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Heavy-Duty Diesel Vehicle Modal Emission Model (HDDV-MEM) Volume I: Modal Emission Modeling Framework

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Heavy-Duty Diesel Vehicle Modal Emission Model (HDDV-MEM) Volume I: Modal Emission Modeling Framework

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Abstract

The research reported in this document outlines a proposed heavy-duty Diesel vehicle modal emission modeling framework (HDDV-MEMF) for heavy-duty diesel-powered trucks and buses. The heavy-duty vehicle modal modules being developed under this research effort, although different from the structure within the motor vehicle emissions simulator (MOVES) model, should be compatible with it. In the proposed HDDV-MEMF, emissions from heavy-duty vehicles are predicted as a function of hours of on-road operation at specific engine horsepower loads. Hence, the basic algorithms and matrix calculations in the new heavy-duty diesel vehicle modeling framework should be transferable to MOVES. The specific implementation approach employed by the research team to test the model in Atlanta is somewhat different from other approaches in that an existing geographic information system (GIS) based modeling tool is being adapted to the task. The new model implementation is similar in general structure to the previous modal emission rate model known as the Mobile Assessment System for Urban and Regional Evaluation (MEASURE) model.

Sponsored by the U.S. Environmental Protection Agency, this exploratory framework is designed to be applied to a variety of policy assessments. The model can be used to evaluate policies aimed at reducing the emission rates from heavy-duty vehicles as well as policies designed to change the on-road operating characteristics to reduce emissions.

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Sally Gutierrez, Director
National Risk Management Research Laboratory

EPA Review Notice

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Acronyms

AADT	annual average daily traffic
ahp	axel horsepower
ARB-HDETL	Air Resources Board Heavy Duty Emissions Testing Laboratory
bhp	brake-horsepower
bhp-hr	brake-horsepower hour
CAEC	Cleaire Advanced Emission Controls
CARB	California Air Resources Board
CBD	central business district
CE-CERT	College of Engineering-Center for Environmental Research and Technology (University of California at Riverside)
CFR	Code of Federal Regulations
CIFER	Colorado Institute for Fuels and High Altitude Engine Research
CMDL	Climate Monitoring Diagnostics Laboratory
CO	carbon monoxide
CPC	Climate Prediction Center
DEM	digital elevation model
DOT	Department of Transportation
EDM	electronic distance measurer
EERC	Engine and Emissions Research Center
EMFAC2000	California Air Resource Board's mobile source emissions model
EMFAC2002	California's mobile source emissions model
EMFAC7G	California Air Resource Board's mobile source emissions model
ESRI	Environmental Systems Research Institute, Inc.
FHWA	Federal Highway Administration
ft/s	feet per second
ft/s^2	feet per second squared
FTP	federal test procedure
g/mi	grams per mile
g/s	grams per second
GDOT	Georgia Department of Transportation
GIS	geographic information system
GPS	Global Positioning System
GRTA	Georgia Regional Transportation Authority
GVW	gross vehicle weight
GVWR	gross vehicle weight rating
HC	hydrocarbons
HDDV-MEMF	Heavy-Duty Diesel Vehicle Modal Emission Modeling Framework

Acronyms (continued)

HDDV-MEM	Heavy-Duty Diesel Vehicle Modal Emission Model
HDDVs	heavy-duty diesel vehicles
HDGVs	heavy-duty gasoline vehicles
HDV	heavy-duty vehicle
HHDDVs	heavy heavy-duty diesel vehicles
HPMS	Highway Performance Monitoring System
HSS	Highway Statistics Series
km	kilometer
lbs	pounds
LDT	light-duty truck
LDV	light-duty vehicle
m/s	meters per second
m/s^2	meters per second squared
MARTA	Metropolitan Atlanta Rapid Transit Authority
MEASURE	Mobile Emissions Assessment System for Urban and Regional Evaluation
MHDDV	medium heavy-duty diesel vehicle
MOBILE6	EPA's mobile source emission factor model
MOVES	motor vehicle emission simulator
mph	miles per hour
mph/s	miles per hour per second
MTBE	methyl tertiary butyl ether
MTPT	Multimodal Transportation Planning Tool
NCDC	National Climatic Data Center
NEPA	National Environmental Protection Act
NOAA	National Oceanic and Atmospheric Administration
NO_X	oxides of nitrogen
NREL	National Renewable Energy Laboratory
NVFEL	National Vehicle and Fuel Emissions Laboratory
NYSDEC	New York State Department of Environmental Conservation and Energy
OBD	on-board diagnostic
OTAQ	EPA's Office of Transportation and Air Quality
PART5	EPA's Highway Vehicle Particulate Emission Factor Model
$PM_{2.5}$	particulate matter less than 2.5 µm in aerodynamic diameter
ReFUEL	Renewable Fuels and Lubricants Research Laboratory
rpm	revolutions per minute
SAE	Society of Automotive Engineers
SAFD	speed/acceleration frequency distributions
SIP	State Implementation Plan
TIUS	truck inventory and use survey
U.S. EPA	U.S. Environmental Protection Agency
UDDS	urban dynamometer driving schedule
VIUS	vehicle inventory and use survey

Acronyms (concluded)

VMT	vehicle miles traveled
VOC	volatile organic compounds
WVU	West Virginia University
WVU-EERC	West Virginia University – Engine and Emissions Research Center
ZML	zero-mile level

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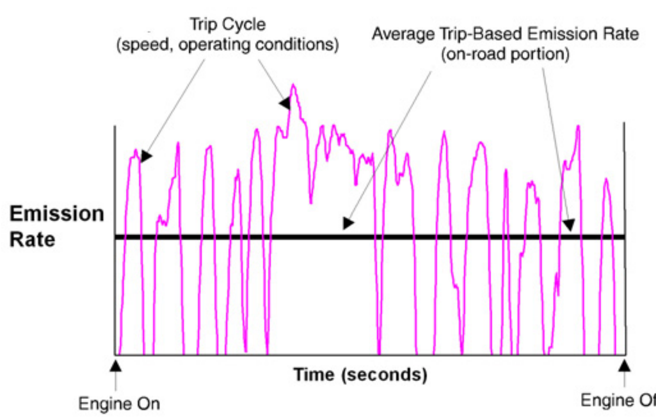
Executive Summary

The research reported in this document outlines a proposed Heavy-Duty Diesel Vehicle Modal Emission Modeling Framework (HDDV-MEMF) for heavy-duty diesel-powered trucks and buses. The heavy-duty vehicle modal modules being developed under this research, although different from the structure within the Motor Vehicle Emissions Simulator (MOVES) model, should be compatible with it. MOVES is the next generation mobile source emissions model being developed by EPA's Office of Transportation and Air Quality (OTAQ) and will replace the current MOBILE vehicle emission factor model. MOBILE is used to calculate current and future emission inventories of hydrocarbons (HC), oxides of nitrogen (NO_X), and carbon monoxide (CO) from passenger cars, motorcycles, light- and heavy-duty trucks at the national and local level. These inventories are used to make decisions about air pollution policy at the local, state, and national level. Inventories based on MOBILE are also used to meet the federal Clean Air Act's State Implementation Plan (SIP) and transportation conformity requirements and are sometimes used to meet requirements of the National Environmental Protection Act (NEPA).

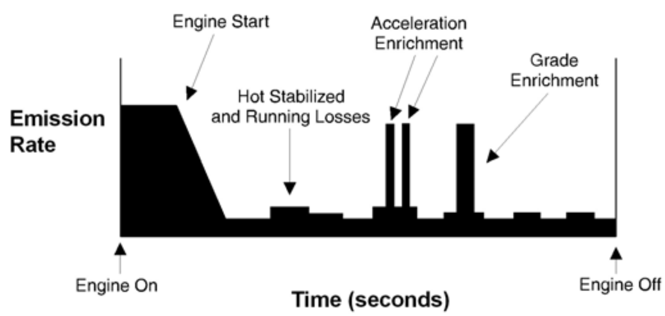
In the proposed HDDV-MEMF, emissions from heavy-duty vehicles are predicted as a function of hours of on-road operation at specific engine horsepower loads. Hence, the basic algorithms and matrix calculations in the new heavy-duty diesel vehicle modeling framework should be transferable to MOVES. The specific implementation approach employed by the research team to test the model in Atlanta is somewhat different in that an existing modeling tool based on a geographic information system (GIS) is being adapted to the task. The new model implementation is similar in general structure to previous modal emission model known as Mobile Assessment System for Urban and Regional Evaluation (MEASURE) model.

Historically EPA's mobile source emission rate model (i.e., MOBILE) has produced emission rate estimates based on average operating characteristics and conditions (i.e., average "trip-based" modeling). Average trip-based modeling refers to the use of average in-use fleet emission factors. These emission factors are developed on the basis of laboratory dynamometer testing that simulates an average vehicle trip. Although different driving cycles have been developed over the years, conceptually dynamometer testing is designed to obtain a "representative sample" of vehicle operations. Appropriate emissions rates are developed and applied to an activity rate such as vehicle-miles traveled to obtain a set of average trip-based emission rates. The first MOBILE model was developed in 1978. The current generation of the model, MOBILE6, was released in 2002 after a lengthy update process. The chart below shows that, even though vehicle speed varies throughout a trip, the emissions are treated as a



constant value with the average trip-based approach.

An additional advantage that the heavy-duty diesel vehicle modal emission model (HDDV-MEM) has over traditional modeling approaches is the implementation of modal modeling. "Modal" refers to the type, or mode, of engine operation that a vehicle may be in at any given point in time. Important vehicle operating modes include engine start, engine idle, hot stabilized operation (on-road operation), enrichment conditions (influenced by high acceleration and power demand), and hot soak evaporation. Appropriate emission rates are developed and applied to the various vehicle modes of operation to obtain a set of modal emissions. The chart below shows a stylistic representation of how emissions could vary by mode for a typical vehicle trip.



Historically, emission rate or emission models have not been implemented in a GIS. This has been due in part to the magnitude of the data required by a GIS, perception and reality of operating GIS software, and the level-of-knowledge required by end-users to manipulate data in a GIS. In the last 10 years, GIS data have become more available in both quantity and quality. Availability of a GIS in a Windows operating system environment, availability of low-cost computer hardware, and the development and implementation of easy to use GIS tools (in a Windows environment) has made implementation of GIS-based emissions models more practical.

Models, such as MOBILE6, do not calculate emissions due to road grade effects—increased emissions due to accelerations going uphill. In addition, spatial resolution of emissions is misrepresented. For example, engine start emissions using earlier modeling regimes did not allocate emissions to the appropriate residential or commercial/industrial locations. Typically, engine starts would be included in the grand total of highway vehicle emissions and would be allocated a given county based on population or some other surrogate. With a GIS, engine start emissions may be calculated and assigned on a sub-county basis using a combination of factors including census block group population, property (parcel) data, trip production/attraction (work, schools, etc.) data.

The use of a GIS-based approach allows for the visualization of such critical phenomena as real-world locations and magnitude of emissions from vehicles during peak commuting hours on major roadways. One of the more difficult highway vehicle emissions modeling questions to answer is how to locate the emissions—where geographically are the emissions coming from? In a large metropolitan area, the highway vehicle emissions occur throughout the city and throughout the day.

There are several key features that make the load-based modeling approach more appropriate for emissions prediction than current emission rate modeling tools:

- Modal models take into account all of the factors in the heavy-duty vehicle operation environment that affect emissions, such as vehicle age, engine type, transmission type, fuel type, on-road driving conditions, and roadway characteristics.
- The statistic methodology approach avoids extrapolation with correction factors beyond ranges under which test data were collected, significantly improving prediction accuracy.
- Modal models are easily verified, calibrated, and improved. Second-by-second vehicle operations can be readily collected in field studies, and new heavy-duty vehicle emission rate monitoring equipment can be deployed to verify instantaneous emission rates. Field test results can be used to calibrate the parameters of the load-based model accordingly.

Phase I of the project has been to develop the modeling concepts and construct a working model. This development effort is described more fully in the body of this report (Volume I and II). Phase II of the project includes: (1) collection of available emission testing data to support proposed load-based emission modeling approaches, (2) development and application of analytical and statistical methods to support the proposed emission modeling approaches, (3) evaluation and refinement of emissions modeling approaches based upon available data, (4) the development of effectively executable model source codes, and (5) model sensitivity analysis through the iterative evaluation of the impacts of structured external data files (with the goal of improving model efficiency without reducing model resolution and predictive capabilities).

Introduction

Heavy-duty vehicles are a major source of pollutant emissions in metropolitan areas. The relative importance of reducing emissions from heavy-duty diesel vehicles (HDDVs) has become critical in solving, for example, Atlanta's air pollution problems. HDDVs constitute a small portion of the fleet but emit a disproportionately large amount of oxides of nitrogen and particulate matter. As light-duty vehicle (LDV) emission rates continue to decline, heavy-duty vehicles (HDVs) are increasingly looked toward as a source for additional emission reductions. Diesel vehicles have also been classified as the largest source of mobile source air toxics.

Emissions from light-duty cars and small trucks have been stringently controlled for many years. Significant research efforts has been conducted to develop models capable of predicting travel demand, on-road vehicle operating conditions, and the emissions generated by these vehicles. Effective control strategies for LDVs have been proposed and implemented through analysis of such detailed research data. However, emission standards for HDDVs have only recently become more stringent, and very little research into the driving activities and patterns, especially in a local area, has been conducted. Therefore, it is difficult to assess the cost-effectiveness of HDV emission reduction strategies.

As it stands today, the emission rate models for HDVs still require significant improvement. Major modeling defects for the heavy-duty components within the U.S. Environmental Protection Agency's (U.S. EPA's) MOBILE models have been widely recognized for more than 10 years (Guensler et al., 1991). The current model used by 49 states and the federal agencies is the MOBILE6 model, developed by the EPA. The release of MOBILE6 contained only marginal improvements to the correction factors employed in the model and has not resolved the fundamental flaws inherent in the modeling approach. Under the current MOBILE6 modeling regime, HDV emissions are essentially predicted as a function of miles traveled and average speed. A major overhaul of the basic modeling approach in the MOBILE6 model is warranted.

Since 2000, the EPA has been developing a new generation mobile source emissions model (motor vehicle emission simulator, MOVES) based on the specific horsepower requirements (horsepower to weight ratio) of vehicles. Specific horsepower is a function of speed, acceleration, and road grade. In general, a vehicle at higher speed, harder acceleration, and steeper road grade requires more specific horsepower for the vehicle to overcome drag forces and to move.

The research reported in this document outlines HDDV-MEMF, a proposed HDDV modal emission modeling framework for heavy-duty diesel-powered trucks and buses. The HDV modal modules being developed under this research, although different from the structure within MOVES, should be compatible with it. In the proposed HDDV-MEMF, emissions from heavy-duty vehicles are predicted as a function of hours of on-road operation at specific engine horsepower loads. Hence, the basic algorithms and matrix calculations in the new heavy-duty diesel vehicle modeling framework should be transferable to MOVES. The specific implementation approach employed by the research team to test the model in Atlanta is somewhat different from other approaches in that an existing GIS-based modeling tool is being adapted to the task. The new model implementation is similar in general structure to the previous modal emission model known as MEASURE (Bachman, et al, 2000; Bachman, 1997).

Sponsored by the EPA, this exploratory framework is designed to be applied to a variety of policy assessments. The model can be used to evaluate policies aimed at reducing emissions from HDVs as well as policies designed to change the on-road operating characteristics to reduce emissions. Once the modeling framework is complete and field tested in Atlanta, the model framework will be applicable to other major metropolitan areas, provided that the required data inputs are assembled for these areas. However, even in the absence of metro-specific data, the default parameters associated with Atlanta can be employed.

Modeling Parameters

Goals and Objectives

The goal of the proposed research is to develop a load-based emission model for on-road heavy-duty diesel trucks and transit vehicles within a GIS framework. The HDDV emissions module will be developed in the same general framework used to develop the MEASURE model (Bachman et al., 2000). Refined HDDV activity estimates will be combined with improved emission rates to produce an HDDV emissions module that can be evaluated for inclusion into the next generation EPA emission model known as MOVES. Thus, both models are expected to be able to more accurately estimate on-road HDDV emissions than current modeling techniques. Once integrated, the improved modeling tools will enable states to develop and implement more effective HDDV emission reduction strategies.

The GIS-based approach provides the ability to spatially and temporally evaluate the criteria pollutant emissions impacts for a variety of freight and transit-oriented policies even when vehicle operating conditions change over time. The model will:

- Operate within a GIS framework, allowing users to evaluate changes in the spatial and temporal distribution of public transit emissions;
- Support alternatives evaluation at the regional as well as microscale levels;
- Allow assessment of the emissions impacts of changes in truck and transit technology purchases (such as vehicle size, engine classification, dedicated fuel type, etc.) and fleet deployment;
- Support evaluation of emissions effects resulting from changes in transit or delivery routes, passenger and freight loading, and operating duty cycles associated with congestion or high speed operations;
- Employ a graphic user interface; and
- Provide transferability to any major urban area in the country.

Pollutants Modeled

The model is designed to directly predict emissions on a load basis for three criteria pollutants: CO, NO_X, and volatile organic compounds (VOCs). Although the model emphasis is on HDDVs and their emissions, heavy-duty gasoline vehicles (HDGVs) are included in the model. For this reason, emissions of benzene, methyl tertiary butyl ether (MTBE), 1,3 butadiene, formaldehyde, acetaldehyde, and acrolein are included in the model. Speciation factors are applied to the VOC emissions to predict emissions of benzene, MTBE, 1,3 butadiene, formaldehyde, acetaldehyde, and acrolein. Although recent research indicates that speciation factors vary as a function of engine load, the data are still too sparse to implement load-related speciation profiles at this time. However, as information continues to improve, load-based speciation factors can be handled by the model. It is simply a matter of creating separate emission rate matrices (gram per second) as a function of brake-horsepower (bhp) load in the calculation methodology rather than applying a uniform speciation faction after VOC emissions are totaled.

Emissions of exhaust particulate matter less than 2.5 µm in aerodynamic diameter ($PM_{2.5}$) are also predicted directly on a load basis, with simple speciation factors applied to the total $PM_{2.5}$ to predict emissions of sulfate, organic carbon, elemental carbon, gaseous PM, and lead. Friction-based $PM_{2.5}$ emissions for tire wear and brake wear are also integrated as a function of miles traveled. As noted with air toxics, separate PM emission rate functions can be implemented for each sub-species as data become available. Separate emission rate matrices (gram per second) as a function of bhp load in the calculation methodology can be developed as new laboratory testing data are made available.

Carbon dioxide emissions are implemented through the integration of brake-specific fuel consumption estimates, with all carbon in the fuel assumed to convert to carbon dioxide. As carbon dioxide emission rates in grams per second become available for analysis, variable emission rates as a function of instantaneous vehicle power demand can be implemented in the Phase II model.

Sulfur dioxide and ammonia (applicable to HDGVs only) emission rate testing results are sparse. As such, implementation of modal algorithms will not likely occur in Phase I modeling. Available gram per brake-horsepower-hour emission rates will be collected from the literature and applied.

Modeling Approach

The proposed model for predicting transit emission is designed for transportation infrastructure implementation on a link-by-link basis. Although the modeling routines are actually amenable to implementation on a vehicle-by-vehicle basis, the large number of vehicles operating on infrastructure links precludes practical application of the model in this manner. As such, the model framework capitalizes upon previous experience gained in development of the MEASURE modeling framework in which vehicle technology groups were employed. However, whereas the MEASURE model employed load surrogates for the implementation of a light-duty modal modeling regime, this new modeling framework directly predicts heavy-duty vehicle operating loads and uses these load predictions directly in the emission prediction process.

Vehicle technology groups are employed more extensively in the HDDV-MEMF than they were in MEASURE. In MEASURE, technology groups were relatively independent of vehicle configuration and based solely upon baseline laboratory emission test results. That is, groups of vehicles that behaved similarly to each other on the baseline tests, and responded similarly to alternative tests, were grouped together into a vehicle technology. In the heavy-duty vehicle world, drive train (engine, transmission, differential, and tires) design, truck and trailer physical configuration, and the cargo loads that they carry all affect on-road operating loads. Hence, in the HDDV-MEMF, technology groups must relate to the subfleet composition (measurable on-road vehicle classifications), the drive train characteristics, as well as the performance of the various engine classes in laboratory testing. This type of model is known as a modal model because it directly predicts second-by-second emissions from any on-road driving mode.

For each technology group, the model predicts engine power demand in response to inertial load, grade load, road friction, accessory load (e.g., air conditioning usage), given the distributions of second-by-second operating modes for the on-road vehicles. Such on-road activity can be developed through empirical observation, using laser guns or instrumented fleets, collecting such data on a second-by-second basis.

Emissions rates for each engine and vehicle family (engine manufacturer, displacement, certification family, drivetrain, fuel delivery system, emission control system) are first established in grams per brake-horsepower hour (from standard engine dynamometer certification data or from on-road emission rate data when available). Basic engine power equations are employed to predict engine load (brake-horsepower) for every second of operation (brake-horsepower-sec) as a function of environmental and operating conditions for the specific vehicle technology. Emissions are then determined by integrating predicted emissions over time (grams per brake-horsepower-hour multiplied by brake-horsepower-hour). This research will include initial model development and supplemental data collection (Phase I) and ongoing data collection, model refinement, calibration, and testing (Phase II). The project will culminate in the application of the modeling system to a case study in Atlanta, Georgia.

There are several key features that make the load based modeling approach more appropriate for emissions prediction than current emission rate modeling tools:

- Modal models take into account all of the factors in the heavy-duty vehicle operation environment that affect emissions, such as vehicle age, engine type, transmission type, fuel type, on-road driving conditions, and roadway characteristics;
- The statistic methodology approach avoids extrapolation with correction factors beyond ranges under which test data were collected, significantly improving prediction accuracy;
- Modal models are easily verified, calibrated, and improved. Second-by-second vehicle operations can be readily collected in field studies, and new heavy-duty vehicle emission rate monitoring equipment can be deployed to verify instantaneous emission rates. Field test results can be used to calibrate the parameters of the load-based model accordingly.

As outlined above, model inputs include load related parameters and grams per brake-horsepower-hour emissions rates under different power demand situations. In the Phase I model, constant grams per brake-horsepower-hour emissions rates are derived from the EPA laboratory test data and will be corrected based on altitude, temperature, humidity and whether the vehicle is assigned to a normal-emitter or high-emitter category (using a probability function). Load parameters will be determined by: (1) vehicle technology, including vehicle type, make, model year, engine type, transmission type, frontal area, drag coefficient, rolling resistance, vehicle maintenance history, and so forth; (2) loading factors, including passenger load and freight load; (3) roadway characteristics, including road grade and, possibly, pavement surface roughness; (4) and inertial load parameters based on the vehicle speed and acceleration profile and the environmental conditions.

As discussed in the model overview section, once the brake-horsepower demands are quantified, engine dynamometer emission rate data (grams per brake-horsepower-hour) can be used in the emissions modeling regime. Note, however, as new emission rate data are collected via chassis dynamometer testing or through actual on-road testing, in which axle horsepower loads are measured concurrently with emission rates (grams per axle-horsepower-hour), these emission rates can be employed directly, without the need for estimating additional power losses associated with drive train and accessory losses.

The remainder of the report describes the details of the modeling framework. The GIS modeling regime is outlined first. Figures 1, 2, and 3 illustrate the combined model regime, the Phase I implementation, and the Phase II implementation. The implementation figures provide blue boxes around each of the major modeling elements. Each major component of the model illustrated in these figures is described in a separate section of this report. The roadway infrastructure section outlines the detailed information needed for the link-by-link model implementation. Because temperature, humidity, altitude, and wind speed affect vehicle loads and emission rates, the tracking of these factors is outlined in one report section. Vehicle activity must be estimated on each link for a variety of heavy-duty vehicle subfleets. The methods proposed for developing the vehicle subsets and for estimating their activity are described in the Subfleet Characterization and Traffic Volumes section. This section also refers to a number of technical appendices. Freight and passenger load estimation are described in one section, and on-road operating characteristics (speed and acceleration profiles) are described in another. The most complex section of the report is the description of the engine power functions. Emission rates are significantly different for Phase I and Phase II modeling approaches, and the figures indicate that there are separate modules associated with each. The emission rate functions section describes the approach differences and outlines the methods proposed for implementing correction factors and more complex time-series relationships. The matrix calculation methods are outlined in the inventory and assembly section. Finally, the report provides a case study citation of the basic power approach to estimation of emisisons from two monitored transit routes in Atlanta.

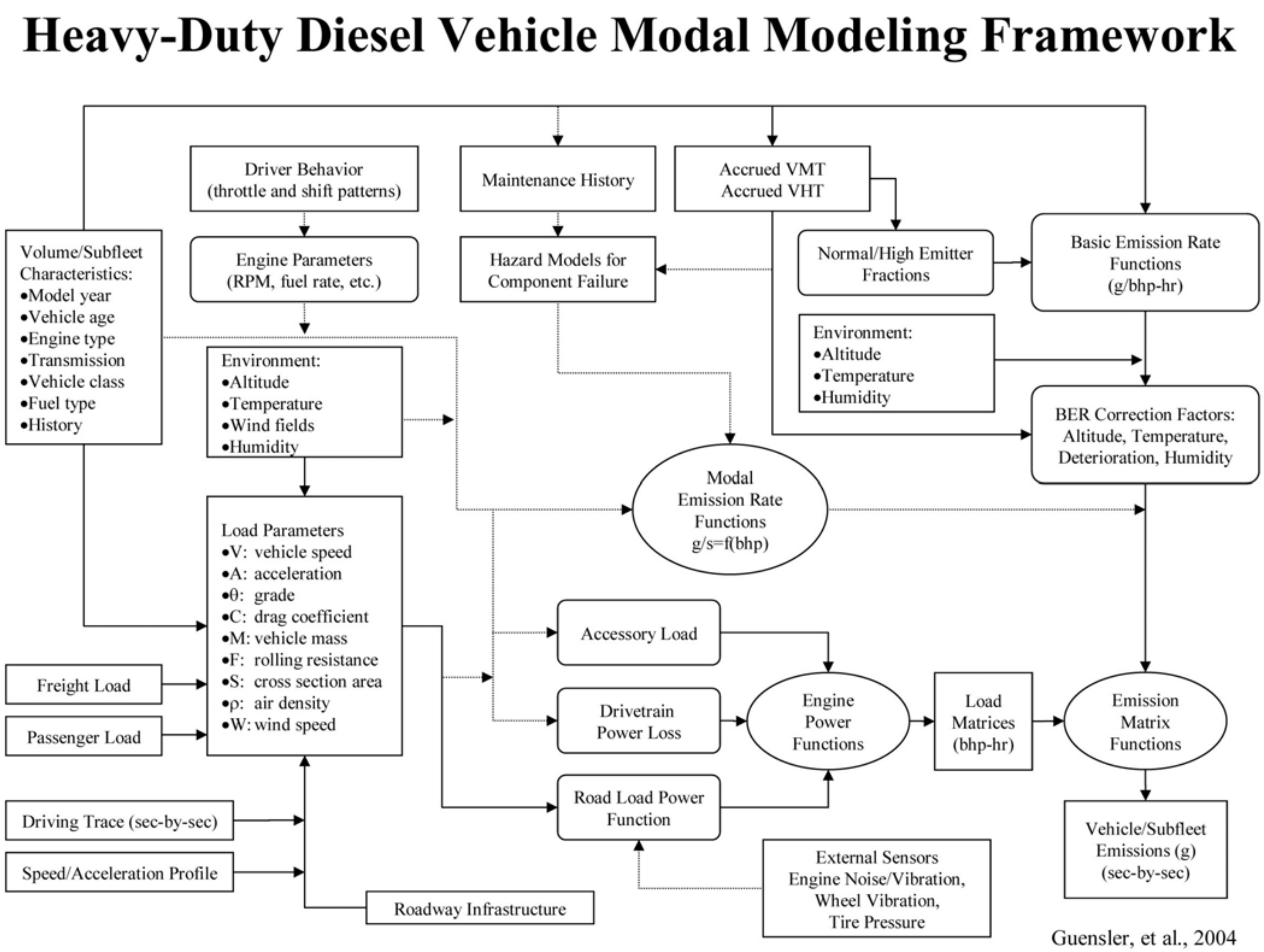


Figure 1. Overview Schematic of the Proposed Model.

