. However, there a few ongoing research activities that integrate MOVES with simulation tools such as VISSIM and DYNU.S.T.

As explained earlier, traffic simulation models are needed to quantify the changes in network performance resulting from operational changes (e.g., advanced traffic signal control or ramp metering) while travel demand models are needed to assess the impacts of user services that affect traveler behavior. In order to capture the impacts of ITS deployment at the regional level regional traffic simulation has to be performed. Once an integrated transportation modeling platform is developed, emissions and fuel consumption models can be linked to this platform to assess the effects of ITS deployment on vehicle emissions and fuel consumption. The graphic below shows the process involved in tracing the emissions and fuel consumption impacts of ITS strategies.[24]

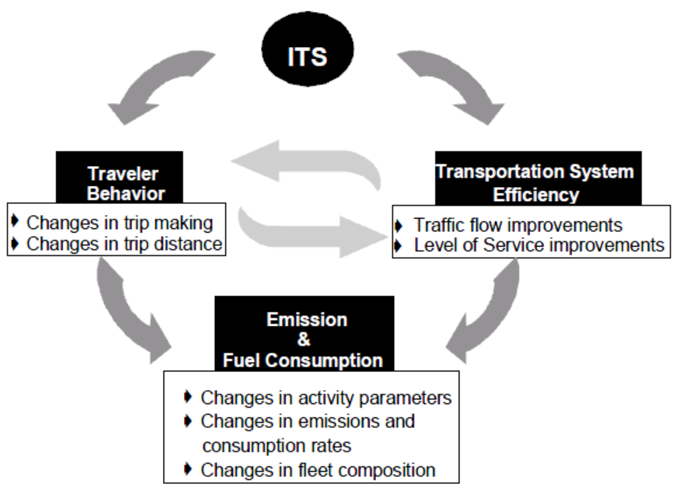

Figure 6: Tracing the Emissions and Fuel Consumption Impacts of ITS strategies[25]

In order to estimate the emissions accurately, it is necessary to use advanced microscopic emissions models such as MOVES and CMEM, which required detailed vehicle activity data as the input. The Operating Mode Distribution Generator (OMDG) in MOVES classifies vehicle

[24] Hagler Bailly Services, Inc., *Assessing the Emissions and Fuel Consumption Impacts of Intelligent Transportation Systems (ITS),* Prepared for U.S. EPA, 1998.
[25] *Ibid.*

operating modes into different bins associated with vehicle specific power (VSP) and speed, and develops mode distributions based on 40 pre-defined driving schedules. While the emission rates in emissions models such as EMFAC and MOBILE are directly related to average speeds that correspond to a fixed VSP distribution embedded in the underlying driving cycles, the MOVES emissions rates are a direct function of VSP, a measure that has been shown to have a better correlation with emissions than average vehicle speeds and users can also input locally specific VSP distributions. Interfacing traffic simulation output with MOVES or CMEM is likely to be well suited to support AERIS program.

3.1 Data and Modeling Gaps

MOVES and CMEM uses several input data tables and parameters as listed in **Table** 2 and **Table 5**. It is important to update some of these data values to match the existing local conditions in order to quantify the emissions accurately. Described below are some key data elements to be considered while modeling emissions:

- **Speed Data:** A key input data needed for MOVES and CMEM is a detailed speed profile or vehicle movement data. EMFAC models use average road speeds to establish driving patterns. The MOVES and CMEM models are more flexible in incorporating vehicle operations into the model and do not need to rely on a set group of cycles to estimate emissions. Instead, actual driving data is used to predict emissions, and it relies on more specific driving parameterization than simply average speed. In this case, it is not always a simple task to obtain the needed driving pattern information. It is possible to interface to vehicle computer systems and record how vehicles drive. However, the interfaces to vehicle computer systems are not always the same and the monitoring equipment can be expensive. An alternate approach is to attach a monitor, such as a global position system (GPS) to a vehicle to record the vehicle speeds. In order to obtain the data needed for the MOVES, and CMEM models, at least second-by-second speed and altitude data must be recorded. GPS units are available that record data several times per second; however, these have not been found to significantly improve the data over second-by-second measurements. One of the major short comings of microscopic emissions models such as MOVES and CMEM is the need for detailed vehicle operation or speed data. The only way to generate the data needed for MOVES and CMEM is to use traffic simulation models if resources and technology are not available to collect the field data. While microsimulation models can be easily applied for small regions, performing region-wide traffic simulation is not feasible.

