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Modal Emissions and Fuel Consumption Models:
State of development, concepts, and issues

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FINAL DRAFT

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EXECUTIVE SUMMARY

There is a need for vehicle emissions and fuel consumption models that are sensitive to changes in vehicle driving pattern. Many Intelligent Transportation Systems (ITS) programs are expected to alter driving patterns in their area of implementation. There is a need for the capability to predict the environmental impact of these changes in driving pattern. Current practice is often limited to predicting emissions and fuel consumption as a function of a velocity measurement, such as trip-average speed, and a vehicle activity measure, such as the distance traveled.

Driving pattern is generally defined as consisting of four modes: acceleration, deceleration, cruise and idle. A modal emissions and fuel consumption model accounts for vehicle driving pattern during its calculation of emissions and fuel consumption. A number of studies have shown that driving pattern changes that alter the frequency or magnitude of vehicle acceleration can have a significant effect on both instantaneous and overall emissions production. A modal emissions model is an important tool for the environmental evaluation of any transportation project that changes vehicle driving patterns.

This report includes a background section, which contains a basic description of the workings of gasoline powered automobiles, and the determinants of vehicle emissions and fuel consumption. The discussion consists of six topics:

- A basic description of an automobile drivetrain,
- Operation of a gasoline automobile engine,
- Exhaust emissions production by an automobile engine,
- Control and reduction of exhaust emissions,
- Factors affecting automobile fuel consumption,
- The effect of driving mode on emissions and fuel consumption.

The applications for emissions and fuel consumption models cover a range of spatial and temporal scales. Spatially, models range in coverage from single intersections to entire cities. Temporally, models may model a few seconds, a day, or an entire year. A modal model can be applied as a stand-alone vehicle models or as part of an integrated traffic, emissions, and fuel consumption model. Stand-alone modal models require the driving pattern input from the user, and are usually single vehicle emissions and fuel consumption simulations. Integrated models link a traffic simulation to a modal emissions and fuel consumption model, so that emissions and fuel consumption are modeled along with vehicle movements and vehicle driving patterns.

As further background, a review of past modal models is included in the report. Modal emissions and fuel consumption models, which have existed in one form or another for the past 20 years. The report also describes two non-modal emissions models, MOBILE and EMFAC. It is likely that any new emissions model will be compared to these two established emissions models.

The report also details the current FHWA activities and goals in the modal emissions and fuel consumption modeling. The FHWA has two projects underway to estimate the hot, stabilized emissions and fuel consumption impacts of changes in driving behavior for light-duty, gasoline-fueled vehicles. The first project will attempt to improve the ability of the ITS Benefits Assessment Framework to estimate the impact of ITS user services on modal emissions and fuel consumption. The goal of the second project is to endow the microscopic traffic simulation model, TRAF-NETSIM, with the capability to estimate the emissions and fuel consumption impacts of traffic improvement projects.

One of this report's stated objectives was to assess the state of the practice in modal emissions and fuel consumption modeling. To this end, the Volpe Center examined the modeling efforts of fourteen organizations. The challenge was to consistently evaluate and compare the many different modal emissions and fuel consumption models and model concepts.

The Volpe Center developed a set of generic modal modeling criteria based in part on the physical processes behind automobile emissions and fuel consumption. The Volpe Center also selected criteria that reflected the interests of the ITS Joint Program Office in applying modal emissions and fuel consumption models to the evaluation of ITS services. Once the evaluation criteria were defined, the fourteen modal modeling efforts covered in this report were compared against them. The comparison pointed out what was or was not included in each model, and allowed the Volpe Center dissect the modeling methodology used by each of the fourteen organizations.

The report includes critiques covering the strengths, limitations, theoretical challenges and logistical challenges for each of the following organizations' modeling efforts:

California Air Resource Board
Georgia Institute of Technology
Lincoln Labs, Massachusetts Institute of Technology
Los Alamos National Laboratory
National Cooperative Highway Research Program
Oak Ridge National Laboratory
Queen's University, Kingston, Ontario, Canada
Sierra Research
University of California, Davis
University of California, LA
University of California, Riverside
University of Michigan
US-Department of Transportation, Volpe Center
US-Environmental Protection Agency, Certification & Testing Division

There are significant challenges involved with the creation of a comprehensive modal emissions and fuel consumption model. Challenges exist in both methodology development and data gathering. After reviewing the state of the practice in emissions and fuel consumption modeling, it is the Volpe Center's conclusion that there are no modal emissions and fuel consumption models operational and available that will fulfill all the modeling needs of the FHWA's ITS Joint Program Office. However, there are some promising modal models under development, and some of the existing models may prove useful for less demanding modal modeling applications.

The methodology described within this document for evaluating modal models as a number of descriptive components and functional modules should act as a framework for consistently identifying and evaluating what simplifications and modeling compromises have been made in a given model. This will help the model user recognize the limitations and appropriate uses of a given model. Evaluating a model as a number of components will also allow model developers to recognize modeling methodologies and data within existing models that can be valuable as components of future emissions and fuel consumption models.

The Volpe Center has identified a number of focus areas for further development of modal emissions and fuel consumption models. The recommendations are based on the Volpe Center's assessment of the state of the practice in modal emissions and fuel consumption modeling, and interviews and discussions with model developers and potential users. The Volpe Center's recommendations are categorized as involving either institutional or technical issues.

The following recommendations address the institutional issues of how and why modal models should be applied to the evaluation of ITS.

- **Acceptance of Modal Models -** With respect to the evaluation of ITS programs, modal models are needed because current emissions inventory models, such as MOBILE and EMFAC, are insensitive to changes in vehicle driving patterns that may be caused by ITS implementation. Changes in vehicle driving pattern can have a significant impact on overall automobile emissions.

- **Integrated Application of Modal Models and Travel, Traffic and Air Quality Models -** The evaluation of most ITS user-services will require modal models that are integrated with traffic and travel models. Modal models should be developed such that their emissions and fuel consumption predictions can be integrated with traffic, travel, and air-quality models

- **Regulatory Requirements and Modal Models** - MOBILE and EMFAC emissions models are currently widely used to establish compliance with regulatory requirements and will most likely continue to be used in this capacity. Users will want to know relationship between emissions predictions based on modal models and those based on these established models.

- **Extent of Fleet Coverage for Modal Models** - Modal emissions and fuel consumption models currently focus on light-duty gasoline-fueled vehicles. For complete coverage of the on-road fleet, modal models should eventually include medium- and heavy-duty vehicles.

The state of the practice in modal emissions and fuel consumption modeling exhibits deficiencies in both methodology development and empirical data. Progress in the following areas is necessary if a flexible and relatively comprehensive modal emissions and fuel consumption model for gasoline fueled light-duty vehicles is to be developed.

- **Catalyst Modeling** - Accurate tailpipe emission predictions have remained a challenge. Modeling catalyst operation may improve modeling of tailpipe emissions. Catalyst reduction can vary by nearly two orders of magnitude, and as a consequence, tailpipe emissions can vary just as much.

- **NO_X Emissions Modeling** - CO and HC emissions modeling are relatively mature compared to NO_X modeling. Both engine-out and tailpipe emissions of nitrogen-oxide compounds do not follow the same trends as emissions of CO and HCs.

- **Fleet Representation** - A number of modal emissions models exist which calculate the emissions of a individual, specific vehicles. These modal models do not capture the variation present in the on-road fleet.

- **Linkage Between Emissions and Traffic Models** - Linkage between modal emissions and fuel consumption models and large-scale traffic models will allow the use of modal models in the evaluation of large-scale programs, such as ITS deployment.

- **Validation and Credibility** - Models require validation and calibration in order to be useful. Modal emissions and fuel consumption models are no exception. Modal models pose serious validation challenges because of their complexity.

INTRODUCTION

This report was prepared for the FHWA's ITS Joint Program Office, in accordance with the project plan agreement, entitled "Intelligent Transportation Systems Research" (HW552).

REPORT PURPOSE

There is a need for vehicle emissions and fuel consumption models that are sensitive to changes in vehicle driving pattern. Current practice is often limited to predicting emissions and fuel consumption as a function of a velocity measurement, such as trip-average speed, and a vehicle activity measure, such as the distance traveled.

Such estimates cannot capture the environmental impact of variations in driving pattern, or "how" a vehicle is driven. As an example, many Intelligent Transportation Systems (ITS) programs are expected to alter driving patterns in their area of implementation. There is a need for the capability to predict the environmental impact of these changes in driving pattern.

Driving pattern is generally defined as consisting of four modes: acceleration, deceleration, cruise and idle. A modal emissions and fuel consumption model accounts for vehicle driving pattern during its calculation of emissions and fuel consumption. For example, emissions during acceleration can be several orders of magnitude higher than during cruise or deceleration. Driving pattern changes that alter the frequency or magnitude of vehicle acceleration can have a significant effect on both instantaneous and overall emissions production. A modal emissions model is an important tool for the environmental evaluation of any transportation project that changes vehicle driving patterns.

Currently, there is a great deal of development activity with the end-goal of producing a modal emissions and fuel consumption model. This document will report recent and ongoing efforts of to quantify and model light-vehicle modal emissions and fuel consumption. The work documented includes two projects that the Federal Highway Administration has funded to estimate the emissions and fuel consumption impacts of changes in driving pattern. This report was written in support of modal emissions and fuel consumption research by the ITS Joint Program Office of the FHWA.

OBJECTIVES

The objectives of this document can be grouped into two tasks:

1. The first task was to assess state of the practice in modal emissions and fuel consumption modeling. To complete this task, ongoing development efforts in modal vehicle emissions and fuel consumption modeling were evaluated.

2. The second task was to recommend future steps in development of modal modeling, based on the assessment of the state of the practice.

While this document is not a comprehensive survey of all the modal emissions and fuel consumption research, it does include those organizations that have active programs, and have expressed an interest in participating in or supporting the FHWA's efforts to develop a modal modeling capability.

There were two specific objectives in completing the first task, the evaluation of the state of the practice:

- We sought to evaluate current modal model development efforts, including the efforts of government agencies, national labs, private firms and universities. We judged particular development efforts in terms of strengths, limitations, theoretical challenges and logistical challenges. We attempted to use a consistent methodology for deconstructing the various development efforts into comparable "components".

- We sought to identify components of existing modal models that could be incorporated into the development of future models. We defined components as consisting of either modeling methodology or empirical data.

The second task also had two objectives in the identification of focus areas for future modal model development.

- Identify common limitations in modal emissions and fuel consumption modeling.

- Based on current modeling limitations and the needs of the FHWA and other potential users, recommend focus areas for the further development of modal models. Both institutional and technical focus areas were identified for development.

RESEARCH METHODOLOGY

To accomplish the tasks described above, five research methods were employed:

1. A literature search on the past and present modeling of modal emissions was completed. Sources of relevant literature included the Volpe Center library, articles in monthly publications, published reports, previous work sponsored by DOT, and CRC Mobile Sources workshop notes. Admittedly, the majority of the literature referenced originated within the United States, for reasons of accessibility.

2. A second major source of information was interviews and correspondence with various developers, in person, by telephone, and through electronic mail. This approach was often tied to attendance at conferences and presentations by model developers, such as the 1994 and 1995 CRC On-Road Vehicle Emissions Workshop.

3. A technical summit to discuss modal emissions and fuel consumption modeling was held at the D.O.T.'s Volpe Center on April 25th, 1994, and representatives from a number of the organizations included in this report participated. Modal modeling issues discussed included:

    - Modeling Engine Performance as a Function of Driving Behavior
    - Fleet Representation in Modal Emissions Models
    - Linkage between Emissions Models and Traffic Models
    - Modal Emissions Modeling
    - Data Sources for Modal Emissions Models
    - Validation and Credibility of Models

4. We derived a methodology for consistently evaluating modal emissions and fuel consumption models. The methodology required the definition of a generic modeling algorithm for modal models. This generic algorithm was then divided into modeling components. The components were derived from the physical processes that determine engine operating conditions, emissions, and fuel consumption, and in effect constitute a distillation of what was learned through the three research methods listed above. The modules used were:

    - Modeling Inputs and Outputs
    - Vehicle Dynamics and Engine Load
    - Catalyst Behavior
    - Fleet Representation
    - Fleet Composition
    - Fuel Selection
    - External Influences

5. A critical analysis of existing development efforts allowed identification of the technical areas that would provide the most benefit through further research, model development and data collection. Each model was subject to a four part critique that incorporated:

   - Strengths
   - Limitations
   - Theoretical challenges
   - Logistical challenges

REPORT CONTENTS

The report contains the following sections and topics.

Background
Modal emissions and fuel consumption models are defined and described. The definition includes a basic description of the workings of gasoline powered automobiles, and the determinants of vehicle emissions and fuel consumption. The capabilities and applications for modal emissions and fuel consumption models are also discussed. Finally, this section contains a detailed description of the methodology developed by the Volpe Center for consistently evaluating modal emissions and fuel consumption models. The modeling process is described as discrete components, with an explanation of how the components fit together to form a modal emissions and fuel consumption model.

Modal Emissions and Fuel Consumption Models
The report contains a review of past modal emissions and fuel consumption models, which have existed in one form or another for the past 20 years. Two non-modal, emissions models, US-EPA's MOBILE and California Air Resources Board's EMFAC, are also described. The report includes MOBILE and EMFAC as it is likely that any new emissions model will be compared to these two established emissions models. The report also details the current FHWA activities and goals in the modal emissions and fuel consumption modeling.

Current Model Development Efforts
The modal model development efforts of 14 organizations are described and critiqued using the methodology described in the section titled **Background**. The following organizations' efforts are described and critiqued:

California Air Resource Board
Georgia Institute of Technology
Lincoln Laboratory, Massachusetts Institute of Technology

Los Alamos National Laboratory
National Cooperative Highway Research Program
Oak Ridge National Laboratory
Queen's University, Kingston, Ontario, Canada
Sierra Research
University of California, Davis
University of California, LA
University of California, Riverside
University of Michigan/Dr. Marc Ross
US-Department of Transportation, Volpe Center
US-Environmental Protection Agency, Certification & Testing Division

Brief descriptions of several international modal modeling efforts are also included in this section

Volpe Center Conclusions and Recommendations
Recommendations were categorized as institutional or technical. The recommendations are based on our assessment of current efforts in modal emissions and fuel consumption modeling, but also reflect input received from interviews and discussions with emissions model developers and potential users.

The institutional recommendations deal with the uses and impact of using modal emissions models:

- Value of Modal Models
- Integration of Modal Models with Travel, Traffic and Airshed Models
- Regulatory Requirements and Modal Models
- Fleet Coverage for Modal Models

There are a number of technical areas in modal modeling that are lacking in methodology development and quality empirical data. Technical areas that need further development were identified through critiques of existing modal emissions and fuel consumption models and as a result of the April 1994 technical summit at the Volpe Center (see **Appendix**). Progress in the following areas is necessary if a flexible and relatively comprehensive modal emissions and fuel consumption model for gasoline fueled light duty vehicles is to be developed:

- Catalyst Modeling
- NO_X Emissions Modeling
- Fleet Representation for Modal Models
- Linkage Between Emissions Models and Traffic Models
- Validation of Modal Emissions Models

Appendix

An appendix is attached to the report, containing the following items:

- Notes/comments/recommendations from the 4/24/94 modal modeling technical summit at the DOT, Volpe Center.
- A glossary of technical terms used in this report.

BACKGROUND

AUTOMOBILE EMISSIONS AND FUEL CONSUMPTION

This first part of this section is designed to explain the fundamentals of automobile exhaust emissions and fuel consumption. Several fine textbooks have been written that cover the subjects of automobile engine operation, emissions and fuel consumption. Much of the following text is based on Heywood's *Internal Combustion Engine Fundamentals*, Taylor and Taylor's *The Internal Combustion Engine*, and Obert's *Internal Combustion Engines and Air Pollution* [Ref. 1,2,3]. The discussion consists of six topics:

- A basic description of an automobile drivetrain,
- Operation of a gasoline automobile engine,
- Exhaust emissions production by an automobile engine,
- Control and reduction of exhaust emissions,
- Factors affecting automobile fuel consumption,
- The effect of driving mode on emissions and fuel consumption.

Automobile Drivetrain
Figure 1 is a simplified view of a passenger car driving at constant speed, along with the car's drivetrain, and the forces acting upon the car as it drives. The driven wheel transmits the force which moves the vehicle, and counteracts the resistive forces acting on the vehicle. For a steady speed case, the forces acting on the vehicle include: aerodynamic drag from the air surrounding the car, rolling drag from the tires and pavement, and the force due to gravity as a vehicle drives up a grade. If a vehicle is accelerating, there must be an additional force to counter-act the vehicle's inertia (Force = mass X acceleration). The drivetrain consists of the engine, transmission, driveshaft(s), differential and wheels.

The engine transmits power to the driven wheels through the transmission, driveshaft and differential. The transmission allows selection of different ratios ("speeds") between the driven wheel speed and engine speed. The engine operates most efficiently in a relatively narrow band of engine speeds, while vehicles are driven over a large range of speeds: the shifting of gears in the transmission makes this possible. The driveshaft and differential transmit the power from the output of the transmission to the driven wheel through shafts and gears.