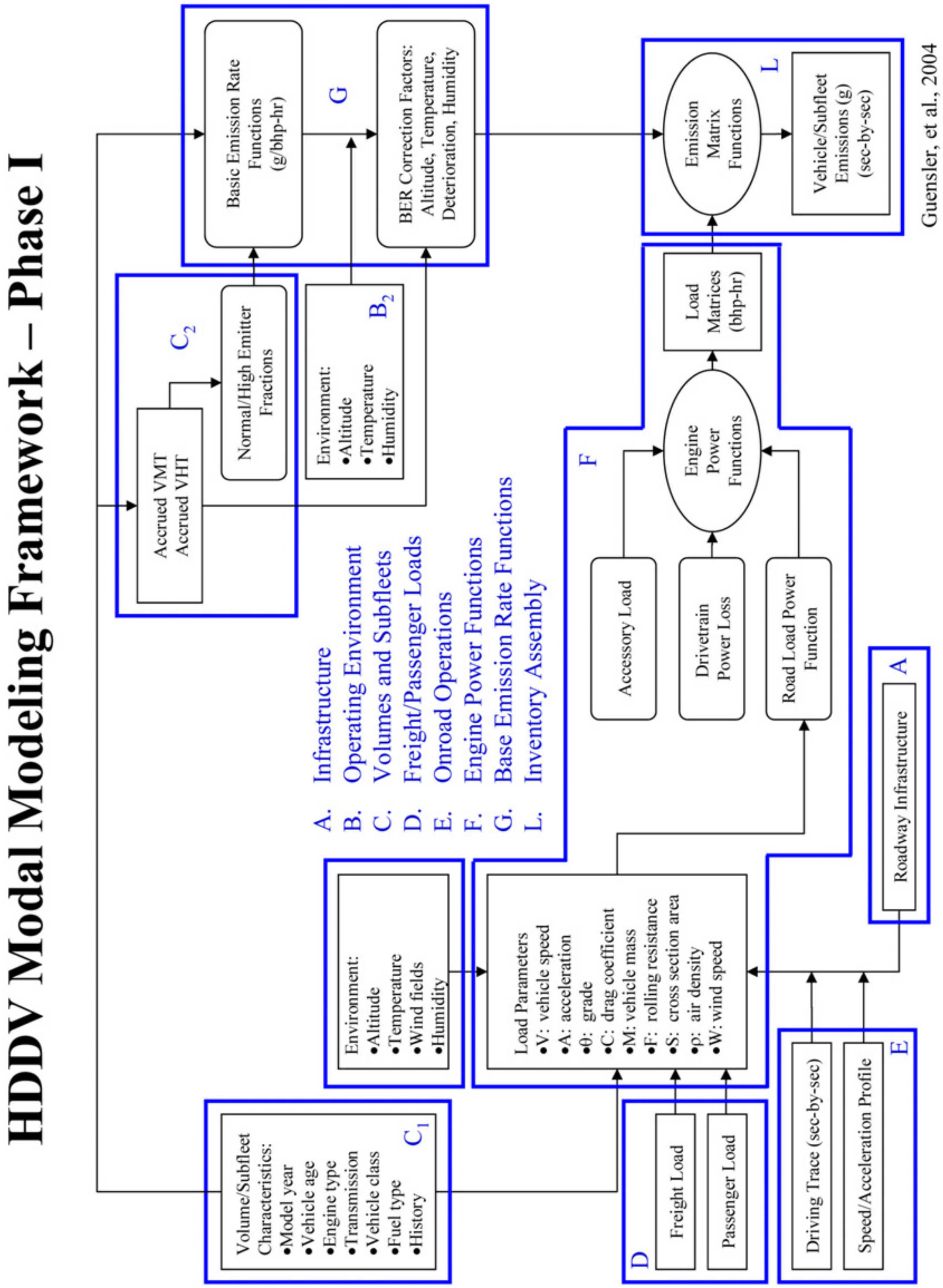


Figure 2. Overview Schematic of the Proposed Model—Phase 1 Model.

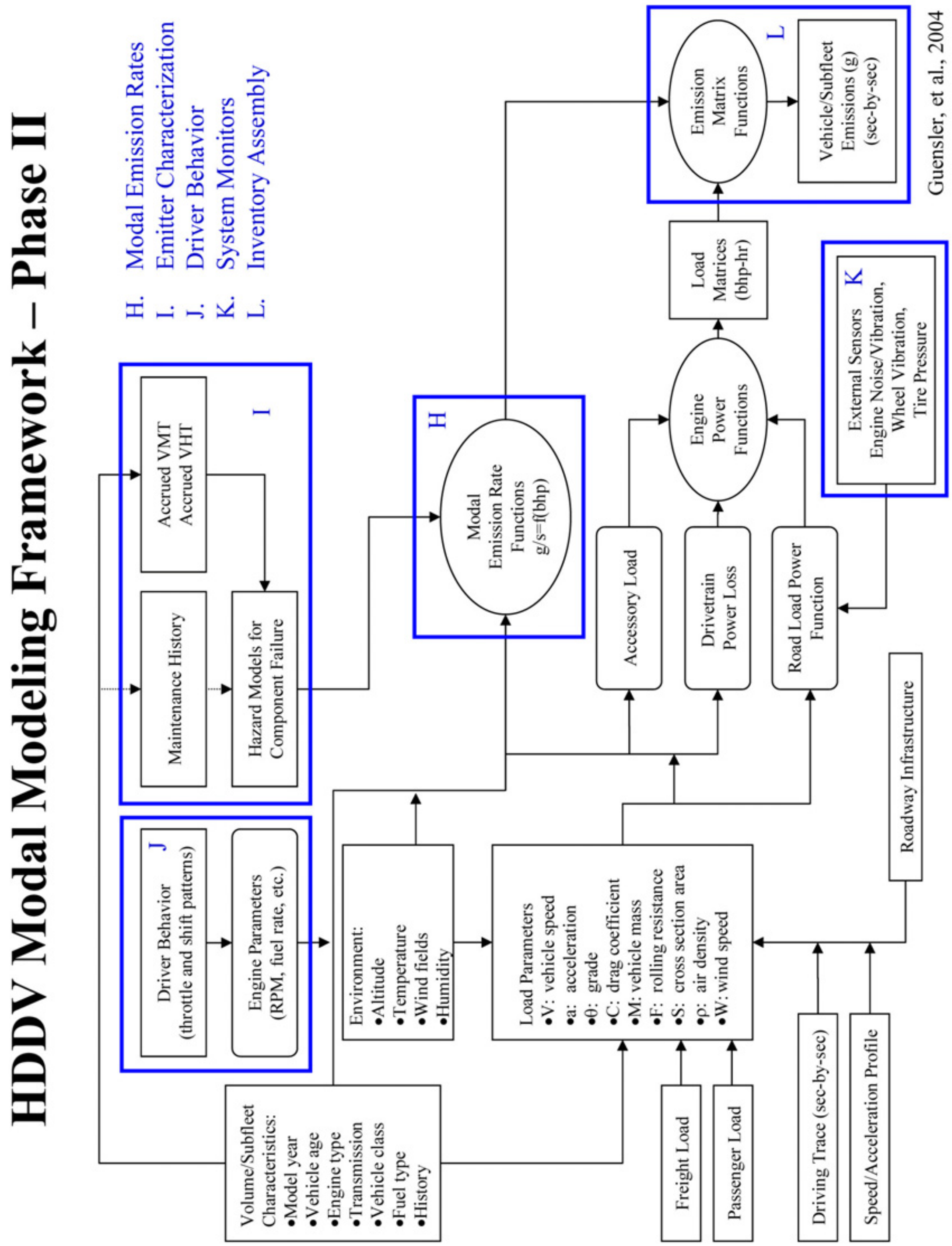


Figure 3. Overview Schematic of the Proposed Model—Phase II Model.

The Geographic Information System

GIS Spatial Analysis Framework

Historically, emission rate or emission models have not been implemented in a GIS. This has been due, in part, to the magnitude of the data required by a GIS, perception and reality of operating GIS software, and the level-of-knowledge required by end-users to manipulate data in a GIS. In the last 10 years, GIS data have become more available in both quantity and quality, while the availability of a GIS in a Windows operating system environment, availability of low-cost computer hardware, and the development and implementation of easy to use GIS tools (in a Windows environment) has made implementation of GIS-based emissions models more practical.

Models, such as MOBILE6, do not calculate emissions due to road grade effects—increased emissions due to accelerations going uphill. In addition, spatial resolution of emissions is misrepresented. For example, engine start emissions using earlier modeling systems did not allocate emissions to the appropriate residential or commercial/industrial locations. Typically, engine starts would be included in the grand total of highway vehicle emissions and would be allocated a given county based on population or some other surrogate. With a GIS, engine start emissions may be calculated and assigned on a sub-county basis using a combination of factors including census block group population, property (parcel) data, trip production/attraction (work, schools, etc.) data.

The use of a GIS-based approach allows for the visualization of such critical phenomena as real-world locations and magnitude of emissions from vehicles during peak commuting hours on major roadways. One of the more difficult highway vehicle emissions modeling questions to answer is how to locate the emissions—that is to say, where (geographically) are the emissions coming from? In a large metropolitan area, the highway vehicle emissions occur throughout the city and throughout the day.

The spatial analysis framework for the heavy-duty diesel modal emission model is an implementation in ArcGIS. The GIS system is essentially a spatial database that tracks the physical location, spatial boundaries (shapes), and associated attributes (physical or performance characteristics) of the modeled elements. The GIS system contains the land use and roadway infrastructure data that are used in a variety of the emissions calculations. Variables included in the proposed research model are those required for use in the quantification of vehicle activity or the calculation of vehicle emissions. Calculations are performed for each roadway link, (i.e., on a link-by-link basis). Hence, the spatial transportation infrastructure must be described with the applicable link-based variables. Modeling is also performed on an hourly basis, so attributes are also maintained for each hour. Given the functional form of the load-based model, the elements listed below are tracked in the GIS system.

Land Use:

- U.S. Census block boundaries,
- Parcel level land use boundaries (to identify truck activity locations),
- Traffic analysis zone boundaries (from the regional travel demand forecasting model), and
- Grid cell boundaries (defined by user for regional air quality modeling).

Roadway Elements:

- Travel demand forecasting network link identi-

fication,
- Link x, y coordinates,
- Roadway length,
- Roadway classification,
- Number of lanes,
- Speed limit,
- Road surface material (e.g., concrete vs asphalt), and
- Grade distribution and average grade.

Temporal Variable:
- Hour of the day (0-24).

Traffic volumes:
- HD diesel vehicle traffic flow (vehicles by link by hour).

On-road Fleet Characterization:
- HD vehicle classification;
  - Model year,
  - Engine size, and
  - Vehicle weight,
- Vehicle configuration group;
- Drive train technology group, and
- Emission control system.

On-road Operating Conditions:
- Speed/acceleration profile.

Environmental Conditions:
- Temperature,
- Humidity,
- Altitude, and
- Wind speed and direction.

The spatial domain is currently the 13-county Atlanta metropolitan area, but will be expanded to the new 20-county nonattainment area, which is designated as an 8-hr ozone nonattainment area, over the next year. The use of each element is described later in the modeling framework documentation associated with that element.

Infrastructure

The roadway elements included in the model are:
- Travel demand forecasting network link identification,
- State DOT/FHWA roadway classification,
- Link x, y coordinates,
- Roadway length,
- Roadway classification,
- Number of lanes,
- Speed limit,
- Surface material (e.g., concrete vs asphalt), and
- Grade distribution and average grade

The travel demand forecasting link identification provides a unique roadway ID for use in all calculations. Link coordinates provide the spatial location of each link. Because the demand modeling framework is a simplified version of the actual on-road system, each link is represented by a straight line (Figure 4). To ensure that the correct distance and travel time is included in all calculations, the actual on-road length of each roadway link is included as a link attribute. Roadway classification, number of lanes, and speed limits are also included for use in later development of applicable on-road operating conditions (speed/acceleration matrices) for each link. Surface materials are tracked for use in roadway friction calculations. Finally, grade is tracked for use in the load-based gravitational resistance calculation.

The four roadway classification definitions that are employed in the modeling framework are freeways, arterial/collector, local roads, and ramps. Both the Federal Highway Administration (FHWA) and the Georgia State Department of Transportation's (DOTs) Multimodal Transportation Planning Tool (MTPT) employ more refined roadway classification systems, but each one is significantly different from the other. A mapping system was developed for the FHWA and State DOT roadway classifications (Table 1) to assign each road link to the four classes (Guensler, et al., 2004).

Operating Environment

Each grid cell used for aggregating emissions (1 km x 1 km, or higher level) is assigned operating environment attributes for temperature, humidity, altitude, and wind speed and direction. The environmental attributes are used in load calculations (temperature and wind speed) and in emission rate adjustments (temperature, humidity, and altitude). The environmental conditions will be established for any given

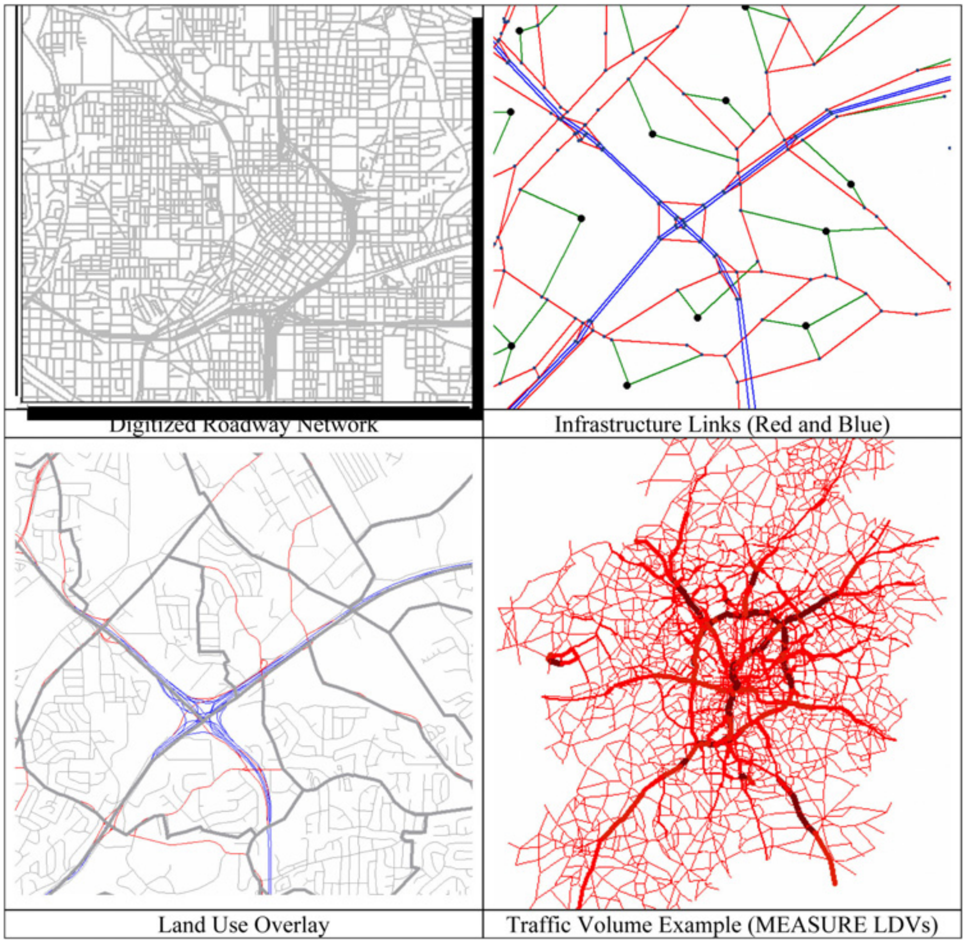


Figure 4. Digitized Roadway Network—Example (Bachman, et al., 2000; Bachman, 1997).

modeling scenario. For example, summertime temperature fields would be employed in estimating the emissions contribution of HDDVs for ozone modeling. Particulate matter impact simulation studies might model hourly emissions using the previous year's hourly temperature fields (24 hours times 365 days). The spatial and temporal distributions of temperature and humidity can be derived from ambient monitoring data. Altitude (low vs high) is a single variable for the entire modeling run. Hourly wind speed and direction from meteorology monitoring networks will be employed in the Phase II model and used for establishing effective velocity in on-road wind drag force calculations, provided that the emissions effect is significant. Variables included in the model are outlined in Appendix A and data sources are outlined in Appendix B.

Table 1. Mapping of Functional Road Classifications for Modeling[a].

MOBILE6.2 Categories	FHWA Corresponding Categories	GA MTPT Corresponding Categories
Freeway	• Interstate Rural, Urban (FHWA Class 1, 11) • Principal Arterial Rural (FHWA Class 2) • Other Freeways & Exp. Urban (FHWA Class 12)	• Interstate Rural, Urban (FHWA Class 1, 11) • Urban freeway and expressway (FHWA Class 12)
Arterial/Collector	• Minor Arterial Rural, Urban (FHWA Class 6, 16) • Major Collector Rural (FHWA Class 7) • Other Principal Arterial Urban (FHWA Class 14)	• Principal Arterial Rural (FHWA Class 2) • Urban principal arterial (FHWA Class 14) • Minor Arterial Rural, Urban (FHWA Class 6, 16) • Major Collector Rural (FHWA Class 7) • NFA Minor Collector Street with speed limit > 40 mph (FHWA Class 8) • Collector Urban (FHWA Class 17) • Non-Ramp Local Rural, Local Urban with speed limit > 40 mph (FHWA Class 9, 19)
Local	• Minor Collector Rural (FHWA Class 8) • Local Rural, Local Urban (FHWA Class 9, 19) • Collector Urban (FHWA Class 17)	• NFA Minor Collector Street with speed limit = 40 mph) (FHWA Class 8) • Non-Ramp Local Rural, Local Urban with speed limit = 40 mph (FHWA Class 9, 19)
Ramp	• None	• Ramps designated at Local Rural, Local Urban (FHWA Class 9, 19) but defined as an RCLINK code 6 (Ramp/ Interchange)in the Georgia database

[a] Source: Guensler et al., 2004

Subfleet Characterization and Traffic Volumes

HDV activity must be estimated for each link on the roadway system. Rather than tracking individual vehicles (given the tremendous number of link-based calculations that would need to be performed), the model employs the concept of technology groups, which are sets of vehicles that behave similarly to each other and are assumed to follow the same load and emissions relationships. This allows the emissions for hundreds to vehicles to be predicted in a single series of calculations. Hence, for each roadway link, the activity of each technology group must be provided. The unit of vehicle activity for each roadway link is vehicle flow (vehicles per link per hour).

On the vehicle activity side, the modeling framework will be flexible. Users can apply a default truck fraction for each link to the link-based traffic volumes output from traditional 4-step travel demand models. Many regions apply a simple 0%, 1%, 2%, or 5% value to the travel demand predictions to estimate the total number of vehicles operating on a link. Such estimations are traditionally based upon truck count observations and do not provide any insight into trip generation for truck activity. Unfortunately, there are no metropolitan areas that are currently operating models that estimate trip generation, distribution, and route choice for HDV activity (this would be a very expensive, data intensive, and resource intensive proposition). Given that there is no current means to integrate a predictive model into the current modeling regimes, it becomes imperative to provide the flexibility for regions to integrate the results of special research studies into the model.

Vehicle Technology Groups

The concept of vehicle technology groups is to identify and track subsets of vehicles that have similar on-road load response and similar laboratory emissions performance. Vehicles within each technology group should respond similarly to change in operating conditions (with respect to increased or decreased load) and perform similarly to each other on baseline emission tests. The basic premise is that vehicles in the same HDV class, employing a similar drive train, and of the same size and shape will respond similarly with respect to load estimation. There is also an important practical consideration in establishing vehicle technology groups; researchers need to be able to identify these vehicles in the field during traffic counting exercises. The starting point for technology group criteria is a visual classification scheme. Justification for the visual classification scheme is provided in a separate publication (Yoon et al., 2004a).

- The vehicle visual classification X-Scheme (Yoon et al., 2004a), from a small single axle truck to a large multiple trailer truck, is illustrated in Figure 5.

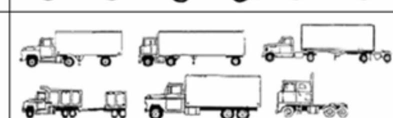
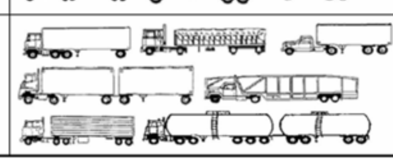
X Class	EPA Class	Typical Vehicles
X1	HDV2b, HDV3, HDV4, HDV5, HDV6, HDV7	
X2	HDV8a	
X3	HDV8b	

Figure 5. X-Classification Scheme (Yoon et al., 2004a).

- Vehicle configuration (bobtail, tanker, single-unit, trailer, double trailer, flat-top, etc.) has a significant impact on engine load at high speeds through the aerodynamic drag load. Therefore, body configuration is also employed as a technology group criterion.
- Three engine size classifications are associated with both engine design and certification, and these will be used in technology group criteria: of light heavy-duty, medium heavy-duty, and heavy heavy-duty.
  1. Light heavy-duty diesel engines are typically rated from 70 to 170 horsepower. Vehicle body types would encompass vans, trucks, recreational vehicles, and some single axle straight trucks. The gross vehicle weight (GVW) rating of the vehicle is usually less than 19,500 pounds [40CFR86.085-2(a)(1)].
  2. Medium heavy-duty diesel engines are typically rated from 170 to 250 horsepower. Vehicle body types include buses, tandem axle trucks, dump trucks, etc. The GVW rating of the vehicle is usually from 19,500 to 33,000 pounds [40CFR86.085-2(a)(2)].
  3. Heavy heavy-duty diesel engines typically exceed 250 horsepower. Vehicle body types are typically tractor-trailer rigs and trucks and buses used in long haul intercity operations. The GVW rating usually exceeds 33,000 pounds [40CFR86.085-2(a)(3)]. Heavy heavy-duty diesel engines are sleeved and designed for multiple rebuilds.
- Vehicle age and model year effects are accounted for through the exploration of engine certification groups as a technology group criteria: pre-1984, 1984-1987, 1988-1990, 1991-1993, 1994-1997, 1998-2003, and 2004+. These seven model year groups represent a combination of drive train and emission control technology integration in response to changing emission testing standards.
  1. It is possible that even within a vehicle and engine class indicator group, there will be specific engine or drive train elements (such as the presence of a turbocharger, torque converter, etc.) that will necessitate splitting the group.
  2. Manual vs automatic transmissions are handled with separate indicator variables within each technology group, due to the additional torque converter power loss.
- Analysis of standard engine dynamometer and second-by-second chassis dynamometer test results, in which axle horsepower is measured or calculated from known test parameters and dynamometer settings, is also an important step in the development of technology groups. Subsets of vehicles within a physical class/drive train/configuration group may behave very differently with respect to emissions. Different fueling strategies and engineering associated with other control systems (engine computer software) can result in major differences in on-road performance from otherwise very similarly configured vehicles.
  1. Add-on control devices will likely need to be included in the criteria as they enter the fleet in greater proportions.
  2. Once physical configurations are established, regression tree analysis will be used to identify other variables that explain variability across emission test results within the physical configuration group. These factors will be used to further subdivide the groups into their final technology groups.

In summary, the vehicle technology groups will be physically and statistically derived. From a physical standpoint, the vehicles will be divided into recognizable and identifiable groups based on physical configuration (three major groups, plus additional subgroups for vehicle-trailer configuration). The evolution of drive train technologies is accounted for by using three engine horsepower groups and seven certification groups. These parameters account for the major differences expected to be noted in the estimation of engine load. The final subdivisions into technology group are based on statistical analysis of the emission test databases to identify any other factors that appear to have a significant impact on vehicle emissions performance within each physical configuration group.

Emitter Classifications

In both the Phase I and Phase II models, vehicles will be classified as either normal-emitters or high-emitters. The vast majority of HDVs are normal emitters, but a small percentage of vehicles have been tampered with or are mal-maintained. In the Phase I model, the EPA and other emissions testing databases will be queried to identify those vehicles that are high-emitters, based on emission test results for each pollutant. As was done in the development of the MEASURE model (Wolf et al., 1998), high-emitter status will be defined via statistical analysis of test results within a single certification category.

For all on-road operations, on-road vehicle activity by vehicle class, configuration, and drive train technology will be divided into two emitter fractions. Higher grams per brake-horsepower-hr emission rates will be applied to the high-emitter fraction based upon review of the literature. Hence, for each technology group on the roadway, a high-emitter fraction will be tracked.

In the Phase II model, the goal will be to include a hazard-type model to predict the fraction of high-emitters on the road as a function of accrued vehicle mileage, vehicle age, applicable inspection programs, and so forth. The model component is identified in the Phase II flowchart as emitter characterization.

On-Road Traffic Volumes

A major problem with the heavy-duty truck emissions modeling frameworks has been the mismatch between EPA engine certification classifications and on-road vehicle classifications employed by the FHWA. Mapping the two classifications to each other is difficult because they were developed for completely different purposes. Current guidance suggests aggregating field observation data to total truck volume and then disaggregating back to EPA classifications using information from sources such as the Polk inventory. However, Yoon (2005b) identified a number of major problems with this technique specifically related to the overestimation of vehicle miles traveled (VMT) fractions for smaller heavy-duty vehicles and the underestimation of heavier rig VMT (Figure 6). To resolve the problems with the current modeling framework, alternative methodologies have been proposed.

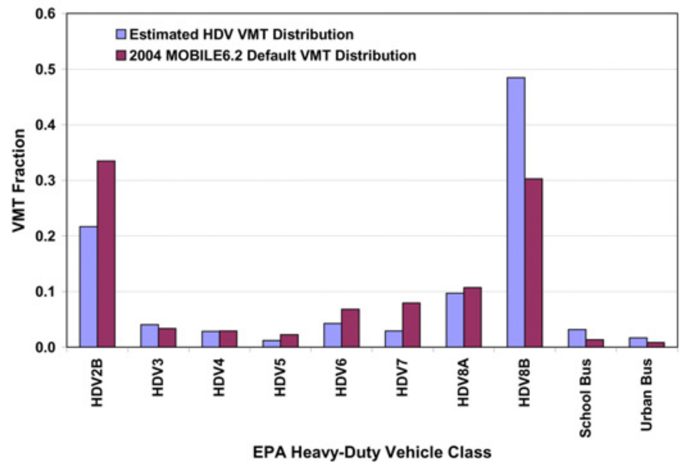


Figure 6. VMT by EPA Classification—EPA Guidance vs Yoon Method (Yoon, 2005b).

The estimation of technology group fractions on each roadway link begins with an estimate of total heavy-duty diesel vehicle volumes, by EPA classification. The goal is to develop a method that allows field observations to be correctly mapped to EPA classes. A key element in this process is to first identify the on-road truck volumes using an observational classification technique designed to maximize the accuracy of initial grouping of similar vehicles and engines. A major research effort was conducted in Atlanta during 2003-2004 to develop the roadway activity estimates, which are outlined in a recent report prepared for the Georgia Regional Transportation Authority (Rodgers et al., 2004). In the Atlanta effort, the researchers developed observation categories and mapping tools (Yoon et al., 2004a).

The visual classification scheme found to work best for field observation is the X-Scheme, which uses simple axle counts as the classification tool (2-axle HDV, 3-axle HDV, and 4+ axle HDV). Given truck weight limitations, the axle-based classification scheme naturally places most observed vehicles into their medium-heavy-duty and heavy-heavy-duty groups. Algorithms were developed to map vehicle observations from the X-scheme to the previous Georgia Tech classification scheme and to the FHWA scheme. This mapping is illustrated in Figure 7, which also indicates the applicable EPA heavy-duty vehicle certification categories.

EPA	X-Scheme	FHWA	Ahanotu
HDV2b, HDV3, HDV4, HDV5, HDV6, HDV7	X1 (2-axle)	3 (HDV), 5	A
HDV8a	X2 (3-axle)	6, 8 (3-axle)	B (3-axle), C (3-axle)
HDV8b	X3 (>3-axle)	7, 8 (4-axle), 9, 10, 11, 12, 13	B (4-axle), C (4-axle), D

Figure 7. Interactive Heavy-Duty Vehicle Mapping Results (Yoon, 2005b).