- **Vehicle Specific Power Distribution:** An important vehicle parameter used by the U.S.EPA MOVES model is vehicle specific power (VSP). VSP is the power per unit weight involved in the vehicle movement. In order to make emissions calculations, the MOVES model breaks the VSP into 17 bins. It is possible to place GPS or other second by second speed recording equipment on a vehicle for a 24-hour period and record the movements of the vehicle. In summary, the most common method of developing driving pattern data is to use GPS equipment that stores speed, location, altitude, and satellite number on a second-by-second basis. This data can then be turned into an average driving pattern for use in a

CMEM type model or it can be binned by vehicle specific speed (VSP) to use in an MOVES type models.[26]

- **Number of Starts and Soak time:** MOVES and CMEM both provide the flexibility to differentiate start emissions from the running emissions. Start-Up emissions are those emissions that occur in the first 200-300 seconds of vehicle operation that are in excess of those that would have been emitted by the vehicle if it had made the same trip with the vehicle fully warmed up. The extra emissions that occur during a start-up can be significant. These emissions depend upon the starting temperature of the catalyst and the engine. The starting engine and catalyst temperatures depend upon the ambient temperature of course, but the temperature of the catalyst and engine are normally well above ambient if the vehicle has been operated in the recent past. Thus, ambient temperature can be less important as an indicator of the amount of start-up emissions compared to the "soak time" of the vehicle. Soak time is the amount of time that a vehicle has been sitting without the engine operating. In order to collect data to estimate start emissions, a vehicle can be outfitted with a device that records when the engine is running and when it is not. [27]

Described below are some key modeling gaps that exist when it comes to interfacing traffic simulation models with emissions models:

- **Modeling Region:** Microscopic emissions analysis using MOVES or CMEM requires running traffic simulation models to generate second-by-second speed profiles of vehicles. However, running simulation models for wide regions is infeasible and estimating regional emissions impacts is not possible using this approach. Recently, a mesoscopic simulation tool (DynusT) has been used to overcome this limitation by generating an operating mode distribution table that can be fed into MOVES. TRANSIMS can also be used to simulate large regions. It must be noted, however, that the emissions results will be sensitive to transportation data aggregation methods employed, and using different simulation tools are likely to yield different results

- **Calibration:** Emissions estimates are extremely sensitive to vehicle speed and travel speed profiles and greatly depend on simulation parameters such as lane changing behavior, gap acceptance behavior, driver reaction time, randomness in driver behavior, etc. Care must be taken to calibrate these parameters such that the observed behavior matches the simulation results

- **Fleet Mix:** One of the major challenges of interfacing traffic simulation models outputs with emissions models is mapping the different vehicle types considered in traffic simulation models with the vehicle types considered in emissions models. Typical traffic simulation models consider three or four vehicle types (passenger car, passenger trucks, light duty

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26 Nicole Davis, Kebin He, Jim Lents, Huan Liu, Mauricio Osses, Sebastian Tolvett, Mike Walsh, *Estimating Emissions from Sources of Air Pollution* (http://www.aqbook.org/read/?page=86 – accessed on My 15, 2011).

27 *Ibid.*

trucks, heavy duty trucks, etc.) whereas emissions models consider 13 different vehicle types as shown in **Table 4.** As vehicle type contributes significantly to emissions, it is necessary to update the default vehicle type tables in the emissions models with the actual field data

- **Non-transportation Data:** Emissions models need several non-transportation related data such as fuel data, meteorological data. I/M program data, vehicle age distribution etc. None of these are considered in a traffic simulation model and needs to be generated using field data if possible.