Gasoline automobile engine
The gasoline internal combustion engine combusts air and gasoline to release the chemical energy stored in the gasoline. The energy flowing from this reaction is converted to mechanical power by the engine and used to drive the vehicle. There is an ideal ratio for the reaction and combustion of air and gasoline. This ratio is referred to as a stoichiometric fuel/air ratio. A stoichiometric mixture of gasoline and air contains just

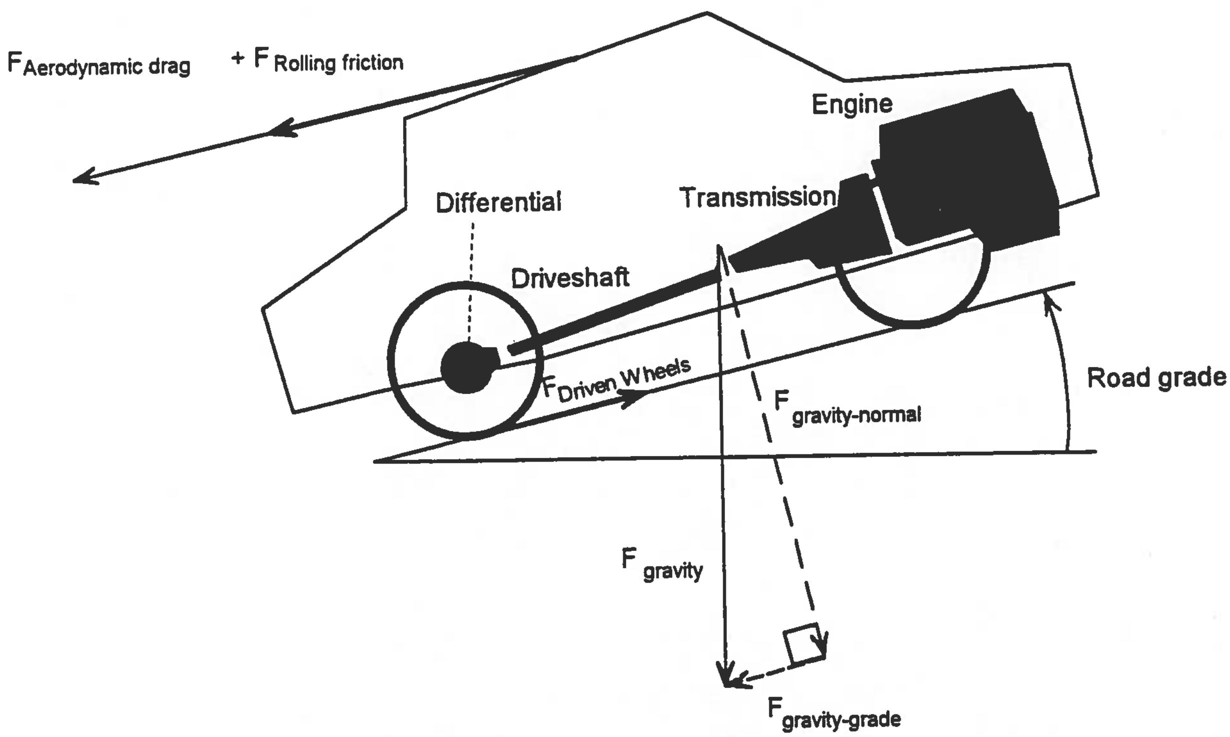

Figure 1 Automobile Force Balance (Constant Vehicle Velocity)

enough oxygen in the air to combust all of the fuel. The stoichiometric fuel/air ratio for gasoline is roughly 1 to 14.6 . If the fuel/air ratio is higher, the mixture is termed "rich"; if the fuel/air ratio is lower it is termed "lean". For most operating conditions, an automobile will operate with a fuel/air ratio very close to the stoichiometric ratio, but there are some operating conditions under which the vehicle is designed to operate with a rich mixture, often termed "enriched" operation.

Figure 2 contains a simplified schematic of an automobile engine and exhaust system. The air flow into the engine is controlled by a throttle, which is connected to the driver's "gas" pedal. The power produced by a given gasoline-fueled engine is closely related to the mass flow, in this case, the flow of fuel/air mixture through the engine.

Fuel flow is controlled in modern vehicles by an electronic engine control unit (ECU). After the fuel and air mixture is burned in the engine cylinders, the combustion products, or exhaust gases, exit the engine through the exhaust manifold. The exhaust gases then pass the oxygen sensor and flow into the catalytic converter. The exhaust gases are referred to as "engine-out emissions" at any point before the catalytic converter. The operation of the catalytic converter is described later in this section. After the converter, the gases pass through a muffler and out the tailpipe. The exhaust gases are referred to as "tailpipe emissions" at this stage.

The ECU attempts to maintain a near-stoichiometric fuel/air ratio by both measuring the inlet airflow, and the oxygen content of the engine-out exhaust gases. If the fuel/air ratio is too rich, that is, there is an excess of fuel, there will be little or no oxygen in the exhaust gases. The ECU will reduce the fuel flow until a designated level of oxygen content is measured in the exhaust gases.

There are conditions during which the engine will be operated "open-loop": that is, the oxygen sensor signal to the ECU is not used to control fuel/air ratio, and the fuel-air mixture is intentionally rich. This operating condition is also referred to as enriched operation or enrichment. The vehicle operations which lead to enriched operation will be discussed further on in this section.

Figure 3 illustrates the engine control unit and the various sensors which provide readings to the ECU. The ECU controls fuel flow primarily as a function of engine airflow and exhaust oxygen content, though most ECUs also take into account a number of other parameters, such as catalyst temperature, throttle position, and ambient air temperature. Figure 3 shows oxygen, catalyst temperature, and airflow sensors connected to the ECU. Note that the ECU controls fuel flow through the fuel injection system.

Exhaust emissions production

Gasoline is a mixture of hydrocarbon compounds, while air largely consists of nitrogen and oxygen. The products of ideal, stoichiometric combustion of gasoline and oxygen are CO_2 (carbon dioxide) and H_20 (water). However, real world emissions also include

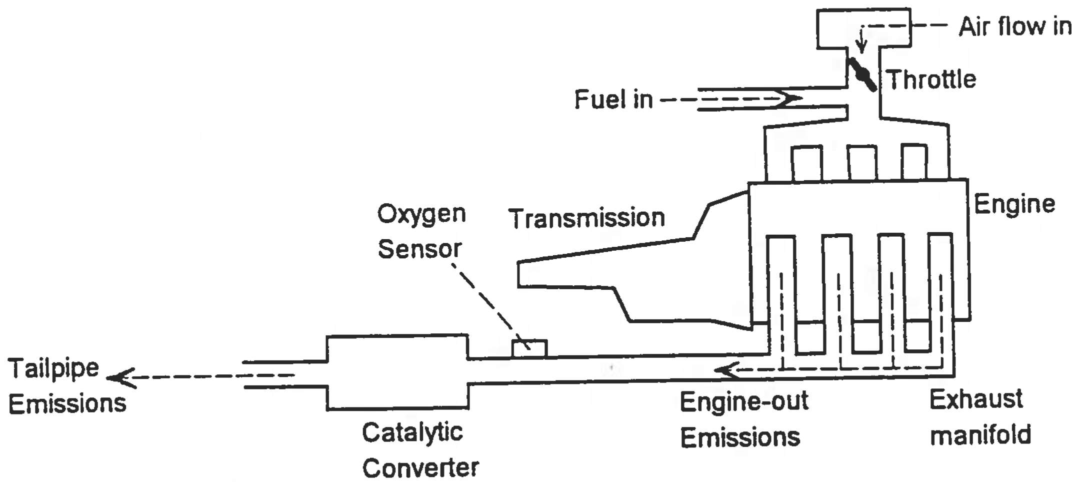

Figure 2 Engine and Exhaust System Components

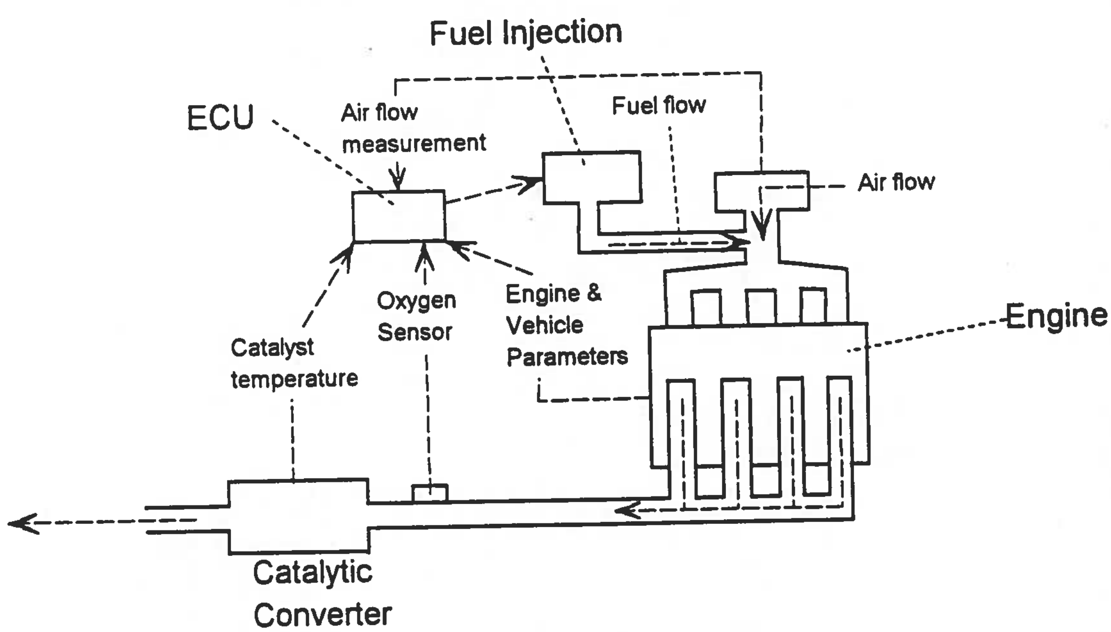

Figure 3 Engine Control Schematic

varying amounts of carbon monoxide (CO), hydrocarbons (HC) and nitrogen-oxygen compounds (NO_X), due to non-ideal combustion. Production rates for emissions are very sensitive to the fuel/air ratio, and CO and HCs tailpipe emissions can increase by several orders of magnitude if the fuel/air ratio is rich, while NO_X tailpipe emissions can increase if the fuel/air ratio is lean.

Three types of exhaust emissions are discussed in this report: carbon monoxide (CO), hydrocarbons (HCs) and nitrogen-oxygen compounds (NO_X). The basic mechanisms in the engine for the production of these pollutants are:

- CO is produced during fuel-rich combustion. If the mixture is fuel-rich, there is insufficient oxygen for complete oxidation of the carbon in the fuel. This leads to the production of CO instead of CO_2.

- HC emissions consist of partially burnt and unburnt fuel, and in mechanically worn vehicles, partially burnt engine lubricants. HCs can be formed due to unstable combustion or a malfunctioning engine, both of which result in some unburnt or partially burnt fuel being passed through the engine.

- NO_X emissions are produced from the nitrogen component of air, and are primarily a byproduct of the heat of combustion, which causes the nitrogen present in the air to react with oxygen in the air. The higher the combustion temperature, the higher the production of NO_X. Lean mixtures can lead to high combustion temperatures, and production of NO_X.

Under high power demand situations, most modern vehicles have been observed to switch from a stoichiometric fuel/air ratio, to an enriched fuel/air ratio. As was mentioned earlier, this mode is commonly referred to as open-loop operation. There are two reasons for open-loop operation: one is to increase the power output of the engine; the second is to protect the catalytic converter from thermal damage.

It is the second effect that is probably more important, since open-loop operation results in only a 5 - 10% increase in engine power.[Ref. 4] As was stated earlier, engine power is closely related to mass flow, and high powers result in high mass flows through the catalytic converter. Since heat is produced by the operation of the catalytic converter, the heat generated by an extended high power episode at a stoichiometric fuel/air ratio could damage or destroy the converter. However, a catalytic converter cannot convert most of the exhaust gases produced from an enriched mixture, due to the lack of oxygen in the exhaust flow. The catalytic converter is effectively shut down by enrichment. A more detailed discussion on catalytic converter operation is included below.

Malfunctioning vehicles that produce very high levels of emissions are commonly referred to as "high-emitters" or "super-emitters", and do not necessarily follow the emissions patterns described above. The emissions behavior is dependent upon the failure mode of the particular vehicle, which can be difficult to generalize.

Exhaust emissions control and reduction
The catalytic exhaust converter plays a strong role in determining what levels of emissions are finally released to the atmosphere. Almost every gasoline-fueled automobile sold in the United States after 1974 is equipped with some sort of catalytic converter. A catalyst is, "a substance that alters the rate of a chemical reaction and is itself unchanged by the process".[Ref. 5] In the case of automobile catalytic converters, the catalysts allow the conversion of exhaust pollutants to less harmful gases while the gases are still within the car, and at much lower temperatures than would otherwise be required without the catalyst present.

New cars generally have three-way converters, which act on CO, HC and NO_X emissions. The mechanisms for reduction of emissions by a three-way converter are as follows:

- CO is converted by oxygen (O_2) to CO_2. The effectiveness of the catalyst is determined by the amount of oxygen present in the exhaust gases, the temperature of the catalyst and the residence time of the exhaust in contact with the catalyst. A fuel-rich mixture will not only cause the engine to produce CO, it will result in a poor rate of conversion of the CO by the catalyst, because there will be little if any oxygen in the exhaust gases.

- HCs are converted by oxygen (O_2) to H_2O, CO, and CO_2. As with CO, the effectiveness of the catalyst is determined by the amount of oxygen present in the exhaust gases, the temperature of the catalyst, and the residence time of the exhaust in contact with the catalyst. Also, as with CO reduction, a fuel-rich mixture in the engine will result in poor catalyst conversion of HCs.

- NO_X emissions are reduced to nitrogen (N_2) and oxygen (O_2) by two mechanisms, depending on whether a platinum or rhodium catalyst is present. Platinum catalysts require O_2 for reduction of NO_X, whereas rhodium catalysts require CO and H_2 to reduce NO_X, and are actually hindered by the presence of O_2. Three-way catalytic converters contain both rhodium and platinum. The effectiveness of the three-way converter in reducing NO_X is determined by the amounts of O_2, CO and H_2 present in the exhaust, the age of the catalyst, the temperature of the catalyst and the residence time of the exhaust in contact with the catalyst. A fuel-rich mixture in the engine will aid NO_X reduction in a three-way catalyst, and hinder conversion in a platinum-only converter.[Ref. 6]

Catalyst conversion of CO and HCs on new automobiles is now in the 90-95% effectiveness range, when the engine is operating near a stoichiometric fuel/air ratio. NO_X conversion rates are in the 90% range.[Ref. 6] It is obvious that catalyst failure could significantly impact tailpipe emissions, since almost all CO, HC and NO_X emissions are converted by the catalyst.

During enriched or open-loop operation, the emissions can increase by an even greater amount, because of the combination of higher engine-out emissions and lack of catalyst effectiveness. Kelly and Groblicki of General Motors measured tailpipe CO emissions from a late-model passenger car that were 2500 times greater in grams per second during open-loop operation than during cruise, and HC emissions that were 40 times greater.[Ref. 7]

One more aspect of catalytic converters that should be mentioned is the phenomenon of oxygen storage. The catalyst material stores oxygen, which is used in the process of converting engine emissions. Test data seems to show that the oxygen storage can cause catalyst conversion effectiveness to remain high for a period on the order of one second after the beginning of enriched operation.[Ref. 8] This implies that short bursts of high engine-out emissions, such as those caused by brief high power operation or decelerations, may be "absorbed" by the catalyst without major changes in tailpipe emissions. This is a topic that we hope will be researched in greater detail in the future.

Air pumps and exhaust gas recirculation (EGR) are also used to reduce emissions on many automobiles. Some vehicles are equipped with air pumps which supply additional oxygen to the catalytic converter, to aid in the reduction of CO and HCs in the catalytic converter. However, this excess oxygen can at the same time hinder the reduction of NO_X. Exhaust gas recirculation reduces NO_X production by diluting the unburned fuel/air mixture in the engine with relatively inert exhaust gases, which in turn reduces combustion temperatures. However, EGR can increase HC emissions. Diluting the unburned fuel/air mixture reduces the combustion rate and combustion stability, which can result in incomplete burning of the fuel, and increased HC emissions.

Automobile Fuel Consumption

Modern vehicles tend to run in a very narrow band of air-fuel ratios near the stoichiometric ratio for reasons of both fuel efficiency and pollution control. Therefore, fuel consumption is basically a constant fraction of engine mass flow, with the mass flow consisting of fuel and air. As was stated earlier, engine power closely follows engine mass flow. Basic physics defines power integrated over time as energy. Therefore, if stoichiometric operation is assumed, the fuel used by a given automobile can be approximated by the energy usage of that vehicle. Again through basic physics, the energy usage of a vehicle can be calculated from the vehicle's velocity and acceleration history, changes in vehicle elevation, the vehicle's energy mass, and the vehicle's energy losses due to aerodynamic drag, rolling friction and braking.

In effect, the simplification above assumes that the vehicle has a constant fuel to energy conversion efficiency. While this is not strictly true, for stoichiometric operation it offers a good approximation for predicting fuel consumption as a function of driving mode. As was mentioned earlier, in some high-power situations, enriched operation is commanded by the engine control. In these cases, a higher air/fuel ratio must be used to calculate fuel consumption. The trends for fuel consumption as a function of driving mode are described below.

Modal Emissions and Fuel Consumption

The effects of driving mode (acceleration, deceleration, cruise, or idle) on engine-out emissions, tailpipe emissions, and fuel consumption, all in terms of mass per second, are described below.

- ***Acceleration:*** In general, acceleration will increase engine-out and tailpipe emissions of CO, HCs and NO_X because the higher engine power will require higher mass flow through the engine. Fuel consumption will also increase due to the higher mass flow through the engine during acceleration.

  Operation under heavy acceleration can also lead to enriched, or non-stoichiometric operation. During enriched operation, CO engine-out emissions increase greatly. HC engine-out emissions also increase, but not as much as CO emissions. Engine-out emissions of NO_X are generally low during enriched operation due to lowered combustion temperatures. Tailpipe NO_X emissions during enriched operation are also lower than during cruise, because the catalyst is effective in reducing NO_X. Enriched operation will increase fuel consumption relative to cruise due to both the increased engine mass flow and the higher fuel to air ratio.

- ***Deceleration:*** Deceleration can result in transient rich and lean fuel/air mixtures, due to poor matching of fuel flow with air flow. This problem is much less pronounced in modern vehicles because of the quicker and more accurate response of modern fuel-injection systems. Transient lean mixtures can result in bursts of NO_X production.

  Transient increases in engine-out emissions during deceleration may not result in significant increases in tailpipe emissions. The catalyst may be able to reduce brief bursts of engine-out emissions using oxygen stored in the catalyst, as was discussed in the description of catalyst operation.

  Decelerations require very little fuel flow, because the vehicle power requirement is essentially zero, and mass flow through the engine decreases greatly. The engine control will usually command a stoichiometric air/fuel ratio to prevent stalling and rough running from a lean mixture.