Emissions Rate Differences

The differences of emissions rates (tons/day) between the EPA guidance and the X-scheme scenarios were compared (Table 2). Emissions rates with the X-scheme scenario increased 15.7%, 34.4%, and 32.5% for VOC, NO_X, and $PM_{2.5}$ as compared to the EPA guidance scenario. However, CO emissions rate with the X-scheme scenario decreased 23.2% less than that of the EPA guidance scenario.

Table 2. Emissions Rates Differences between the X-Scheme and EPA Guidance.

Pollutant	Emission Rate Difference (%)
VOC	15.7
CO	-23.2
NO_X	34.4
$PM_{2.5}$	32.5

The proposed methodologies use observational data, registration databases, and survey data. Figure 8 illustrates the combined methodologies employed in estimating heavy-duty vehicle activity. The detailed text description of the combined system is provided in Appendix C.

Once the EPA classifications are derived, the next step is to develop engine classification splits and

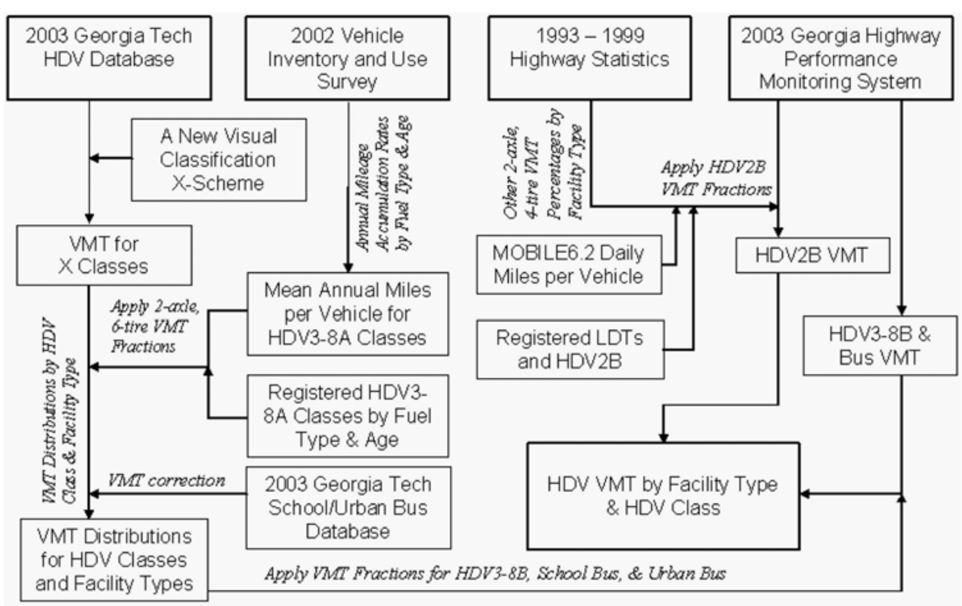


Figure 8. Heavy-Duty Vehicle VMT Estimation Procedure.

vehicle configuration splits to finalize technology groups. Engine size distributions are taken directly from Ahanotu (1999), in which truck classes and engine HP ratings were derived. Engine size classes will help to further subdivide the certification groups into those that are likely to have different emissions performance under on-road conditions. Vehicle configuration classifications are important from the perspective of estimating road load power demand. For example, bobtails, single unit trailers, double trailers, flattops, and automobile carriers will all have significantly different frontal areas and drag coefficients. Subdivisions will be developed when estimated loads at high speeds are significantly different for separate groups of vehicles within the EPA and engine size class.

Transit Buses

In most metropolitan areas, the majority of bus miles of travel are occurring on specific routes at specific times of the day. The Metropolitan Atlanta Rapid Transit Authority (MARTA) fleet is composed of approximately 760 heavy-duty buses. Table 3 provides the distribution of the model years and their NO_X emission rates. Information is readily available on the exact bus configuration and drive train technologies employed, and similar information is available for the Georgia Regional Transportation Authority (GRTA), Clayton County, and Cobb County fleets. Given that complete fleet and route information can be obtained by transit agencies, the Phase I model will employ the actual data for heavy-duty transit buses. One interesting finding from a recent field study in Atlanta is that the buses are not matched to specific routes. When drivers arrive at the staging yard, they are randomly assigned buses from the pool. Hence, in Atlanta, there is no need to tie specific bus technologies to specific routes.

Off-Road Activity

A significant portion of heavy-duty vehicle emissions occur off-road, in freight yards, at truck stops, and at pickup and delivery points. A large portion of this activity is simple idling, usually to provide cabin comfort (i.e., air conditioning and heating). On the other hand, emissions are usually elevated for the first few minutes of vehicle start-up operation while engine combustion stabilizes and emission control systems come online, and light-duty vehicle emission rate models are handling engine start emissions as discrete events (as if all of the emissions associated with the start were emitted in a puff). In the Atlanta metropolitan area, a major review of on-road, off-road, and non- road vehicle activity has recently been completed. This study provides insight into engine start and idling activity. The engine start and idle factors for Atlanta will be built into the ArcGIS framework using the land use layer to assign the activity.

Table 3. MARTA Bus Age Distribution.

Year	Number	Fraction	NO_X Emission Rate (g/bhp-hr)
2001	106	0.1397	4
2000	81	0.1067	4
1999	1	0.0013	4
1998	0	0.0000	4
1997	1	0.0013	5
1996	116	0.1528	5
1995	0	0.0000	5
1994	51	0.0672	5
1993	0	0.0000	5
1992	40	0.0527	5
1991	49	0.0646	5
1990	172	0.2266	6
1989	0	0.0000	10.7
1988	77	0.1014	10.7
1987	18	0.0237	10.7
1986	47	0.0619	10.7

As discussed later in this report, engine start emissions are not employed in the Phase I model due to lack of statistically significant evidence identified in the assessment of the EMFAC2000 model development data. Based on the data, engine starts appear likely to elevate emissions and may be significant when larger data sets are available for analysis. However, chassis dynamometer data used in the development of EMFAC2002 will be analyzed over the coming year. If engine start emissions from diesel are significant, engine start emission rates (gram per start) will be coupled with engine start activity estimates by parcel-level land use in Phase II model implementation.

Idle emissions do not need to be handled through a load estimation model. Use of grams per brake-horsepower-hour emission rates from certification test results will not be useful because the databases provide only the average emission rates rather than test component emission rates. To the extent that second-by-second Federal Test Procedure (FTP) test data are available, the idle emission rates can be quantified on a grams per second basis. Idle emissions can be derived from the existing second-by-second chassis dynamometer and on-road emission testing databases. Thus, the input data required to estimate idle emissions will be hours of vehicle idle per technology group by land use activity.

A potentially more significant and difficult modeling problem is the estimation of emissions associated with freight yard creep activity. The high inertial loads associated with repetitive acceleration as vehicles move through queues will likely need to be quantified through new field studies. The standard load-based modeling approach can be applied once hours or miles of creep activity are compiled and speed/acceleration distributions are defined for this activity.

Freight and Passenger Loads

The load-based modal model requires estimates of vehicle weight for each technology group. The combined weight of the vehicle and the trailer significantly affects power demand through the grade load and road friction terms.

Truck Loads

The combined weight of vehicle and trailer is employed in road load calculations (road friction and grade load). Hence, characterization of vehicle capacity and utilization factors (i.e., actual on-road vehicle weights) is required input to the model. However, most emissions-related HDV classifications are based on gross vehicle weight rating (GVWR) as a result of the availability of accessing this data from vehicle registration data bases. These ratings are based on the maximum weight that a vehicle can carry relative to the horsepower capacity and safety considerations of the vehicle. Many HDVs are classified with the same weight rating despite having different on-road activity, weight, and horsepower characteristics. For example, a vehicle with a GVWR of 80,000 pounds can be a 5-axle, long-haul, tractor-trailer combination with a 600 horsepower engine used for dry goods shipment or can be a 3-axle, local, and single-unit vehicle with a 350 horsepower engine used for hauling loose materials. The on-road weight distribution of the 5-axle vehicle would range from an empty weight of 35,000 pounds up to the legal maximum of 80,000 pounds. The on-road weight distribution of 3-axle vehicles generally ranges from an empty weight of 20,000 pounds up to the legal maximum of 54,000 pounds. So, heavy-duty vehicle classification methods simply based on gross vehicle weight rating do not match on-road vehicle activity categories.

Between 1997 and 1999, Ahanotu (1999) undertook a series of weigh-in-motion studies and weigh station interviews to examine the spatial and temporal distribution of vehicle loads in the Atlanta region. These study results serve as the basis for integrating truck loads into the heavy-duty load-based modeling framework. Ahanotu (1999) developed a modified truck classification based on axle-trailer configurations which allows for the development of weight and horsepower distributions. The vehicle classification scheme—a four-class system based upon axle-trailer configurations—will use the FHWA classification as a base for all ground counts and field observations:

- A: 2-axle, single unit trucks (Class 5 trucks)
- B: 3 or more axle, single units trucks (Class 6-7 trucks)
- C: 3 or 4 axle, truck and single trailer combinations (Class 8 trucks)
- D: 5 or more axle single trailer trucks, plus double trailer trucks (Class 9-13 trucks)

The four observational classifications are composed of FHWA vehicle classes that were aggregated based on three criteria: (1) range of gross weights across truck classes, (2) engine horsepower differences across truck classes, and (3) ease of classifying during field observations (Rodgers et al., 2004).

Ahanotu (1999) developed this scheme with relationships between engine horsepower and gross vehicle weight in mind. From the survey data collected by Georgia weight enforcement stations, Ahanotu found that the Class 9-13 truck classifications averaged significantly higher horsepower ratings (about 370) relative to the Class 8, Class 6-7, and Class 5 truck classes, which had average ratings of 293, 279, and 188 hp respectively. Figures 9 and 10 illustrate the horsepower distributions and average values by

FHWA truck class. Figure 11 illustrates the shift in engine horsepower ratings over time, as newer engines have become larger.

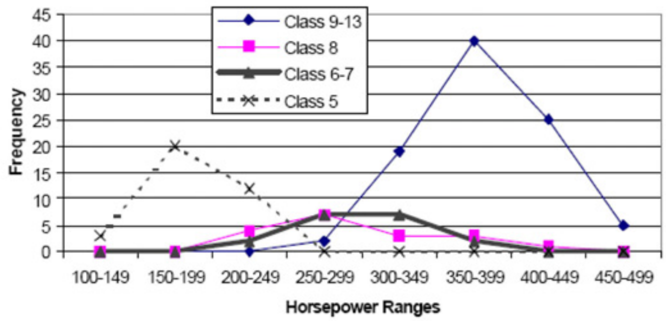


Figure 9. Horsepower Distributions by Class for Preliminary Surveys.

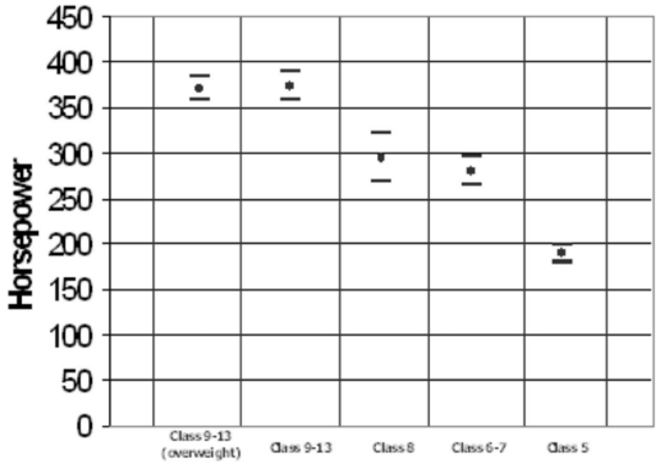


Figure 10. Mean Horsepower by FHWA Truck Class.

Ahanotu's analyses indicated that a 4-class HDV classification scheme would be suitable for describing both horsepower and weight distributions. This classification system allows data from numerous truck data sources (i.e., roadside surveys, vehicle counts, emission rate estimates, commercial vehicle surveys, etc.) to be easily incorporated into emissions models. However, Yoon et al. (2004a) later determined that a revised system (X-scheme, or axle scheme) would potentially improve on-road classification recognition. This is because the previous

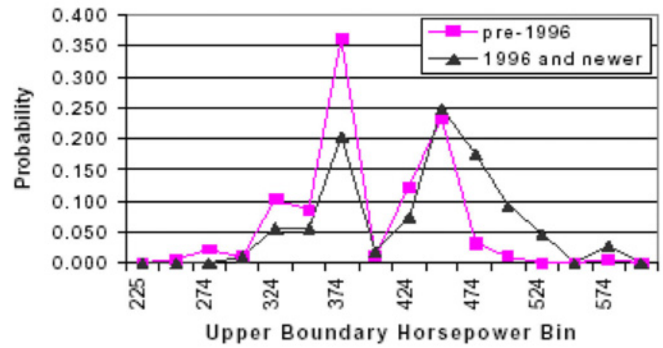


Figure 11. Engine Horsepower Distributions by Model Year Grouping.

system was more difficult to map back to the EPA heavy-duty vehicle boundaries (based upon GVWR). The X-scheme better bridges the FHWA truck and EPA HDV classification system. Table 4 shows the mapping between the classification schemes.

Table 4. X-Scheme—HDV Reclassification Map Among HDV and Truck Classification Schemes.

X Classes	EPA Classes	FHWA Classes	Ahanotu's Classes	Axles
X1	HDV2b, HDV3, HDV4, HDV5, HDV6, HDV7	3 (HDV), 5	A	2
X2	HDV8a	6, 8 (3-axle)	B (3-axle), C (3-axle)	3
X3	HDV8b	7, 8 (4-axle), 9, 10, 11, 12, 13	B (4-axle), C (4-axle), D	>3

The X1 class includes pick-ups, vans, and delivery trucks. The X2 class includes dump trucks and articulated delivery trucks having three axles. The X3 class includes all more than three-axle, articulated or single HDVs. With the X-scheme, FHWA truck classes can be more accurately mapped into EPA HDV classes, or vice versa.

In developing the X-scheme, corresponding engine horsepower data were not available. Hence, it is not clear at this time how to best map the horsepower distributions back to the X-scheme vehicle classes. For the time being, it will be assumed that the horsepower distributions determined through Ahanotu's research can be allocated proportionally to the X-scheme. That is, if 40% of one Ahanotu class is now allocated to class X3 and 60% of another class is mapped to X3, the X3 engine horsepower distribution will be a weighted sum of the Ahanotu distributions. The noted effect of engine age on horsepower distributions will be similarly integrated. As combined engine horsepower, model year, and classification (X-class) data become available in future, updated horsepower distributions will be integrated into the model.

Ahanotu (1999) also examined the spatial and temporal distribution of engine horsepower and GVWR for the Atlanta metropolitan area. These analyses can be directly integrated into the model, given the spatial and temporal nature of the modeling framework. Figure 12 illustrates the load distribution of trucks operating during the early afternoon period, with the weight distribution being a combination of empty, full, and partially loaded trucks. Ahanotu's research also provides temporal effects, with different distribu tions applied in the morning, noon, and afternoon periods (more fully-loaded trucks are operating in the morning peak). Figure 13 shows the differences in these distributions by day of week. Ahanotu's on-road findings for vehicle load will be integrated into the model directly so that the road load power demand can be established for each class using the data in the load matrices (by hour of day and day of week for each class).

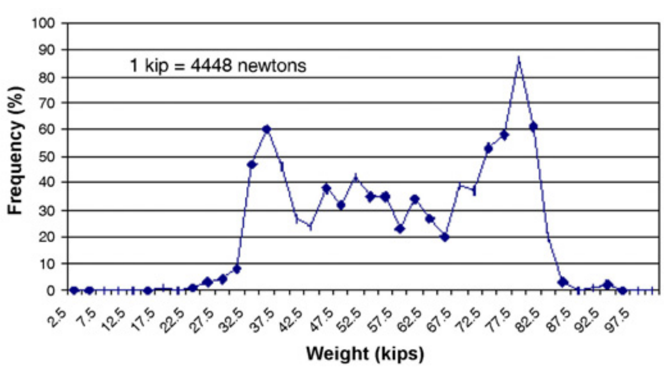


Figure 12. Class 9-13 Weight Distribution, Monroe County Weigh Station (4/12/98, 12-2PM).

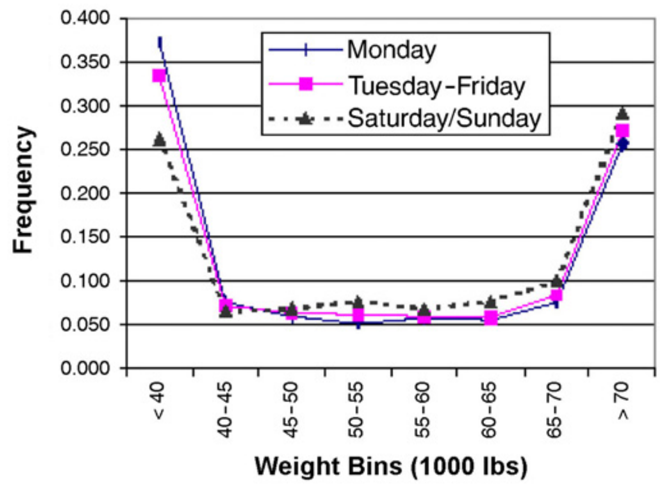


Figure 13. Midday Time Period Weight Distributions, Class 9-13 Trucks.

Considering that all of the engine horsepower, vehicle class, and weight distribution data were collected in 1998, it would be advisable to perform this research effort again in the future to ensure that relationships have not changed. However, in the absence of updated data, the research team will continue to use Ahanotu's results.

Transit Passenger Loads

Initial estimates for Atlanta indicate that passenger loading can have a 10% to 15% impact on load-predicted emissions. Transit passenger loads can either be provided to the model via input from the 4-step travel demand model (in which each transit route is its own link) or be manually entered based upon field studies. In Atlanta, MARTA has conducted detailed passenger loading studies and can provide boarding and alighting data for each route. In the absence of such agency data, it is a relatively simple matter to conduct such studies in an urban area.

On-Road Operating Characteristics

The heart of the implementation approach for the modal model is the application of speed/acceleration frequency distributions (SAFDs), which describe the fraction of vehicle activity that occurs under specific speed and acceleration conditions. The matrix is composed of cells that are binned by speed (0 to 2.5 mph, 2.5 to 5 mph, and then 5 to 100 mph in 5 mph increments) and acceleration (0 to 10 mph/s in 0.5 mph/s bins). In the model implementation described here, each second of vehicle activity is assigned to a single speed acceleration matrix cell. Idle activity is defined as vehicle activity falling into four cells, bounded by –0.25 to 0.25 mph and –0.5 to 0.5 mph/s. The definition of cruise activity is somewhat arbitrary, but a reasonable range for cruise might be non-idle activity at any speed falling into an acceleration range of –1.0 and 1.0 mph/s. Figure 14 illustrates a speed/acceleration plot for an interstate ramp operating at level of service D (peak afternoon commute) in the MEASURE modeling system based on data collected for the Atlanta Ramp metering Study (Guensler et al., 2001).

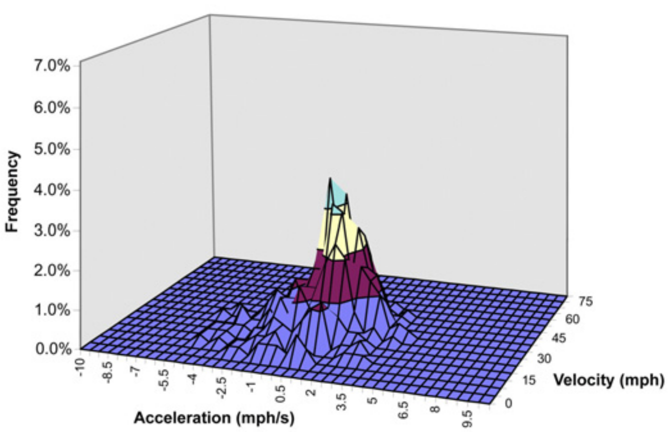


Figure 14. Speed/Acceleration Profile, Interstate Ramp, LOS D (Bachman, 1997).

The goal is to represent the vehicle activity on any link at any given time as total traffic volume (flow per hour) under a specific set of speed and acceleration conditions. That is, a specific SAFD should apply to any roadway for each hour of the day and day of the week. The data necessary to create the SAFDs to represent on-road operating conditions can be derived from a variety of on-road monitoring methods and techniques, the most common sources being stationary laser gun studies or instrumented vehicle studies (chase car or instrumented fleets).

HDV acceleration rates are significantly lower than LDVs (an interactive function with vehicle load). For example, the maximum acceleration rate from 0 to 50 mph for a 100 lb/hp tractor-trailer is 1.0 mph/s^2, with decreasing acceleration rate as the initial speed is higher, compared to a compact LDV with an acceleration rate of 5.3 mph/s^2 (Grant, 1998). Thus, different speed/acceleration profiles should be used for light-duty and heavy-duty vehicles, especially on freeways.

For freeways and ramps, the Phase I model will employ basic speed/acceleration distributions developed for the MEASURE model from Atlanta metropolitan area data collected by Grant (1998). Grant's research focused on the development of statistical relationships between power surrogates (positive kinetic energy and wind load surrogates) using second-by-second vehicle data collected by the extensive laser gun study. In his research, power surrogates were determined as a function of road type, location (central business district, suburban, or rural), design speed, number of lanes, lane width, shoulder width, grade, congestion levels, and presence of trucks (on grades). Plus, Grant (1998) observed that the presence of trucks on uphill freeway grades affects not only the truck speed and acceleration conditions, but the speed and acceleration conditions of the LDVs operating on the system as well. Thus, the speed/acceleration matrices employed in link-by-link calculations must also incorporate the effect of grade. Because the focus is now to generate speed and acceleration profiles and calculate power demand directly, rather than estimate power demand surrogates from the data and apply them to MEASURE modal emission rates, the second-by- second data will be de-archived and reanalyzed to develop more refined freeway speed and acceleration profiles for the Phase II model.

For arterials and local roads, the research team plans to use the Commute Atlanta instrumented vehicle data to represent on-road operating conditions for HDVs. The Commute Atlanta study collects approximately two million vehicle-seconds of on-road operating data every day from a fleet of 460 instrumented LDVs. In addition, two transit buses operating on MARTA routes have also been instrumented. The trip data collector consists of a global positioning systems (GPS) receiver, a wireless communication device, data storage, and on-board diagnostic (OBD) systems. As a new, emerging vehicle speed data collection tool in transportation research field, GPS receivers provide highly accurate speed data calculated with the Doppler shift theory. In studies of vehicle speed accuracy using GPS receivers, vehicle speed from GPS receivers is as accurate as that obtained from a conventional distance measuring instruments or travel time data acquisition systems. Although the LDV speeds and accelerations are different than those of heavy-duty trucks, until enhanced truck operating profile data are made available, the team believes that these profiles should be used.

The research team recently developed transit bus speed-acceleration matrices using speed data obtained with a Commute Atlanta trip data collector (Yoon et al., 2005a). Given the limited number of routes driven by transit buses in major metropolitan areas, the instrumented vehicle approach is recommended by the research team. The application of these speed acceleration profiles is described in the case study chapter of this report.

Engine Power Functions

Internal combustion engines translate linear piston work (force through a distance) to a crankshaft, rotating the crankshaft and creating engine output torque (work performed in angular rotation). The crankshaft rotation speed (engine speed in revolutions per minute) is a function of engine combustion and physical design parameters (mean effective cylinder pressure, stroke length, connecting rod angle, etc.). The torque available at the crankshaft (engine output shaft) is less than the torque generated by the pistons because there are torque losses inside the engine associated with operating a variety of internal engine components. Torque is transferred from the engine output shaft to the drive shaft via the transmission (sometimes through a torque-converter, or fluid coupling) and through a series of gears that allow the drive shaft to rotate at different speeds relative to engine crankshaft speed. The drive shaft rotation is then transferred to the drive axle via the rear differential. The ring and pinion gears in the rear differential translate the rotation of the drive shaft by 90 degrees; from the drive shaft running along the vehicle to the drive axle that runs across the vehicle. Torque available at the drive axle is then delivered directly to the drive wheels, which generates the tractive force used to overcome road friction, wind resistance, road grade (gravity), and other resistive forces, allowing the vehicle to accelerate on the roadway. Figure 15 illustrates the primary components of concern.

Vehicle performance depends on how much of the available engine torque can be transmitted to the

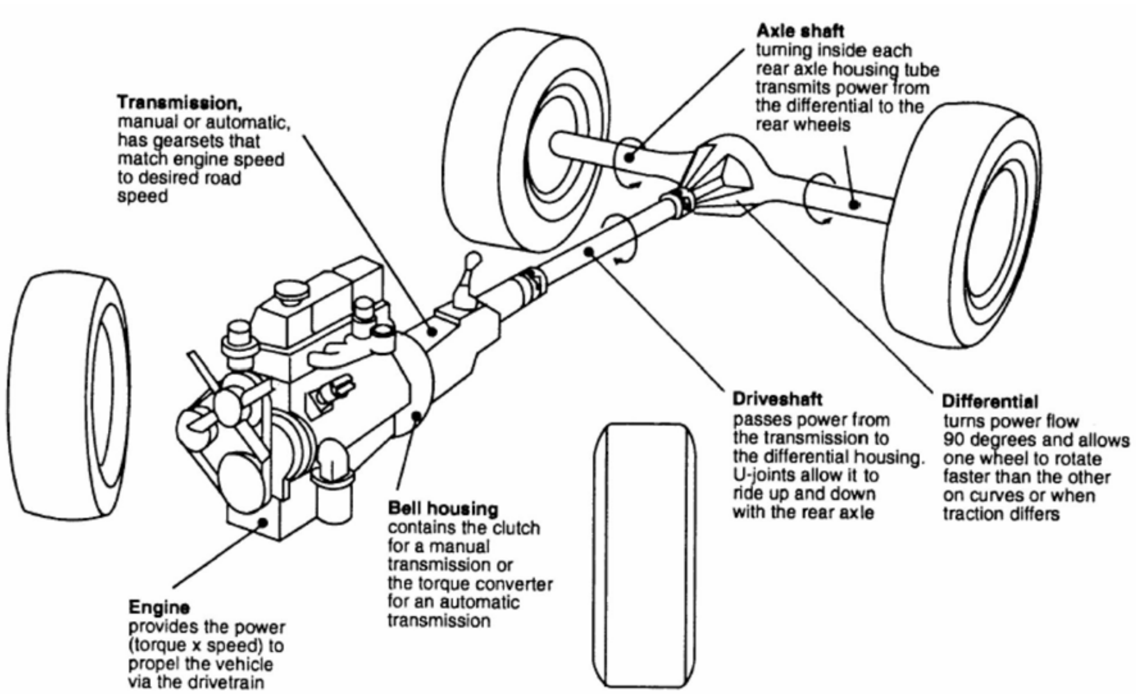


Figure 15. Primary Elements in the Drive Train (Gillespie, 1992).

wheels and used to overcome the resistive forces acting against the vehicle. Torque losses arise in the conversion of engine torque to wheel torque. Work must be performed to overcome resistive and inertial forces within the drive train system. Plus, engines are often called upon to provide power to operate accessories (e.g., air conditioning or refrigeration compressors).

Hence, engine load is composed of observable road load components (to perform the work necessary to overcome external forces such as wind resistance and road friction) as well as for internal components associated with overcoming drive train friction and component inertia and for running accessories.

Power is a measure of how quickly work is performed. Tire rotation (i.e., wheel work) is equal to the force delivered by the wheel torque (torque divided by wheel radius) times the distance traveled by the tire (2π times the radius), or wheel torque times the angular distance per rotation (2π). The power is then the work times the rotational speed (in revolutions per second), where the rotational speed of the tire is a function of engine speed and gear ratios. The formula for axle power is

$$P_A = 2\pi T_A \left(\frac{N_E}{G_t \times G_d}\right)\left(\frac{1 \text{ min}}{60 \text{ sec}}\right)\left(\frac{1\,hp}{550\,\frac{ft \cdot lbf}{\text{sec}}}\right) \qquad (1)$$

where P_A is axle-horsepower (ahp) available for tractive work,
T_A is torque available at the drive axle in foot-pounds force,
N_E is the engine speed in revolutions per minute (rpm),
G_t is gear ratio at the engine transmission, and
G_d is gear ratio in the final drive (differential).