3.2 Modeling Gaps

Some of the key modeling gaps identified in emissions models are listed below:

MOVES

- MOVES uses VSP to estimate emissions and since VSP has been shown to be more closely correlated with on-road emissions than speed, use of MOVES-generated emissions factors should represent a more accurate characterization of on-road vehicle emissions than emission factors generated using MOBILE or EMFAC. However, the emissions models accuracy greatly depends on the quantity and quality of the default VSP data available in MOVES and it is unclear as to which portions of the MOVES VSP dataset are most robust, and which require supplemental data to augment the creation of reasonable emission factors. EPA has specified that the medium- and heavy-duty truck portions of the MOVES dataset are less populated than those applicable to the light-duty fleet.

- Also, in order in perform project level or link level analysis in MOVES, the user has to generate driving cycle profiles for vehicles on the link or generate the operating mode distribution models. Traffic simulation models are needed to generate this data. Also, "There are limits to the number of Link Drive Schedules that can be input into MOVES. A complicated network with dozens of intersections may challenge the processing capability of the software while also requiring substantial sophistication from the modeler." (Chamberlin, 2010). So the current usage of project level analysis in MOVES is cumbersome.

- While MOVES is the most advanced modeling tool available to model GHG emissions, the current version of MOVES has some limitations related to energy/GHG analysis that will be addressed in future versions. For example, Energy/GHG effects of biofuels (E85, biodiesel) not fully accounted for and some vehicle types (hybrid, fuel cell) are present in the model but not active[28].

CMEM

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28 Jeff Houk, FHWA Resource Center, *19th International Emission Inventory Conference, Greenhouse Gas Emissions Analysis of Regional Transportation Plans with EPA's MOVES Model,* September 2010 (http://www.epa.gov/ttnchie1/conference/ei19/session6/houk_pres.pdf - accessed May 13, 2011).

- *Inability to estimate Particulate Matter emissions* – Particulate Matter (PM) emissions can cause significant health problems by aggravating asthma, causing difficulty breathing, and decreasing lung function. Vehicles, especially heavy duty vehicles, generate PM from fuel combustion (i.e., tailpipe emissions) as well as from normal brake and tire wear. These PM emissions could be significant when modeling emissions from a large number of vehicles on a macroscale. CMEM currently does not estimate PM emissions; however, a module for PM emissions has been under development for a number of years (Lee, 2009).

- *Vehicle Speed Limitation* – CMEM was developed from emission rates based on speeds up to 80 mph. For situations where speeds on roadways exceed 80 mph (such as the proposed high speed corridor systems in Texas), the model may not accurately estimate emissions (Park, 2010).

- *HDDV emissions after model year 2002* – Heavy-duty vehicles are a significant source of emissions. It is important to accurately estimate emissions from this segment of a vehicle fleet when conducting transportation studies. CMEM does not estimate HDDV emissions for model years after 2002, which has a direct impact on the accuracy of the emission results from this model (Lee, 2009).

- *Microscale vs. Macroscale* – CMEM works well on the microscale level, but estimating larger, regional emissions (macroscale) is more complicated and possibly less accurate. Microscale models typically require extensive data on the system and vehicles included in the study in order to generate accurate emissions estimates. The level of complexity increases dramatically with larger networks given the interconnectivity of freeways, intersections, rural highways, and other roadway elements along with the variability of vehicle operation (e.g., varying degrees of congestion in different parts of the network). To overcome this limitation, statistical emission rates can be derived using CMEM from the microscale components as a function of roadway facility type and congestion level and then applied to individual links in a macroscale traffic assignment model (Scora, 2006).

EMFAC

- For the extremely low-emitting vehicles, updating the EMFAC modeling approach with actual data instead of standard based emission factors will significantly improve model performance (Barth, et al., 2006).