- ***Cruise:*** CO and HC engine-out emissions are low, because the fuel/air mixture is usually very close to stoichiometric and combustion is stable. NO_X engine-out emissions can be high, and can increase as the vehicle cruises at higher speeds. This is because stoichiometric mixtures tend to produce complete combustion and high combustion temperatures, leading to engine-out NO_X emissions. Tailpipe emissions are very low at cruise because the catalyst is very effective when the fuel/air ratio is stoichiometric. Older vehicles are an exception to this trend, as they have limited

NO_X reduction capability, and can show increased NO_X emissions as cruise speeds increase.

For operation on a level road, vehicle power demand and fuel consumption is determined by the aerodynamic drag , rolling friction, accessory power requirements, and vehicle velocity. A vehicle climbing a grade at a constant velocity has an increased power demand and the effect is similar to acceleration in terms of fuel consumption. Descending a grade can be treated as a deceleration in terms of power demand and fuel consumption.

- ***Idle:*** CO and HC engine out emissions may be caused poor mixture control at idle powers. Both of these factors are mitigated by the low engine mass flows at idle, and are also not really a problem for modern fuel-injected vehicles which have much better mixture control than older vehicles. Engine out emissions of NO_X at idle are extremely low. For most vehicles, idle tailpipe emissions are very low because of the high effectiveness of the catalyst and the low mass flow.

  Idle fuel consumption is very low and more a function of engine size than anything else. Large engines have higher internal friction and therefore higher idle fuel consumption. Older engines have less accurate fuel systems at very low powers, and may be configured to run rich to prevent stalling, which in turn drives up idle fuel consumption.

  Accessory loads, such as air conditioners, can have a strong impact on idle emissions and fuel consumption. This is because the power demands of the accessories become a significant portion of the total power demand at idle. There is also indication that some ECUs operate in an alternate mode if the air-conditioning system is on, and that this leads to significantly emissions than idle without the air-conditioner. [Ref. 9]

APPLICATIONS OF MODAL EMISSIONS AND FUEL CONSUMPTION MODELS

Modal emissions and fuel consumption model have a wide range of potential applications. These applications include a range of spatial and temporal scales. A modal model can be applied as a stand-alone vehicle model or as part of an integrated traffic, emissions, and fuel consumption model.

Scale of Applications

Modal emissions and fuel consumption models can cover a range of spatial scales, temporal scales and model any number of vehicles. Spatially, models range in coverage from single intersections to entire cities. Temporally, models may model a few seconds, a day, or an entire year. The emissions and fuel consumption of any number of vehicles may be modeled.

Resolution is the degree to which an analysis is capable of distinguishing between similar substances, properties, events or adjacent parts [Ref. 5] and is related to the scale of modal emissions and fuel consumption. In the case of emissions and fuel consumption models, resolution can vary in terms of vehicle movements, emissions production and fuel consumption.

It is important to realize that the resolution of a model is limited by the resolution of the input. For example, second by second vehicle movements must be described to define a vehicle's driving mode; parameters such as average trip speed, do not contain second by second data, and therefore do not have the temporal or spatial resolution needed by modal models

Though modal emissions and fuel consumption models generally require fairly detailed, high-resolution input, the resultant output can be aggregated to yield results that can be compared on a consistent basis with large-scale models in current use, such as MOBILE and EMFAC (see ***Modal Emissions and Fuel Consumption Models***).

Stand-alone Applications

Stand-alone modal models require the user to input driving pattern, and usually model the emissions and fuel consumption of a single vehicle. Stand-alone modal models can be used to model a number of vehicles, but individual vehicle driving patterns, including those that result from interactions between the modeled vehicles, must be input by the user.

Stand-alone applications could include the evaluation of different vehicles over a fixed drive pattern, such as the drive cycles which make up the Federal Test Procedure (FTP). This would be useful for comparing the emissions and fuel consumption characteristics of vehicles having different fuels, engines, payloads, or other characteristics. A stand-alone application might also evaluate a single vehicle over a varying drive pattern to estimate the effect on emissions and fuel consumption.

Integrated Applications

Integrated models link a traffic simulation to a modal emissions and fuel consumption model, so that emissions and fuel consumption are modeled along with vehicle movements and vehicle driving patterns. Integrated modal models can be categorized as microscopic, macroscopic, and mesoscopic, based on the traffic modeling component.

- ***Microscopic:*** The movements of individual vehicles are modeled. Traffic flow and driving patterns are largely determined by individual vehicle movements and interactions between individual vehicles. This includes lane changing and merges.

  The output of microscopic traffic models is usually compatible with the driving pattern input required by modal models to predict modal emissions and fuel consumption. If a microscopic traffic simulation is used, generally the emissions are calculated for each vehicle in the traffic simulation as its movements are predicted. Vehicle emissions can be assigned spatial and temporal coordinates as the emissions are generated, which would allow identification of potential emissions "hot-spots" in a traffic network.

  An example of an integrated microscopic emissions and traffic model is the TRANSIMS model currently under development by Los Alamos National Laboratory, which is described in the section, ***Current Modeling Efforts***.

- ***Macroscopic:*** Vehicle movements are modeled in terms of bulk traffic parameters, such as vehicles per hour over a roadway, vehicle miles traveled for an area, and average traffic speed over a freeway segment. Individual vehicle movements are not modeled.

  Integrating a macroscopic traffic model with a modal emissions model requires linking macroscopic traffic parameters, such as link-based average speeds and traffic volumes, to intrinsic driving patterns. This approach assumes that the scenario being analyzed does not change the historical relationship between macroscopic parameter (e.g. link average speed) and driving pattern. It is most viable for roadways with very consistent driving patterns, such as freeways.

- ***Mesoscopic:*** Mesoscopic models use a hybrid of macroscopic and microscopic techniques to model a scenario. Often microscopic traffic modeling is used to analyze intersections, on-ramps, merges, or other facilities where interactions between vehicles strongly effect traffic flows. Macroscopic traffic modeling is used to link together the microscopic sub-models, and perhaps to model freeways or other very regular traffic flows. Emissions and fuel consumption calculations may occur at the microscopic level and be aggregated for the entire scenario, or two different emissions and fuel consumption models may be used with each of the macroscopic and microscopic traffic models.

  University of California at Riverside is developing a large-scale, mesoscopic traffic model with an integrated modal emissions model. This modeling effort is described in the section, ***Current Modeling Efforts***.

Modal emissions and fuel consumption models can also be integrated with more comprehensive simulations. For its ITS Benefits Assessment Framework, the Federal Highway Administration plans to link travel demand modeling with traffic models, which will in turn be integrated with modal emissions and fuel consumption models. This project is described in the section, ***Modal Emissions and Fuel Consumption Models***. Modal emissions models could also be linked with air-quality models to yield estimates of the changes in air quality as a a result of changes in driving pattern. Lincoln Laboratory's model, described in the section ***Current Modeling Efforts***, will integrate traffic, emissions and tunnel-airflow models.

COMPONENTS OF MODAL EMISSIONS AND FUEL CONSUMPTION MODELING

One of this report's stated objectives was to assess the state of the practice in modal emissions and fuel consumption modeling. To this end, the Volpe Center examined the modeling efforts of fourteen organizations. The challenge was to evaluate and compare the many different modal emissions and fuel consumption models and model concepts consistently.

The Volpe Center developed a set of generic modal modeling criteria based in part on the physical processes behind automobile emissions and fuel consumption. The beginning of this section contains a description of the physical processes that lead to vehicle emissions and affect fuel consumption (see **Background, Automobile Emissions and Fuel Consumption**). The Volpe Center also selected criteria that reflected the interests of the ITS Joint Program Office, the sponsoring organization for this report. As was stated in the introduction, the ITS Joint Program Office is particularly interested in applying modal emissions and fuel consumption models to the evaluation of ITS services.

Eight major components were identified for the evaluation and comparison of the various modal emissions and fuel economy modeling approaches examined in this report.

1. **Model Input** - Driving pattern data required for modal emissions and fuel consumption. The model input defines the interface required to use a modal model as part of an ITS simulation.

2. **Model Output** - Emissions of CO, HCs, and NO_X, and fuel consumption, are of prime interest for environmental impact evaluations. The model output defines the interface required to use a modal model as part of an ITS simulation.

3. **Vehicle Dynamics and Engine Modeling** - This modeling component establishes the link between a vehicle's motion (driving pattern) and the operation of the vehicle's engine. The level of detail for this component varies greatly between models. The component was divided into five subtopics to isolate distinct physical processes: transmission modeling, engine torque and engine speed, air/fuel ratio, engine-out emissions and fuel consumption.

4. **Catalyst Operation** - The catalytic converter effectiveness is a major factor in determining the eventual tailpipe emissions of a given vehicle. The modeling of catalytic converters is important enough to be treated separately from

vehicle dynamics and engine modeling. Catalytic converter modeling was divided into steady-state and time-dependent effectiveness.

5. **Fleet Representation** - This modeling component determines how the emissions and fuel consumption of a fleet of vehicles are modeled, in contrast to a single-vehicle simulation. Real world scenarios will usually model the emissions and fuel consumption of a diverse fleet of vehicles. In order to make modal emissions predictions compatible with US-EPA emissions predictions and inventories, it may also be valuable to model the emissions of the by calendar year, by geographic region, and for future vehicle fleets.

6. **Fleet Composition** - Fleet composition is related to fleet representation, but specifically refers to the classes of the vehicles being modeled. For the purpose of this paper, the vehicle classes were defined as: light-duty passenger cars, light-duty trucks, medium-duty trucks, heavy-duty trucks and buses, and motorcycles. This system of vehicle classification is based on the US-EPA practice contained in the MOBILE 5a model.

7. **Fuel Selection** - Fuel type has a significant impact on vehicle emissions, especially in the case of non-gasoline fuels. The ability to model the use of fuels other than gasoline would allow modeling of real-world scenarios where a distribution of several different fuels are in use simultaneously. Five categories of fuel that the Volpe Center felt could be valuable to include in modal emissions and fuel consumption studies: are conventional gasoline, reformulated gasoline, oxygenated gasoline, diesel fuel, and alternative fuels.

8. **External Influences** - In order to model real-world scenerios, the Volpe Center felt that a modal model could include the vehicle emissions and fuel consumption impact of a number of external factors. These factors include the influence of road-grade, the influence of carrying a payload in excess of the 300 pound standard set by the US-EPA, and the influence of engine accesory operation, primarily air-conditioning.

Once the evaluation criteria were defined, the 13 modal modeling efforts covered in this report were compared against them. The comparison pointed out what was or was not included in each model, and allowed the Volpe Center dissect the modeling methodology used by each of the 13 organizations.

The evaluation of the models defined the strengths and limitations of each modeling approach. Areas still requiring development were labeled as either theoretical challenges or logistical challenges. Because many of the models were still under development, some could be evaluated more completely than others. For example, Sierra Research's VEHSIM/VEHSIME model is an operational piece of software, whereas the NCHRP has only recently awarded a development contract for its modal model.

The strengths, limitations, theoretical challenges and logistical challenges for each modal model development effort are listed in the next section, ***Current Model Development Activities***, along with brief descriptions of each organization's efforts.

A more detailed description of each modeling component follows, along with the physical processes each component is based on and the potential significance of each modeling component in the calculations of modal emissions and fuel consumption. Any distinct subcomponents within each modeling component are described.

1. **Model Input** - Driving pattern is generally described as a vehicle's velocity history. To be useful for modal models, the driving pattern must have enough definition to allow identification of vehicle driving mode (e.g. acceleration, deceleration, cruise, or idle). To capture a vehicle's driving mode, the modeled vehicle's driving pattern be updated at a regular time interval, typically once per second. The time interval may also be referred to as a time increment or time frame. If vehicle velocity is updated once per second, it is referred to as second by second velocity, or second by second driving pattern. An important point to make is that if second by second emissions and fuel consumption are to be modeled, then vehicle driving pattern must also be defined on a second by second basis.

   Several of the modal emissions and fuel consumption models are integrated with traffic simulations, which provide the modal model with vehicle driving patterns for each vehicle being simulated. Integrated traffic and emissions models also have the potential to spatially and temporally coordinate vehicle activity with emissions and fuel consumption.

2. **Model Output** - The outputs of interest are tailpipe emissions of CO, HCs and NO_X., and vehicle fuel consumption. By definition, modal emissions and fuel consumption predictions must be sensitive to changes in vehicle driving pattern. In general, modal emissions and fuel consumption rates are expressed in terms of mass per unit time (e.g. grams/sec), and are updated every time the vehicle velocity and acceleration are updated. For example, if vehicle driving pattern is defined as second by second vehicle velocity, then emissions and fuel consumption rates would be updated once a second.

   Typically, modal models will be used on a microscopic scale, and modal emissions and fuel consumption output will be generated for each modeled vehicle, and assigned to that vehicle both temporally and spatially. However, modal emissions and fuel consumption estimates can also be aggregated to more convenient scales if necessary. For example, fuel consumption could be expressed on a second by second basis for a fleet of vehicles, or on an hour by hour basis for an geographic area, or on a per trip basis for an individual vehicle.

The spatial assignment, temporal assignment, and scale of emissions predictions are also important criteria in determining how the model output can be used.

3. **Vehicle Dynamics and Engine Modeling** - This component establishes the link between a vehicle's motion (comprised of acceleration and velocity) and the required response of the vehicle's engine. The energy or work required to move an automobile is provided by the engine. The rate at which the work is provided is the engine power. The engine power can also be described by the product of two components: engine speed (RPM) and engine torque. Engine air/fuel ratio is sometimes estimated as a function of engine speed and torque. Engine air/fuel ratio, engine speed and engine torque are the parameters often used to describe an engine's operating point, and to calculate engine emission characteristics and fuel consumption.

   - ***Transmission Modeling:*** A transmission model describes the relationship between vehicle velocity and engine speed. Given the vehicle power requirements, if the vehicle's transmission is modeled, the engine's operating point (in terms of engine torque and engine speed) can be defined. Transmission operation can be complex and is often greatly simplified for modeling purposes.

   - ***Engine Torque and Speed:*** The engine torque and speed can be used to estimate emissions, fuel consumption, and air/fuel ratio if engine data in the form of "maps" is available. Figure 4 is an example of a three dimensional engine emissions map. [Ref. 10]

   - ***Air/fuel ratio:*** Air/fuel ratio is a prime parameter in determining the combustion processes within the vehicle's engine, which in turn determines the engine-out emissions.

   - ***Engine-out Emissions:*** Engine emissions are often modeled as a function of air/fuel ratio, engine torque and engine speed, or vehicle power and vehicle speed, or a combination of these parameters.

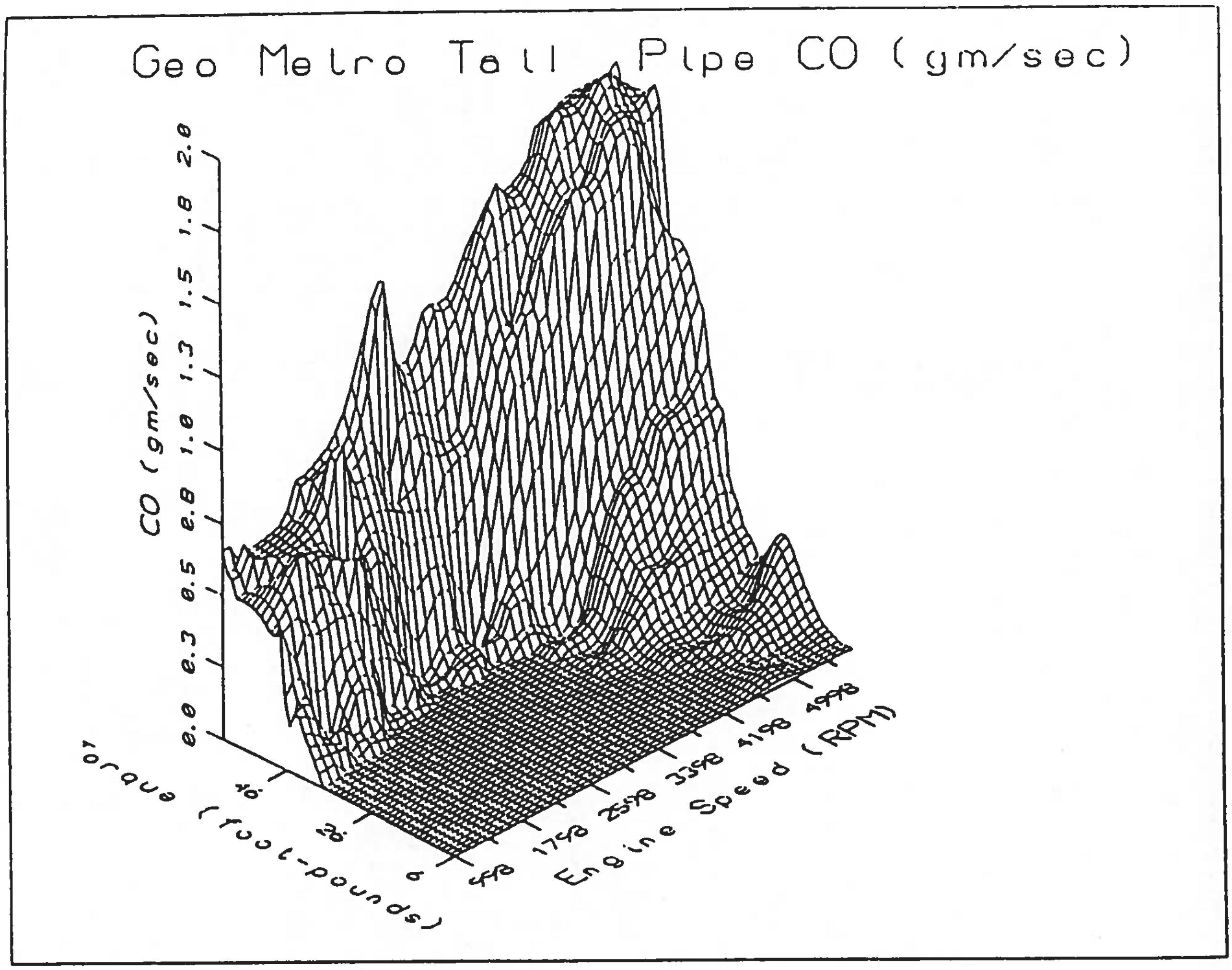

Figure 4 Engine Map Example [Ref. 10]

4. **Catalyst Behavior** A catalytic converter converts engine-out emissions into less harmful or non-harmful gases that exit the vehicle tailpipe. A discussion of catalyst operation is included in the section ***Vehicle Emissions and Fuel Consumption***. Catalytic converter performance is described in terms of catalyst effectiveness. It is the ratio of the particular emission concentration exiting the catalyst (and hence the vehicle tailpipe) over the emission concentration entering the catalyst (engine-out emissions). Given engine-out emissions and catalyst effectiveness, the resultant tailpipe emissions can be computed.