Vehicle velocity is determined directly by engine speed, gearing, and drive wheel radius. Depending upon the operating gear ratio and differential ratio, each rotation of the engine crank shaft provides a different number of rotations of the drive shaft and then of the drive axle (and therefore the drive wheels). Transmission and differential gear ratios allow the wheels to rotate at lower rotational speeds than the engine (which may be operating at more than 4000 rpm). The gear ratio at the differential (G_d), or final drive unit, can range from as low as 3.5:1 to as high as 5.4:1. Higher differential ratios provide greater torque for towing, and lower ratios provide better on-road fuel economy at high speeds. Transmission ratios range from around 2.7:1 (first gear) down to 0.75 (overdrive). Larger heavy-duty trucks tend to operative with five or six gears and with larger ratios in first gear to provide additional torque multiplication to accelerate from a standing stop. In first gear, rotational speed is lower, but torque output is higher. Each wheel rotation results in a distance traveled that is a function of wheel radius. Vehicle velocity is

$$V = 2\pi r \left(\frac{N_E}{G_t \times G_d}\right)\left(\frac{1 \text{ min}}{60 \text{ sec}}\right) \qquad (2)$$

where V is vehicle speed in feet per second, and
r is the radius of the drive wheel in feet.

The relationship between engine speed, gearing, and vehicle velocity can be used to translate the axle power equation to

$$P_A = \frac{V \times T_A}{r \times 550} \qquad (3)$$

At any given instant, the axle horsepower available for tractive work can be quantified through observation of a vehicle's activity. Vehicle velocity can be observed directly. Given that axle torque provides the vehicle motive force at the pavement (torque divided by wheel radius), axle power can be re-written as

$$P_A = \frac{V \times F_m}{550} \qquad (4)$$

where F_m is the motive force available at the pavement in pounds force.

The motive force delivered at the pavement overcomes the variety of resistance forces (road friction, wind resistance, road grade, etc.). These forces can also be quantified if specific vehicle and environmental parameters are known. Any remaining motive force that is in excess of the resistance forces provides vehicle acceleration. Because the vehicle acceleration rate can also be observed, road load horsepower can be modeled as a function of vehicle and operating environment characteristics.

Engine power is equal to the accessory power loss, drive train power loss, and available axle power

$$P_E = P_A + P_{DT} + P_a \tag{5}$$

where P_E is engine brake-horsepower,
P_{DT} is brake-horsepower loss in the drive train, and
Pa is brake-horsepower loss from accessory operations.

Overall brake-horsepower demand on the engine can be estimated when power losses associated with the drive train and accessory operation can be quantified and when axle horsepower demand can be predicted as a function of vehicle characteristics and observed on-road operating parameters. As discussed in the model overview section, once the brake-horsepower demands are quantified, engine dynamometer emission rate relationships (gram per brake-horsepower-hour) can be used directly in emissions modeling.

Larger and larger heavy-duty vehicle emission testing data sets are currently being developed on chassis dynamometers and through on-road testing in which axle horsepower loads (axle horsepower per second) are being measured concurrently with emission rates (grams per second). Chassis dynamometers measure the change in roller drum speed (drum acceleration) produced by excess tractive force delivered by the heavy-duty drive wheels. Axle torque can be calculated, given the rotational inertia of the roller drum. Axle torque and drum speed provide axle horsepower. When such data sets are sufficiently robust, axle-load emission rates (grams per axle-horsepower-hour) can be employed directly without the need for estimating the drive train and accessory power losses. This will require strict accounting within vehicle technology groups to ensure that all vehicles within a technology group are substantially similar with respect to both drive train power loss relationships and parasitic accessory loads, but modeling should improve as a result.

Accessory Power Loss

Engines dynamometer tests measure engine output torque and engine speed (revolutions per minute), and engine horsepower output can be calculated as

$$P_E = \frac{T_E \times N_E}{5252} \tag{6}$$

However, the gross torque and power output reported from these tests represent the operation of the engine with only its internal engine accessories in place. Complete intake and exhaust systems add additional resistance to working gases. The maximum on-road engine power output for an engine equipped with complete intake, exhaust, and cooling systems can be 14% less than the maximum gross power output (Heywood, 1988).

Air conditioning compressor unit physical design and operating pressures determines the engine torque loss (and associated power loss) from cabin comfort operations. In LDVs, as much as 15 peak horsepower can be lost from running an air conditioner. Moreover, air conditioning compressors often operate intermittently, compressing and throttling fluids as needed, meaning that the power demand on the engine for air conditioning can vary.

About 15% to 20% of the available engine horsepower can be lost in the process of overcoming internal backpressures, providing cabin comfort, and operating other engine/cabin peripherals. To predict engine load, any observations of road load horsepower would need to be adjusted upwards to account for these accessory power losses. The Phase I model employs a very simplistic approach to account for accessory losses, which are equivalent to the sum of SAE default power requirement from individual accessories (SAE, 2004).

Engine power takeoffs can also deliver power necessary to operate refrigeration units, alternators, generators, or other major devices. Unfortunately, little information is currently available in the literature regarding power consumption associated with power takeoffs. Additional power losses associated with other accessory loads will not be implemented in the Phase I model. The Phase II model provides the capabilities to implement accessory power loss algorithms as a function of simulated air conditioning draw (as a function of temperature and humidity for each vehicle technology) and will be able allocate large accessory loads to specific heavy-duty vehicle configurations (such as refrigeration trucks). This is accomplished by running each technology group through the power loss calculation, weighted by the fraction of vehicles to which the algorithm applies. The ongoing literature review, future truck stop inspections to identify accessory use relationships, and data becoming available from agencies regarding air conditioning usage and power loss will help to quantify these relationships.

As emission testing provides improved grams per axle-horsepower-hour emission rate relationships, vehicle class-configurations combinations that have large accessory loads can be modeled as their own unique technology groups. This would allow field test axle-horsepower emission rate data to be used directly without further quantification of these accessory loads because the loads are already inherent in the emission rate relationship, essentially in the intercept term.

Drive Train Power Loss

After engine horsepower at the output shaft has been reduced by power losses associated with fluid pressures, air conditioning operation, and other accessory loads, there is still an additional and significant drop in available power from the engine before reaching the wheels. Power is required to overcome (1) mechanical friction in the transmission and differential and internal working resistance in hydraulic couplings, and (2) friction of the vehicle weight on axle bearings. The combined effect of these components will be described as drive train efficiency. The more difficult and more significant component of power loss in the drive train is associated with the inertial resistance of rotating drive train components and their inertial resistance to acceleration.

Mechanical Friction

Friction is inherent in the fluid and mechanical couplings in the drive train (clutch, transmission, and differential). Power demand to overcome these friction forces is a function of the specific technologies employed. Laboratory testing can readily quantify the power demand to overcome these forces, which are functions of drive train design and material composition. Although each engine and vehicle manufacturer undertakes specific testing to quantify these forces (and to develop system improvements designed to reduce them), little information on mechanical drive train loss by vehicle technology is readily available. Most sources show the combined power loss through the drive train system, without isolating the mechanical friction effects.

Torque Converter Losses

Automatic transmissions employ torque converters (a fluid coupling between the engine output shaft and transmission) to transfer rotation from the engine output shaft to the transmission, and power loss in them is a function of input and output rotation speeds. Large differences (i.e., when starting from a standing stop and shifting gears) lead to large power loss. Higher rotational speeds can yield around a 3% loss in power at high speed (best performance conditions). The model will assume that a drive train equipped with torque converters will experience an additional 5% drop in available engine horsepower.

Axle Bearing Friction

The weight of a vehicle must be supported by the tires at the roadway surface. Axle bearings transfer the weight of the vehicle and cargo to the axles, and therefore to the tires, while still allowing the axles to spin freely within the bearing with a minimum of frictional resistance. Due to current bearing technology, this frictional resistance is minimal. Thus, axle friction will not be included in the modeling framework.

Inertial Losses

The engine, transmission, drive shaft, axles, and wheels are all in rotation. The rotational speed of each component depends on the transmission gear ratio, the final drive ratio, and the location of the component in the drive train (i.e., the total gear ratio between each component and the wheels). The rotational moment of inertia of components in the drive train constitutes a resistance to change in motion. The torque delivered by each rotating component to the next component in the power chain (engine to clutch or torque converter, clutch or torque converter to transmission, transmission to drive shaft, drive shaft to axle, axle to wheel) is reduced by the amount necessary to increase angular rotation of the spinning mass during vehicle acceleration. Work has to be performed to accelerate these rotating components. Given the torque loss at each component (Gillespie, 1992), the reduction in motive force available at the wheels due to inertial losses along the drive train can be modeled as

$$F_I = \frac{a \times \left[I_W + \left(G_d^2 \times I_D \right) + \left(G_t^2 \times G_d^2 \right) \times \left(I_E + I_T \right) \right]}{r^2} \tag{7}$$

where a is the acceleration of the vehicle in the direction of motion in feet per second squared,
F_I is force required to overcome inertial resistance in pounds force,
I_W is the rotational moment of inertia of the wheels and axles in foot-pounds (force)-second squared,
I_D is the rotational moment of inertia of the drive shaft in foot-pounds (force)-second squared,
I_T is the rotational moment of inertia of the transmission in foot-pounds (force)-second squared, and
I_E is the rotational moment of inertia of the engine in foot-pounds (force)-second squared.

Inertial resistance is a function of speed, gearing, acceleration, and the specific drive train technologies that affect the mass moment of inertia components of the equation. This force component can be employed directly to estimate power loss from inertial resistance

$$P_I = \frac{V \times F_I}{550} \tag{8}$$

An alternative, but not recommended, approach to modeling inertial power loss is the use of "effective vehicle mass" in all load calculations. This approach indirectly accounts for the inertial load impact by artificially increasing the vehicle mass. By increasing the effective vehicle mass of the vehicle, the available power for acceleration is decreased, and the same effective decrease in power can be incorporated into the model. However, implementation of the indirect approach requires reasonable knowledge of the inertial load relationship for the engine and drive train employed.

To account for effective vehicle mass, the effective moment of inertia is first calculated as

$$I_{Eff} = \left[I_W + \left(G_d^2 \times I_D \right) + \left(G_t^2 \times G_d^2 \right) \times \left(I_E + I_T \right) \right] \tag{9}$$

where I_{Eff} is the effective moment of inertia in foot-pounds (force)- second squared.

The effective moment of inertia for the drive train is a function of the moments of inertia of the drive train components as well as the on-road vehicle operating conditions (transmission gear ratio). The gear ratio of first gear is much higher than fifth gear; moreover, first gear is physically larger and has higher component moment of inertia. Given that the inertial terms employ gear ratio squared, the effective inertia in first gear can be a factor of 40 higher than the inertia in overdrive.

The effective inertia can be translated into an effective weight

$$
\begin{aligned}
M_{Eff} &= \left(I_{Eff}\right)\big/ r^2 \\
W_{Eff} &= \left(I_{Eff}\right)\times g\big/ r^2
\end{aligned}
\tag{10}
$$

where M_{Eff} is the effective mass in pounds (mass),
W_{Eff} is the effective weight in pounds (force), and
g is the acceleration of gravity (32.2 ft/s^2).

This effective weight for any given operating condition can be added to the vehicle weight in developing road load power demand estimates. The effective vehicle weight increase applies only to the drive vehicle and not to towed trailers. The impact of gear selection on effective vehicle weight is illustrated in Table 5.

Table 5: Typical Percent Increase in Effective Vehicle Weight (Excluding Trailer).[a]

Vehicle	Operating Gear			
	High	Second	First	Low
Small Car	11	20	50	140
Large Car	9	14	30	–
Truck[b]	9	12	60	150

[a] Source: Gillespie, 1992
[b] Truck classification not specified.

Gillespie (1992) provides an example calculation for a passenger car illustrating an effect of effective weight contribution due to inertial resistance in first gear of around 880 pounds (or 35% of the vehicle's stationary weight), yet the effective weight contribution in fifth gear is only around 300 pounds (or 12% of the vehicle's stationary weight). A heavy-duty truck drive train is significantly more massive than its light-duty counterpart. Nevertheless, the net effect of drive train inertial mass losses, relative to the weight of the vehicle, when operating in higher gears on freeways, may not be significant enough to include in the model. However, recent studies have shown very high truck emission rates (grams per second) in "creep mode" stop and start driving in ports and rail yards. This may indicate that the inertial loads associated with accelerating drive train rotation in low gear operations may be the most significant factor contributing to emissions from mobile sources in freight transfer yards.

It is important to keep in mind that the effective vehicle mass approach relies on knowledge or measurement of the engine and drive train inertial resistance. Thus, it makes much more sense to model the inertial resistance directly than it does to use an effective mass surrogate.

Driver Behavior

The driver behavior element is planned as a potential enhancement to the inertial load component of the load calculations. Drive train inertial loss depends on transmission gear in which the vehicle is operating for a given speed and acceleration condition. The base approach is to model gear selection for each cell as a probability function. That is, for a given speed and acceleration bin, the vehicle is 80% likely to be in second gear and 20% likely to be operating in 3rd gear. Such estimates will be based solely on empirical evidence from on-road studies. The driver behavior enhancement would predict the likelihood of operating in a specific gear (and therefore at a specific rotations per minute) as a function of driver demographic characteristics and experience level. This approach cannot be implemented without a substantial data collection effort. However, once in place, the module would allow policymakers to model the potential effects of driver training on emissions and fuel consumption.

Drive Train Power Loss Modeling Approach

Each drive train is developed and configured as a system. The transmission and differential systems are 'tuned' to run with the specific engine and tire radius. Engines achieve maximum torque at different engine speeds, but the gearing systems and tires determine the on-road performance of these engines. A single drive train system may be used on many vehicle configurations, and the weight of the various vehicle configurations will significantly affect the vehicle performance. Combined power loss due to the transmission and differential systems can range from 10% to 15%. Older vehicles lose significantly greater power through the gearing system due to older design parameters used in gear tooth profiles. The losses are a function of a wide variety of physical drive train characteristics (transmission and differential types, component mass, etc.) and on-road operating conditions.

Drive Train Efficiency

Given any set of specific coupling, transmission, and differential technologies, the power losses associated with the drive train mechanical friction and axle bearing friction can be determined through laboratory testing. The total efficiency of power transmission from the engine to the road (η_{tot}) can be determined by experiment, provided that parameters necessary to separate rotational moment of inertia losses from drive train mechanical losses are collected or known. In the Phase I model, drive train frictional losses will be set at 4%, with the remaining average efficiency loss from the drive train will be assumed to arise from rotational inertia losses.

As with the accessory load module, the Phase II model provides the capabilities to implement different drive train loss modules as a function of drive train configuration (i.e., based upon laboratory test results as data become available), vehicle configuration, and vehicle weight. This module will likely become increasingly important in the future because the same resistive forces that increase engine load also increase fuel consumption. Technologies designed to reduce losses in the drive train have significant paybacks in fuel savings, and some will pay for themselves over the lifetime operation of the vehicle. This means that the technology makeup of the fleet is very likely to continue to evolve.

Rotational Moment of Inertia Losses

In the Heavy-Duty Diesel Vehicle Modal Modeling Framework, drive train rotational losses are calculated as a direct power loss rather than using the method of modifying vehicle mass in subsequent road load power equations. This method was selected because the inertial power demand is a direct function of drive train component design (component weights and rotational speeds) and independent of the factors that affect road load power demand, with the exception of transmission gear selection. In either method, gear selection would need to be addressed, so the direct power loss function was deemed more practical.

Drivers can achieve a given instantaneous speed and acceleration condition in more than one gear, using a higher gear ratio (e.g., 2nd gear) and lower throttle position, or lower gear ratio (e.g., 3rd gear) and higher throttle position. However, for any given instantaneous speed and acceleration condition, the driver is much more likely to be in one gear than another. This is because the next second of operation depends on the current operation. Selection of the most favorable gear ensures that the vehicle will continue to cruise, accelerate, or decelerate at close to the same rate.

In the Phase I model, the drive train losses will be determined for the fleet. The team will assemble the specifications and performance tests of approximately twenty heavy-duty drive train configurations and will calculate the inertial power losses as a function of various speed/acceleration on-road operating conditions. The researchers will either assume gear selection, or use gear selection information from on-road tests. The average power loss results for each speed/acceleration matrix cell will be calculated for various vehicle configurations. The power loss associated with drive train moment of inertia will then be available for each vehicle configuration and speed/acceleration condition and can be added to the road load power demand and accessory loss to estimate total engine power demand.

In the Phase II model, provided that the inertial power loss is significant enough to warrant complete integration rather than parameterization, the drive train power loss function will employ

- Gear selection probability matrices for each drive train technology class (lookup tables that provide gear ratio probability by speed/acceleration matrix cell),
- Gear and final drive ratio lookup tables for each drive train technology class,
- Gear and final drive moment of inertia lookup tables for each drive train technology class, and
- Power loss matrices (lookup tables specifying power loss as a function of speed and acceleration matrix cell, given the gear selection, gear ratios, and moments of inertia).

Axle Horsepower Relationships

To the extent that emission testing can provide improved grams per axle-horsepower-hour emission rate relationships, combinations of drive train technology and vehicle configurations can be further refined into technology groups. Axle-horsepower emission rate data from field testing could be used directly for each technology group. However, average axle-horsepower emission rates cannot be employed. Specific axle-horsepower emission rates will need to be defined by speed/acceleration matrix cell, to ensure that inertial load power losses emission rates are accounted for. The effects of transmission and drive train resistance would become parameterized within the emission rate relationship as part of the intercept term for the technology group.

System Monitors

To the extent that engine onboard diagnostic data become available from instrumented truck and bus studies, researchers will be able to factor in sensor readings in the hazard component failure models. For example, when onboard systems identify a drop in rpm for given conditions, the change may indicate a maintenance problem, increasing the likelihood of component failure. Once in place, such modules could be used to evaluate the potential benefits of instrumented vehicle automated inspection and maintenance requirements. This will not be included in the Phase I or Phase II models, since such data are not yet available.

Road Load Power Functions

For a vehicle to remain in motion, the tractive force delivered at the drive wheels must overcome resistance forces, including

- Tire rolling resistance forces (F_R), to overcome losses associated with tire/road friction and tire deformation,
- Gravitational force (F_W) associated with vehicle weight when operating on a grade,
- Aerodynamic drag force (F_D) associated with air resistance to vehicle motion, and
- Curve resistance forces (F_C) to overcome the additional frictional force associated with turning the vehicle.

Providing the exact amount of tractive force to balance the resistive forces will maintain the vehicle in motion at its existing speed. Any extra tractive force delivered to the wheels will accelerate the vehicle according to Newton's 2nd law

$$m \times a = F_T - F_R - F_W - F_D - F_C$$
$$\frac{W}{g} \times a = F_T - F_R - F_W - F_D - F_C \tag{11}$$

where m is the vehicle mass in pounds (mass), and FT is the tractive force available at the wheels in pounds force.

The road load prediction component is the heart of the modal model. Engine technologies and on-road operating conditions affect the ability of the vehicle to translate available horsepower into speed and acceleration performance. Given that the on-road speed/acceleration patterns can be observed (or empirically modeled), the modal modeling approach works backwards from observed speed and acceleration to estimate the tractive force (and power) that was available at the wheels to meet the observed conditions. Then, working backwards from tractive force, the model accounts for additional power losses that occurred between the engine and the wheels to predict the total brake-horsepower output of the engine. Each force component that reduces available wheel torque and tractive force is discussed in turn.

Rolling Resistance Force (F_R)

Rolling resistance force (F_R) is the sum of the force required to overcome the combined friction resistance at the tires. Tires deform at their contact point with the ground as they roll along the roadway surface. Rolling resistance is caused by contact friction, the tires' resistance to deformation, aerodynamic drag at the tire, and so forth. Deformation and friction resistance are functions of tire size and type, pavement type, temperature, vehicle weight, and vehicle speed. The force required to overcome the total rolling resistance can be expressed with the coefficient of rolling resistance (C_r), total vehicle weight (W), and road grade

$$F_R = C_r \times W \times \cos(\theta) \tag{12}$$

where θ is the roadway grade angle

The calculations can be performed at each tire, using the dynamic weight component attributed each tire (calculated with using the location of the center of mass and moments relative to the wheel contact points). However, given the linear relationship between weight and resistance and given that neither the coefficient of rolling resistance nor grade varies from tire to tire, there is no need to estimate for each tire. The net coefficient of rolling resistance can be estimated as a function of vehicle speed and the road surface coefficient by using the SAE equations for various tire types (Tables 6 and 7).

$$C_r = b_1 + \left[b_2 \times \text{speed}\left(\text{mi/h}\right) \times SC\right] \qquad (13)$$

where b_1 and b_2 are parameters from Table 6, and SC is the road surface coefficient from Table 7.

Table 6. The Coefficient of Rolling Resistance Tire Parameters.

Tire Type	b_1	b_2
Bias-ply	0.636	0.00530
Standard Radial	0.424	0.00495
Profile Radial	0.350	0.00495
Wide Base Single Radial	0.303	0.00495

Table 7. Road Surface Coefficient.

Road Surface Type	SC
Wet Black Top	0.8
Smooth Concrete	1.0
Worn Concrete, Brick, or Cold Black Top	1.2
Hot Black Top	1.5
Hard Packed Soil	1.5–2.0
Packed Gravel	12.0
Loose Gravel	7.5
Sand	12.0

Tire temperature also has a slight impact on rolling resistance. Tire temperatures increase to their final equilibrium operating temperature over a distance of approximately 40 miles of travel. During the initial 40 miles of travel, rolling resistance is higher than predicted by the above equation. The coefficient of rolling resistance starts at about 120% of the value achieved at equilibrium, and the drop-off is fairly linear. Given the small impact that this factor will have on overall engine load, the Phase I model will assume that all vehicles have traveled 40 miles before reaching the network. The Phase II model may contain an enhancement if the phase I sensitivity analysis indicates that tire temperature has a significant effect on operating load.

Gravitational Weight Force (F_W)

The gravitational force components account for the effect of gravity on vehicle weight when the vehicle is operating on a grade. It is the component of the vehicle weight parallel to the road. The grade angle is positive on uphill grades (generating a positive resistance) and negative on downgrades (creating a negative resistance or a positive tractive force).

$$F_W = m \times g \times \sin(\theta) \qquad (14)$$

Gravitational force of vehicle weight (F_W) is expressed in units of pounds (force) and can be re-written as a function of vehicle weight (W) and road grade

$$F_W = W \times \sin(\theta) \qquad (15)$$

The combined vehicle weight includes the towing vehicle plus the trailer load. The weight is not dispersed evenly throughout the combined vehicle, but the units are assumed to always be operating on the same grade.

To implement the gravitational force calculation in the model, it is necessary to have information on road grade. The relationship between F_W and θ is fairly straightforward. The sin(θ) relationship, means that an increase tractive force demand on a positive grade exactly cancels a tractive force demand decrease on the same negative grade. That is, if 50% of the activity on a roadway link is on a 2% upgrade and 50% is on a 2% downgrade, the effect is the same as if 100% of the activity had occurred on a flat roadway. The effect is also nominally linear at grades experienced on major arterials and freeways in urban areas. That is, the net effect of averaging grade on a roadway link is not significant when the grades in question are less than 10%. For a 60,000 pound truck operating 50% of the time on a 10% grade and 50% of the time on flat road, the net difference between calculating each half separately and performing the entire calculation at 5% grade is less than a difference of 20 lbf. This is less than a 0.4% difference in the F_W calculation and is completely insignificant in terms of the net change in tractive force when other factors such as aerodynamic drag and roadway friction are included in the calculations. Therefore, grade averaging will be undertaken in implementing the gravitational force algorithm on a link-by-link basis.

Although the effect of grade on power demand is effectively linear and the average grade for that roadway segment can be used in calculations that employ a speed/acceleration matrix, this does not mean that grade variability has the same linear effect on on-road operations. For roadway segments that contain variable grade, the on-road speed/acceleration operations on the uphill segments can differ significantly from the downhill segments. Similarly, operations on the extreme uphill segments will be different than those on the level segments. In the example provided above, a 5% grade can be used to reflect the gravitational effect when half of the activity occurs at 10% grade and half is on level road. This is not the case with the speed acceleration profiles. Grant (1998) observed that the speed acceleration profiles of trucks are significantly different on uphill grades than on level terrain. In addition, Grant (1998) observed that the presence of trucks on the uphill freeway grades affects not only the truck speed/acceleration conditions, but the speed/acceleration conditions of the LDVs operating on the system as well. Thus, the speed/acceleration matrices employed in link-by-link calculations must also incorporate the effect of grade.

Aerodynamic Drag Force (F_D)

As a vehicle moves forward through the atmosphere, drag forces are created at the interface of the front of the vehicle and by the vacuum generated at the tail of the vehicle. In fact, the flow of the air around the vehicle creates a very complex set of force vectors providing both resistance to forward motion as well as vehicle lift. The sum of the drag forces is typically expressed as aerodynamic drag (F_D) in pounds (force). Aerodynamic drag is a function of air density, drag coefficient (C_d), vehicle frontal area, and effective vehicle velocity.

$$F_D = \left(\frac{\rho}{2g}\right) \times C_d \times A_f \times V_e^2 \tag{16}$$

where ρ is air density in pounds (mass) per cubic foot,
A_f is the vehicle frontal area in square feet, and
V_e is the effective vehicle velocity in feet per second.

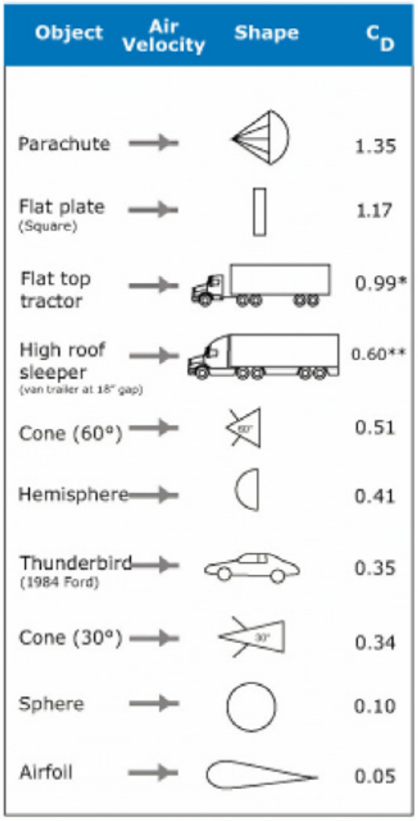
At standard conditions (59 °F and 29.92 in of mercury) air density is 0.076 lb/ft^3. The air density, is a function of atmosphere pressure and temperature, and can be estimated in English units as

$$\rho = 0.07552\left(\frac{P_r}{29.92}\right)\left(\frac{519}{460 + T_r}\right) \tag{17}$$

where P_r is the atmospheric pressure in inches of mercury, and
T_r is the atmospheric temperature in degrees Fahrenheit.

In the load model, each HDV configuration will be assigned a drag coefficient ranging from 0.6 to 0.99, depending on the design and any aerodynamic information that can be located in the literature. Typical aerodynamic drag coefficients provided by Ford Motor Company are shown in Figure 16.

Effective Vehicle Velocity (V_e) is the sum of vehicle speed and wind speed, where wind speed is positive if it blows toward the vehicle (headwind) and nega-



Drag Coefficient of Various Shapes
'Source: Ford Motor Co. *National Research Council of Canada, **NASA)

Figure 16: Typical Aerodynamic Drag Coefficients.

tive if it blows in the direction of travel (tailwind). Atmospheric winds vary in intensity, with typical mean values of 10-20 mph. Given the nature of the nonlinear relationship between effective velocity and aerodynamic drag (a squared effect), ignoring on-road winds (i.e., using a single average value of zero for wind speed) will introduce a negative bias into the predicted effect on engine load. Take, for example, a single truck (i.e., constant drag coefficient and frontal area) operating at a constant temperature (i.e., constant air density). If this vehicle drives at 60 mph on the freeway 50% of the time with a 15 mph headwind and 50% of the time with a 15 mph tailwind, the net drag force will be about 6% higher than if all travel were undertaken with wind speeds equal to zero. Introducing hourly wind fields into the model is possible over the long term. However, link based calculations would increase geometrically to reflect the interactions between each vehicle configuration and wind speed. In the Phase I model, a regional wind rose will be used with the standard drag force calculation equation to develop a correction factor that will increase each drag force calculation by a percentage to reflect the effect of variable wind speeds and directions. Side wind velocities will be ignored in the modal model, even though they do contribute to vehicle yaw, which must be compensated for through increased road load.