4 SUMMARY

In order to quantify the emissions impacts of ITS strategies, it is necessary to adopt a modeling approach that integrates travel demand models with traffic simulation models and feed the results from traffic simulation models to emissions models. The graphic below shows the sequencing of steps to estimate emissions impacts of ITS strategies.

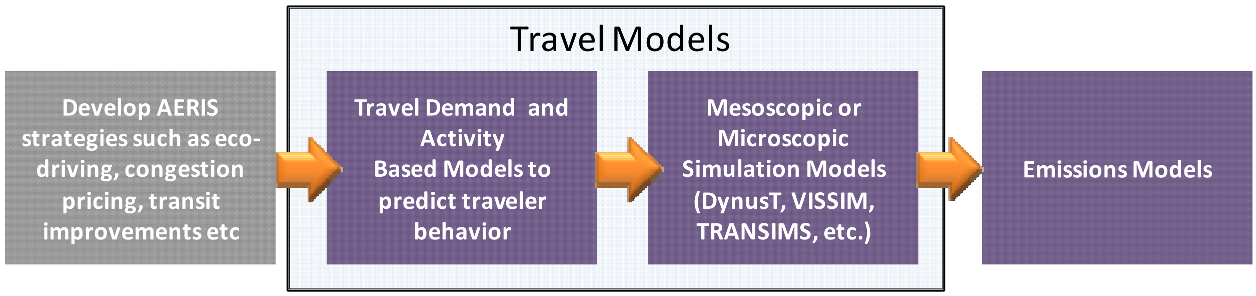

Figure 7: Emissions Modeling Steps for ITS Evaluation

In recent years, it has been well-documented that the aggregate network performance data created by traditional static assignment models is not suitable for estimating emissions accurately. Microscopic simulation models are best suited to capture the network performance change in response to implementation of ITS strategies. Without using microsimulation models, it is not possible to perform detailed "project-level" or micro analysis with advanced emissions models such as MOVES. The state-of-the-practice of behavior and activity-based models and the suitability of these models for use to evaluate ITS strategies is discussed in the "State-of-the-Practice Scan of Behavior and Activity-Based Models Report" developed as a part of this project.

Activity-based models are best suited to predict traveler behavior changes and microsimulation models are best suited to estimate the transportation system efficiency changes. The key inputs to emissions models are "speed" and "vehicle activity data" (if advanced emission models such as CMEM and MOVES are used). Once detailed speed data is generated from the traffic simulation, establishing the linkage between traffic simulation models and emissions models is relatively straightforward.

4.1 Data Inputs Requirements

Emissions models need both transportation and non-transportation data to estimate emissions. The key data needed to run MOVES micro level or project level analysis include the following:

- **Travel Data:** Driving Schedule, Vehicle Operating modes, Link characteristics (such as grade) and vehicle fleet characteristics

- **Non Transportation Data:** Meteorological data (such as humidity, temperature, pressure, etc.), fuel supply data and Inspection and Maintenance Program data

While some data can be easily collected or generated, some data needed by advanced emissions model, such as MOVES or CMEM, is not easily available. In order to run the project-level analysis, the most detailed level of emissions analysis supported by MOVES, advanced traffic simulation models such as Paramics, VISSIM, etc. should be used to produce the operating mode distribution of the vehicles or the second-by-second drive cycles.

4.2 Sensitivity and Validity of Models

Emissions models in general require a number of input data values and parameters to estimate emissions. For example, MOVES has default VMT distributions by month, day of week, and hour of day. Before applying the model, the user should update these data values so that the values reflect the "local" conditions of the region being modeled. Also, as the emissions generated from the vehicles are very sensitive to the speed, it is very important that the vehicle speeds are captured accurately from traffic simulation models to predict the emissions impacts of ITS strategies. Using aggregates of average speed values is likely to produce wrong estimates of emissions. Emissions rates are also very sensitive to the vehicle type (passenger truck, light duty vehicle, transit bus, combination long-haul truck, etc.) and specifying the correct vehicle type proportions is very critical. Non-transportation data such as temperature and humidity also have impacts on the emissions results and these values should be adjusted to meet the "local" conditions. It must be noted that significant data processing is needed to use simulation model outputs as inputs to emissions model and the results are highly sensitive to the data processing methods used. This is especially true while using MOVES for project level analysis. Caution should be used while aggregating transportation data needed as inputs to MOVES.