    - ***Catalyst effectiveness (steady state):*** Value for catalyst effectiveness with engine-out emissions of a constant composition, mass flow, and temperature.

    - ***Catalyst effectiveness (time dependent):*** Value for catalyst effectiveness with engine-out emissions of a changing composition, mass flow, or temperature. Catalytic converters have been observed to lag behind changes in engine operation and vehicle motion, which may have important effects on the temporal link between tailpipe emissions and driving pattern, if tailpipe emissions are calculated as a function of catalyst effectiveness.

5. **Fleet Representation** A modal emissions and fuel consumption model must be representative of the expected on-road fleet for the scenario being modeled. Emissions can vary greatly from vehicle to vehicle.

    - ***Expansion of simulation results to fleet:*** Expanding emissions predictions from a single vehicle or even a small group of vehicles to a large and diverse fleet of vehicles is challenging, if not impossible. Several approaches have been proposed, including using a single generic but representative vehicle, using a small fleet of carefully chosen representative vehicles, and using a model that can have a few key parameters changed to make it representative of a wide range of vehicles. The alternative is to use a large number of vehicle-specific emissions and fuel consumption models to represent the fleet. The disadvantage of this approach is that vehicle-specific models require a huge amount of empirical data from a large number of vehicles.
    - ***On-road fleet by calendar year:*** Environmental impact projections are often done by year or region . This also makes the results comparable to other emissions and fuel-use estimates from models such as MOBILE, CALINE and EMFAC.
    - ***On-road fleet by region:*** Environmental impact projections are often done by year or region . This also makes the results comparable to other

emissions and fuel use estimates from models such as MOBILE and EMFAC.

- ***Future fleets:*** Modal emissions and fuel consumption models may be used to estimate the environmental impacts of future transportation projects. The fleet composition should reflect the calendar year in which the project will be operational.

6. **Fleet Composition** - Emissions and fuel consumption estimates may be done for the entire on-road fleet, or only for certain vehicle classes. The categories listed below follow the US-EPA's practice for vehicle classification, as contained in the MOBILE emissions model.

   - ***Light-duty passenger cars:*** Many modal models only cover light-duty passenger cars and light-duty trucks, as these constitute a large part of total vehicle miles traveled, and there is more emissions and fuel consumption data available for these segments than the others. Light-duty passenger cars are almost exclusively gasoline-fueled in the current U.S. fleet.
   - ***Light-duty trucks:*** Light-duty trucks are similar to passenger cars, but have different certification standards that are reflected in different emissions and fuel consumption characteritics. Light-duty trucks area mostly gasoline-fueled in the current U.S. fleet, though there are diesel-fueled vehicles, too.
   - ***Medium-duty trucks:*** Composed of a mix of gasoline-fueled and diesel-fueled vehicles, with substantially different driving characteristics due to different usage, larger size, and higher weight.
   - ***Heavy-duty trucks and buses:*** These consist primarily of diesel-powered vehicles, with substantially different driving characteristics due to different usage, larger size, and higher weight.
   - ***Motorcycles:*** Motorcycles are rarely considered in modal emissions and fuel consumption modeling, however they are included in the US-EPA's definition of the on-road fleet.

7. **Fuel Selection** - Emissions are directly affected by the fuel type used. Fuel consumption can be affected to a lesser degree through changes in fuel economy. Both engine operation and catalyst operation may be affected by changes in fuel composition. There are five major categories of fuels to be considered:

   - ***Conventional gasoline:*** Most existing emissions data is for conventional gasoline-powered vehicles.
   - ***Reformulated gasoline:*** Reformulated gasoline has a lower Reed Vapor Pressure (RVP) than conventional gasoline, and therefore is less volatile. The intent is to reduce evaporative emissions of fuel.

- ***Oxygenated gasoline:*** Oxygenated gasoline has an additive, which increases oxygen content of the fuel. The additional oxygen reduces CO and HC emissions. Methanol, ethanol and methyl tertiary butyl ether (MTBE) are examples of oxygenates.
- ***Diesel fuel:*** Diesel powered vehicles generally use a light-weight oil as fuel. Diesel vehicles differ from gasoline vehicles in their emissions and fuel consumption characteristics due to differences in engine operation and fuel composition.
- ***Alternative fuels:*** Alternative energy sources for automobiles include compressed natural gas (CNG), chemical batteries, and alcohol.

8. **External Influences** - These are factors that can change engine load independent of a vehicle's driving pattern. This will in turn affect emissions and fuel consumption. The following are the three most prominent factors:

- ***Load due to road grade:*** A vehicle driving uphill at a given speed and acceleration rate will require more power than a vehicle driving at the same speed and acceleration on level ground.
- ***Load due to payload:*** Payload can add to engine load, especially uphill, independent of driving pattern.
- ***Accessory load modeling:*** Accessories, including the alternator, air pump, and air-conditioner add to the engine power demand when operating, independent of the vehicle's driving pattern. The load can be a significant portion of total power demand at idle and even at cruise for smaller vehicles. Air conditioning operation also apparently has a direct effect on ECU operation for some vehicles, which can increase emissions.[Ref. 9]

MODAL EMISSIONS AND FUEL CONSUMPTION MODELS

HISTORY OF MODAL MODELS

Modal emissions and fuel consumption models are not new. A number of models have been developed over the last twenty years. Some models were developed by the US-EPA and the US-DOT, some by private consulting firms, some by automobile manufacturers. Development has been evolutionary in most cases, with newer models building on the foundation of existing models.

Automobile Manufacturers' Modal Models

Not surprisingly, domestic automobile manufacturers developed what were probably the earliest modal models. These were developed to predict vehicle performance capability and fuel consumption, and to serve as a design tool to help designers select engine, transmission, and overall vehicle configurations. These models were also proprietary to each manufacturer. Ford developed a model called the Vehicle Course Fuel Economy Projection Method (VCFEPM) which dates back to 1969. General Motors developed a model called the General Purpose Simulator (GPSIM) during the early 70s, which could predict vehicle second by second fuel consumption as a function of driving pattern input. [Ref. 11] It is probably safe to assume that the modeling capabilities of automobile manufacturers have progressed over the past 20 years, and that some powerful, but proprietary predictive tools have been developed. These models probably would have limited applicability because they were not designed for the evaluation of driving pattern changes due to transportation programs such as ITS.

Modal Analysis Model

One of the first modal emissions models was developed by the Calspan Corporation under contract to the US-EPA. The Modal Analysis Model was designed to calculate vehicle emissions as a function of a user defined drive pattern. The model input was instantaneous speed and acceleration. Second by second emissions were calculated using a quadratic function of the vehicle velocity and acceleration.

The Modal Analysis Modal was developed from emissions data recorded for a large sample of on-road vehicles during 1972. The vehicles were tested on dynamometers over a drive cycle known as the Surveillance Driving Sequence (SDS). The SDS cycle consisted of 16 constant acceleration rate events, 16 constant deceleration rate events, and constant speed cruise segments at 15 mph, 30 mph, 45 mph and 60 mph.

Each vehicle's emissions for the entire test cycle were collected in a sample bag and then analyzed to determine the concentrations of CO, HCs and NO_X emissions over the SDS cycle. Quadratic formulas were developed for each type of emissions through linear regression of the SDS cycle modal driving components against the bagged emissions. A total of 1020 vehicles were dynamometer tested over the SDS cycle, and their emissions were measured. For the regression analysis described above, the test results were first stratified into 11 groups, based on the vehicle model year and the city where testing occurred. [Ref. 12]

CALINE4 Intersection Link Option

CALINE is the abbreviation for the California Line Dispersion Model, which was developed by the California Department of Transportation in 1972, and most recently updated in 1984 to CALINE4. The CALINE4 Intersection Link Option is a modal CO emissions model contained within CALINE4, specifically designed for modeling intersection CO emissions and air quality.

This model uses the approach of multiplying a base emission rate, which is a calendar year fleet average, by a function of driving mode, vehicle acceleration, and vehicle velocity. The base emission rates are from Federal Test Procedure (FTP) dynamometer measurements, and represent hot-stabilized emissions of CO.

The modal correction functions were derived in a manner similar to that used in the development of the Modal Analysis Model described above. Emissions measurements from 81 vehicles, gathered over the Surveillance Driving Sequence (SDS), were used in a regression to derive the modal correction functions. Two acceleration functions were derived, one for vehicles acceleration from rest, and one for vehicles accelerating from a velocity of 15 mph or greater. A cruise correction function was also derived. Idle emissions are simply taken directly from FTP idle emissions rates. Idle emission rates are multiplied by 1.5 to estimate deceleration emissions. [Ref. 13]

VEHSIM

VEHSIM was developed during the 1970s by the Department of Transportation's Volpe Center based on General Motor's modal fuel consumption models.[Ref.15] VEHSIM is detailed vehicle model that estimates instantaneous fuel consumption as a function of vehicle driving pattern.

VEHSIM calculates the forces acting on the modeled vehicle from road friction, aerodynamic drag, acceleration, and road grade. The resultant force and the vehicle velocity are used as input to a detailed drivetrain model, which ultimately computes the engine speed and torque. VEHSIM includes a detailed transmission model to simulate transmission shift logic for automatic transmissions. VEHSIM uses the calculated engine speed and torque to read an instantaneous fuel consumption rate from a three-dimensional map of engine fuel consumption. Figure 4 in the ***Background*** section is an example of an engine emissions map. A fuel consumption map is of the same format, but with fuel consumption rate as a function of engine speed and engine torque. [Ref. 11]

MOBILE and EMFAC Emissions Models

MOBILE and EMFAC are mobile source emissions models that are in widespread use. Both models use a similar methodology to predict vehicle emissions rates in grams per mile. Exhaust emissions are modeled largely as a function of vehicle average trip speed, vehicle miles traveled (VMT), calendar year, and vehicle classification (e.g. light-duty gasoline truck, heavy-duty diesel vehicle). These are not modal models, as the emissions data contained within both models reflect assumed driving patterns that are directly linked to the average trip speed. Each average trip speed reflects a specific drive pattern.

MOBILE - MOBILE calculates vehicle exhaust emissions, as a function of a vehicle's average trip speed and the distance traveled. Average trip speed is a vehicle's trip distance divided by the time required to complete the trip. Exhaust emissions calculated include CO, HCs, and NO_X, in grams per mile.

MOBILE's coverage includes the entire on-road fleet. The on-road fleet is divided into eight vehicle classes, including four for gasoline cars and trucks, three for diesel cars and trucks, and one class for motorcycles. The vehicle population for any year between 1960 and 2020 is modeled through registration, sales and fleet projection data and projections. Emissions predictions are average values for the vehicle class and calendar year modeled.

MOBILE calculates emissions for a vehicle class and calendar year by using a fixed-speed, fixed-trip length base emissions rate, which is then modified by a trip speed correction factor. Cold-start, hot-start, and hot-stabilized emissions can be calculated separately, or a composite emissions rate can be calculated.

For hot-stabilized operation, the base emissions rates were measured over the EPA's Federal Test Procedure (FTP) drive-cycle, which has an associated average speed of 19.6 mph. The speed correction factors were derived from a regression of a number of other drive-cycles for which there are emissions test results. The speed correction factors cover the range from zero to 64.4 mph.

There are other emissions corrections included in MOBILE to account for non-standard local conditions, tampering frequency, fuel vapor pressure, refuelling emissions, and inspection and maintenance program impact. MOBILE also has default values for most inputs, which include assumptions for average trip length, average start time, fuel vapor pressure, and ambient conditions. [Ref. 15, 16]

EMFAC - EMFAC is very similar to MOBILE (see above), and in fact has the same base emissions rates as MOBILE, but uses an alternate set of correction factors specifically tailored to California. The primary difference between MOBILE and EMFAC is in the ambient temperature and speed correction factors for passenger cars, light-duty trucks, and medium-duty trucks.

EMFAC also differs from MOBILE in the vehicle classifications used to divide the fleet. EMFAC classifies vehicles by type (e.g. light-duty vehicle, medium truck), gasoline or diesel, and in more recent versions, by pollution control and fuel-delivery system. EMFAC vehicle class distributions are built into the model, and are selected by the calendar year being modeled.

Speed correction factors for EMFAC's base emission rates operate in the same manner as MOBILE's. As with MOBILE, base emissions rates are derived from the EPA's FTP drive-cycle, with the associated average speed for that cycle of 19.6 mph. For modeling emissions other than the FTP average speed, California specific speed correction factors are used.

Temperature correction factors primarily affect vehicle evaporative emissions of gasoline. The temperature correction factors are a function of fuel delivery system (e.g. carbureted, multi-port fuel injected, throttle body injected) and model year. Ambient temperature is entered by the user.

As is the case with MOBILE, EMFAC provides average emission rates for each vehicle class. To use EMFAC for exhaust emission estimates, a fleet calendar year, operating mode (cold-start, hot-start, or hot-stabilized) and average trip speed are input. The results include average CO, HCs, and NO_X exhaust emission rates in grams/mile.[Ref. 16]

FHWA ACTIVITIES RELATED TO MODAL EMISSIONS AND FUEL CONSUMPTION

The FHWA has two projects underway to estimate the hot, stabilized emissions and fuel consumption impacts of changes in driving behavior for light-duty, gasoline-fueled vehicles. The first project will attempt to improve the ability of the ITS Benefits Assessment Framework to estimate the impact of ITS user services on modal emissions and fuel consumption. The goal of the second project is to endow the microscopic traffic simulation model, TRAF-NETSIM, with the capability to estimate the emissions and fuel consumption impacts of traffic improvement projects.

The enhancements to the ITS Benefits Assessment Framework are under development at the DOT's Volpe Center, while the second project is based at Oak Ridge National Labs (ORNL).

Enhancement of Modal Emissions and Fuel Consumption Prediction Capabilities of the ITS Benefits Assessment Framework

The ITS Benefits Assessment Framework is an integrated systems model that will be used to evaluate various ITS implementations. ITS will be implemented in the form of the following user service bundles.[Ref. 17]

Travel and Transportation Management - These user services gather information on the operation of the transportation system, disseminate the information to travelers, and use the information to command traffic control devices.
Travel Demand Management - These user services attempt to encourage travel my modes other than single occupancy vehicles.

Public Transportation Operations - These user services will provide improved transit and mode choice information to travelers.
Electronic Payment - This user service will allow travelers to pay for tolls, transit fares and parking electronically.
Commercial Vehicle Operations - These user services will improve the safety and efficiency of commercial fleet operations. Two of the services included will be electronic clearance, to minimize stops, and fleet management, to aid vehicle routing.
Emergency Management - These user services will improve the response to, and management of, emergency situations.
Advanced Vehicle Control and Safety Systems - These user services will (work with vehicle mounted systems to improve the safety of vehicle operation,) and in the longer term, Automated Highway Systems (AHS), which will allow hands-off operation of vehicles on freeways.

Changes in travel behavior and traffic operations due to ITS user services will impact transportation mode choice, the number of trips, traffic flow patterns, and vehicle miles traveled (VMT). These ITS impacts are in turn expected to affect vehicle driving patterns. In the longer term, Advanced Vehicle Control user services will directly affect freeway driving patterns.

The Volpe Center has incorporated the following elements into the ITS Benefit Assessment Framework:

- The Framework will integrate several levels of travel and traffic modeling: a regional planning model (SYSTEM II), a freeway/ramp model (FREQ) and an arterial model (TRANSYT-7F). In the future, microscopic traffic models (INTEGRATION, CORFLO) will be added.

- Basic emissions are based on the MOBILE5A and EMFAC7F models, using factors from those models to distinguish the impact of changes to trip number, mode choice, and vehicle miles travelled (VMT).

- Another emissions and fuel consumption model has been added, which calculates exhaust emissions and fuel consumption as a function of facility type, number of lanes, level of service, and average speed on the facility. This emissions model is derived from Sierra Research's VEHSIM/VEHSIME modal emissions and fuel consumption model.

The emissions and fuel consumption model that was derived from VEHSIM/VEHSIME was developed by Sierra Research under contract to the Volpe Center. During 1992 and 1993, Sierra Research gathered a database of second by second driving behavior with an instrumented chase car. Driving behavior of other vehicles was recorded by the chase car over a variety of facilities, including freeways, arterials, merges, and freeway ramps. Driving behavior was recorded as second by second velocity and acceleration. The data were then sorted into bins by facility type, number of lanes, and level of service on the roadway.

The contents of each bin was used to as input to the VEHSIM/VEHSIME modal emissions and fuel consumption model (see ***Current Model Development Efforts*, *Sierra Research***). Total quantities of fuel consumption and CO, HCs, and NO_x emissions were generated for each bin. The total quantities were converted to emission and fuel consumption rates by dividing the totals predicted by VEHSIM/VEHSIME by the total travel distance represented by each bin.

The emissions and fuel consumption rates described above were actually averages for 14 of the light-duty vehicles VEHSIM/VEHSIME models. The grams per mile emissions predictions were corrected based on a comparison of VEHSIM/ VEHSIME predictions and Federal Test Procedure fleet emissions rates, with the goal of making the emissions predictions representative of the on-road, light-duty fleet. This resulted in the final emissions rates which are contained in the Benefits Assessment Framework.[Ref. 18]

Update and Improvement of Emissions and Fuel Consumption Prediction Capability of TRAF-NETSIM Model

The FHWA is enhancing the emissions and fuel consumption prediction capabilities of the TRAF-NETSIM traffic model. TRAF-NETSIM is a microscopic traffic model, which predicts individual vehicle, hot-stabilized emissions of CO, HCs, and NO_x as a function of vehicle velocity and acceleration.

The FHWA hopes to use TRAF-NETSIM to:

- Assess and predict vehicle fuel consumption and emissions, based on traffic volume and flow characteristics.
- Enhance roadway designs and traffic control strategies, with fuel consumption and emissions as a consideration.
- Generate a fuel consumption and emissions database for the various traffic models in use.