Drag forces do increase when a vehicle encounters resistance air flow from a side angle. The flow of air around the vehicle becomes uneven, with more drag created on one side of the vehicle than the other. Crosswinds increase the effective drag coefficient in the relationship expressed above as a function of wind angle. For example, a 10 degree angle of crosswind can increase the drag coefficient of a pickup truck by 0.10 (Gillespie, 1992). In the Phase I model, crosswinds will not be included.

Aerodynamic Lift Adjustment

The same flow of air across the vehicle that creates an aerodynamic drag force also produces aerodynamic lift. Lift force is proportional to air density, vehicle speed squared, the coefficient of lift, and frontal area. The lift generated by wind flow can change the dynamic loading at each tire. The net effect is to reduce the effective vehicle weight, which will effectively reduce rolling resistance forces and gravitational weight forces. Until reliable lift data can be compiled for truck-trailer technologies, the lift force will not be included in the modal model.

Curve Resistance Force (F_C)

Curve resistance is the additional frictional force on the roadway associated with turning the vehicle and resulting from the angled alignment of the front wheels. The dynamic power loss can be estimated as:

$$F_C = \frac{0.00215 \times V^2 \times W}{R_m} \tag{18}$$

where R_m is the radius of curvature in feet.

This resistance force may not be significant on high speed highways because the radius of curvature is very large. Sensitivity analysis will be performed on Atlanta freeways to determine if freeway estimation can be ignored. However, curve resistance should be relatively high at intersections when vehicles make 90 degree tight radius turns. For instance, the curve resistance would be a large component of transit bus tractive force, because the buses make numerous 90 degree intersection turns during daily service. Because bus routes are known commodities in the GIS-based modeling system, transit vehicle modeling will incorporate this function unless sensitivity analysis determines that the effect is minimal and can be ignored.

Payload Inertial Resistance (F_P)

When a vehicle or trailer is at rest, the load is distributed across the wheels such that the sum of the moments about the center of mass cancel. That is, when weight is placed toward the front of a trailer, more of the weight is carried by the front axle and the front tires. If the moments did not cancel, the trailer would rotate about its center of mass.

When a vehicle and trailer accelerate, a new moment is created, causing the vehicle and trailer to shift load forces toward the rear axle. The front of the vehicle and the trailer rotate upwards until the load on the tires is sufficiently redistributed to stop the rotation. Similarly, when a vehicle decelerates, the vehicle and trailer rotate slightly forward and the load is shifted toward the front axles and tires. A portion of the motive force being delivered to the wheels is lost in compensating for the rotational moment of inertia of the vehicle and trailer load. Although the change in rotational speed is small, changing from zero rotations per second to a very slow rotational speed caused by the temporary weight shift, the payload involved may be quite large. The research team is currently working through the calculation methodology that can be implemented by vehicle and trailer configuration type to incorporate the inertial loss from the overall vehicle and trailer weights, as well as from the spatial distribution of the payload within the trailer. The Payload Inertial Loss (F_P) factor will be included in the Phase II model for vehicle classifications and configurations for which the force is significant.

Available Tractive Force (F_T)

For "theoretically correct calculations," the dynamic weight of the vehicle should include the effects of acceleration, towing forces, curve forces, and even the lift component of air resistance (Gillespie, 1992). However, Gillespie (1992) also notes that introducing some of the dynamic weight components in vehicle performance estimation can complicate the calculations "without offering a significant improvement in accuracy." In Phase II model development, sensitivity analyses will help ascertain which dynamic components should be added.

Any remaining tractive force after removing rolling resistance force, gravitational weight force, and aerodynamic drag force is available to accelerate the vehicle. According to Newton's 2nd law, net remaining force is equal to vehicle mass (m) times acceleration (a).

$$\begin{aligned} m \times a &= F_T - F_R - F_W - F_D \\ \frac{W}{g} \times a &= F_T - F_R - F_W - F_D \end{aligned} \tag{19}$$

The tractive force equation can be rewritten into the power equation

$$\begin{aligned} P_A &= \frac{V \times F_T}{550} \\ &= \frac{V \times \left(m \times a + F_R + F_W + F_D \right)}{550} \\ &= \frac{V \times \left(\frac{W}{g} \times a + F_R + F_W + F_D \right)}{550} \end{aligned} \tag{20}$$

For any vehicle and drive train technology groups and for any given speed and acceleration combination (from a speed/acceleration matrix for the technology group), the tractive horsepower load can be estimated. The first step is to calculate each of the resistance coefficients using the relationships defined earlier in this section. Using the average speed and acceleration value in a matrix cell, the tractive horsepower is calculated. Then, engine horsepower is derived by solving for other horsepower losses

$$P_E = P_A + P_{DT} + P_a \tag{21}$$

where P_E is brake engine horsepower,
P_{DT} is horsepower loss in the drive train, and
P_a is horsepower loss from accessory operations.

Hence, for every vehicle and drive train technology group, and every speed/acceleration matrix cell, the brake engine horsepower demand can be calculated.

Emission Rate Functions

In the Phase I model, basic work-related emission rates (grams per brake-horsepower-hour) will be established for each technology group in the model. As discussed earlier, technology groups are developed in an effort to group vehicle class, drive train, and configuration combinations with similar laboratory performance and on-road load performance. Appendix D provides the laboratories and contact names from whom data have been requested. Appendix E outlines some of the testing programs and data that are available for development of the Phase I and Phase II emission rate models.

Phase I modeling employs base emission rates (grams per brake-horsepower-hour) for each technology group derived from in-use engine testing certification compliance data. Actual certification values will be used for groups for which in-use testing data are available to derive statistically significant emission rates. The U.S. EPA and California Air Resources Board (CARB) in-use observational databases will provide these values.

The Phase II model will employ load-related emission rates. Regression analysis will provide the emission rate relationship between grams per second emission rate and axle-horsepower, as revealed through preliminary analysis of chassis dynamometer data (Ramamurthy and Clark, 1999; see Figure 17). The data required for analysis must come from chassis dynamometer and on-road test programs in which second-by-second grams per second emission rate data have been collected concurrently with axle-horsepower loads. A linear or generalized relationship is established between grams per second

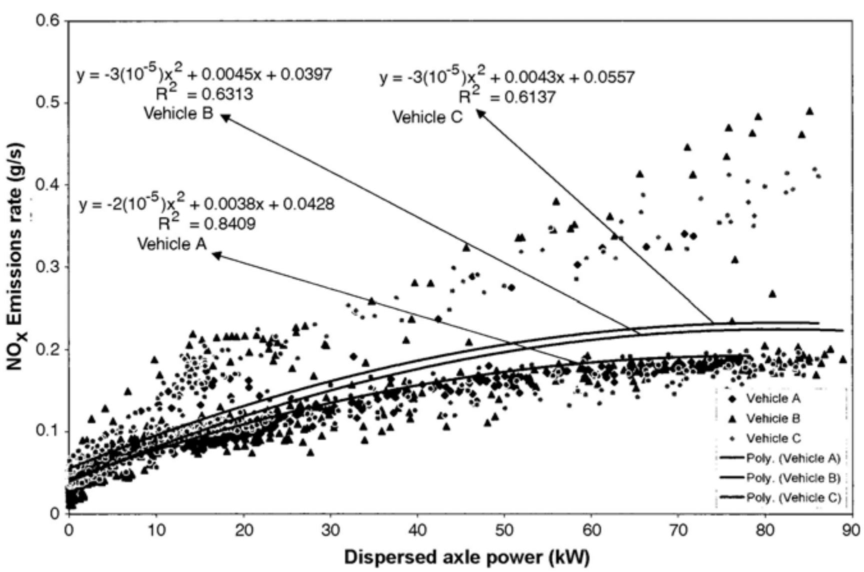


Figure 17. Example Emissions vs Axle-Horsepower (Ramamurthy and Clark, 1999).

emission rate and tractive horsepower (axle horsepower). Sufficient testing data are required to establish statistically significant samples for each technology group.

Emitter Category

As discussed in the fleet characterization section, on-road vehicles are classified as either high-emitters or normal-emitters. The vast majority of HDVs are normal emitters, but a small percentage of vehicles have been tampered with or are poorly maintained. For all on-road operations, on-road vehicle activity by vehicle class, configuration, and drive train technology will be divided into two emitter fractions. Higher grams per brake-horsepower emission rates will be applied to the high-emitter fraction based upon review of the literature. Hence, for each technology group on the roadway, a high-emitter fraction will be tracked. The applicable emission rates for each technology group will be determined through regression tree analysis of high emitting data (Wolf, et al., 1998). For all on-road operations, on-road vehicle activity by vehicle class, configuration, and drive train technology will be divided into two emitter fractions. Higher grams per brake-horsepower-hour emission rates will be applied to the high-emitter fraction, based on review of the literature. Hence, for each technology group on the roadway, a high-emitter fraction will be tracked. In Phase II model development, the goal will be to include a hazard-type model to predict the fraction of high-emitters on the road as a function of accrued vehicle mileage, vehicle age, applicable inspection programs, and so forth.

Commanded Fuel-Lean Operation

A significant percentage of on-road heavy-duty trucks are subject to a recent EPA enforcement action. The emissions from these vehicles were found to be significantly lower in the laboratory under standard certification test procedures compared to the emissions noted under alternative testing conditions that better reflect on-road operations. These engines tended to jump into a lean-on-cruise (enleanment) operating condition under extended cruise operations on freeways, which provides significant fuel economy benefits for truck owners but significantly increases emission rates for oxides of nitrogen. Although many of the vehicles have been retrofitted and reprogrammed to minimize the problem, recent studies indicate that non-compliance may still be a significant issue.

Information provided by the University of California Riverside CE-CERT Mobile Heavy-Duty Vehicle Laboratory (CE-CERT, 2004) illustrates the difficulty in implementing a purely load-based model. The "stylized" plot shown in Figure 18 illustrates NO_X emission rates vs horsepower.

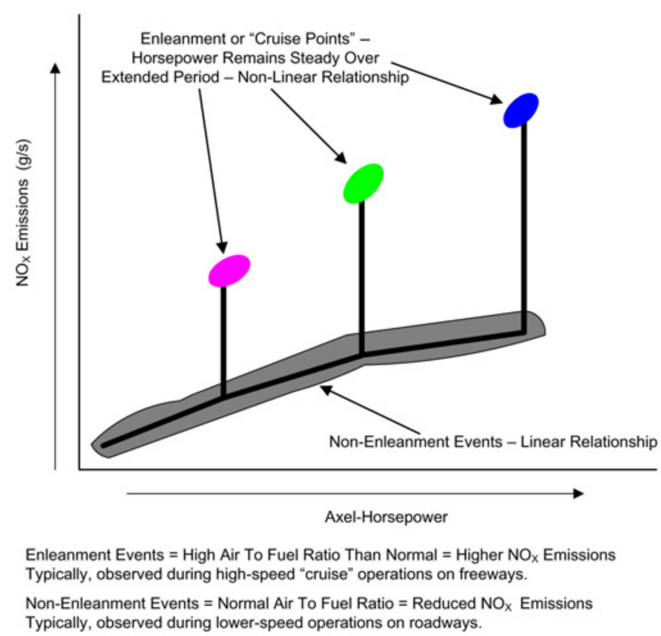


Figure 18. Stylized Plot of Axle-Horsepower vs NO_X Emissions (grams/second).

Although it is possible to examine the instantaneous relationships between NO_X emissions rates and axle horsepower, the figure shows three "cruise" points where the horsepower load remained steady for an extended period. The activity represented by the extended cruise conditions represents approximately 30% of the test data. When these data points are removed from the data and placed in their own model regime, the remaining 70% of the data follow the linear relationship between emission rate and load.

The first step toward modeling the effects of extended cruise is to establish the criteria under which extended cruise emissions elevate. This can be defined through analysis of laboratory testing results. The definition would be established in terms of time at speed and acceleration range. For example, laboratory testing may indicate for a vehicle class and drive train technology that extended cruise begins once a vehicle spends more than 45 seconds a single speed (±5 mph) and acceleration rate (±1 mph/s) and ends when the vehicle activity falls outside this window. To incorporate the effect of extended cruise on emissions, a third dimension will be added to the speed/acceleration matrices for the vehicle class, configuration, and technology groups affected by extended cruise. This dimension will carry the percentage of activity in each speed/acceleration matrix cell that occurs under extended cruise. Once in place, this percentage of activity in each call can be assigned elevated emission rates appropriate for the noted load.

Correction Factors and Environmental Factors

The current modeling regime includes adjustments to basic emission rates to account for the effects of accrued vehicle mileage (deterioration), temperature, humidity, and altitude. The basic modeling approaches employed in the current emission rate models are outlined in Appendix F. In the MOBILE6 modeling regime, all correction factors are assumed to have independent effects on basic emission rates. The same will be true in this modeling regime, sufficient data are collected with adequate controls over multiple variables such that interaction effects can be determined. Each correction factor is discussed in turn.

Deterioration Rates

As LDVs age and accrue vehicle miles of travel, emission rates (gram per hour or gram per mile) tend to increase. Evidence of the deterioration of vehicle combustion and control systems are evident in the LDV fleet through in-use laboratory testing programs, inspection and maintenance testing programs, and remote sensing programs. The current MOBILE6 Model includes a deterioration rate effect on emissions. However, based upon review of the emission testing data used in the development of the EMFAC-2000 motor vehicle emission factor model, the increase in emissions rates over time were not adequately demonstrated within the heavy-duty diesel truck test fleet used to develop the EMFAC2000 emission rates.

In developing EMFAC2000, CARB compiled chassis dynamometer test results for medium-heavy-duty (14,001 to 33,000 pounds GVWR) diesel vehicles (MHDDVs) and heavy-heavy-duty (more than 33,001 GVWR) diesel vehicles (HHDDVs).Three data sets were available for HHDDVs (14 vehicles tested for New York by West Virginia University, 5 vehicles tested at high-altitude by the Colorado School of Mines, and 5 additional vehicles tested by West Virginia University). MHDDV tests included 21 vehicles tested for New York by West Virginia University and 6 vehicles tested at high-altitude by the Colorado School of Mines. All vehicles ranged from 1981 to 1998 model year. Each vehicle was tested from two to six times (replicate testing), and test results were averaged for each vehicle.

In assessing the West Virginia testing data employed in EMFAC2000 development (leaving out the high-altitude tests due to problems noted in the altitude correction factor discussion that follows), dummy variables were created for engine certification model year groups (i.e., when different certification standards for various pollutants applied to each group of engines). The dummy variables serve as surrogates for changes in emissions control systems and engine computer algorithms that may have helped reduce emissions. Certification groupings were pre-1984, 1984-1987, 1988-1990, 1991-1993, 1994-1997, and 1998-2002. Interaction variables were created for the certification groups to test the interactions of these groups with odometer reading. From a theoretical perspective, use of certification group coupled with deterioration interactions is preferable to emissions derived as a function of model year.

Regression analysis results indicated that modeling PM emissions is significantly improved when modeled as a function of certification groups rather than model year. Accrued vehicle mileage was not a significant explanatory variable, probably because the accrued mileage effect is already partly explained by the certification group (i.e., is correlated with vehicle model year).

Based on the limited data examined, deterioration cannot be differentiated from vehicle age as reflected in the certification group. Heavy-duty diesel engines are sleeved for rebuild, so it is possible that engine overhauls minimize any deterioration effect within a certification group. Larger samples would likely support the development of accurate deterioration rates.

A significantly expanded data set, tested under a wider variety of conditions and in both altitude locations, would help determine the factors likely to dominate the emissions effect. In updating the heavy-duty emission rates for upgrading EMFAC2000 to EMFAC2002, CARB employed 75 engine tests (CARB, 2002). These data will be procured and analyzed in the same manner. The Energy and Environmental Analysis, Inc. (EEA, 2000) report that provides the basis for the deterioration rates will be critically reviewed as well. In the Phase I model, deterioration rates will not be included. Deterioration rates will be incorporated into the Phase II model if statistically significant effects can be determined from data analysis.

Temperature

In the MOBILE6 model, temperature correction factors adjust exhaust emissions to temperatures that fall outside of the standard laboratory conditions (within a window surrounding 75 °F). Tests are performed on vehicles or engines at a variety of temperatures, and the ratios of observed test results and baseline test results establish the relationship between emission rates and temperature. Temperature correction factors are not applied to diesel vehicles, so from the perspective of model implementation this is not a problem.

High ambient temperature can also increase engine load due to increased air conditioner use. If data are available to provide relationships between temperature and humidity and air conditioning usage, these relationships will be integrated into the accessory load module in the Phase II model.

Humidity

Data used to develop humidity correction factors have not yet been compiled and assessed. Previous assessments performed by the research team indicate that the correction factors are likely based on small samples (and may not be statistically significant). The test results will be compiled and reassessed. If the correction factors are defensible, they will be incorporated into the model as a linear adjustment factor.

Altitude

MOBILE6 employs a high-altitude HDV emission rate correction factor of 1.47, based on EPA’s report prepared during the development of MOBILE6 (CARB, 2000). Although this correction could be built directly into the model and applied to all technology groups and operating conditions, the researchers believe that this should not be done until such a relationship is clearly established through statistical analysis. Based on review of the emission testing data used in the development of EMFAC2000, the increase in emissions rates over time were not adequately demonstrated within the test fleet.

In assessing the West Virginia and Colorado (high-altitude) test data employed in EMFAC2000 development, dummy variables were created for engine certification model year groups (pre-1984, 1984-1987, 1988-1990, 1991-1993, 1994-1997, and 1998-2002), and interaction variables were created for the certification groups to test the interactions of these groups with testing at high altitude. Altitude was entered into the equation as a dummy variable, and the Colorado data appeared to show altitude effects with respect to PM emissions. This impact appeared to influence the intercept term of the equation. However, when modeled as an interaction variable across the certification groups, the analyses indicated that altitude interactions were only present for some (older) certification groups. The findings indicated that altitude corrections should probably be modeled separately across certification groups.

Larger data sets will be required to make this determination. The data set employed in the development of EMFAC2002 will be similarly reviewed. A remote sensing study also appears to indicate that there is a significant relationship between altitude and HDV performance (Bishop, 2001). Bishop reported the remote sensing measurements of emissions from 5772 heavy-duty diesel trucks between 1997 and 1999 at five locations in the United Sates and Europe. The results show a statistically significant increase in carbon monoxide, hydrocarbons, and nitric oxide with altitude. The report also indicates an increase in fuel consumption as well (Bishop, 2001). This study will be reviewed by the research team.

The Phase I model will not incorporate an altitude correction factor (which, in any case, is not needed for Atlanta). If the results from the review of the EMFAC2002 database and the Bishop (2001) study indicate that high-altitude correction factors are statistically defensible, they will be integrated in the Phase II model as a linear adjustment factor by pollutant.

Inventory Assembly and Model Output

The inventory assembly process is essentially a set of link-by-link emissions calculations using the link attributes, subfleet technology group attributes, and the load-based equations. The calculations are processed as follows:

Emission Matrix Calculations

- Speed/Acceleration Matrix - For each vehicle class, configuration, and drive train technology group, an applicable speed/acceleration matrix is selected.
- Total Link Vehicle Hours - Given the technology group traffic volumes (vehicles per hour traversing the link), the road length, and average travel speed for the road, total technology group vehicle-hours of travel are computed for the link.
- Vehicle-Hour Matrix - The speed and acceleration frequency distributions provide the fraction of on-road hours of travel that are undertaken in each speed/acceleration bin. Multiplying the matrix by total vehicle-hours of travel provides the vehicle-hours of travel for each speed/acceleration bin.
- Road Load Matrix - The road load power demand (brake-horsepower) associated with each speed/acceleration matrix cell can be calculated using (1) the average speed and acceleration rate in each matrix cell and (2) the various vehicle and roadway parameters from each vehicle class and configuration technology group.
- Inertial Loss Matrix – The inertial loss matrix associated with specific drive train technology provides the inertial power loss for each matrix cell.
- Accessory Load Matrix – The accessory load matrix provides the accessory power loss for each matrix cell.
- Power Demand Matrix – The values in the road load matrix are added to the technology group inertial loss matrix and accessory load matrix to estimate total engine power demand (brake-horsepower) for the specific operating conditions in that cell.

Phase I Model Emission Calculations:

- Work Matrix - The power demand matrix (brake-horsepower in each cell) is multiplied by the vehicle-hour matrix (hours in each cell) to obtain a matrix of brake-horsepower-hour engine work by speed/acceleration matrix cell.
- Average Work-Related Emission Rate - For each technology group, the average work-related emission rate (grams per brake-horsepower-hour) from dynamometer testing is quantified.
- Emission Calculation - The work matrix is multiplied by the average work-related emission rates for the technology group (grams per brake-horsepower-hour).
- Cell Addition - Total grams per cell are added to develop the hourly total emissions (grams per hour).

Phase II Model Emission Calculations:

- Emission Rate Matrix – Emission rates (grams per second) are modeled as a function of brake-horsepower load. Using the values in the power demand matrix (brake-horsepower) for each cell, a matrix of emission rates (grams per second) is created for each technology group and converted to grams per hour, where the emission rate in each cell applies to the activity in that cell.
- The emission rate matrix values are multiplied by their counterparts in the vehicle-hour matrix to estimate grams of emissions for each matrix cell.

- Cell Addition - Total grams per cell are added to develop the hourly total emissions (grams per hour).

Integration of Link-Based Emissions

Working in the GIS system and using a graphic user interface similar to the one developed for MEASURE (Figure 19), the user can either examine link-by-link emissions (grams per link per hour) or aggregate the emissions predictions to any grid cell size. Because the hourly predicted emissions become link attributes in the GIS system, the user can create useful graphics to illustrate the source and intensity of heavy-duty diesel emissions. Figure 20 illustrates the graphic output capabilities of the MEASURE model, and similar capabilities will be integrated into the Heavy-Duty Modal Model (Bachman, 1997). Because the emissions are retained at the link level and also aggregated on a grid cell basis, the emissions predictions can be used in line source microscale impact assessment as well as in regional ozone or particulate matter dispersion modeling.

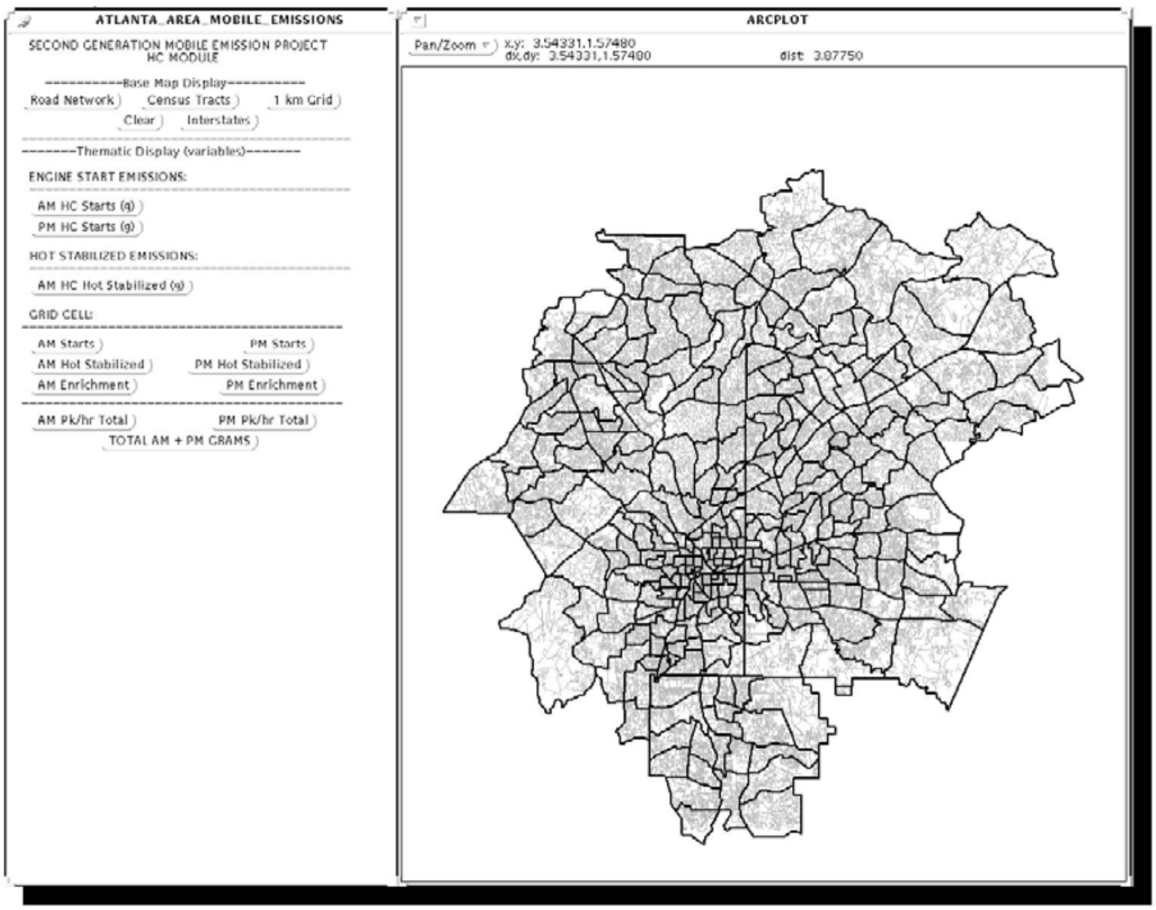


Figure 19. Graphic User Interface Developed for MEASURE.

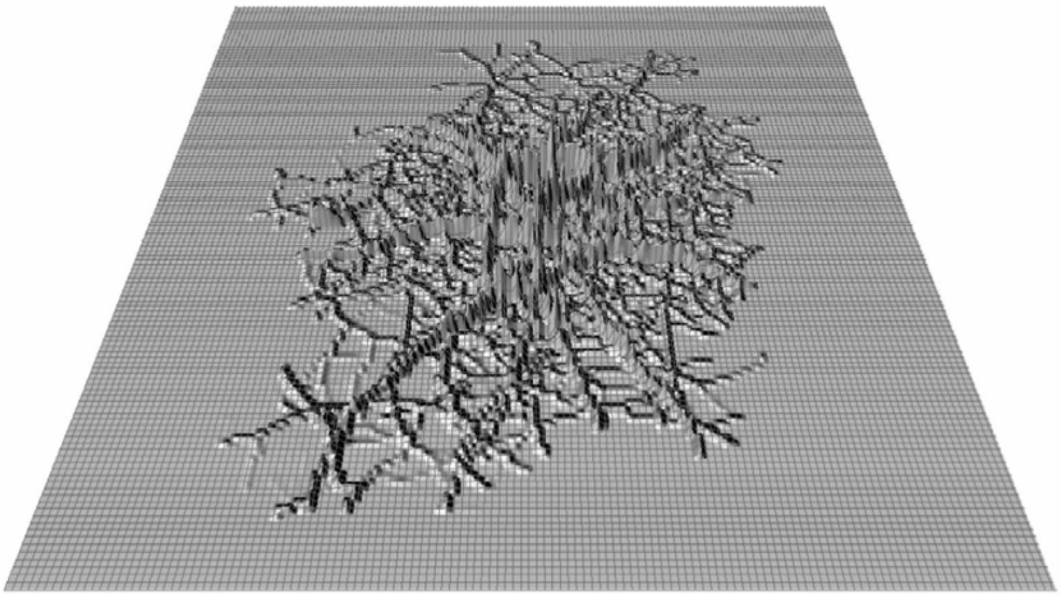


Figure 20. Example of Grid 8-9 AM Cell Emissions from MEASURE.

Case Study of Two MARTA Transit Bus Routes

In late summer 2004, the research team equipped two MARTA transit buses with the same Georgia Tech trip data collectors used in the Commute Atlanta instrumented vehicle study. Second-by-second data were collected from these two vehicles over a period of months while the buses served on a wide variety of metro routes. The MARTA bus SAFD is truncated at 55 mph (rather than extending to 100 mph) because speeds higher than 50 mph do not take place on the city routes. Acceleration bins in the example matrix range from -15 to +15 ft/s^2, in 1 ft/s^2 bins. Accelerations that are greater than 15 ft/s^2 or less than -15 ft/s^2 are placed in the last bin. Cells on speed-acceleration matrices were filled with acceleration frequency fractions for corresponding speed and acceleration bins. For each roadway type and for each time of day, a unique speed-acceleration matrix can be created.