4.3 Applicability to ITS Strategies

MOVES and CMEM have been used recently as a part of research studies to evaluate ITS strategies. Sample applications of using advanced emissions models to evaluate ITS strategies are as follows:

- Using TRANSIMS, the University of Buffalo is evaluating the likely environmental benefits of lowest fuel consumption route guidance in the Buffalo-Niagara metropolitan region. This study will conduct an assessment of the likely environmental benefits of a new application for an environmentally optimized route guidance system for a medium-sized metropolitan area. Activities in this project include developing an integrated simulation modeling framework capable of calculating time-dependent fuel consumption factors; using TRANSIMS-MOVES modeling to estimate environmental benefits to be expected from implementing low fuel consumption routing; assessing the impact of market penetration on the likely benefits of the strategy; assessing additional benefits to be expected from taking into account real-time information about traffic disturbances; and assessing modal benefits
- Sample vehicle trajectory files generated by VISSIM and Paramics were processed and interfaced with MOVES software to demonstrate the use of traffic simulation model outputs for MOVES project level analysis[29]

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[29] Robert Chamberlin, Ben Swanson, Eric Talbot, Jeff Dumont, Steve Pesci, *Utilizing MOVES' Link Drive Schedule for Estimating Project-Level Emissions*, TRB Workshop on Integrating MOVES

- An ongoing "Impact of Operational Improvements on Induced Demand and Emissions" is looking at using the MOVES model to quantify the emissions impacts of Operational Improvements[30]
- A recent study demonstrated through a case study, an integrated, automated modeling framework of MOVES and simulation-based dynamic traffic assignment (SBDTA) model, i.e., DynusT, especially for project level emission analyses. This project demonstrates integration of MOVES with a dynamic traffic assignment model in order to perform project level estimation in MOVES and investigate the differences in using MOVES default drive schedule (i.e., specifying only link average speed) versus using local specific operating mode distribution input[31]
- As a part of the "Optimizing Traffic Control to Reduce Fuel Consumption and Vehicular Emissions" study being carried out by Florida Atlantic University, CMEM is used to model field fuel consumption using an integrated approach with VISSIM, CMEM, and VISGAOST
- El Paso Comprehensive Modal Emissions Model (CMEM) Case Study: This project looked at methodologies and data requirements for running the comprehensive modal emissions model (CMEM) and documents the results of a case study conducted in the El Paso, Texas, area. The main purpose of the model was to estimate vehicle tailpipe emissions for various categories of vehicles, with consideration given to the length of time the vehicle is operating and vehicle operations such as accelerating, decelerating, idling, and cruising[32]
- ECO-ITS Study: This project is being carried out by the University of California – Riverside (UCR) under the Research on ITS Applications to Improve Environmental Performance Broad Agency Announcement (BAA) contract. Previous UCR research developed a microscopic emissions CMEM model capable of predicting second-by-second fuel consumption and tailpipe emissions. This study will build upon previous research to synthesize results and recommend the following: data collection methods; environmental

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with Transportation Microsimulation Models, 2011 (http://trbairquality.org/wp-content/uploads/2011/02/Chamberlin-Presentation.pdf - accessed on May 14, 2011).

30 Richard Margiotta, *Impact of Operational Improvements on Induced Demand and Emissions,* Preliminary findings presented at TRB Workshop on Integrating MOVES with Transportation Microsimulation Models, 2011.