The current effort to improve TRAF-NETSIM builds on previous efforts by FHWA. A 1984 Oak Ridge National Labs (ORNL) study tested the fuel consumption of fifteen 1984 vehicles, both on dynamometers and on-road. Six vehicles were tested for emissions as well. The resultant test data was included in TRAF-NETSIM as emissions and fuel consumption tables.

FHWA plans to upgrade TRAF-NETSIM by the following means:

- Expand traffic simulation capabilities by linking TRAF-NETSIM to TRAF-NETFLO, a macroscopic traffic model. This will allow larger spatial scales to be used in traffic modeling. TRAF-NETSIM is primarily used to model single intersections, freeway segments, or freeway ramps at this time.

- Expand the range of driving behavior covered by TRAF-NETSIM's modal emissions and fuel consumption to cover velocities between 0 and 110 feet per second, and accelerations between +/- 9 feet/sec^2 .
- Adding modal emissions and fuel consumption tables that are specifically for a number of different facilities, such as freeways, arterials, and freeway ramps. Tables would also be added that are cover specific driving activities, such as lane changing.
- The emissions database currently used in TRAF-NETSIM will be updated by Oak Ridge National Labs (ORNL) to better represent the on-road fleet. ORNL will complete a testing and development program designed to deliver the improved and expanded emissions maps described above. ORNL hopes to model the on-road light-duty fleet by developing tables for up to sixteen representative vehicle types. ORNL's planned methodology for developing the maps is covered in the section, ***Current Model Development Efforts, Oak Ridge National Laboratory***.

By using a macroscopic traffic model along with the upgraded TRAF-NETSIM, the FHWA hopes to analyze the impact of implementing various ITS programs. The FHWA plans to use the simulations to gather Measures of Effectiveness (MOEs) for ITS travel and traffic programs, along with estimates of emissions and fuel consumption impacts.

CURRENT MODELING EFFORTS

CRITIQUES OF MODELING EFFORTS

Fourteen modal modeling efforts were compared against the modal emissions and fuel consumption modeling criteria described in the previous section. The results of the comparisons pointed out the strengths and limitations of each model, along with the parts of each model that require further development.

This section contains a brief description of each of the fourteen models, in terms of input and output and the basic modeling algorithm. The strengths, limitations, theoretical challenges and logistical challenges are also listed.

Strengths

These are favorable points of a given model or modeling approach. These can be anything that might make the model useful as part of the FHWA's modal modeling effort. Some examples of favorable points could be: the methodology or algorithm used; the empirical data contained within the model; or the development status of the model (e.g. working prototype or in-use model).

Limitations

These are drawbacks of a given model or modeling approach. Some examples of drawbacks could: modeling elements that are missing or poorly modeled; insufficient or unreliable empirical data; or uncertain development status.

Theoretical Challenges

These are the major theoretical challenges that must be met so that the model meets the ITS Joint Program Office's modal emissions and fuel consumption modeling goals. These challenges most often deal with model algorithm development or the planning of data collection. Validation of models can also be a theoretical challenge.

Logistical Challenges

These are the challenges in terms of creating a working model that meets once the theoretical model or algorithm is defined. These challenges are primarily related to empirical data collection, though there can be other technical issues, such as the computational requirements of large-scale models. Executing validation plans can also be a logistical challenge.

DEVELOPMENT EFFORTS BY ORGANIZATION

The development efforts of the following organizations are included:

California Air Resource Board
Georgia Institute of Technology
Lincoln Labs, Massachusetts Institute of Technology
Los Alamos, National Labs
National Cooperative Highway Research Program
Oak Ridge, National Labs
Queen's University, Kingston, Ontario, Canada
Sierra Research
University of California, Davis
University of California, LA
University of California, Riverside
University of Michigan
US-Department of Transportation, Volpe Center
US-Environmental Protection Agency, Certification & Testing Division

Two other studies involving modal emissions simulation, one completed at Graz University in Austria, and one by CSIRO in Australia, are briefly described.

CALIFORNIA AIR RESOURCE BOARD

Model
Not named yet

CARB is in the process of developing a modal emissions model. CARB will model hot-stabilized emissions of light-duty, gasoline-fueled cars and trucks. The model will require input in terms of individual vehicle second by second velocity, along with instantaneous road-grade. Output will be second by second tailpipe emissions of CO, HC and NO_X.

CARB's model will be similar to Sierra Research's VEHSIM/VEHSIME model, upon which it is based. CARB will model vehicle emissions as a function of driven-wheel load, and vehicle velocity. The main difference between CARB's model and VEHSIM/VEHSIME is that CARB plans to use emission maps that are a function of external vehicle parameters, namely, driven-wheel load and vehicle velocity, while VEHSIM/VEHSIME uses emission maps which are a function of engine torque and engine speed.

CARB will develop vehicle emissions maps through extensive dynamometer tests. CARB will record second by second CO_2, CO, HC, and NO_X emissions, along with driven-wheel torque, vehicle velocity, and air-conditioner operation. CARB's testing will cover vehicles registered within the Southern California Air Basin and manufactured within the last 8 years. The vehicles will be divided into approximately 16 "technology groups". The grouping will be based on fuel delivery system, catalyst type, and the emissions standard at the time of the vehicle's manufacture. CARB plans to represent each technology group with an emissions map in the modal model.

CARB also plans to model second by second fuel consumption, based on the predicted emissions of CO_2, CO, and HCs, which will allow a prediction of an exhaust carbon count. [Ref. 8]

Strengths
Development of this model will include extensive vehicle testing. Between 250 and 500 light-duty gasoline vehicles, taken from the on-road, southern California fleet. CARB's fleet selection and characterization exercises could also be useful in the development of a generalized fleet representation methodology.

Limitations
This model is still under development. The use of vehicle-specific maps of emissions versus driven-wheel load will make it difficult to extrapolate from these emissions maps to predictions for other vehicles. CARB's model will only cover California vehicles.

Theoretical Challenges
Modeling vehicle rear-wheel load and engine speed as a function of drive pattern, may require vehicle specific load maps, and a transmission simulation shift logic for individual vehicle types. Also, it is unclear whether high-emitters will be represented in the tested fleet, and how they would be represented in the model.

Logistical Challenges
Testing a such a large group of vehicles, over the entire range of vehicle operations, will require a large amount of dynamometer time.

GEORGIA INSTITUTE OF TECHNOLOGY

Model
Not named yet

Georgia Institute of Technology is in the process of developing a modal emissions model, which will provide second by second estimates of individual vehicle emissions of CO, HCs and NO_X. Georgia Tech's model will require input in the form of second by second velocity and acceleration for each vehicle modeled. Georgia Tech's model will calculate vehicle emissions as a function of vehicle power demand, with separate emissions "modules" for hot-start, cold-start, hot-stabilized and enriched operating modes, as well as separate modules for the modeling of super-emitter and heavy-duty vehicle emissions.

Georgia Tech's model will be integrated with a GIS (Geographical Information System) database, which will represent an actual geographic region (initially Atlanta). Modeled vehicles will be assigned locations on the GIS-based geographic representation, allowing for spatial assignment of vehicle emissions as they are produced. The GIS database will also contain road-grade data for the roadways modeled, allowing the influence of road-grade on vehicle emissions to be modeled.

Georgia Tech plans to calculate vehicle power demand as a function of second by second vehicle velocity, vehicle acceleration, road-grade, and basic vehicle parameters, such as weight and rolling friction. As described above, enriched operation will be modeled by a separate emissions prediction module. The enriched operation module will predict emissions when power demand exceeds a preset power threshold.

Vehicles will be statistically assigned as normal, super-emitter, or heavy-duty vehicles. Similarly, the distribution of vehicles in hot-start, cold-start and hot-stabilized operating mode will be determined by statistics derived from real-world observations. Georgia Tech has gathered data from Atlanta Nashville, Baltimore, and Phoenix, and plans to add data from a number of other cities in the future.

Georgia Tech's modeling of emissions as a function of vehicle power demand will be based on existing EPA dynamometer tests, remote sensing measurements gathered by Georgia Tech, and data recorded from Georgia Tech's fleet of 5 instrumented passenger cars. Enrichment threshold modeling will be based on remote-sensing tests designed specifically for the identification of enriched operation, and measurements taken from Georgia Tech's instrumented vehicles.

Georgia Tech does not plan to model fuel consumption. Georgia Tech does plan to upgrade their model continuously. The model's modular structure will facilitate future upgrades. [Ref. 19, Ref. 20]

Strengths
Georgia Tech's modular approach to constructing a modal emissions model will allow on-going upgrades. Explicit modeling of enriched, hot-start, and cold-start operation separately from hot-stabilized operation is a strength, as is the inclusion of super-emitter vehicle and heavy-duty vehicle modeling. Emissions data from a number of different sources should allow cross-checking of data validity. Integration of GIS database with model will allow spatial and temporal assignment of vehicle emissions predictions.

Limitations
Georgia Tech's model is still under development, so some limitations may not be apparent at this time. Fuel consumption is not modeled.

Theoretical Challenges
Integrating remotely-sensed emissions measurements, instrumented vehicle data, and EPA dynamometer data, in a consistent manner, will be a challenge. Modeling super-emitter and heavy-duty vehicle emissions as a function of power demand will be a challenge as well.

Logistical Challenges
Determining the exact power level at which enrichment onset occurs using remote sensing will be difficult because each remote sensor can only measure an instant of vehicle emissions. A logistical challenge will be gathering large enough samples of synchronized emissions and driving pattern data to create stochastic models for each operating condition (e.g. cold-start, hot start, enriched, and hot-stabilized) and vehicle type (e.g. normal emitter, high-emitter and heavy duty vehicle).

LINCOLN LABORATORY, MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Model
Vehicle Emissions Model (Module of MIT ITS Traffic Simulator)

Lincoln Laboratory will be modeling modal emissions of CO as part of a larger simulation of the Boston Central Artery project. Lincoln Laboratory is planning to model CO concentrations in the underground portion of the Boston Central Artery. Hot-stabilized tailpipe CO emissions will be modeled as a function of vehicle instantaneous speed, with additional emissions factors to account for the effect of road-grade, acceleration, and enriched operation.

The Vehicle Emissions Model will be integrated with MIT ITS Traffic Simulator, which is a microscopic traffic simulation for tunnels and roadways. The MIT ITS Traffic Simulation will provide individual vehicle movements, in terms of second by second velocity, turning movements and lane changes, as input to the Vehicle Emissions Model. The traffic simulation will also provide road-grade, ambient conditions, and vehicle fleet distribution to the emissions model. The MIT ITS Traffic Simulator contains a tunnel airflow and ventilation model, and a CO dispersion model.

Second by second tailpipe CO emissions from light-duty gasoline powered vehicles will be modeled. Base emissions rates will be a function of instantaneous speed and will be taken from the EPA's MOBILE5 emissions model, with emissions multipliers to account for acceleration and enriched operation. The enrichment threshold will be defined at a power level that is a function of vehicle class and model year. The acceleration factor will be a function of estimated power demand. The Vehicle Emissions Model will estimate vehicle power demand based on vehicle velocity, acceleration and road-grade. Emissions for a particular vehicle will also be multiplied by a high-emitter factor if the vehicle is identified as a high-emitter. [Ref. 21]

Strengths
Emissions model is integrated with a microscopic traffic simulation which provides second by second drive pattern to emissions model, and also assigns spatial coordinates to emissions. Enriched operation is explicitly modeled. High-emitter vehicles are modeled.

Limitations
HC and NO_x emissions are not modeled. Fleet coverage is presently limited to light-duty cars and trucks. Vehicle representation is only in terms of vehicle class and model year. Fuel consumption is not modeled at this time. Model is still under development.

Theoretical Challenges
Deriving factors to relate MOBILE trip-based emission rates to vehicle emission rates based on instantaneous speed. Deriving realistic multipliers on MOBILE emissions rates for the representation of acceleration, enriched operation and high-emitter operation. Defining a realistic power level for enrichment onset.

Logistical Challenges
Procuring data on enrichment threshold and enriched operation emissions for the modeled fleet. Procuring data that quantifies high-emitter emissions.

LOS ALAMOS NATIONAL LABORATORY

Model
TRANSIMS (Emissions Module)

The TRANSIMS emissions module will be part of an integrated traffic and emissions model. TRANSIMS will contain a large-scale microscopic traffic simulation, which will provide the emissions module with individual vehicle movements in terms of second by second velocity-trace, turning movements and lane changes. Driving pattern may be generalized for certain facilities and intersections to reduce the overall number of calculations, but the parameters describing driving pattern in these cases have not been defined.

It is planned that the TRANSIMS emissions module will provide second by second driving pattern data to a model based on Sierra Research's VEHSIM/VEHSIME model. The output will be second by second tailpipe emissions of CO, HCs and NOX. For more details on the operation of VEHSIM/VEHSIME, see the entry in this section for ***Sierra Research***.

Coverage will be limited to light-duty gasoline automobiles and trucks. Fuel consumption is not included at this time but may be added as the program progresses. [Ref. 22]

Strengths
Detailed large-scale model will individually simulate a large number of vehicles, allowing the input of detailed fleet characteristics. Microscopic emissions and fuel consumption results can be examined for individual vehicles or aggregated to any level of analysis, up to complete system parameters (e.g. Vehicle Miles Traveled).

Limitations
Preliminary stage of long-term project (5-years). Fuel consumption is not modeled. The emissions module will be limited to modeling the 29 light-duty vehicles contained in the VEHSIM/VEHSIME database.

Theoretical Challenges
How to represent the variety of the on-road fleet, both in terms of driving behavior, and emissions and fuel consumption characteristics.

Logistical Challenges
Because every vehicle is modeled individually, the fleet description will be very large. Computational requirements for TRANSIMS will also be very large. Procuring emissions models and/or emissions data to allow expansion of the emissions modeling capability beyond the 29 vehicles represented by VEHSIM/VEHSIME will be a challenge.

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Model
Not named yet

The National Cooperative Highway Research Program (NCHRP) is sponsoring a three year program to develop a modal emissions model. The NCHRP program is a very early stage of development, and the only published description of the final model planned is in the form of the Request For Proposal (RFP) issued by the NCHRP in late 1994. The development contract was recently awarded to the College of Engineering, Center for Environmental Research and Technology (CE-CERT) at the University of California in Riverside. See the entry under University of California, Riverside's for details on current modal modeling activity by that organization.

The NCHRP has specified that vehicle emissions will be modeled such that they reflect any sensitivity to changes in vehicle driving pattern. NCHRP has also specified that the resultant model must cover the full range of vehicle operations, and specifically include enriched engine operation. Model may also include an interface that will allow integration with various travel and traffic models.

The NCHRP RFP specified coverage of light-duty vehicles, reflecting current and near-term technologies. In-use vehicle driving patterns will be quantified, and used to establish a dynamometer testing procedure that is representative of typical vehicle operation. The NCHRP has also specified that 300 in-use vehicles will have their emissions measured. The 300 vehicles are to be selected from three different sites.

The NCHRP has specified that the resultant model will be validated through comparison of emissions measurements from instrumented vehicles driving on-road, and model predictions. It is unclear if modal fuel consumption will be included in the model. [Ref. 23]

Strengths
RFP (Request For Proposal) drafted by panel with a broad range of modal modeling interests, and from several potential user organizations. This should result in a proposal and product that is a flexible tool, with a wide range of applications.

Limitations
Development risk at this early stage of the project. Operational model will not be available for several years: prototype is scheduled for completion in late 1996, with an operational model available during 1998.

Theoretical Challenges
Methodology has not been defined yet, so entire model is a challenge at this early stage.

Logistical Challenges
The NCHRP RFP specifies a large vehicle database of 300 on-road vehicles which are to be tested at three separate locations.

OAK RIDGE NATIONAL LABORATORY

Model

Not named yet (Enhancement to TRAF-NETSIM)

Oak Ridge National Laboratory (ORNL) is developing a modal emissions model based on the existing TRAF-NETSIM microscopic traffic model. TRAF-NETSIM currently can predict modal emissions and fuel consumption rates for a limited fleet of light-duty vehicles. ORNL is planning to expand the emissions and fuel consumption modeling capabilities of TRAF-NETSIM to be representative of the on-road fleet of light-duty vehicles, and to cover the full range of vehicle operation in terms of vehicle velocity and acceleration. ORNL only plans to model the emissions and fuel consumption of hot-stabilized, well-functioning vehicles.

TRAF-NETSIM predicts second by second emissions and fuel consumption rates as a function of each modeled vehicle's second by second velocity and acceleration. TRAF-NETSIM is currently limited to a database from a small fleet of vehicles tested by ORNL in 1984. The database contains emissions data from 6 vehicles and fuel consumption data for 15 vehicles.

ORNL has subcontracted the University of Michigan to develop simplified emissions and fuel consumption relationships, and to identify what vehicle parameters determine an individual vehicle's emissions and fuel consumption characteristics. For details on University of Michigan's work, see the entry under ***University of Michigan*** in this section.

ORNL will record extensive emissions and fuel consumption data from a single test car, both on-road and on a dynamometer. ORNL's test vehicle is equipped with a programmable engine control unit (ECU), which allows for control of the engine's air-fuel ratio. There is hope that this will complement the University of Michigan effort to model emissions, which also involves air-fuel ratio.

Ultimately, ORNL plans to develop conceptual vehicle and emissions models to identify the parameters that will allow extrapolation from a group of 15 to 20 test vehicles to the on-road fleet with the minimum number of measurements. It is planned that the emissions and fuel consumption predictions will be in the form of tables that will be compatible with the TRAF-NETSIM traffic model. [Ref. 24, Ref. 36]

Strengths

Access to test-vehicle with fully reprogrammable engine control should allow extensive control over experimental conditions. This should help with the development of a generalized emissions and fuel consumption model that can be expanded to model a vehicle fleet.

Limitations
This project is still in early stages of data gathering. As currently envisioned, TRAF-NETSIM will still require vehicle specific modal emissions and fuel consumption tables, even if additional tables are generated with a minimum of vehicle testing.

Theoretical Challenges
Identification of measurable parameters that will allow expansion of modeling capabilities from a small fleet to a large representative fleet, with minimum additional testing.

Logistical Challenges
Data collection from instrumented vehicles and dynamometers, with time-synchronized parameters. Recruiting vehicles for fleet representation, even if testing requirements are minimal.