The months of second-by-second on-road bus operating data collected during the late summer of 2004 was processed to develop matrices for use in load modeling. Figure 21 is an example of some of the MARTA routes sampled in Atlanta over a three week period. In order to secure data samples from a variety of buses, the Georgia Tech research team also installed a trip data collector on a MARTA transit bus different from the ones used in the late summer 2004 program and collected second-by-second speed data for three weeks, from June 28 to July 17, 2004, as part of a six month data collection program. Data are collected during all times of vehicle operation, as the bus travels MARTA service routes and during deadhead operation. Transit bus speed and location data collected with the GPS receiver and stored in the data storage are remotely transmitted to a server computer managed by Georgia Tech. From the second-by-second speed data, researchers calculate corresponding second-by-second acceleration. Then, speed and acceleration data are grouped by roadway type and by time of day and used to create road and time-of-day specific speed/acceleration matrices.

After the map matching process, transit bus trips for three weeks were identified on ArcGIS, a desktop mapping product by Environmental Systems Research Institute (ESRI). From the transit bus locations, four types of activities were observed: regular bus service, approach for service, return after service, and idling at garages. Among the four types of services, only the regular bus service activity was considered for the speed and acceleration analyses. During the three-week study period, the bus served ten regular bus routes for more than fifteen vehicle-days total. The data points on the bus service routes provided 249,022 seconds of activity. Among the data points, 64% of data were on arterial roads, 35% on local roads, and 1% on freeways. Relatively few data points were observed on freeways, so they were excluded from analyses. Researchers removed data points with speed of zero mph (representing idling at intersections, bus stops, and terminal) before beginning speed and acceleration analyses on arterial and local roads. In total, 244,203 data points (157,471 on arterial roads and 86,732 on local roads) were analyzed for transit bus speed and acceleration characteristics. The data clouds are provided in Figures 22 and 23, while Figures 24 and 25 provide the data in traditional Watson plots format. Finally, the binned results can be employed as a calculation matrix described previously (Figure 26).

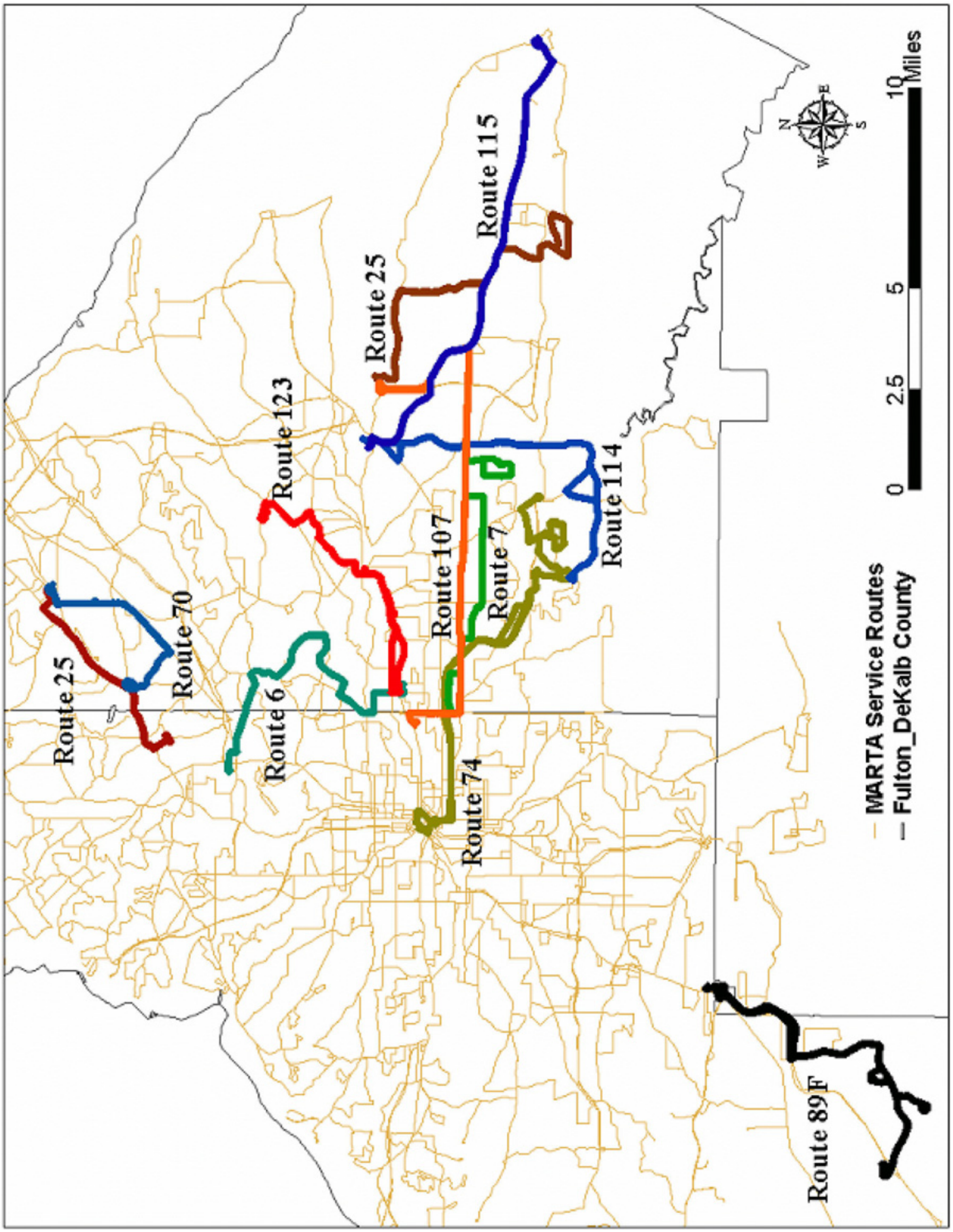


Figure 21. Example MARTA Transit Bus Routes on which Speed and Location Data were Collected.

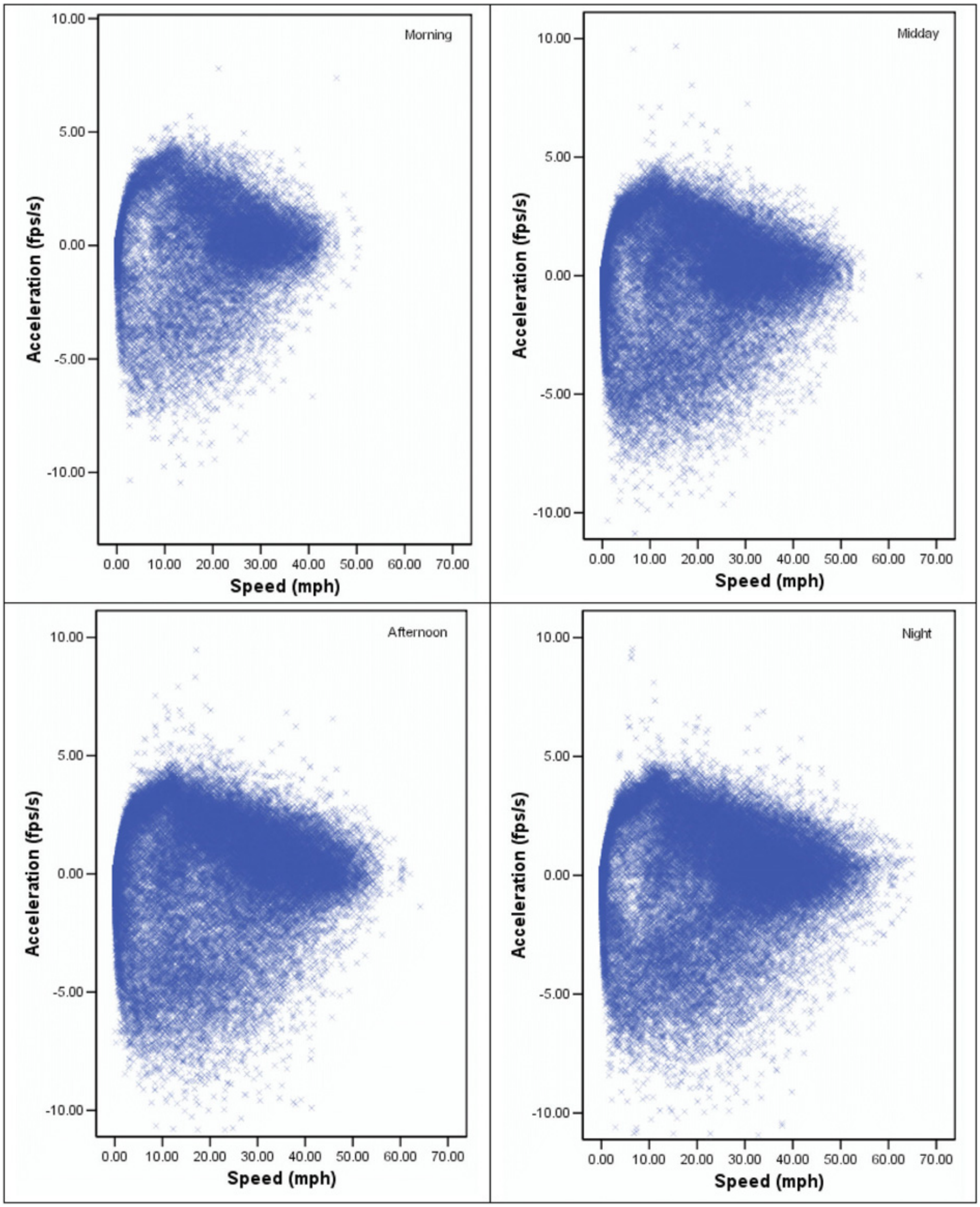


Figure 22. Speed-Acceleration Scatter Plots for Arterial Roads by Time of Day.

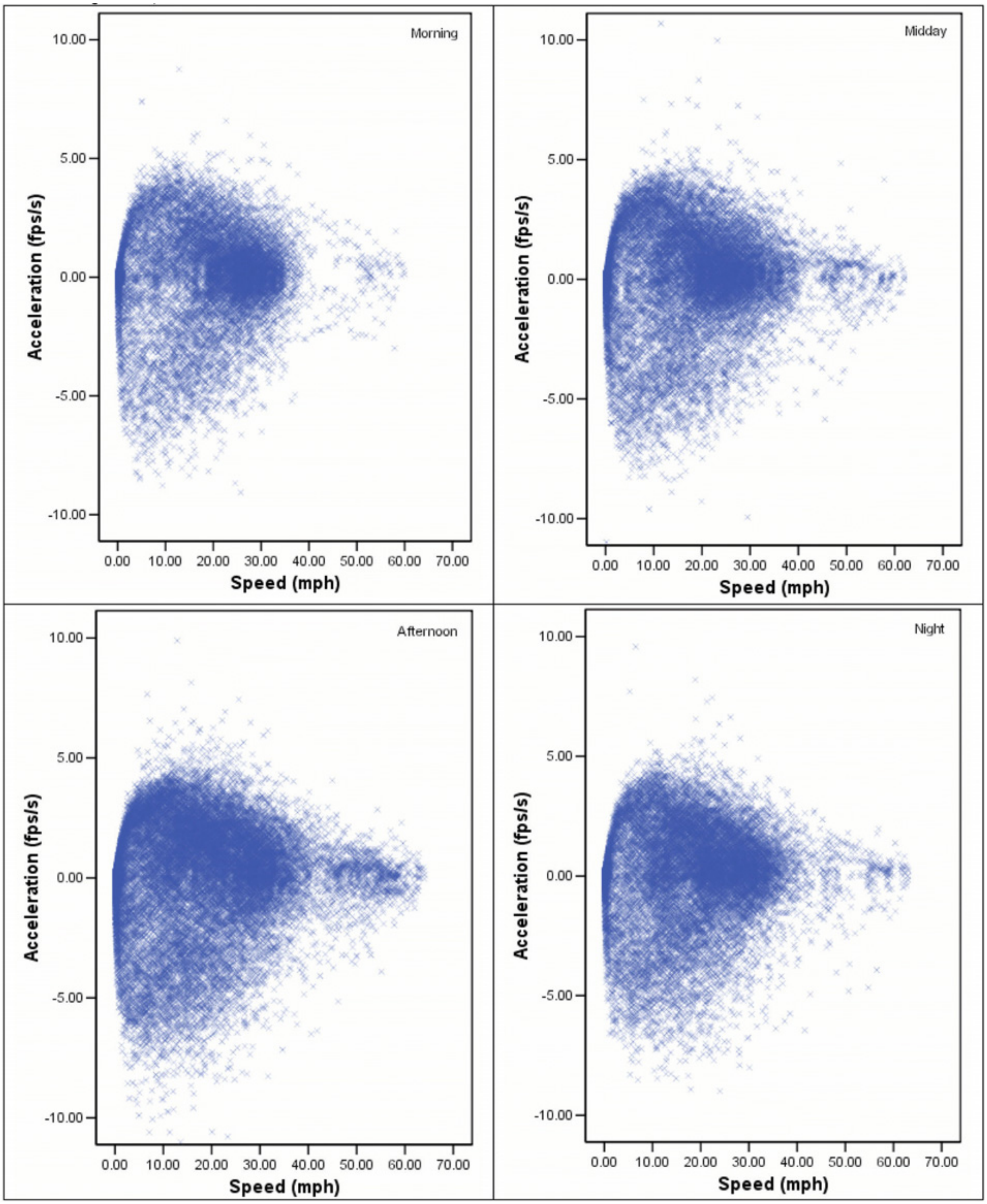


Figure 23. Speed-Acceleration Scatter Plots for Local Roads by Time of Day.

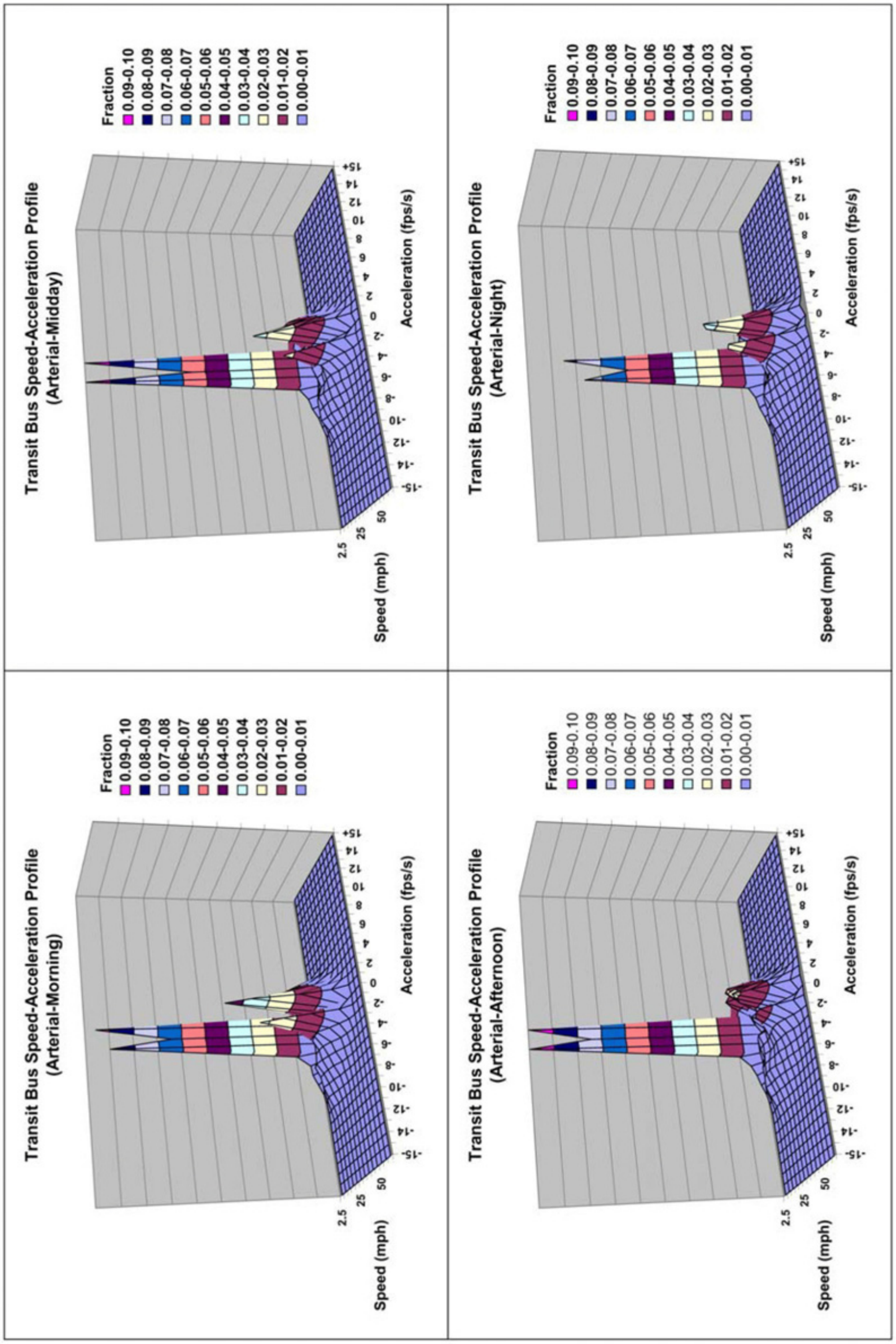


Figure 24. Speed-Acceleration Profiles for Arterial Roads by Time of Day.

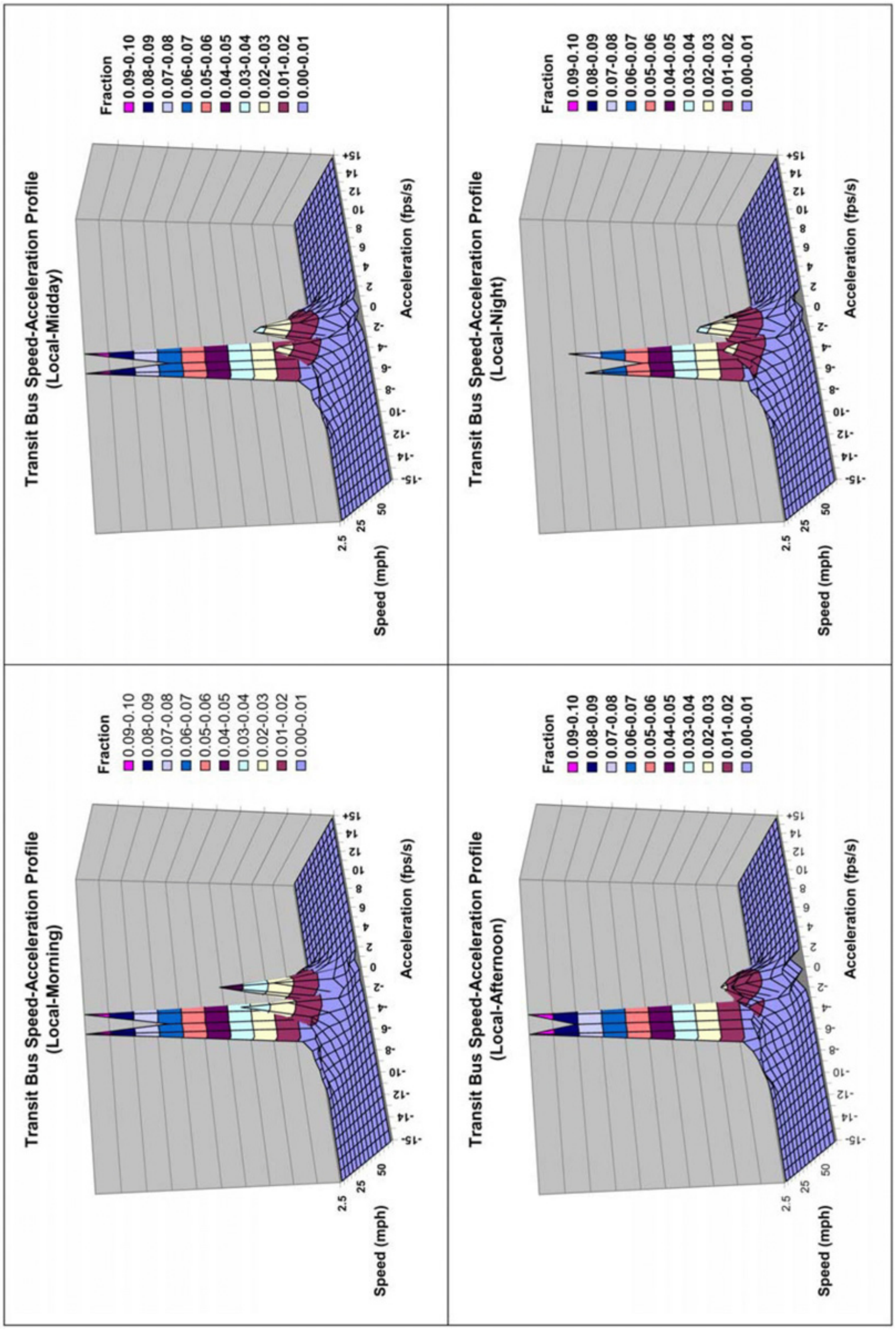


Figure 25. Speed-Acceleration Profiles for Local Roads by Time of Day.

Acceleration (fps/s) Bins	Speed (mph) Bins											
	2.5	5	10	15	20	25	30	35	40	45	50	55
-11	-	0.000	-	0.000	-	-	-	-	-	-	-	-
-10	-	-	0.000	0.000	0.000	0.000	-	-	-	-	-	-
-9	-	-	0.000	0.000	0.000	-	0.000	-	-	-	-	-
-8	-	0.001	0.001	0.000	0.000	0.000	0.000	-	-	-	-	-
-7	0.000	0.001	0.003	0.002	0.001	0.001	0.000	0.000	-	0.000	-	-
-6	0.001	0.002	0.004	0.003	0.003	0.001	0.001	0.000	-	-	-	-
-5	0.003	0.002	0.005	0.005	0.004	0.003	0.001	0.001	0.000	-	-	-
-4	0.005	0.003	0.006	0.007	0.006	0.005	0.003	0.001	0.000	-	-	-
-3	0.005	0.002	0.005	0.007	0.007	0.007	0.005	0.002	0.001	0.000	0.000	-
-2	0.010	0.003	0.004	0.007	0.009	0.010	0.010	0.006	0.004	0.001	0.000	-
-1	0.090	0.002	0.005	0.007	0.011	0.020	0.033	0.025	0.015	0.004	0.000	0.000
0	0.064	-	0.000	0.000	0.001	0.001	0.002	0.001	0.001	0.000	-	-
1	0.096	0.002	0.006	0.010	0.013	0.032	0.047	0.037	0.018	0.006	0.000	0.000
2	0.011	0.004	0.006	0.011	0.019	0.020	0.022	0.013	0.006	0.002	0.000	-
3	0.003	0.011	0.013	0.014	0.020	0.015	0.008	0.002	0.001	0.000	0.000	-
4	-	0.003	0.016	0.013	0.008	0.004	0.002	0.001	0.000	-	-	-
5	-	0.000	0.001	0.004	0.002	0.001	0.000	0.000	0.000	-	-	-
6	-	-	-	0.000	0.000	-	-	-	-	-	-	-
7	-	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	0.000	-	-	-	-	0.000	-
9	-	-	-	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-	-	-	-

Figure 26. Example of a Speed-Acceleration Matrix (Arterial Road, Morning Peak Period).

Required horsepower for each speed bin can be weighted by acceleration frequency fractions on corresponding speed-acceleration bins from the matrix, and weighted required horsepower are aggregated as a unique required horsepower for the selected roadway type and by time of day. Then, the unique required horsepower is multiplied by each bus model year emissions level in grams per brake-horsepower-hour (in this case the 4.0 g/bhp-hr certification rate was used), to calculate an emissions in grams per hour for the selected bus service route. In this example, inertial and accessory loads are ignored.

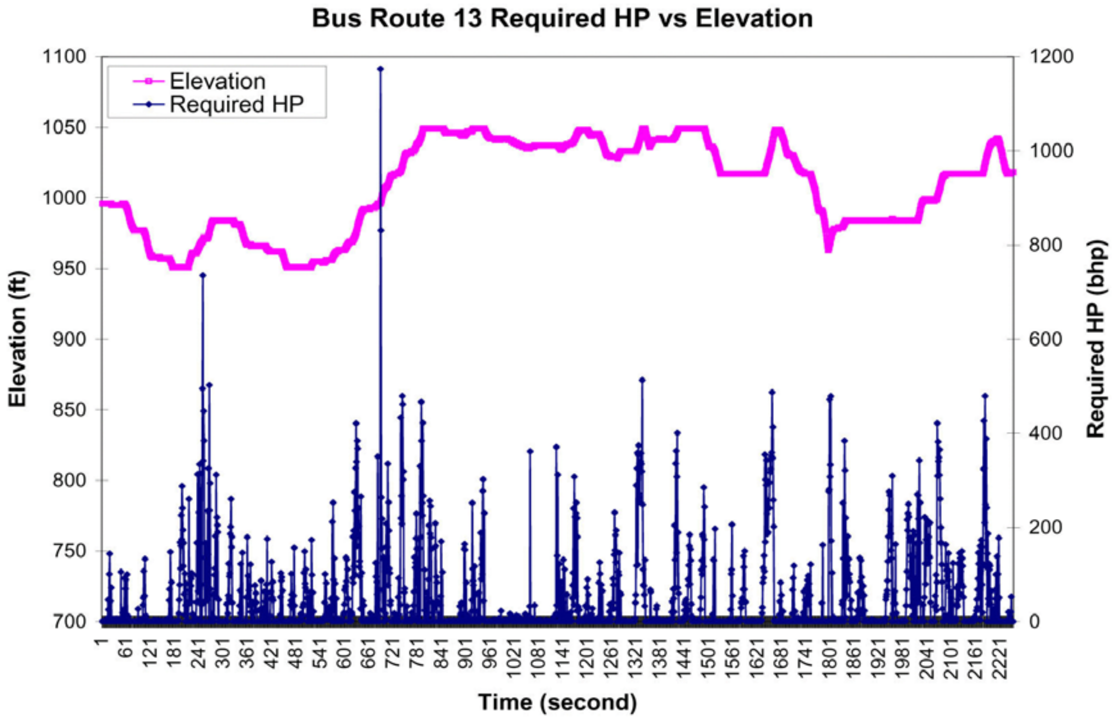
$$EM_{i,j} = \sum_{k} EL_k \left[\sum_{l} \sum_{m} \left(P_{l,m} \times AF_{l,m} \right)_{i,j} \right]$$

where EM is the transit bus emissions in grams per hour per vehicle,
EL is the transit bus emissions rate in grams per brake-horsepower-hour,
P is the engine power demand in brake-horsepower-hour,
AF is the acceleration/deceleration activity frequency,
i is the roadway type (arterial or local road),
j is the time of day (morning, midday, afternoon, or night),
k is the engine model year,
l is the speed in a speed/acceleration matrix, and
m is the acceleration in a speed/acceleration matrix.

To demonstrate emissions differences between different operating speeds, two cells (7.5 and 37.5 mph at +1 mph/s), which have same acceleration frequency fractions (0.009), were selected from the speed-acceleration matrix for morning arterial roads, and load-based transit bus required horsepower was calculated. Required acceleration forces at 7.5 and 37.5 mph are the same. However, the sum of the other forces (rolling resistance, gravitational drag, and aerodynamic drag) at 37.5 mph was 2.2 times greater than at 7.5 mph. This is because aerodynamic and rolling resistance drags increase as vehicle speed increases. Total engine power demand estimated at 37.5 mph was 5.7 times greater than at 7.5 mph; that implies that transit bus emissions at 37.5 mph will be 5.7 times greater than at 7.5 mph for +1 mph/s acceleration at the condition of linear relationships between emissions level and engine power demand. Demonstration of the differences between emission estimates using this modeling approach vs MOBILE6 will be provided in Phase II of the project.

The net difference in grams per hour for operation on each of the routes is significant. The second-by-second road loads for vehicles operating on two different routes are primarily a function of speed and acceleration and grade (Figure 27). Using the load-based estimation tools, buses traveling on Route 13 are predicted to emit approximately 279 g/h and the same buses traveling on Route 23 are predicted to emit approximately 404 g/h. The difference in grams per hour emission rates is approximately 45%. Given that the average sped on Route 13 is 11 mph and the average speed on route 23 is 15 mph, the net difference in grams per mile emission rates is approximately 22%.

The spreadsheet transit modal model provides the input necessary to complete most of the algorithms in the ArcGIS framework. Over the next few months, the coding of the Phase I model will be completed in the GIS system, so technology groups can be tracked and tabulated within the model as they are developed.