31 Jane Lin, Yi-Chang Chiu, Song Bai, Suriya Vallamsundar, *Integration of MOVES and Dynamic Traffic Assignment Models for Fine-Grained Transportation and Air Quality Analyses*, TRB 90th Annual Meeting Sunday Workshop #137, Washington DC, January 23, 2011. (http://trbairquality.org/wp-content/uploads/2011/02/Lin-Presentation.pdf - accessed on May 15, 2011)

32 Stephen P. Farnsworth, *El Paso Comprehensive Modal Emissions Model (CMEM) Case Study*, November 2001 (http://tti.tamu.edu/documents/2107-2.pdf - accessed on May 15, 2011).

analysis methods; integration of simulation and environmental modeling tools; and suggestions for environmental ITS applications and strategies.[33]

Based on the state-of-the-practice scan, the table below shows the behavior changes associated with different ITS or potential AERIS strategies and the travel demand and emissions models capable of evaluating these strategies.

Table 7: Capabilities of Models to evaluate ITS/potential AERIS strategies

ITS or Potential AERIS Strategy	Behavior Change Description	Potential Models or Tools for Predicting Behavior Changes	Potential Emissions Models or Tools for Predicting Environmental Impacts*
Behavior Changes that Impact VMT			
Demand and Access Management Strategies, Traffic Management and Control Strategies, Transit Improvement Changes	Change in routes (targeted at minimizing travel distance)	Traditional four-step models, activity based model, Mesoscopic or Microscopic Simulation Models	MOVES, CMEM or EMFAC
	Change in mode of travel (take transit, carpool, non-motorized travel such as walking, biking, etc.)	Traditional four-step models or activity based models in combination with mesoscopic simulation models	MOVES, CMEM or EMFAC
	Change in number of trips	Activity based models in combination with mesoscopic models	MOVES, CMEM or EMFAC
	Change in trip chaining patterns	Activity based models in combination with mesoscopic models	MOVES, CMEM or EMFAC
Behavior Changes that do not directly impact VMT			
Speed Harmonization, Eco-Routing	Compliance with variable speed limits that improves the smoothness of travel	Microsimulation models	MOVES or CMEM
	Change in driving behavior (eco-driving)	Microsimulation models	MOVES or CMEM

33 *Research on ITS Applications to Improve Environmental Performance Broad Agency Announcement (BAA) project details* published at http://www.its.dot.gov/aeris/baa_factsheet.htm – accessed on May 15, 2011).

ITS or Potential AERIS Strategy	Behavior Change Description	Potential Models or Tools for Predicting Behavior Changes	Potential Emissions Models or Tools for Predicting Environmental Impacts*
	Eco-routing (note that eco-routing sometime can also lead to reduced VMT)	Microsimulation models	MOVES or CMEM

*Note that this is not an exhaustive list, but rather an illustrative example of emissions models that can be used.

4.4 Recommendations

The state-of-the-practice scan of emissions models indicate that MOVES and CMEM microscopic emissions models allow fine level emissions analyses and calculate emissions impacts of ITS strategies. However, the project team makes the following recommendations on how to improve these models:

- Further research is needed to determine the most effective way to integrate travel demand model outputs with microscopic emissions models to estimate regional emissions impacts more accurately
    - Microscale emissions models typically require extensive data on the system and vehicles included in the study in order to generate accurate emissions estimates. The data needed can be generated only using simulation models and the level of complexity increases dramatically with larger regional networks. In particular traffic simulation models cannot be used to generate detailed vehicle movement data needed for micro analyses (for example project level analyses in MOVES) of regional networks

- Further research is needed to determine which essential non-transportation data (meteorology, tire pressure, fuel types, vehicle age distribution, etc.) needs to be updated in the emissions models using real-time data (that might be collected using data acquisition technologies) to capture the emissions impacts accurately

- Most emissions models are built based on field data collected through various data collection programs. Where applicable, using the advanced data collection technologies available, the emissions models should be validated. For example the VSP bin distribution in MOVES needs to be reviewed and validated using field data.

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