QUEEN'S UNIVERSITY, KINGSTON, ONTARIO, CANADA

Model
INTEGRATION (Emissions and Fuel Consumption Models)

Queen's University has developed a model which predicts tailpipe emissions of CO, HCs and NO_x as a function of vehicle fuel consumption and vehicle speed. The emissions and fuel consumption models are integrated with a traffic simulation, as part of the INTEGRATION model. The traffic simulation portion of INTEGRATION provides the emissions module with vehicle movements. Fleet coverage can be expanded to model the emissions of any gasoline-fueled, light-duty vehicle for which the EPA fuel economy ratings are known.

For the purpose of predicting vehicle fuel consumption, INTEGRATION divides driving pattern into three modes, which are constant speed cruise, velocity change, and idle. For a given vehicle, fuel consumption rate (liters/hour) is modeled as a function of speed for cruise segments, initial and final speed for velocity changes, and as a constant during idle. The effect of cold-start operation, hot-start operation, and ambient temperature are modeled by correction factors applied to the fuel consumption rates calculated above.

Queen's University developed the INTEGRATION fuel consumption model from empirical data taken from tests of a 1992 Oldsmobile Toronado. The tested vehicle was part of the 1992 TravTek IVHS operational test in Orlando, Florida. The base fuel consumption rates developed from the Oldsmobile data were corrected to model the fuel consumption rates of other vehicles, based on the relative EPA city and highway fuel economy ratings of those vehicles versus the 1992 Oldsmobile.

Queen's University correlated the fuel consumption of the 1992 Oldsmobile at average speeds of 0 mph, 19.6 mph and 55 mph to the MOBILE5A tailpipe emissions predictions for the same speeds. The MOBILE emissions predictions used were for all 1992 gasoline fueled passenger cars. Through curve-fitting, three curves of grams CO, HCs and NO_x emissions per gram of fuel used versus average speed were derived. These three emissions curves are applied to modeling the emissions of all vehicles modeled within the INTEGRATION model. For a further description of the MOBILE emissions model, see the section titled ***Modal Emissions and Fuel Consumption Models***.

INTEGRATION differentiates between vehicle models (e.g. Honda Civic versus Oldsmobile Tornado) in predicting fuel consumption, but the emissions to fuel-use relationships are not sensitive to the individual vehicle model. As was stated earlier, INTEGRATION contains emissions and fuel consumption models that are integrated with a traffic model. [Ref. 25]

Strengths

This model is operational. This model could yield relative emissions and fuel consumption estimates for scenarios in which vehicle drive patterns do not vary greatly from the drive cycles used in the derivation of the MOBILE speed correction factors. A possible application would be modeling the relative emissions for changes in large-scale driving patterns.

Limitations

Emissions rates as a function of fuel use are calculated from vehicle specific fuel consumption estimates and fleet average emissions, making the resultant gram per gram rates highly dependent on the baseline vehicle that is selected. Vehicle emissions appear to be calculated on a per cycle basis, not a second by second basis. This would prevent accurate spatial and temporal assignment of emissions, especially for smaller-scale scenarios, such as on-ramps or intersections. Similarly, enrichment is not explicitly modeled, and cannot be accurately assigned spatially and temporally. The effect of road-grade on emissions is not modeled.

Theoretical Challenges

For the fuel consumption model, extrapolating from sparse fuel economy data to a modal fuel consumption model should be verified by testing a number of vehicles. Vehicle specific emissions data should be compared to vehicle specific fuel consumption data to derive a more rigorous relationship between fuel use and tailpipe emissions.

Logistical Challenges

A number of vehicles should be tested to measure fuel consumption as a function of driving pattern. The fuel consumption and emissions models should be validated against data gathered from several test vehicles.

SIERRA RESEARCH

Model
VEHSIM/VEHSIME

Sierra Research has developed a modal emissions model named VEHSIM/VEHSIME, which, like the EPA's VEHSIM/VEMISS model, is based on the VEHSIM vehicle simulation. VEHSIM was developed during the 1970's by the Department of Transportation's Volpe Center, as a detailed vehicle model that could estimate fuel consumption as a function of vehicle driving pattern. Sierra Research developed the VEHSIME component to add an emissions prediction capability to VEHSIM. The VEHSIM/VEHSIME model requires input in the form of second by second velocity for an individual vehicle. The output is second by second tailpipe emissions of CO, HCs and NO_X, along with second by second fuel consumption.

VEHSIM calculates the forces acting on the modeled vehicle from road friction, aerodynamic drag, acceleration, and road grade. The resultant force and the vehicle velocity are used to compute the torque and rotational speed of the wheels. The model then computes the changes in torque and rotational speed across the driven axle, gear box and torque converter, using a transmission shift-logic model, to obtain engine speed and torque.

VEHSIME in turn, calculates tailpipe emissions and fuel consumption from mapped data that are a function of engine speed and torque (see Fig. 4, ***Background***). The engine maps contain engine-out and tailpipe emission rates, and fuel consumption rates, for specific vehicles. The engine maps contain steady-state data for 31 new light-duty cars and trucks: 29 of these are model year 1990 through 1992 vehicles, and the remaining two are 1977 model year passenger cars.

All the data was recorded by vehicle manufacturers during chassis dynamometer tests. Sierra research received engine maps for 29 of the vehicles from the US-EPA (see **US-EPA**). Sierra Research received the engine maps for the two 1977 vehicles directly from General Motors. [Ref. 26, Ref. 14]

Strengths
The model is operational. Vehicle simulation is a detailed model, and reliably predicts engine load as a function of vehicle driving pattern.

Limitations
EPA emissions maps may not be accurate, and may not cover the full operating range of the vehicles for which maps are included. Emissions and fuel consumption predictions are limited to 31 light-duty vehicles for which emissions and fuel consumption maps are available.

Theoretical Challenges
How to expand fleet coverage, other than procuring or generating more vehicle-specific engine maps.

Logistical Challenges
Procuring accurate and sufficient engine map data for a representative fleet of vehicles will be difficult. VEHSIME requires a large amount of vehicle specific data, which in the past has been provided by manufacturers. This data will be even harder to procure for older vehicles.

UNIVERSITY OF CALIFORNIA, DAVIS

Model

DITSEM (Davis Institute of Transportation Studies Emission Model)

This model predicts the total tailpipe emissions of CO over a user-specified vehicle drive cycle. Emissions over the user-specified cycle are predicted based on Federal Test Procedure (FTP) base tailpipe emission rates, and several drive pattern correction formulas. Normal-emitters and high-emitters are modeled by separate formulas.

For a normal emitter, the user-specified drive cycle is described by three modal parameters. The modal parameters are the percent time at idle, the percent time the vehicle is accelerating at a rate greater than 3 mph/sec, and the percent time the vehicle has an acceleration-speed product greater than 60 mph^2/sec.

The modeled vehicle's hot-stabilized emissions rate over the standard Federal Test Procedure is used as a base emissions rate. The base emissions rate is normalized by engine displacement, and then entered into an emissions prediction formula, along with the three modal parameters described above, and a correction for the vehicle model year.

For a high-emitter vehicle, the user-defined drive cycle is described by the percent time idle, and the cycle average speed. A similar formula as for normal-emitters is used with these two drive-cycle parameters to predict tailpipe emissions.

The two formulas were derived through a regression analysis of vehicle tailpipe emissions over a number of dynamometer test cycles. Fourteen test cycles were used in the regression. Thirteen of the cycles were components of the MOBILE5 speed correction test cycle set. One cycle was a high performance test cycle developed by California Air Resources Board, called the Unified cycle. The regression was performed against the total CO emissions for each one of the above cycles, and also included as variables vehicle engine displacement, vehicle inertia, transmission type, and model year.

DITSEM only models tailpipe CO emissions at this time, though it is planned that prediction of HC and NO_X emissions will be added in the future. Fuel consumption is not modeled. [Ref. 27]

Strengths

Emissions estimates are based on FTP emissions tests, which are easily available, cover the majority of the on-road fleet, and are updated annually. The model is operational.

Limitations

Vehicle emissions are on a per cycle basis, not a second by second basis. This may prevent spatial and temporal assignment of emissions, especially for smaller-scale scenarios, such as on-ramps or intersections. Similarly, enrichment is not explicitly modeled, and cannot be accurately assigned spatially and temporally. HCs and NO_X emissions modeling capability still under development. The effect of road-grade on emissions is not modeled. Fuel consumption is not predicted.

Theoretical Challenges

Addition of HC and NO_X emissions modeling. Definition of minimum time-scale that can be accurately modeled by DETSIM, as this will define the spatial and temporal resolution of the emissions prediction.

Logistical Challenges

This model is derived entirely from existing data, so there are no logistical challenges in completing its development. Validation may present some logistical challenges if vehicle emissions testing is required.

UNIVERSITY OF CALIFORNIA, LA

Model
ASBVE (Acceleration/Speed Based Vehicle Emissions)
LSBVE (Load/Speed Based Vehicle Emissions)

University of California, Los Angeles has developed two modal tailpipe emissions models. The ASBVE (Acceleration/Speed Based Vehicle Emissions) model predicts second by second emissions of CO, HCs and NO_X as a function of vehicle speed and vehicle acceleration. The LSBVE (Load/Speed Based Vehicle Emissions) model predicts second by second emissions of CO, HCs and NO_X as a function of vehicle speed and driven -wheel load.

Both models are based on a single test vehicle, a gasoline-fueled 1991 Ford Taurus passenger car. Neither emission model has been expanded to represent other vehicles in the on-road fleet.

Emissions are modeled as a direct function of vehicle velocity and acceleration by the ASBVE model. Emissions are modeled as a direct function of vehicle velocity and driven-wheel load LSBVE model. Both models use look-up tables of CO, HCs and NO_X emissions rates, so there is no calculation of vehicle performance or engine operation involved.

The Ford Taurus test vehicle was instrumented to record second by second vehicle velocity and acceleration, and then driven on a variety of facilities, and in a variety of traffic conditions. The observed driving behavior was used to derive dynamometer test cycles that covered the full range of vehicle operations. Second by second tailpipe emissions were measured for the Ford Taurus over the dynamometer test cycles described above. Equivalent vehicle velocity, driven-wheel load, and equivalent vehicle acceleration were recorded along with emissions during the dynamometer tests.

The second by second emissions rates from the dynamometer tests were then grouped by velocity and acceleration rate for the ASBVE model, and velocity and driven-wheel load for the LSBVE model. This resulted in the look-up tables used in the two models. Fuel consumption is not modeled by either model. [Ref. 28]

Strengths
Both the ASBVE model and the LSBVE model are operational. The ASBVE model could run directly on the output of a typical microscopic traffic simulation, such as TRAF-NETSIM, which specifies individual vehicle second by second velocities and accelerations. The model was calibrated over a well-defined Federal Test Procedure cycle.

Limitations
Both models only represent a single vehicle specific vehicle. It does not appear that either model incorporates road grade into emissions calculations. Fuel consumption is not modeled.

Theoretical Challenges
Expansion of the model to a representative fleet of light-duty vehicles is a major challenge. The effect of road-grade on tsecond by second tailpipe emissions should be incorporated into the load based model, as an additional load, and into the speed based model as an acceleration.

Logistical Challenges
A logistical challenge will be procurement of emissions data in the required format for a representative fleet of vehicles. Extensive dynamometer testing would be required if the same modeling approach is used.

UNIVERSITY OF CALIFORNIA, RIVERSIDE

Model
Not named yet.

University of California, Riverside is developing an integrated traffic and emissions model. At the present stage of development, the U.C., Riverside modal emissions model is integrated with a microscopic traffic model, which in turn is integrated with a macroscopic traffic model. The microscopic traffic model provides the modal emissions model with individual vehicle movements in terms of second by second velocity and acceleration. The macroscopic traffic model contains GIS (Geographic Information System) data for the area of southern California surrounding Riverside. Second by second road grade for each modeled vehicle is passed from the macroscopic traffic simulation to the microscopic traffic simulation.

U.C. Riverside's modal emissions model calculates second by second tailpipe emissions of CO, HCs and NO_X. Emissions are calculated as a function of the estimated second by second vehicle power demand. The vehicle power demand is based on driving pattern and the vehicle's weight, aerodynamic drag coefficient, rolling resistance coefficient, acceleration, velocity, and road grade. Enriched operation and the associated elevated emissions are predicted by U.C., Riverside's model whenever the power demand exceeds a pre-set threshold level. At this time, U.C., Riverside models the emissions of a single type of light-duty vehicle, which is a 1991 Ford Taurus.

U.C., Riverside was recently awarded a three-year development contract under the National Cooperative Highway Research Program (NCHRP) to develop a modal emissions model. For a discussion of the NCHRP development program, see the profile titled ***National Cooperative Highway Research Program.*** As part of the NCHRP contract, U.C., Riverside will be expanding the capabilities of its current modal emissions model to be more representative of the on-road fleet of light duty, gasoline-powered cars and trucks. U.C., Riverside plans to measure the emissions of 300 light-duty vehicles over the next three years. U.C., Riverside also plans to expand the geographic coverage of it's traffic model to include most of greater Los Angeles.

U.C.,Riverside's current model does include any fuel consumption predictions, and it is unclear if this capability will be added in future versions. [Ref. 29, Ref. 30]

Strengths
The integration of U.C.,Riverside's modal vehicle emissions simulation with macroscopic and microscopic traffic models. The model is operational with the

Ford Taurus emissions data. Emissions from enriched vehicle operation are explicitly modeled using a power threshold model.

Limitations

The vehicle model covers only a single vehicle, so fleet modeling must be developed. Fuel consumption is not modeled.

Theoretical Challenges

A generalized emissions modeling methodology that is representative of the on-road fleet will be required for expansion of this simulation from one vehicle to a number of vehicles. Otherwise modeling the modal emissions of a realistic on-road fleet may require extensive dynamometer testing and a large quantity of vehicle specific emissions data.

Logistical Challenges

It will be challenging to procure and dynamometer test 300 light-duty vehicles. Validation of the integrated traffic and emissions models, and interactions between the various levels of modeling, will be difficult.

UNIVERSITY OF MICHIGAN

Model
Not named yet

The University of Michigan is in the process of developing a modal emission prediction methodology. University of Michigan's goal is to derive a methodology for predicting modal emissions that can be expanded to cover a fleet of vehicles without requiring extensive emissions measurement for each vehicle.

University of Michigan plans to model vehicle emissions and fuel consumption as a function of vehicle power demand, vehicle-generic emissions and fuel consumption models, and basic vehicle parameters, such as weight, rolling resistance, aerodynamic drag coefficient and peak horsepower rating.

Specifically, the University of Michigan plans to model engine-out emissions of CO, HCs and NO_X as a function of air-fuel ratio, which in turn will be a function of vehicle power demand. It is planned that a catalyst model will be used to predict tailpipe emissions based on engine-out emissions.

University of Michigan is currently utilizing an emissions dataset provided by the EPA's Certification and Testing Division for the development of emissions models. The dataset contains modal emissions measurements for 30 light-duty cars and trucks from the 1991 and 1992 model years. Second by second tailpipe and engine-out emissions are included for the majority of the vehicles, along with second by second fuel consumption, dynamometer load, engine speed, air/fuel ratio and catalyst effectiveness.

University of Michigan is currently carrying out its emissions modeling development work under contract to Oak Ridge, National Laboratory (ORNL) in support of ORNL's effort to develop a modal emissions and fuel consumption model. See the profile in this section titled ***Oak Ridge, National Laboratory*** for a further description of this effort. The University of Michigan plans to further develop and eventually validate emissions and fuel consumption models through comparisons with ORNL vehicle emissions and fuel consumption test results. [Ref. 31]

Strengths
Simplifying the vehicle, engine and catalyst models down to functions of a few variables would greatly reduce the vehicle specific data needed to model relative emissions and fuel consumption. A generalized emissions and fuel consumption model might also lend itself to modeling the emissions of alternative vehicles or alternatively-fueled vehicles.

Limitations

The emissions and fuel consumption methodology is still under development. The catalyst model to allow derivation of tailpipe emissions from engine-out emissions has also not been developed yet. The University of Michigan's plans do not explicitly call for the development of an executable software package, so the translation of the developed emissions and fuel consumption methodology into an operational model is uncertain.

Theoretical Challenges

Finding the key parameters that control CO-, HC- ,and especially, NO_X-production in gasoline engines, may be difficult, given the variety of engine designs in the fleet. Identifying conveniently measurable parameters that determine emissions and fuel consumption characteristics may be even more challenging. Developing a generalized catalyst model will be difficult, in part due to a lack of reliable catalyst performance data.

Logistical Challenges

Acquiring high quality test data, with all the required parameters, so that theoretical models can be tested and calibrated to real-world cases, will be a logistical challenge.

US-DEPARTMENT OF TRANSPORTATION, VOLPE CENTER

Model
Vehicle/Highway Performance Predictor

The Volpe Center developed the Vehicle/Highway Performance Predictor (V/HPP) model during the 1980's as a means of predicting the fuel consumption and emissions impact of changes to highway geometry and vehicle driving pattern. The model requires input in the form of vehicle velocity versus distance profile, with the corresponding highway geometry in terms of turn radius and grade. The V/HPP model predicts fuel consumption, and CO, CO_2, HC and NO_X tailpipe emissions for an individual vehicle, at a rate of once per modeled distance increment.

The V/HPP model treats each modeled distance increment as a short, constant speed segments, with an average acceleration if there is a velocity change between adjacent segments. The V/HPP model contains relationships between drive-shaft torque, and vehicle speed, acceleration, turn radius, tire type and road grade. Each vehicle type represented in the V/HPP model has a dedicated set of drive-shaft torque relationships. The V/HPP model predicts driveshaft torque for the modeled vehicle, and then predicts fuel consumption, and CO, CO_2, HC and NO_X emissions as a function of drive shaft torque.

The Volpe Center tested three passenger cars equipped with instrumented drive-shafts to derive three sets of drive-shaft torque relationships. The vehicles were tested extensively on-road and at a paved test site. The V/HPP also contains drive-shaft torque relationships for a further ten vehicles, which were derived using the VEHSIM vehicle simulation (see entry for **US - Environmental Protection Agency**).

The Volpe Center also measured CO, CO_2, HC and NO_X emissions for the one of the vehicles with an instrumented drive-shaft, during dynamometer tests. The Volpe Center collected emissions in modal "bags" over repeated accelerations, decelerations and steady speed cruises: for example, tailpipe emissions produced during all accelerations were diverted into a dedicated acceleration collection bag. The V/HPP model contains emissions rates derived from these tests, which are a function of the modeled vehicle's driving mode.