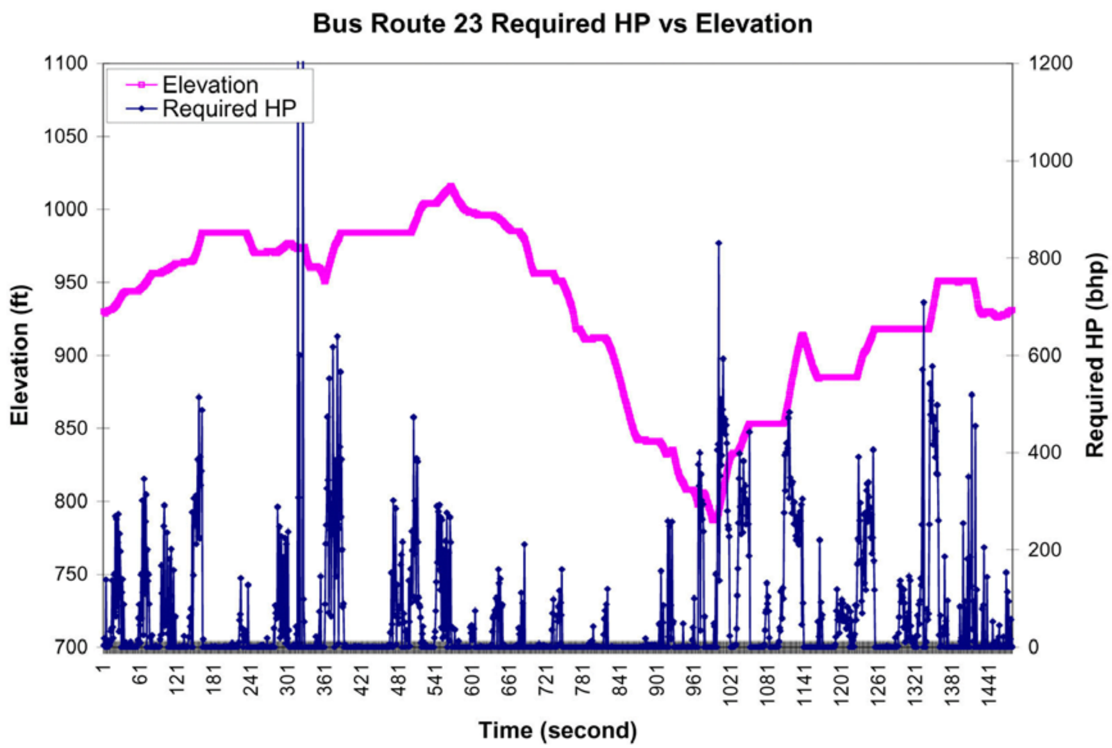


Figure 27. Load Calculations for two Bus Routes with Different Grades and Operating Profiles.

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Appendix A
Model Equation Parameters

Table A-1. Model Equation Parameters.

Variable	Definition	Unit	Source
P_E	Brake engine horsepower	bhp	$P_E = \dfrac{T_E \times N_E}{5252}$ *or* $P_E = P_A + P_{DT} + P_a$
P_A	Axle-horsepower available for tractive work	ahp	$P_A = 2\pi(T_A) \times \left(\dfrac{N_E}{G_t \times G_d}\right)\left(\dfrac{1\text{ min}}{60\text{ sec}}\right)\left(\dfrac{1\text{ hp}}{550\dfrac{\text{ft}\cdot\text{lb}_\text{f}}{\text{sec}}}\right)$
P_{DT}	Horsepower loss in the drive train	hp	Parameterized estimation 5%~12%
P_a	Horsepower loss from accessory operations	hp	Parameterized estimation
N_E	Engine rotational speed	rpm	Field measurement
V	Vehicle speed	ft/s	$V = 2\pi r \times \left(\dfrac{N_E}{G_t \times G_d}\right)\left(\dfrac{1\text{ min}}{60\text{ sec}}\right)$ field measurement
η_{tot}	Power transmission efficiency		Engine data books or typical value
G_t	Transmission gear ratio		Engine data books or typical value
G_d	Final drive gear ratio		Engine data books or typical value
I_{Eff}	Effective moment of inertia	$\text{ft}\bullet\text{lb}_\text{f}\bullet\text{s}^2$	$I_{Eff} = \left[I_W + \left(G_d^2 \times I_D\right) + \left(G_t^2 \times G_d^2\right) \times \left(I_E + I_T\right)\right]$
I_W	rotational moment of inertia of the wheels and axles	$\text{ft}\bullet\text{lb}_\text{f}\bullet\text{s}^2$	Parameterized estimation
I_D	Drive shaft rotational moment of inertia	$\text{ft}\bullet\text{lb}_\text{f}\bullet\text{s}^2$	Parameterized estimation
I_E	Engine rotational moment of inertia	$\text{ft}\bullet\text{lb}_\text{f}\bullet\text{s}^2$	Parameterized estimation
I_t	Transmission rotational moment of inertia	$\text{ft}\bullet\text{lb}_\text{f}\bullet\text{s}^2$	Parameterized estimation

continued

Table A-1. Model Equation Parameters (concluded).

Variable	Definition	Unit	Source
M_{Eff}	Effective mass	lb_m	$M_{Eff} = \left(I_{Eff}\right) / r^2$
r	Drive wheel radius	ft	Field measurement
F_T	Tractive force at the drive wheel	lb_f	$F_T = m \times a + F_R + F_W + F_D$
m	Total vehicle mass	lb_m	Field measurement
a	Vehicle acceleration	ft/s^2	Field measurement
F_R	Rolling resistance force	lb_f	$F_R = C_r \times m \times g \times \cos(\theta)$
F_W	Gravitational force	lb_f	$F_W = W \times \sin(\theta)$
F_D	Aerodynamic drag force	lb_f	$F_D = \left(\frac{\rho}{2}\right) \times C_d \times A_f \times V_e^2$
C_r	Rolling Resistance coefficient		Typical road surface coefficients concrete, wet asphalt, asphalt, hot asphalt
W	Total vehicle weight	lb_f	$W = m \times g$
g	Acceleration of gravity	ft/s^2	32.2 ft/s^2
θ	Inclination angle of the road	degrees	Field measurement or road construction database
ρ	Air density	$lb_f \bullet s^2/ft^4$	$\rho = 0.00236\left(\frac{P_r}{29.92}\right)\left(\frac{519}{460 + T_r}\right)$
P_r	Atmospheric pressure	in. mercury	Field measurement
T_r	Atmospheric temperature	°F	Field measurement
C_d	Drag coefficient		Typical C_d for a flat top tractor (0.99) & high roof sleeper (0.60)
A_f	Vehicle frontal area	ft^2	Field measurement
V_e	Effective vehicle velocity	ft/s	$V_e = V + V_W$
V_W	Head wind velocity	ft/s	Field measurement

Appendix B
Potential Data Sources for the Heavy-Duty Vehicle Modal Emission Modeling Framework

V: vehicle speed (ft/s or m/s)
a: vehicle acceleration (ft/s^2 or m/s^2)

Method	Description	Suitability	Note
Car chip	An electronic device that is mounted in-vehicle to record information such as vehicle speed as a function of time	Vehicle-specific	Need to mount on a vehicle and have someone to run the test vehicle.
VASCAR	An in-car speed measuring computer that records time taken to cover a distance, thereby allowing average speed to be calculated.	Vehicle-specific	Need to mount on a vehicle and have someone to run the test vehicle. Mainly for police use
Non-contact speed sensor	A sensor that is mounted on a vehicle, pointing at the ground to measure the speed of the vehicle relative to the ground.	Vehicle-specific	Need to mount on a vehicle and have someone to run the test vehicle. More info: http://www.gmheng.com/pdf/an1001.pdf (accessed August 2005)
Calibrated Speedometer	This allows one to measure vehicle speeds for evidential purposes when following a vehicle.	Vehicle-specific	For police use.
Loop detector	An inductive that is embedded in the ground to collect traffic data such as volume, speed, occupancy, etc.	Location-specific	Automatic data and widely available at traffic management centers.
Video detector	Video cameras that is mounted along roadside to collect traffic data such as volume, speed, occupancy, etc.	Location-specific	Time-consuming and labor-consuming.
Radar and laser gun	A handheld device to measure vehicle speed or distance.	Location-specific Time-specific	Time-consuming and labor-consuming.
Racelogic Velocity Box	Non Contact speed and distance measurement using GPS (called VBOX) which measures the speed, position, acceleration figures, braking distances of a moving vehicle.	Vehicle-specific	Resource-consuming. More info: http://www.m-techautomotive.co.uk/vbox/VBox_Index.htm (accessed August 2005)

V_W : Head wind velocity(ft/s)

Atmospheric winds vary in intensity throughout the United States, with typical mean values of 10-20 mph, and gusty winds to 50 and 60 mph. The atmospheric wind will be random in direction with respect to the vehicle direction of travel.

Method	Description	Suitability	Note
Anemometer	Mounted on the roof of a vehicle to measure the wind that results from vehicle speed and direction as well as the wind speed and direction.	Vehicle-specific	Need to mount on a vehicle and have someone to run the test vehicle.
Air Velocity Flow Sensor	Inserted into a duct or pipe through an access hole to measure air velocity.	Not clear	More info: http://sensors-transducers.globalspec.com/SpecSearch/Suppliers?Comp=289 (accessed August 2005)
Weather Vanes	Weather vanes are one of the oldest of all weather instruments, working by swinging around in the wind to show which direction it is blowing from.	Wind direction	http://www.rcn27.dial.pipex.com/cloudsrus/measurewind.html (accessed August 2005)
Wind Socks	Wind Socks show visual indication of the wind.	Wind direction Wind speed	http://www.rcn27.dial.pipex.com/cloudsrus/measurewind.html (accessed August 2005)
Weather station	It may have collected such information systematically.		Details will be on “Online Resources of Climatic Database” part

θ: Roadway Grade Angle

Numerous methods exist that can be employed to determine roadway geometric characteristics such as the grade and super-elevation. Depending on the purpose, location, and available resources, these methods span from conventional land surveying techniques to advanced technologies such as photogrammetry and digital terrain models. Several factors are important in selecting any one method, and these include cost, time, work-crew safety, and the desired accuracy (dissertation of H. Ikwut-Ukwa).

Method	Description	Note
Leveling Survey	This method relies on the determination of relative elevations between points along the road to determine the longitudinal and lateral slopes; these are translated into roadway grade and banking, respectively.	Relative elevations with leveling survey are typically accurate to a hundredth of a foot. Since surveyors need to be physically present on the road, the use of this method sometimes involves some restricted traffic operation; on high speed roads such as freeways this is either unsafe or impractical.
Grade Gauge	A reading is taken by simply placing the gauge on the roadway where the slope is to be measured, adjusting the arm that gives the reading.	Surveyors need to be physically present on the road. It is impractical to apply this method on freeways.
Vangarde 505	An infrared electronic distance measurer (EDM) and a theodolite that allows measurements to targets on the road surface from a static, remote location.	This system provides data to an accuracy of two millimeters. Though most of the work is done from the vehicle, the system still requires conventional survey to establish controls. The system does not perform well on new asphalt and on wet pavement because of the light absorbing/scattering effect of these surfaces. It is also very costly and time intensive.
Remote Sensing	Remote Sensing data are collected from high altitude satellites, such as the LANDSAT, or from high altitude aerial photography.	The grade data obtained are inaccurate since most existing Digital Elevation Models (DEM) data have very low resolution.
Roadway design blueprint	May have grade information labeled on the blueprint.	The final construction details of a road may differ significantly from the original plans because of unanticipated conditions in the field.
Contour map	GIS centers may provide such electronic maps and use AutoCAD to read contour lines.	

W: Total vehicle weight (lb_f)

The weight data can be measured from the field.

Method	Description	Note
Wight-in-motion (WIM) Site	Permanent WIM locations are selected to monitor the weights experienced by bridges and specific roads.	
Weight Stations	Weigh stations are located along Interstate highways, usually near the border between states. All trucks are required by law to be weighed at the weigh station during its hours of operation.	Generally weigh stations are open only during the day, depending on the nature of the specific WIM equipment at a particular station.
National Truck Survey	Currently, there are four major national truck travel data sources available which feature heavy-duty vehicle characteristics: the Truck Inventory and Use Survey, the Commodity Flow Survey, the Nationwide Truck Activity and Commodity Survey, and the National Truck Trip Information Survey.	The Bureau of the Census conducts the Truck Inventory and Use Survey (TIUS) every five years as part of the Census of Transportation.
Regional Commercial Vehicle Surveys	The two most common types of truck surveys are trip diaries and roadside surveys.	
Bending plate technology	The device typically consists of a weigh pad attached to a metal frame installed into the travel lane. A vehicle passes over the metal frame causing it to slightly "bend." Strain gauge weighing elements measure the strain on the metal plate induced by the vehicle passing over it. This yields a weight based on wheel/axle loads on each of two scales installed in a lane. The device also is used to obtain classification and speed data.	

Source http://ntl.bts.gov/DOCS/arizona_report.html (accessed August 2005).

η_{tot}: the total efficiency of power transmission

This number is determined from experiment. Typically, this value(s) may be determined by testing a truck engine(s) using a chassis dynamometer. If a chassis dynamometer is unavailable for the testing, then 80% to 85% can be used as the default value.

G_t : the transmission gear ratio

The gear ratios in the transmission for 1st through *n*th gear vary by vehicle make, model, and model year. For example, a heavy-duty, "deep low" 5-speed manual transmission, as used in a 2500 Series pickup, has the gear ratio of 5.61:1, 3.04:1, 1.67:1, 1:1, and 0.75:1. The transmission gear ratio for many models can be found online: http://www.vibratesoftware.com/html_help/html/Diagnosis/Transmission_Gear_Ratios_main.htm . Also, the diesel truck index includes this information for many models. A library of drive train technologies will be assembled over the coming months.

G_d : the differential, or the final drive, gear ratio

Differential gear ratio determines the number of times the drive shaft (or pinion) will rotate for each turn of the wheels (or ring gear). Gear ratio is calculated by dividing the number of teeth on the ring gear by the number of teeth on the pinion gear. The higher the number, the lower the ratio. Larger, heavier vehicles tend toward the higher numeric ratios in the differential.

A_f : Vehicle frontal area

The frontal area is the projected area of the vehicle relative to its direction of travel and is expressed as square feet. It is used to determine aerodynamic drag losses on the vehicle. The diesel truck index includes this information for many models.

C_r: Rolling resistance coefficient

Rolling resistance is a measure of the amount of resistance that is generated as a tire, which is deformed at the contact to the ground, rolls on the road surface. This deformation, which is a function of tire size and type, pavement type, vehicle weight, and vehicle speed, can create rolling resistance. Rolling resistance increases with increasing softness of the road surface. The rolling friction coefficient gives the force of friction needed to maintain the uniform motion when it is multiplied by the normal force between two bodies rolling with each other. This coefficient is determined from experiment. The typical value for truck ranges from 0.006 to 0.01.

Coefficient of Friction[a]

Surfaces	Rolling Friction	Kinetic Friction
Low-rolling-resistance car tire on dry pavement	0.006-0.01	0.8
Ordinary car tire on dry pavement	0.015	0.8
Truck tire on dry pavement	0.006-0.01	0.8
Train wheel on steel track	0.001	0.1

[a] Source: http://www.school-for-champions.com/science/frictionrolling.htm (accessed August 2005).

Typical Coefficient Values[a]

Vehicle Type	Surface		
	Concrete	Medium Hard	Sand
Passenger cars	0.015	0.08	0.30
Heavy Trucks	0.012	0.06	0.25
Tractors	0.02	0.04	0.20

[a] Source: Gillespie (1992)

Typical Coefficient of Rolling Resistance

Road Surface	C_r
Pneumatic tires on:	
Concrete asphalt	0.015
Rolled coarse gravel	0.02
Tarmacadam	0.025
Earth	0.05
Farmland	0.1–0.35
Wheel on rail	0.001–0.002

C_d: drag coefficient

The drag coefficient is determined from experiment. Typical aerodynamic drag coefficients provided by Ford Motor Company are shown in Figure B-1. Drag coefficient for heavy-duty vehicle varies, but a value of 0.99 is commonly used for flat top tractor and 0.60 for high roof sleeper.

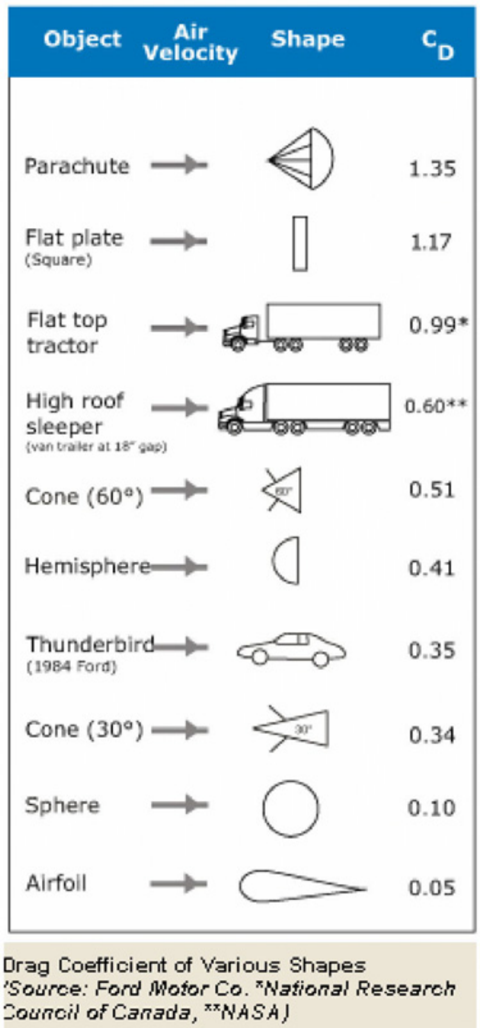


Figure B-1. Typical Aerodynamic Drag Coefficients.

ρ: air density

Air density is used to calculate the aerodynamic drag. If this number is not available directly, it can be calculated from atmosphere pressure and temperature. The function is

$$\rho = 0.00236\left(\frac{P_r}{29.92}\right)\left(\frac{519}{460 + T_r}\right)$$

where, P_r is the atmospheric pressure in inches of mercury (Hg) and

Tr is the atmospheric temperature in degrees Fahrenheit

At standard conditions (59 °F and 29.92 in. Hg), the density is 0.00236 $lb_f\text{-}sec^2/ft^4$.

Online air density calculators can provide air density by altitude, temperature, altimeter setting, and dew point information from a climatic database at either http://wahiduddin.net/calc/calc_da.htm or http://www.denysschen.com/catalogue/density.asp (both accessed August 2005).

- NCDC's Weather and Climate Resources:
  - Get/View Online Surface Data http://www.ncdc.noaa.gov/ol/climate/climatedata.html#SURFACE (accessed August 2005),
  - Hourly (Temperature, Precipitation, Winds, Pressure, Etc, from 1997-present, sorted by station). Fee will be charged!
  - Daily (Temperature, Precipitation, Winds, Pressure, Snow, Etc, CD-rom 1948-present),
  - Monthly (Temperature, Precipitation, Pressure, Etc, from 1800-1996),
  - Modeled (1900 - present, monthly temperature and precipitation),
- Climate Monitoring and Diagnostic Laboratory: ftp://ftp.cmdl.noaa.gov/met/ The directories contain hourly average observations of air temperature, station pressure, and surface wind direction and speed at the four NOAA/CMDL observatories, Point Barrow, Alaska (brw), Mauna Loa Observatory, Hawaii (mlo), American Samoa Observatory (smo), and Amundsen-Scott, South Pole Observatory, Antarctica (spo).
- Climate Prediction Center (CPC) data: http://www.cpc.ncep.noaa.gov/data/ (accessed August 2005):
  - Selected Historical Data,
  - Weekly/Monthly Degree Days http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/pastdata/degree_days/ (accessed August 2005); contains degree days data for the country for 3 weeks prior to current

date and 3 months prior to current date,

- ◦ Weekly/Monthly Precip/Temp Tables http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/pastdata/prcp_temp/ (accessed August 2005); contains precipitation and temp-erature data of the country for most recent 3 weeks and most recent 3 months,

- NOAA Server:
  Access to NOAA data and information:
  http://www.esdim.noaa.gov/noaaserver-bin/NOAAServer/
  Searchable interface to NOAA's data holdings. Users can download and plot data. It is a place where you can search database based on keywords, time range, geographical coverage, database searched, and search criteria. Search results are given in forms like Description, Preview, Obtain, and Ordering info.

Drive Wheel Radius

R_w: the outer radius of the drive wheel (inches)
r_w: the inner radius of the drive wheel (inches)

The radius data can be gotten from the tire itself directly. There is some small print on the tire's sidewall to specify the design information, and the radius of the tire can be calculated from them. For example, Figure B-2 shows a "P 215/65 R 15" tire. The 215 is the width of the tire in millimeters measured from sidewall to sidewall. The 65 is called "aspect ratio" and is used to tell height of the tire from the bead to the top of the tread. This number is described as a percentage of tire width. That means the height is 215 × 65% = 139.75mm (5.59in). The 15 is the rim diameter in inches to specify the wheel rim diameter the tire is designed for. So the tire diameter is 2 × 5.59in +15 inches = 26.18 in (654.5 mm). After these calculations, the outer radius of the drive wheel is 13.09 in, the inner radius of the drive wheel is 7.5 in (half of the rim diameter).

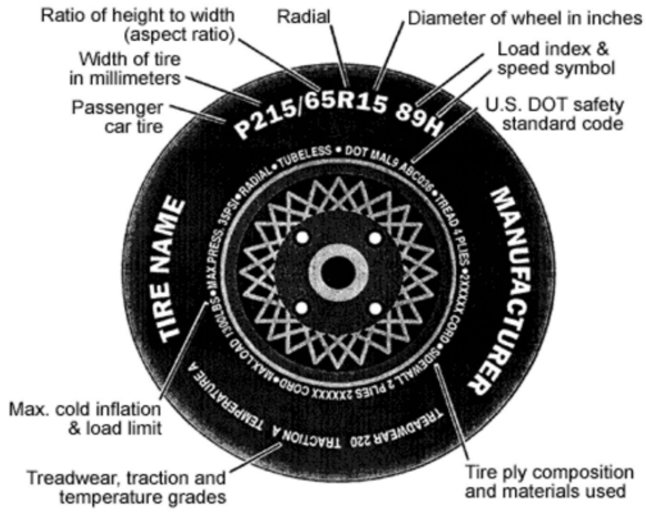


Figure B-2. Tire Detail Information.

Moments of Inertia

The diesel truck index includes tire information for many models.

I_D: mass moment of inertia of drive train
I_E: mass moment of inertia of engine
I_R: mass moment of inertia of wheel

These moment of inertia data can be used to calculate the rational inertia coefficient (e). Generally, these data can be obtained from laboratory experiments.

Appendix C
Estimating Heavy-Duty Vehicle Miles Traveled

Heavy-Duty Vehicle Activity Data Sources

Publicly available transportation databases managed by Federal and State agencies were used to estimate heavy-duty VMT within the 20-county Atlanta region. To estimate HDV2b VMT, 2-axle, 4-tire vehicle VMT percentages for road types from the Highway Statistics Series (HSS) of FHWA were used. To distinguish light-duty trucks (LDTs—gross vehicle weight ranges from 6,001 to 8,500 lbs) and HDV2b (gross vehicle weight ranges from 8,501 to 10,000 lbs) from the 2-axle, 4-tire VMT, Georgia statewide LDT and HDV2b VMT was obtained from the Vehicle Inventory and Use Survey (VIUS) of U.S. Census Bureau. Truck percent, segment length, and annual average daily traffic (AADT) from Georgia Department of Transportation (GDOT) Highway Performance Monitoring System (HPMS) were used to estimate classes HDV3 to 8b VMT. The Georgia Tech HDV/BUS database developed in 2003 was used in addition to Federal and State databases to separate aggregated truck VMT from HPMS into EPA HDV classes.

Highway Statistics Series

The annually published HSS provides highway vehicle activity information such as statewide annual total VMT by road type and by FHWA truck class, which is classified with the number of axles and truck-trailer combinations (FHWA, 2001). Until 1999, the HSS had provided other 2-axle, 4-tire vehicle VMT percentages, which are the mixture of LDT and HDV2b VMT, for each road type except collectors and locals (FHWA, 2000). However, since 2000, the HSS has not provided the other 2-axle, 4-tire vehicle VMT percentages by road type. Therefore, the Class Two vehicle VMT percentages from pre-2000 HSS were used in this study. From the 1993 to 1999 HSS, seven year average other 2-axle, 4-tire vehicle VMT percentages, which are statistically significant means at 5% significant level, were used for each road type in this study. Table C-1 shows the average other 2-axle, 4-tire vehicle VMT percentages by road type in Georgia statewide.

Table C-1. Georgia Statewide Other 2-Axle, 4-Tire VMT Percentages.

	Road Types	Average 2-Axle, 4-Tire VMT Percentages
1	Rural interstates	20.5
2	Other principal rural arterial roads	13.3
6	Minor rural arterial roads	15.2
11	Urban interstates	26.1
12	Other urban freeways and expressways	25.9
14	Principal urban arterial roads	23.0
16	Minor urban arterial roads	21.6

Due to differences in HDV (or Truck) definitions between EPA and FHWA, HPMS databases do not provide HDV2b VMT. These other 2-axle, 4-tire VMT percentages can be also used to calculate total other 2-axle, 4-tire VMT from total VMT from HPMS databases. Then, total other 2-axle, 4-tire VMT should be separated into each LDT VMT and HDV2b VMT because the 2-axle, 4-tire vehicle VMT is the mixture of LDT and HDV2b VMT.

Vehicle Inventory and Use Survey

A VIUS conducted by U.S. Census Bureau in 2002 provides statewide 2-axle, 6-tire HDV VMT with vehicle GVWR, which can direct the conversion of surveyed HDV VMT into EPA HDV class VMT (FHWA, 2004). Because the VIUS does not provide countywide HDV VMT, HDV VMT fractions from statewide HDV VMT were used to separate the observed HDV VMT in the Georgia Tech HDV database in 2003 into EPA HDV classes 3 to 8, which correspond to HDV class X1 (see the section, Georgia Tech HDV/BUS Database, below) from the observed HDV VMT (Table C-2).

Table C-2. Georgia Statewide HDV VMT Fractions for the Class X1 Conversion.

GVW Ranges (lbs)	X Class	EPA HDV Classes	VMT Fraction
10,001–14,000	X1B	HDV3	0.2577
14,001–16,000		HDV4	0.1824
16,001–19,500		HDV5	0.0773
19,501–26,000		HDV6	0.2726
26,001–33,000		HDV7	0.1861
33,001–60,000		HDV8a	0.0239

Highway Performance Monitoring System

HPMS databases provide roadway segment lengths, AADT, and truck percentages from which total VMT and truck VMT can be calculated for each road type. However, truck percentages do not count 2-axle, 4-tire HDV because the definition of "truck" encompasses vehicles more than or equal to 2-axle, 6-tire. That means that EPA HDV2b VMT may not be included in the truck VMT estimated from HPMS database. Using 2-axle, 4-tire vehicle VMT percentages from HSS and the LDT/HDV2b VMT ratio from VIUS, HDV2b VMT can be estimated with total vehicle VMT from HPMS databases.

Georgia Tech HDV/BUS Database

HDV volumes were observed on a freeway and arterial roadway network within the 21-county Atlanta region. The highway network was composed of 90 freeway and 202 major arterial roadway segments falling within one mile of the region's major warehouses and truck stops. The 292 roadway segments were aggregated into 59 segment groups by roadway geometry similarity (contiguous interchanges, roadway merges, and separations). The goal was to combine similar traffic activity within a segment group, so that one segment from each of the 59 segment groups could be randomly selected as representative of the group. HDV volumes collected on a selected segment were then used for all segments in a segment group. HDV volumes for the selected segments were counted at sites using a visual HDV classification scheme, which employed four HDV classes according to engine horsepower and vehicle weight similarities (Ahanotu, 1999), for consecutive 2 hours. Not only were HDV volumes counted, but school bus and other bus volumes were also counted at the selected sites. Since HDV volumes for each segment were observed only for 2 hours, a scale-up method was used to scale up 2-hour HDV volumes to 24-hour HDV volumes with representative 24-hour HDV volume profiles for each Ahanotu HDV class observed on two freeway segments (I-285 and I-20) and one arterial segment (US-41) for consecutive 24 hours on a weekday. HDV 24-hour volume profiles with each Ahanotu HDV class on I-285, I-20, and US-41 were scaled up 2-hour HDV volumes observed on the segments of freeways and arterials. After the scale-up, HDV VMT for each segment and each Ahanotu HDV class were estimated. However, the Ahanotu HDV classes can not be directly converted into EPA HDV classes, so that a method(s) was needed for HDV class conversion.