The V/HPP model predicts fuel consumption as a function of drive-shaft torque. The V/HPP fuel consumption model is based on fuel flow-meter and drive-shaft torque measurements for two dynamometer tested vehicles, and on output from the VEHSIM vehicle model. [Ref. 32]

Strengths
Methodology is compact and flexible, and allows for future incorporation of additional modeling capabilities. Modular structure allows updating of components within the same basic program.

Limitations
The model only contains emissions values for a single vehicle, and fuel consumption values for 12 vehicles. Vehicle emissions were collected by mode, rather than recorded as second by second values, so the emissions cannot be correlated to instantaneous power or drive-shaft torque levels.

Theoretical Challenges
Adequacy of modeling emissions as a function of drive-shaft torque alone must be evaluated. Emissions as a function of driveshaft torque assumes that the engine operates along a single torque/engine-speed curve, an assumption which may miss extreme engine operating points that lead to enrichment. The viability of using a the VEHSIM vehicle simulation to expand the emissions and fuel consumption database is dependent on the accuracy of VEHSIM, which must be verified.

Logistical Challenges
Every additional vehicle modeled will require vehicle specific emissions and fuel consumption maps, which will require extensive dynamometer measurements of emissions and fuel consumption. Updated emissions and fuel consumption data must include the parameter drive-shaft torque; this parameter is not recorded in most available datasets, such as the recent EPA 30-car dataset.

US-ENVIRONMENTAL PROTECTION AGENCY, CERTIFICATION & TESTING DIVISION

Model
VEHSIM/VEMISS

The US-EPA has developed a modal emissions model named VEHSIM/VEMISS based on a previous vehicle simulation called VEHSIM. VEHSIM was developed during the 1970s by the Department of Transportation's Volpe Center, as a detailed vehicle model that could estimate fuel consumption as a function of vehicle driving pattern. In 1987, US-EPA began development of the VEMISS component to work in conjunction with VEHSIM to add an emissions prediction capability. The development of VEMISS followed in the footsteps of a similar model, named VSIME, which was developed in the late-70s by the Aerospace Corporation, under contract to US-EPA. The VEHSIM/VEMISS model requires input in the form of second by second velocity for an individual vehicle. The output is second by second engine-out and tailpipe emissions of CO, HCs and NO_x, along with second by second fuel consumption. [Ref. 14]

VEHSIM calculates the forces acting on the modeled vehicle from road friction, aerodynamic drag, acceleration, and road grade. The resultant force and the vehicle velocity are used to compute the torque and rotational speed of the wheels. The model then computes the changes in torque and rotational speed across the driven axle, gear box and torque converter, using a transmission shift-logic model, to obtain engine speed and torque.

VEMISS in turn, calculates emissions and fuel consumption from mapped data that are a function of engine speed and torque. The engine maps contain engine-out and tailpipe emission rates, and fuel consumption rates, for specific vehicles. The engine maps contain steady-state data for 29 light-duty cars and trucks, that were teted as new between 1990 and 1992.

Vehicle manufacturers tested the vehicles on chassis dynamometers, and measured second by second engine-out and tailpipe emissions of CO, CO_2, HC, and NO_X , along with engine rpm, manifold absolute pressure, catalyst temperature and vehicle speed. The manufacturers supplied the test data to the US-EPA, who in turn compiled the measurements into 29 vehicle specific emissions and fuel consumption maps.

US-EPA assessments of VEHSIM/VEMISS performance showed that though predictions of engine-out emissions agreed fairly well with test results, tailpipe emissions estimates were inaccurate. US-EPA feels that the tailpipe emissions maps are inaccurate because they may represent unstable emissions because of catalyst transients, and because the maps did not cover a sufficient range of engine speed/load operation. [Ref. 33]

Strengths

The model is operational. Vehicle simulation is a detailed model, and reliably predicts engine load as a function of vehicle driving pattern.

Limitations

EPA emissions maps may not be accurate, and may not cover the full operating range of the vehicles for which maps are included. Emissions and fuel consumption predictions are limited to 29 light-duty vehicles for which emissions and fuel consumption maps are available.

Theoretical Challenges

Developing an accurate model of tailpipe emissions as a function of engine-out emissions. How to expand fleet coverage, other than procuring or generating more vehicle-specific engine maps.

Logistical Challenges

Procuring accurate and sufficient engine map data for a representative fleet of vehicles will be difficult. VEMISS requires a large amount of vehicle specific data, which in the past has been provided by manufacturers. This data will be even harder to procure for older vehicles.

Graz University of Technology, Graz, Austria
A model called DGV has been created to forecast the emissions impact of changes in driving pattern and traffic, for the city of Graz. Emissions are modeled as a function of passenger car on-road fleet composition, average speed, road grade and altitude. The passenger car fleet was broken into three categories: non-catalyst gasoline fueled, catalyst gasoline fueled and diesel. Several cars from each category were dynamometer tested over a range of accelerations and velocities intended to cover the range of vehicle operations. Emissions and fuel consumption data was gathered and binned by vehicle category, speed and acceleration. This resulted in three dimensional maps of fuel consumption and HC, CO and NO_X emissions as a function of speed and acceleration for each vehicle category. The maps were for average vehicles in each category, with differences in shift pattern assumed to be averaged out.

The suggested use of the DGV model is for the derivation of emissions factors that are a function facility type, level of use and average speed. These factors would be derived by running the DGV model through a drive cycle that was appropriate to each facility, level of use and speed. The drive cycles could either come from established sources or be derived from instrumented test vehicle data. The emissions factors would be used with an existing traffic and pollution dispersion model of Graz. Results are discussed, but it is unclear how many of the steps described above were actually completed.

CSIRO, Division of Coal & Energy Technology, Australia
CSIRO has developed a power or load based emissions and fuel consumption model, so that the impact of grade and acceleration can be estimated. The CSIRO model covers gasoline light-duty vehicles, light-duty diesels and heavy-duty diesels. Fuel consumption, HC, CO and NO_X emissions are modeled as linear functions of instantaneous power. For gasoline powered vehicles, a separate cold-start factor is also added to CO and HC emissions when appropriate. The effect of a catalytic converter is also modeled as a set of factors on emissions.

The linear functions of instantaneous power for fuel consumption and emissions are apparently based on previously published research by K. Post and J.H. Kent. There are two catalyst relationships: one for CO and HC emissions, and one for NO_X emissions. The catalyst emissions factor is a function of fuel consumption rate, time from start and age of the vehicle (more or less than two years old). An explicit statement is made in the catalyst discussion that enrichment is <u>not</u> modeled.

A vehicle simulation that uses an average light-duty vehicle and an average heavy-duty vehicle is used to determine the instantaneous power requirements. Validation experiments were carried out by taking air samples near an even, long incline and then using the CALINE emissions dispersion model to back-calculate the average vehicle emissions. [Ref. 34]

VOLPE CENTER CONCLUSIONS AND RECOMMENDATIONS

PROSPECTS FOR MODAL EMISSIONS AND FUEL CONSUMPTION MODELS

There are significant challenges involved with the creation of a comprehensive modal emissions and fuel consumption model. Challenges exist in both methodology development and data gathering. After reviewing the state of the practice in emissions and fuel consumption modeling, it is the Volpe Center's conclusion that there are no modal emissions and fuel consumption models operational and available that will fulfill all the modeling needs of the FHWA's ITS Joint Program Office. However, there are some promising modal models under development, and some of the existing models may prove useful for less demanding modal modeling applications.

The user must recognize the limitations of a given model, and to keep the modeling task within these limitations. Simplified modal models can be valuable for doing sensitivity analyses and other less detailed studies until more comprehensive models are developed. For example, emissions and fuel consumption models that are sensitive to changes in driving pattern, but aren't complete in terms of fleet coverage, could still provide valuable insight.

Many of the organizations profiled in this document are making practical compromises in their modeling efforts. The methodology described within this document for evaluating models as a number of descriptive components and functional modules should act as a framework for consistently identifying and evaluating what simplifications and modeling compromises have been made in a given model. This will help the model user recognize the limitations and appropriate uses of a given model. Evaluating a model as a number of components will also allow model developers to recognize modeling methodologies and data within existing models that can be valuable as components of future emissions and fuel consumption models.

We have identified a number of recommended focus areas for further development that enable the achievement of the FHWA's modal modeling goals and improve the state of the practice in modal emissions and fuel consumption modeling. The recommendations are based on the Volpe Center's assessment of the state of the practice in modal emissions and fuel consumption modeling, and interviews and discussions with model developers and potential users. The Volpe Center's recommendations are categorized as involving either institutional or technical issues.

FOCUS AREAS FOR FURTHER DEVELOPMENT - INSTITUTIONAL ISSUES

The following recommendations address the institutional issues of how and why modal models should be applied to the evaluation of ITS. The topics that should be focused on by modal model developers include the acceptance of modal models by users, the applications that models should be designed for, the relationship between modal models and established non-modal models, and the portion of the vehicle fleet that modal models should attempt to cover.

Acceptance of Modal Models

There is a need for developers and public agencies to publicize the need for modal emissions and fuel consumption models. With respect to the evaluation of ITS programs, modal models are needed because current emissions inventory models, such as MOBILE and EMFAC, are insensitive to changes in vehicle driving patterns that may be caused by ITS implementation. Changes in vehicle driving pattern can have a significant impact on overall automobile emissions.

Acceptance of modal models will also be improved if development efforts include input from potential users. This will ensure that the resulting model reflects the needs of potential users.

Integrated Application of Modal Models and Travel, Traffic and Air Quality Models

There are a number of uses for stand-alone modal emissions and fuel consumption models. However, the evaluation of most ITS user-services will require modal models that are integrated with traffic and travel models. With the exception of Automated Highway Systems (AHS), ITS user services will indirectly affect driving pattern. For a listing of ITS user services, see the ***Modal Emissions and Fuel Consumption*** section.

Modal models should be developed such that their emissions and fuel consumption predictions can be integrated with traffic, travel, and air-quality models. This will maximize the utility of modal models and encourage their use.

Regulatory Requirements and Modal Models

MOBILE and EMFAC emissions models are currently widely used to establish compliance with regulatory requirements and will most likely continue to be used in this capacity. Users will want to know relationship between emissions predictions based on modal models and those based on these established models. Users of modal models should be given the option of expressing modal emissions predictions relative to established emissions models.

Extent of Fleet Coverage for Modal Models

Modal emissions and fuel consumption models currently focus on light-duty gasoline-fueled vehicles. Heavy-duty vehicles, such as trucks and buses are largely ignored in modal modeling, even though they can constitute an important segment of on-road traffic. The Commercial Vehicle Operations (CVO) bundle of ITS user services specifically addresses commercial vehicles, including heavy-duty vehicles, such as fleet delivery vehicles and tractor-trailer combinations. Commercial vehicles are likely candidates for ITS user services, such as on-board navigation and electronic tolling. For complete coverage of the on-road fleet, modal models should eventually include medium- and heavy-duty vehicles, along with the commonly modeled light-duty vehicles.

FOCUS AREAS FOR FURTHER DEVELOPMENT - TECHNICAL ISSUES

The Volpe Center identified focus areas for technical development through critiques of existing modal emissions and fuel consumption models and as a result of feedback from a April 1994 technical summit at the Volpe Center. Notes from the technical summit are included in the Appendix. The state of the practice in modal emissions and fuel consumption modeling exhibits deficiencies in both methodology development and empirical data. Progress in the following areas is necessary if a flexible and relatively comprehensive modal emissions and fuel consumption model for gasoline fueled light-duty vehicles is to be developed.

Catalyst Modeling

US-EPA and Sierra Research have had a fair amount of success in modeling engine-out emissions (see ***Current Modeling Efforts***). Accurate tailpipe emission predictions have remained a challenge. Modeling catalyst operation may improve modeling of tailpipe emissions.[Ref. 14] Catalyst reduction can vary by nearly two orders of magnitude, and as a consequence, tailpipe emissions can vary just as much due to variations in catalyst effectiveness.[Ref. 1]

Changes in catalyst effectiveness can lag behind changes in vehicle operation due oxygen storage in the catalyst. Catalyst lag can be roughly 1 to 2 seconds, which is on the same time-scale as some modal driving events. Catalyst lag could be an important effect in the modeling of second by second tailpipe emissions, and relating these emissions to second by second driving patterns. [Ref. 6]

The Volpe Center recommends dedicated tests of catalyst conversion effectiveness, with measurements of both steady-state and time-dependent catalyst effectiveness. Whenever possible, vehicle emission measurements should include engine-out and tailpipe emissions measurements.

NO_X Emissions Modeling

CO and HC emissions modeling are relatively mature compared to NO_X modeling. Both engine-out and tailpipe emissions of nitrogen-oxide compounds do not follow the same trends as emissions of CO and HCs.[Ref. 35] Similarly, modeling of catalytic reduction of NO_X emissions is not as advanced as similar efforts for CO and HCs. The Volpe Center recommends the detailed testing of engines and exhaust systems to better characterize the effects of engine operation on engine-out and tailpipe NO_X emissions.

Fleet Representation
A number of modal emissions models exist which calculate the emissions of a individual, specific vehicles. These models base their emissions and fuel consumption estimates on vehicle-specific empirical data, and are limited to the modeling of vehicles for which the proper data is available. These modal models do not capture the variation present in the on-road fleet. Modeling the emissions and fuel consumption of realistic on-road fleet, or even a vehicle class (e.g. light-duty gasoline vehicles), will require a huge amount of vehicle specific information if each vehicle is modeled in detail. An attempt should be made to develop alternative fleet modeling techniques that are more generic in nature, and minimize the amount of vehicle testing required for representation of additional vehicles.

Linkage Between Emissions and Traffic Models
Linkage between modal emissions and fuel consumption models and large-scale traffic models will allow the use of modal models in the evaluation of large-scale programs, such as ITS deployment. Most large-scale traffic simulations are currently limited to modeling large scale traffic parameters, such as traffic flow rates and average speeds, and do not model vehicle driving patterns. Prediction of modal emissions and fuel consumption requires that vehicle driving pattern be defined or modeled in some manner.

One approach is to integrate a microscopic traffic model with a macroscopic traffic model, and in turn link the microscopic model to a modal model. An alternative approach is to use modal emissions and fuel consumption models to create tabulated emissions and fuel consumption rates that incorporate modal results, but are expressed as functions of macroscopic traffic parameters. This is similar to the approach being used by the Volpe Center in the ITS Benefits Assessment Framework, which is described in section, ***Modal Emissions and Fuel Consumption Models***. Another alternative is to use large-scale but microscopic traffic models. This is the approach that Los Alamos National Laboratory is pursuing with their TRANSIMS model, which is described in the section, ***Current Model Development Efforts***.

Validation and Credibility
Models require validation and calibration in order to be useful. Modal emissions and fuel consumption models are no exception. Modal models pose serious validation challenges because of their complexity.

Individual vehicles can be evaluated on a dynamometer and the emissions and fuel consumption measurements compared to predictions for individual vehicles. However, representation of real-world vehicle fleets requires the inclusion of a large variety of in-use vehicle types and a wide range of vehicle operation, which might be logistically impossible to test on dynamometers. Validation of integrated traffic, emissions and fuel consumption simulations can be further complicated by the interactions between the various levels of modeling. It may be impractical to validate integrated modal emissions and traffic models through controlled experiments, because of the large physical scale.

Development of validation techniques for modal models will require progress in both methodology and data collection. It may be possible to use newer technologies such as instrumented vehicles, the global positioning system (GPS), and remote emissions measurement, along with established techniques, such as tunnel studies and air quality measurements, to piece together validations of modal models.

NOTES FROM APRIL 1994 MODAL EMISSIONS TECHNICAL SUMMIT AT THE VOLPE CENTER

A meeting to discuss modal emissions and fuel consumption modeling was held at the D.O.T.'s Volpe Center on April 25th, 1994, and representatives from a number of the organizations included in this report participated. The discussions centered on emissions modeling, with limited discussion of fuel consumption modeling. Where possible, discussions and comments have been attributed to the appropriate meeting attendee. In the case of roundtable discussions, major points are listed by the participants coolectively. Modal emissions modeling issues discussed during the meeting can be grouped into six major topics:

- Engine Performance as a Function of Driving Behavior
- Fleet Representation
- Linkage to Traffic Models
- Modal Emissions Modeling
- Data Sources
- Validation and Credibility

Comments and recommendations, extracted from both presentations and round-table discussions, are grouped into these six topics below.

Engine Performance as a Function of Driving Pattern

A number of approaches to modeling engine performance as a function of driving pattern, or vehicle velocity-time profile, were discussed. The approaches discussed can be categorized into three groups:

- Detailed modeling of the vehicle, including the entire drive-train, to deduce engine torque and engine speed.
- Simplified modeling of vehicle with many parameters are generalized to fit a group or type of vehicle.
- Estimate vehicle power requirements based on rolling and aerodynamic losses, vehicle mass, and vehicle driving pattern. Enrichment threshold defined by a percentage of vehicle maximum power; above which enriched operation is assumed.

DOT Volpe Center

Herb Gould of the DOT's Volpe Center spoke on the VEHSIM vehicle performance model. It was stated that VEHSIM is a reliable tool for calculating engine load and RPM as a function of drive cycle, if all vehicle specific parameters (e.g., shift logic, air/fuel ratio, gear ratios, rolling resistance) are available. Input data should not be that hard to procure - with the possible exception of shift logic. Certification data and automobile publications are both possible sources.

Sierra Research

Larry Caretto of Sierra Research spoke about Sierra's VEHSIME model. VEHSIME was developed from the VEHSIM vehicle model. VEHSIM was developed at the Volpe Center during the late-70's, and has the capability to estimate fuel usage. VEHSIME has the added capability to estimate second by second emissions. VEHSIME is designed to simulate vehicle operation from component data, and requires a great deal of vehicle specific input data, including:

- vehicle speed profile
- vehicle specific drive-train parameters
- vehicle specific engine fuel consumption and emissions maps
- road grade and winds

University of Michigan

Professor Marc Ross of the University of Michigan suggested using less specific automobile data to model vehicle and engine performance. By using linearized relationships for vehicle fuel consumption and emissions production, the number of parameters needed to describe vehicle performance could be reduced substantially. As an example, Professor Ross described a fuel-use model that is a function of just three variables: engine displacement, final gear ratio and vehicle weight. If the relationships can derived for a small fleet, then only a limited amount of additional data would required for additional vehicles.

Georgia Institute of Technology

Peter Groblicki discussed Georgia Tech's methodology for modeling vehicle performance and relating it to remotely sensed emissions data. Georgia Tech characterizes vehicle performance in terms of vehicle power demand as part of an effort to establish an enriched engine operation threshold.

Georgia Tech uses remote sensing is used to record vehicle velocity, tailpipe emissions and license plate number. Vehicle registration data is accessed using the license plate number, which in turn leads to the vehicle model, year and EPA certification data, such as vehicle weight, rated horsepower and 55-mph power requirement.

Enrichment onset is estimated using remote sensing data: if CO emissions jump sharply for an observed vehicle, enriched operation is assumed. Engine power demand during enrichment is calculated from the vehicle's measured acceleration and velocity, and certification weight. Power demand is put in the form of percentage of rated horsepower. Instrumented vehicles have also been tested, in order to further characterize driving patterns that lead to enrichment. Georgia

Tech's conclusion is that for light-duty vehicles, operation above 70 percent of rated horsepower generally results in enriched operation.

Fleet Representation

Creating a modal model that reflects the emissions and fuel consumption characteristics of a vehicle fleet, as opposed to a single vehicle, is quite a challenge because of the huge variety of vehicles that constitute the on-road. Some suggestions included:

- Test enough vehicles to represent on-road fleet.
- Use a generic formula to model the entire fleet, with variable parameters to model different types of vehicles.
- Use EPA and CARB vehicle certification databases
- Base representative fleet on vehicle distribution built into MOBILE and EMFAC emissions models.

Georgia Institute of Technology

Georgia Tech has remotely-sensed emissions and driving behavior data for a very large sample of vehicles; several thousand at this point. The ability to sample a large number of vehicles is an advantage of remotely sensed measurements over dynamometer measurements. As was described earlier, Georgia Tech uses the EPA certification database containing weight, displacement, horsepower, and 55 mph power requirement data, to fill out its modeling. Georgia Tech did screen all remotely sensed data for high-emitters, as it is felt that these vehicles should be dealt with separately.

Sierra Research

Larry Caretto of Sierra Research, stated that using VEHSIM and VEHSIME to model a fleet rather than an individual vehicle is a challenge. If a sizable number of vehicles are to be modeled, then a large amount of vehicle specific data is needed, including emissions and fuel consumption engine maps. John German (EPA) pointed out that even the input data in the current used in the VEHSIM, VEHSIME and VEMISS models is suspect, and also does not cover any older model vehicles.

A possible alternative would be to develop a year-specific "composite vehicle" instead of a representative fleet. This would be created by using VEHSIME to generate a set of fleet-averaged tables of emissions and fuel consumption as a function of vehicle speed and acceleration. A large amount of vehicle data would still be needed, but VEHSIME would only have to be used once to generate the tables.

Oak Ridge National Laboratory

Oak Ridge National Labs will use the approach of developing conceptual models emissions based on EPA 30-car set of automaker data. ORNL palns to extrapolate from a base of well-functioning, hot-stabilized vehicles to a fleet model, based on the above conceptual models. The goal will be to minimize the number of additional vehicle-dependent parameters that need to be measured to extrapolate to a fleet.

General Motors

Peter Groblicki of General Motors has been involved with an attempt to minimize the number of vehicles necessary for representation of a fleet. GM has collected sales data by engine family, and then distributed the engine family by vehicle power to weight ratio. GM has found that 24 engine families make up 2/3rds of the new car sales. Emissions characteristics may follow engine families, so this may be a better way of grouping vehicles for emissions purposes than by vehicle body-style or engine size.

US - Environmental Protection Agency

Light-duty trucks were discussed briefly. Light-duty trucks have emissions characteristics that differ from passenger cars several reasons. John German, EPA, stated that light duty trucks aren't as accurately calibrated, in terms of air/fuel ratio control, as passenger cars, leading to higher CO and HC emissions in many cases. Payload or loading is also a distinguishing characteristic for modeling this fleet segment, as the load can vary from empty to a significant portion of the total vehicle weight. More highly loaded vehicles are more prone to go into enrichment, so payload is significant from an emissions point of view. Modeling the distribution of loading for light-duty trucks may be difficult.

Emissions Modeling

A number of the meeting participants described the approaches being used to model modal emissions, and discussed obstacles they had encountered during their efforts.

Oak Ridge National Laboratory

Ralph McGill restated that ORNL also plans to identify the parameters that will allow extrapolation the emissions characteristics of a small group of test vehicles (approximately fifteen vehicles) to a large group, with the minimum number of measurements.

Georgia Institute of Technology

Peter Groblicki described Georgia Tech's method for modeling vehicle emissions in the Atlanta area. Georgia Tech is concentrating on modeling enriched operation emissions. Georgia Tech's staff feels that emissions during stoichiometric operation are probably relatively predictable and easy to model, but emissions during enriched operations are much more complicated.

Georgia Tech has used an approach for area-wide emissions estimates that attempts to quantify the frequency and duration of enrichment during on-road operation, and then use a time-based factor on top of normal stoichiometric emissions to account for the contribution of enriched operations. Currently, the estimate is that 1 percent of vehicle operation time is spent in enrichment. Some effort has also gone into breaking down enrichment time by facility (e.g., freeway, ramp, arterial).

Sierra Research
Larry Caretto of Sierra Research suggested that improving the engine maps contained in VEMISS and VEHSIME could improve the models' prediction accuracy. The available engine maps for VEHSIME are a major limitation on the accuracy of results. The existing maps might be improved by investigation and "repair", though collection of new map data may be necessary. Current maps consist of steady-state points with no allowance for transient engine or catalyst phenomena; if these effects are included, modeling will improve.

University of Michigan
Marc Ross presented a generalized and simplified methodology based on linearizing as many fuel consumption and emission relationships as possible, by using chemistry and physics to interpret fuel-use and emissions data, rather than statistical analysis. Vehicle fuel use and emissions for a specific vehicle can be reduced to a function of a few parameters, rather than vehicle specific engine maps. Only a limited amount of additional data would required for added vehicles.

Ross' model assumes that given driving pattern, vehicle fuel use is a function of just three variables: engine displacement, final gear ratio and vehicle weight. What is actually being modeled is air/fuel ratio. Calculated air/fuel ratio is used to model engine-out emissions. For properly functioning, hot-stabilized vehicles, the model will have a simplified algorithm for the enrichment scheme. The catalyst effectiveness will be modeled separately from engine emissions, and will function on an "episode" basis for operation during enrichment; to take into account catalyst oxygen storage and timers. Ross' emissions modeling will be based upon a previous CO emissions model, called COMOD.

US - Environmental Protection Agency
John German, of the EPA's Vehicle and Fuel Emissions Laboratory, described the EPA's VEMISS model. VEMISS provides CO, HC and NO_X emissions and fuel consumption, based on engine RPM and load. VEMISS was a follow on to the DOT's VEHSIM, and is very similar to Sierra's VEHSIME. The EPA completed the engine mapping of 29 vehicles for VEMISS; developed a model that would cover vehicle cold-start operation; and updated the VEHSIM parts library.

VEMISS predictions were compared to engine-out and tailpipe emissions for a GM Saturn and a Ford Caravan, over the Federal Test Procedure and CAC(??) drive cycles. The results showed that tailpipe emissions predictions were quite far off but engine-out emissions were closer to the measurements.

As with VEHSIME, VEMISS uses steady-state emissions maps, which are inaccurate for transient events. The steady-state maps assume that the catalyst is working at its ultimate conversion efficiency. Catalysts tend to handle the first second or so of enrichment quite well, whereas steady-state modeling would give a conversion efficiency of near zero. Catalysts also have time-dependencies during other throttle transients.

The EPA hopes to update VEMISS or derive a new emissions model based new data from the automobile industry for thirty new vehicles. This data will be in the form of second by second data, with engine parameters, fuel consumption, engine-out & tailpipe-out emissions included. Modeling of the time dependency of catalyst effectiveness, etc. should be possible, since time-coordination between the various parameters, such as air-fuel ratio and catalyst effectiveness, should be good.

As a final point in his presentation, German pointed out that changes in the Federal Test Procedure will probably precipitate changes in engine control schemes for new cars, making emissions modeling during enrichment more complicated. A new driving cycle for the FTP may go into full effect during 1998.

A round-table discussion of each of the major emissions groups, CO, HCs and NO_X, followed. The major points made by the group were as follows:

Carbon Monoxide (CO)

- Enrichment is the primary concern; stoichiometric emissions are relatively low and easy to model.
- As vehicles get cleaner, and CO levels get lower, accurate CO measurements will become more difficult, and more sensitive to factors besides air/fuel ratio.
- CO emissions from malfunctioning cars are probably not as variable with driving mode as for normally functioning cars. CO emissions from malfunctioning cars can probably be modeled as proportional to fuel consumption.

Hydrocarbons (HCs):

- HC emissions during deceleration are still a problem for in-service vehicles, and are difficult to measure and model.

- Fuel injection's replacement of carburetion has been reducing reducing HC exhaust emission in general.
- Evaporative emissions enroute should also be considered , as they may be significant for very slow traffic, and high ambient temperatures.

Nitrogen Oxygen Compounds (NO_X)

- NO_X emissions more complicated than CO and HC emissions to model, as they are a function of air-fuel ratio, peak cylinder temperatures and oxygen content in the catalyst, and often, but not always, follow opposite trends than do CO and HC emissions.
- Modeling NO_X emissions accurately will be very difficult. Biggest emissions modeling risk without detailed engine maps.
- Relationship to peak cylinder temperature and EGR (exhaust gas recirculation) operation is very strong; these are difficult parameters to model.
- Catalyst conversion efficiency of NO_X more sensitive to air/fuel ratio than CO and HC concersion efficiency.
- A drawback of both VEHSIME and VEMISS is that air/fuel ratio is not used to calculate emissions in either. NO_X emissions are very sensitive to air/fuel ratio (calibration), so air/fuel ratio will have to be accurately modeled to accurately model NO_X.
- Range of vehicle NO_X emissions is less than range for CO and HC emissions (4:1 for NO_X vs. 1000:1 for CO).

Data Sources

Ralph McGill and Peter Groblicki both spoke about sources for the data required for modal emission model development.

Oak Ridge National Laboratory

Ralph McGill described the data collection planned for ORNL's project. Vehicles will be track tested to cover the full range of vehicle operation. Engine operating parameters including engine vacuum as a surrogate for engine torque, vehicle velocity and vehicle acceleration will be recorded. Vehicle operating points will be replicated on a chassis dynamometer, so that high quality emissions, fuel consumption and engine parameters can be recorded. Emissions (HC, CO, CO_2, NO_X and O_2) will be measured simultaneously both before and after the catalytic converter.

Dynamometer data will be supplemented by on-road emissions data to identify enrichment thresholds and other "emissions-confounding factors". Test procedures will be developed using an ORNL test vehicle, which has a reprogrammable engine control unit. This will allow detailed analysis of different control schemes that affect fuel/air ratio and enriched operation. The data will also incorporate the effects of grade and ambient temperature. As a follow-up, ORNL plans to gather modal emissions and fuel consumption data for hot-stabilized operation of a number of vehicles.

Georgia Institute of Technology
Peter Groblicki emphasized that a great deal of data has been collected using remote sensing: vehicle velocity and acceleration data with laser range-finders, and enriched operation emissions with HC and CO sensor systems. As described before, by recording license plate numbers, and using the plate numbers to access registration and certification data, Georgia Tech had estimated vehicle operating power levels and enrichment thresholds. Groblicki also pointed out that the automotive press could be a valuable source for engine and vehicle specifications.

US - Environmental Protection Agency
As an aside, John German pointed out that the values for "certification" or 55 mph horsepower in the certification database can be inconsistent, due tire effects. Rolling resistance on a dynamometer is not directly comparable to rolling resistance on a roadway because of tire distortion caused by the dynamometer's rollers, which serves to increase the rolling resistance.

Linkage to traffic models
ITS programs will often only directly affect macroscopic traffic parameters, such as vehicle miles traveled, or traffic volume on a link. Changes in driving pattern can be indirect effects of chabges in macroscopic traffic. Linkage is needed between large-scale programs, which affect "macro" parameters, and may not affect driving pattern directly, to modal emissions, which are a result of "microscopic" vehicle driving pattern.

Oak Ridge National Laboratory
ORNL is developing a vehicle emissions and fuel consumption model that is to be used with TRAF-NETSIM, and is planning on a number of vehicle emissions and fuel consumption tests in support of this task.

Sierra Research
Larry Caretto of Sierra Research pointed out that accurately predicting the linkage between traffic flow mean speed and traffic simulation data is a problem area in modeling network emissions and fuel consumption. The key problem is the merging of a traffic model with a vehicle/engine simulation model.

Caretto suggested that additional instrumented driving be used to gather emissions in addition to driving data, and that the database be expanded to include metered ramps, high-occupancy vehicle lanes, and driver to driver variation. Also validate speed/accel profile dependency on average speed and facility by focused testing on study area corridor (I-880, in California).

Use VEHSIM/VEHSIME to run a representative fleet over the situation(s)/facilities of interest. Also run the fleet over the FTP to generate a correction/calibration factor. Compare results for different facilities and drive patterns to get relative emissions and fuel consumption.
Facility Specific Speed Correction Cycles - rather than having MOBILE or EMFAC correction factors that are just a function of speed, use different correction drive cycles to generate different facility-type, speed correction factors.

Validation and Credibility
A brief discussion on validation methods for modal emission and fuel consumption models was held, but this is an area that will need more attention in the future.

Oak Ridge National Laboratory
Ralph McGill stated that ORNL planned to compare MOBILE5 emission predictions with emissions predictions by their modal model to demonstrate the relative advantages and disadvantages of the two. Presumably, the comparison would take place over a number of fixed "trips" or drive cycles.

Sierra Research
Larry Caretto of Sierra Research suggested using the large amount of emissions data being gathered by CARB to do a second-by-second comparison with VEHSIM/VEHSIME tailpipe emission predictions.

The attendees at the meeting also had the following suggestions for validating modal models:

- Check model emissions and fuel consumption predictions versus actual data for specific vehicles.
- Perform detailed engine emissions and fuel consumption map check on dynamometer.
- Compare remotely sensed measurements of vehicle emissions to model predictions.
- Compare results of tunnel studies to model predictions.
- Use tracer studies to identify the source of emissions measured in atmospheric samples. Fuel used by vehicles in the study is laced with a tracer substance.

GLOSSARY OF TERMS

catalytic converter - The catalytic converter allows the conversion of exhaust pollutants (e.g. CO, HCs and NO_X) to less harmful gases while the gases are still within the vehicle's exhaust system, and at much lower temperatures than would otherwise be required without the catalyst present.

drive cycle - A fixed drive pattern that is used in vehicle testing and simulation to represent real-world driving behavior and driving patterns in a compressed form. Vehicles are often dynamometer tested for emissions and fuel consumption over standardized drive cycles, such as those contained in the EPA's Federal Test Procedure, for purposes of consistency.

driving mode - Driving mode qualitatively describes a vehicles straight-line movement, taking into account whether or not a vehicle is moving, and if it is, if there is any change in velocity as well. For the purposes of this paper, four driving modes are defined: acceleration, deceleration, cruise and idle.

drive pattern - Vehicle velocity versus time, with sufficient definition to allow identification of the vehicle's driving mode, e.g. acceleration, deceleration, cruise, or idle. Drive patterns can be recorded using instrumented vehicles, or can be generated by microscopic traffic simulations.

driven-wheel load - The sum of the propulsive force exerted by a vehicle's driving wheels, on the roadway. For a four-wheel drive vehicle, the driven-wheel load is divided between all four wheels. Driven-wheel load can be expressed in pounds-force or Newtons.

engine load - The torque produced at an engines output, expressed in foot-pounds or Newton-meters.

engine speed - The rotational speed of an engine's output shaft and/or flywheel, expressed in revolutions per minute, or RPM.

enrichment or enriched operation - An automobile operating condition during which the engine operates with a fuel to air ratio that is higher or "richer" than stoichiometric. Modern vehicles will operate in enrichment under very high power demands or when they are malfunctoning.

operating mode - For a gasoline-powered vehicle, operating mode refers to whether or not the engine and exhaust system are warmed up to a stabilized operating temperature. For purposes of emissions prediction, three operating modes are generally defined: **cold-start, hot-start**, and **hot-stabilized**. Cold-start operation covers vehicle operation after a long shutdown, such that the engine and exhaust are at or near ambient temperature and the catalyst is not efffective, Hot-start , covers operation of a vehicle shortly after a shut-down, such that the engine may still be wam, but the catalyst is not working. Hot-stabilzed operation covers operation with the entire engine and exhaust system warmed up to a stabilized conditio.

road grade - The slope of a roadway in the direction of travel. Road grade is in units of percent, and is calculated as the roadway slope($\Delta y/\Delta x$) times 100 percent.

roadway link - A section of roadway with relatively homogeneous characteristics, such as the number of lanes, signalization, and traffic flow.

shift logic - An algorithm that simulates the shift points of a transmission in an automobile. The gear shifting of an automatic transmission is usually a function of engine speed, engine torque, vehicle speed and throttle position. Modeling the shift logic for a manual transmission requires a simulation of the drivers behavior.

stoichiometric operation - Stoichiometric operation of an automobile implies that the automobile's engine is operating with a stoichiometric fuel/air ratio. A stoichiometric mixture of gasoline and air contains exactly enough oxygen in the air to combust all of the fuel. The stoichiometric fuel/air ratio for gasoline is roughly 1 to 14.6 . Modern automobiles operate at very close to a stoichiometric fuel/air ratio most of the times, for reasons of fuel economy and emissions control.

traffic flow - The number of vehicles passing a particular point, on a particular roadway or section of roadway, such as a lane. Traffic flow is expressed in terms of vehicles per unit time.

vehicle power demand - The power required by a vehicle to meet a particular driving condition. Instantaneous vehicle power demand is calculated as the product of the instantaneous driven wheel load and the instantaneous vehicle velocity, and can be expressed as horsepower or Watts.

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