To convert observed HDV volumes by Ahanotu HDV class into EPA HDV classes, a new HDV visual classification scheme—which is a hybrid HDV visual classification scheme between FHWA and EPA HDV classification schemes with FHWA truck weight limitations (FHWA, 1994; FHWA, 2002) and EPA GVWR—was developed in 2003 (Yoon, et al., 2004a). The new HDV classification scheme (called the X-scheme) has three HDV classes from the modification of the Ahanotu HDV classification scheme. The three HDV classes are 2-axle HDVs (X1), 3-axle HDVs (X2), and more than 3-axle HDVs (X3) (Figure C-3). The X1 class corresponds to the Ahanotu HDV class A, which is 2-axle, single unit HDVs, and corresponds to EPA HDV3 to HDV7. Observed HDV volumes of the X1 class can be apportioned to EPA HDV3 to HDV7 by multiplying their VMT fractions obtained from 2002 VIUS. The X2 class corresponds to parts of Ahanotu HDV class B (3-axle, single unit) and C (3-axle, two units), which correspond to FHWA HDV classes 6 or 8, and directly mapped into the EPA HDV8a. The X3

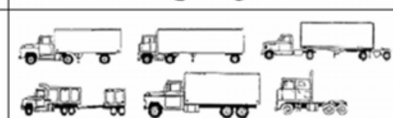
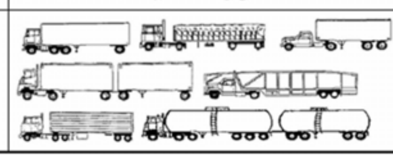
X HDV Classes	EPA HDV Classes	Typical Vehicles
X1	HDV2b, HDV3, HDV4, HDV5, HDV6, HDV7	
X2	HDV8a	
X3	HDV8b	

Figure C-1. Typical X-Scheme HDV Class Examples.

class corresponds to the part of Ahanotu HDV class B (4-axle, single unit) and C (4-axle, 2-unit) and all of the class D. The X3 class corresponds to FHWA classes 7 and 9 to 13, and directly maps into the EPA HDV8b.

Georgia Tech also developed a school bus activity database, which is a part of the Georgia Tech HDV database, through letter/telephone survey in 2003 within a 21-county Atlanta region. The school bus database includes the number of school buses and daily miles for each bus. With the number of school buses and daily miles, school bus VMT was calculated for each county. It was found that total school bus VMT from the database was more than two times higher than the observed school bus VMT on the roadway network. This apparently is due to the fact that school buses operate mostly on minor arterial and local roads, while the roadway network database includes only a small fraction of minor arterial roads and no local roads. In essence, the roadway network database does not reflect the real-world road network. Therefore, observed school bus VMT on the roadway network should be corrected with school bus VMT from the database. School bus VMT correction will be conducted after HDV VMT estimation on and off the roadway network because the correction should be applied to only minor arterial and local roads.

Heavy-Duty Vehicle VMT Estimation

All data sources discussed in the Heavy-Duty Vehicle Activity Data Sources section are integrated to estimate HDV VMT by road and by EPA HDV class within a 20-county Atlanta region. The overall process of HDV VMT estimation with databases is described in Figure C-4. Heavy-duty vehicle VMT from 2003 Georgia Tech HDV database was assigned to each roadway segment to identity road types through GIS analysis techniques. Roadway segments on the freeway/arterial network (not including collectors and locals) were assigned each corresponding FHWA road types. HDV VMT with the Ahanotu HDV classification scheme (Ahanotu, 1999) for each road type was translated into EPA HDV class VMT through an intermediate conversion via the X- scheme. For the translation of the X1 HDV VMT into EPA HDV classes 3 to 7, HDV VMT fractions from VIUS (2002) were applied. After VMT translation into EPA HDV classes, HDV VMT fractions with EPA classes were calculated and applied to apportion truck VMT estimated from the GDOT HPMS database for each road type within the 20-county Atlanta region.

The reason for using HDV VMT fractions from the Georgia Tech HDV database instead of using national default vehicle class adjustment factors (U.S. EPA, 2002b and U.S. EPA, 1998) is to avoid underestimating VMT, especially for HDV8a and HDV8b classes. Yoon et al. (2004b) studied HHDDV travel patterns at seven truck stops in and around the 21-county Atlanta region boundary and found that over 50% of HHDDVs did not make

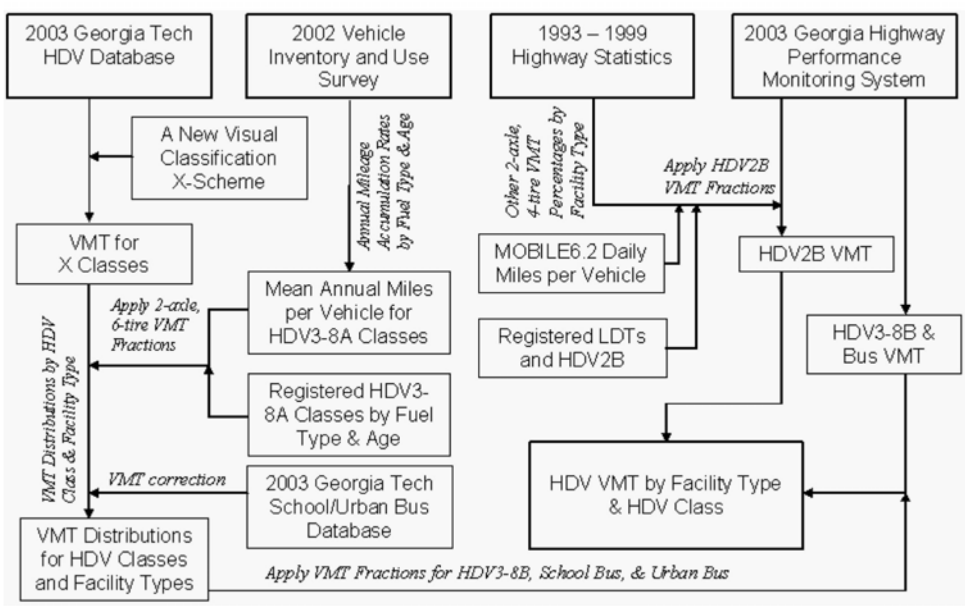


Figure C-2. Overall Process of HDV VMT Estimation.

Table C-3. EPA HDV VMT Fractions for Road Types.

Road Type	EPA HDV VMT Fractions								
	HDV3	HDV4	HDV5	HDV6	HDV7	HDV8a	HDV8b	School Bus	Other Bus
Freeway	0.058	0.041	0.018	0.062	0.042	0.101	0.651	0.009	0.018
Arterial	0.046	0.032	0.014	0.048	0.033	0.165	0.610	0.025	0.028
Local	0.034	0.024	0.010	0.036	0.025	0.130	0.487	0.231	0.022

Table C-4. HDV and Bus VMT Fractions within the 20-County Atlanta Region.

Road Type	EPA HDV VMT Fractions									
	HDV2 b	HDV3	HDV4	HDV5	HDV6	HDV7	HDV8 a	HDV8 b	School Bus	Other Bus
1	0.170	0.048	0.034	0.015	0.051	0.035	0.083	0.540	0.008	0.015
2	0.242	0.035	0.024	0.010	0.037	0.025	0.125	0.462	0.019	0.021
3	0.339	0.022	0.016	0.007	0.024	0.016	0.086	0.322	0.153	0.015

any stops within the region but passed through. That means that over 50% of HHDDVs may not be registered within the region. If VMT fractions are generated with registration data, HHDDV VMT may be severely underestimated while lighter HDV VMT may be highly overestimated. Table C-3 shows EPA HDV VMT fractions obtained from the Georgia Tech HDV database for road types within the 20- county Atlanta region.

From total HPMS-estimated VMT, 2-axle, 4-tire VMT was calculated from the average 2-axle, 4-tire vehicle VMT percentages in the HSS. Then, the average 2-axle, 4-tire vehicle VMT percentages were divided by the LDT/HDV2b VMT ratio to obtain HDV2b VMT for each road type. From the HPMS database, total truck VMT was also calculated using AADT and a truck percentage for each link. After the estimation of HDV2b VMT, HDV VMT fractions were generated for each road type within the 20-county Atlanta region (Table C-4).

Total HDV VMT within the 20-county Atlanta region can be downsized into each county HDV VMT through the GIS spatial analysis. Because HPMS database was built with unit segment information—which includes the road typeand length and truck percent—county level HDV VMT can be generated through database management techniques. In addition, the Georgia Tech school bus database was also built by city and county bases, and therefore, school bus VMT can be generated for each county.

Application in Road Load-Based Emissions Modeling

Estimated HDV VMT by road type and by EPA HDV class can be directly used in modal activity-based emissions models for the regional on-road mobile source emissions inventory development. In modal activity-based emissions models, HDV VMT will be associated with emissions rates in grams per brake-horsepower, tractive horsepower, road length, and the fraction of a road grade-length matrix at given conditions.

$$E_{i,f} \sum_{j,k,l} \left(P_{j,k} \times AFF_{j,k} \times ER_l \right)_{i,f} \times VMT_{i,f} \,/\, LM_f$$

where E is the emissions in grams per day,
i is the heavy-duty vehicle class,
f is the road type,
j is the speed in the speed-acceleration matrix,
k is the acceleration in the speed-acceleration matrix,
l is the engine model year,

P is the tractive power in brake-horsepower-hour,
AFF is the acceleration frequency fraction in the speed-acceleration matrix,
ER is the emissions rate in grams per brake-horsepower-hour,
LM is the total lane length in miles, and
VMT is the total vehicle miles traveled in miles per day.

Appendix D
Emission Testing Contacts

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Appendix E
Heavy-Duty Vehicle Emission Rate Data Sources and Applications

MOBILE series models, which were developed by U.S. EPA and are used in 49 states for regulatory purposes, estimate HDV emissions rates based on certified engine dynamometer test results. Certified engine dynamometer emissions expressed in grams per brake-horsepower-hour will be converted into emissions in grams per mile with conversion factors for each HDV classes from HDV2b to HDV8b. Emissions rates from engine dynamometer tests will be corrected with various correction factors to represent real-world emissions rates. In addition, the EMFAC-2000 emissions model that is only used in California estimates HDV emissions rates based on chassis dynamometer test results. Chassis dynamometer emissions rates expressed in grams per mile can be directly used to estimate emissions rates without using conversion factors. However, emissions rates from both dynamometer test results may not correctly represent horsepower corresponding emissions rates on the road. That is because horsepower requirement varies by road grades, weight, speed, and acceleration according to real road conditions.

The load-based (required horsepower) HDV emissions model framework, which is under development by Georgia Institute of Technology (Georgia Tech), has the same model framework concept used for MOVES. To link required horsepower at a specific road and vehicle operating conditions to emissions rates in grams per brake-horsepower-hour, grams per axle-horsepower-hour, or grams per mile, the research team has reviewed available data from various HDV emissions test laboratories and developed strategies on how to incorporate the data to Georgia Tech load-based HDV emissions model framework.

Emission Rate Data Available for Analysis

NVFEL (National Vehicle and Fuel Emissions Laboratory, EPA)

NVFEL provides engine dynamometer test emissions rates (zero mile emission levels plus deterioration rates) in grams per brake-horsepower-hour, which were tested with the Federal test procedure (FTP) HDV transient cycle (U.S. EPA, 2004). Emissions rates provided from this laboratory are used in MOBILE5 and MOBILE6 mobile source models. Before incorporating the engine dynamometer test emissions rates with required horsepower from the proposed emissions model framework, horsepower losses through the drive train and differential should be considered. Because the brake-horsepower from engine dynamometer tests indicates the net horsepower available at the engine crankshaft, horsepower losses through the drive train and differential should be excluded from the net available horsepower from engine dynamometer tests. For use in MOBILE6, Tables E-1 to E-3 show heavy-duty engine emission rates by model year group for HC, NO_X, and CO. All the emissions rate data are available from Lindhjem and Jackson, 1999.

Table E-1. Heavy-Duty Vehicle HC Emission Rates (Grams per Brake-Horsepower-Hour) for Use in MOBILE6.

Year	Light				Medium				Heavy			
	ZML[a]		Det @ 110k[b]		ZML		Det @ 185k[c]		ZML		Det @ 290k[c]	
	G[d]	D[e]	G	D	G	D	G	D	G	D	G	D
1989	0.62	0.64	0.023	0.002	0.62	0.66	0.023	0.002	0.62	0.47	0.023	0.001
1990	0.35	0.52	0.023	0.001	0.35	0.52	0.023	0.001	0.35	0.52	0.023	0.000

continued

1991–	0.33	0.47	0.021	0.001	0.33	0.40	0.021	0.001	0.33	0.30	0.021	0.000
1994–	0.33	0.26	0.021	0.001	0.33	0.31	0.021	0.001	0.33	0.22	0.021	0.001
1998–	0.33	0.26	0.021	0.001	0.33	0.31	0.021	0.001	0.33	0.22	0.021	0.001
2004+	0.33	0.26	0.021	0.001	0.33	0.31	0.021	0.001	0.33	0.22	0.021	0.001

[a] ZML = zero mile level.
[b] Det @ = deterioration rate at 110k mi.
[c] The useful life of all heavy-duty gasoline engines is 110k mi.
[c] G = gasoline engine.
[d] D = diesel engine.

Table E-2. Heavy-Duty Vehicle NO_X Emission Rates (Grams per Brake-Horsepower-Hour) for Use in MOBILE6.

Year	Light				Medium				Heavy			
	ZML[a]		Det @ 110k[b]		ZML		Det @ 185k[c]		ZML		Det @ 290k[c]	
	G[d]	D[e]	G	D	G	D	G	D	G	D	G	D
1989	4.96	4.34	0.044	0.002	4.96	6.43	0.044	0.009	4.96	6.28	0.044	0.010
1990	3.61	4.85	0.026	0.011	3.61	4.85	0.026	0.006	3.61	4.85	0.026	0.004
1991–	3.24	4.38	0.038	0.003	3.24	4.53	0.038	0.007	3.24	4.56	0.038	0.004
1994–	3.24	4.08	0.038	0.001	3.24	4.61	0.038	0.001	3.24	4.61	0.038	0.003
1998–	2.59	3.26	0.038	0.001	2.59	3.69	0.038	0.001	2.59	3.68	0.038	0.003
2004+	2.59	1.61	0.038	0.001	2.59	1.84	0.038	0.001	2.59	1.84	0.038	0.003

[a] ZML = zero mile level.
[b] Det @ = deterioration rate at 110k mi.
[c] The useful life of all heavy-duty gasoline engines is 110k mi.
[c] G = gasoline engine.
[d] D = diesel engine.

Table E-3. Heavy-Duty Vehicle CO Emission Rates (Grams per Brake-Horsepower-Hour) for Use in MOBILE6.

Year	Light				Medium				Heavy			
	ZML[a]		Det @ 110k[b]		ZML		Det @ 185k[c]		ZML		Det @ 290k[c]	
	G[d]	D[e]	G	D	G	D	G	D	G	D	G	D
1989	13.84	1.21	0.246	0.022	13.84	1.70	0.246	0.009	13.84	1.34	0.246	0.010
1990	6.98	1.81	0.213	0.012	6.98	1.81	0.213	0.006	6.98	1.81	0.213	0.004
1991–	7.10	0.40	0.255	0.004	7.10	1.26	0.255	0.007	7.10	1.82	0.255	0.004
1994–	7.10	1.19	0.255	0.003	7.10	0.85	0.255	0.001	7.10	1.07	0.255	0.003
1998–	7.10	1.19	0.255	0.003	7.10	0.85	0.255	0.001	7.10	1.07	0.255	0.003
2004+	7.10	1.19	0.255	0.003	7.10	0.85	0.255	0.001	7.10	1.07	0.255	0.003

[a] ZML = zero mile level.
[b] Det @ = deterioration rate at 110k mi.
[c] The useful life of all heavy-duty gasoline engines is 110k mi.
[c] G = gasoline engine.
[d] D = diesel engine.

Table E-4. Heavy Heavy-Duty Diesel Vehicle Emission Rates from NREL.

Vehicle Model Year	Engine Model Year	Test Cycle	Max bhp	GVWR (lbs)	Emission Test Year	Odometer Reading	Avg. Emission Rate (g/mi)		
							HC	NO_X	CO
1989	1989	CBD[a]	350	46,000	1995	496,232	1.37	12.7	27.9
1994	1994	WVU[b]	[c]	68,000	1995	11,300	2.02	33.2	3.0
1996	1996	5 min	330	80,000	1997	132,700		35.2	2.0
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1996	1996	5 min	330	80,000	1998	204,200		31.8	1.7

[a] CBD = central business district.
[b] WVU = West Virginia University.
[c] Max bhp unknown.

NREL (National Renewable Energy Laboratory, DOE)

National renewable energy laboratory provides chassis dynamometer test average emissions rates in grams per mile (NREL, 2004). The chassis dynamometer average emissions rates come with detailed vehicle and engine type information such as vehicle model year, engine model year, maximum brake horsepower, test fuel type, vehicle type, odometer readings, GVWRs, test year, average emissions rates, and test cycles. All information provided from the NREL is only for HHDVs. Table E-4 shows a sample of information available from NREL. Before incorporating NREL emissions rates with required horsepower from the proposed model framework, average emissions rates in grams per mile can be divided by maximum brake horsepower and multiplied by test length in miles (given by test cycle). Because vehicles were tested multiple times with various test cycles, it is possible to conduct meaningful statistical analysis for emissions rates. However, the maximum horsepower values provided by NREL are not clearly described. The values may be interpreted to denote rated (maximum) horsepower or actual horsepower used in the tests. Measured horsepower (actual) or a "book value" may have been used in the tests. Depending on which horsepower value may have been used in the tests and subsequent calculations, the converted emissions rates in grams per brake-horsepower may be greater or smaller than actual emissions rates. Table E-4 is an example of the emission rates that may be obtained from the data.

EERC (Engine and Emissions Research Center, WVU)

Chassis dynamometer test results by WVU-EERC are available through various research reports; those are CRC Project No. E-55/E-59 (Gautam and Clark, 2003), CRC Project No. E-55-3 (Clark and Gautam, 2004), and HDDV emission test data from New York State Department of Environmental Conservation (EEA, 2000). Available data are in various units such as grams per brake-horsepower-hour, grams per axle-horsepower-hour, and grams per mile. If raw data from WVU-EERC are provided, the research team can easily convert them into emissions rates in grams per axle-horsepower-hour units before incorporating them with the required horsepower in the proposed model framework. Table E-5 shows the example emissions rates with axle horsepower from CRC Project No. E-55/E-59.

Table E-5. Emissions Rates from CRC Project No. E-55/E-59.

Truck ID	Test Cycle	ahp-hr	Emission Rates (g/ahp-hr)			
			CO	NO_X[a]	NO_X[b]	HC
E55CRC-1	D	14.88	4.72	13.38	13.29	0.09
E55CRC-1	D	15.37	5.60	12.81	13.22	0.09
E55CRC-1 avg	D	15.12	5.16	13.10	13.25	0.09

continued

E55CRC-2	D	16.74	1.29	6.38	6.54	0.28
E55CRC-2	D	17.04	1.37	6.25	6.29	0.26
E55CRC-2 avg	D	16.89	1.33	6.32	6.41	0.27

[a] Analyzer number 1.
[b] Analyzer number 2.

New York State Department of Environmental Conservation and Energy (NYSDEC) test data are also available from EMFAC2000 documentation (CARB, 2000), which provides engine model year, gross vehicle weight ratings, actual vehicle weight, and emissions rates (Table E-6).

Table E-6. NYSDE Test Data Used in EMFAC2000.

Model Year	GVWR (lbs)	Test Weight (lbs)	Odometer (miles)	Emission Rates (g/mi)		
				HC	CO	NO_X
1985	26,000	18,200	21,600	0.15	2.33	12.10
1989	33,000	23,100	66,300	0.63	6.09	18.80
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1997	33,000	23,100	3500	0.08	4.93	16.60

CIFER (Colorado Institute for Fuels and High Altitude Engine Research)

CIFER at the Colorado School of Mines provided chassis dynamometer test results from the northern front range study and opacity inspection (Colorado IFHAER, 2004). The test results were also used to develop emission rates in EMFAC2000. In EMFAC2000 documentation, CIFER data shows engine model year, gross vehicle weight ratings, actual vehicle weight, odometer, start status (hot or cold), and emissions rates (Table E-7).

Table E-7. CIFER Test Data Found in EMFAC2000 Document.

Model Year	GVWR (lbs)	Test Weight (lbs)	Odometer (miles)	Start (hot or cold)	Emission Rates (g/mi)		
					HC	NO_X	CO
1990	33,000	23,667	142,242	hot	0.26	15.41	4.93
1993	25,500	18,049	122,406	cold	1.24	14.97	18.41
1993	25,500	18,049	122,406	hot	0.56	13.82	
1993	25,500	18,049	122,406	hot	0.62	13.39	

CAEC (Cleaire Advanced Emission Controls, LLC)

CAEC provided the research team with a set of HDV chassis dynamometer test results. The test results show second-by-second emissions rates and engine parameters during chassis dynamometer testing (CAEC, 2004). However, the test results do not provide second-by-second brake (or axle) horsepower, instead providing only rated horsepower at a given RPM.

EMFAC2000

Emissions rates in EMFAC2000 model are based on chassis dynamometer test results unlike MOBILE6, which is based on engine dynamometer test results. To develop emissions rates in the EMFAC2000 model, California Air Resources Board (CARB) used data tested by NYSDEC, WVU-EERC, and CIFER. Through statistical analysis, emissions rates in grams per mile for diesel light, medium, and heavy HDVs were estimated. Table E-8 shows the diesel HHDV average emissions rates (zero mile emissions plus deterioration rates) used in EMFAC2000.

Table E-8. Diesel HHDV Emissions Rates (grams per mile).

Year	HC		CO		NO_X	
	ZML[a]	10k[b]	ZML	10k	ZML	10k
1987–	0.34	0.009	2.48	0.065	16.79	0.015
1991–	0.28	0.009	1.74	0.056	15.97	0.030
1994–	0.19	0.016	0.84	0.068	19.06	0.042
1998	0.18	0.014	0.63	0.049	23.01	0.037
1999–	0.18	0.009	0.63	0.031	13.36	0.013
2003	0.14	0.003	1.01	0.023	6.68	0.007
2004+	0.14	0.003	1.01	0.023	6.68	0.007

[a] ZML = zero mile level (engine has zero miles).
[b] engine deteriorated to 10k miles.

NCSU (North Carolina State University)

Recently NCSU measured instantaneous medium HDV engine activity and emissions using an onboard portable monitoring system while the vehicle was running on the road. They measured NO_X, PM, CO, and CO_2 emissions with fuel use, vehicle speed, and location. However, they did not measure horsepower from the vehicle.

Application in the Load-Based HDDV Modal Emission Modeling Framework

Emissions rates from chassis dynamometer test laboratories described above could be used for the development of the load-based HDV emissions model framework. Chassis dynamometer test results from WVU-EERC would be the most reliable because they have tested an extensive number of HDVs (light HDVs for NYSDEC, medium HDVs for CRC Project No. E-55-3, and heavy HDVs for CRC Project No. E-55/E-59) and provided emissions rates in grams per axle-horse-power-hour, test methods, and axle horsepower in axle-horsepower-hour. These data can be directly incorporated with required horsepower for vehicle activity.

$$LER = ER \times P/3600$$

where, *LER* is the load-based emissions rate in grams per second,
ER is the chassis dynamometer test result in grams per axle-horsepower-hour,
P is the tractive power for vehicle activity in axle-horsepower per second, and
3600 is the conversion factor from hours to seconds

For further detailed load-based emissions modeling with WVU-EERC data, more detail data than is available in the published reports (raw data) should be provided.

However, emissions rates from the chassis dynamometer test do not extensively incorporated with second-by-second vehicle activities involved in road grades and off-test cycle acceleration and speed. That means that the emissions rates from the chassis dynamometer test may not represent second-by-second emissions rates although they can be expressed in grams per second after multiplying required horsepower. In this case, emissions rates and axle (wheel) horsepower measured at the same time by CE-CERT would be more real-world representing emissions data. However, CE-CERT does not provide test route elevation incorporated with second-by-second emissions rates and horsepower. In addition, their data may not statistically significant because they do not provide enough data.

Appendix F
Modeling Approaches On-road Heavy-Duty Diesel Vehicle Oxides of Nitrogen and Particulate Matter Emissions: PART5, MOBILE6, EMFAC7G, and EMFAC2000

This appendix discusses the basis of oxides of nitrogen (NO_X) and diesel PM emission rate modeling from on-road HDDVs in current models.

HDDVs are the major on-road NO_X and diesel PM emissions sources, which impacts high concentrations of ground level ozone and fine particulate matter in the atmosphere. To analyze the air quality impact of the pollutants from HDDVs, national and state air quality agencies develop on-road emissions inventories using mathematical emission models such as PART5, MOBILE6, EMFAC7G, EMFAC2000, and later models. PART5, developed by U.S. EPA in 1995, was designed to estimate particulates from tailpipes, tires, and brakes. Since then, PART5 became the prototype of a PM emission model for other emission models. As PART5 descendants in diesel PM emissions estimation, EMFAC7G and MOBILE6 were developed by California DOT in 1997 and by U.S. EPA in 2001. In 2000, California DOT developed a new generation emission model (EMFAC-2000), which adopted a new concept to estimate emission rates from on-road HDDVs. EMFAC2000 estimates emission rates with chassis dynamometer test results, whereas the other models predict the emission rates with the engine dynamometer test results. Diesel PM emission rates estimated with EMFAC2000 were significantly different from its predecessor, EMFAC7G. In this report, this diesel PM emission rate difference will not be discussed because that is beyond the objective. CARB provides detailed information of the difference in diesel PM emissions rates between the two models. Table F-1 shows the emissions models capable of diesel PM emissions estimation.

MOBILE6, EMFAC7G, and EMFAC2000 can estimate NO_X emissions from on-road HDDVs. NO_X emission estimation with MOBILE6 and EMFAC7G are based on engine dynamometer test results. From these engine dynamometer tests, base NO_X emission rates were determined and then are corrected with series of correction factors. Conversely, base NO_X emission rates on EMFAC2000 are determined from chassis dynamometer test results, which were provided by U.S. EPA, NYSDEC, and WVU. The base NO_X emission rates are corrected with series of correction factors as well. Like diesel PM emissions rates, NO_X emissions rates estimated with EMFAC2000 were significantly different from EMFAC7G. This NO_X emissions rate difference will also not discussed in this report for the same reason the diesel PM emission rate difference is not discussed. CARB released enhanced EMFAC models in 2001 and 2002. However, the concept for estimating NO_X emissions is same as with the EMFAC-2000. Therefore, only EMFAC2000 will be discussed in this report. Table F-2 shows the emission models capable of NO_X emission estimation.

Table F-1. PM Emissions Estimation—Primary Model Components.

Model	Core Components
PART5	• BER[a] determined by **engine dynamometer test** results • BER = *f*(model year, speed, speed cycle, number of tires • TotPM = ExhPM + BrakePM + TirePM • ExhPM = OCPM[b] + ECPM[c] + sulfate • CarbonPM (g/mi) = BER (g/bhp-hr) × CF[d] (bhp-hr/mi) • Idling ER[e] (g/hr)

continued

EMFAC7G	• BER determined by **engine dynamometer test** results • BER = *f*(model year, speed, speed cycle, number of tires) • BEL[f] = *f*(ZML, DETR[g]) • TotPM = ExhPM + BrakePM + TirePM • ExhPM = OCPM + ECPM + Sulfate • CarbonPM (g/mi) = BER (g/bhp-hr) × CF (bhp-hr/mi)
MOBILE6	• BEL determined by **engine dynamometer test** results • BEL = *f*(model year, speed, speed cycle, number of tires) • BEL = *f*(ZML, DETR) • TotPM = ExhPM + BrakePM + TirePM • ExhPM = OCPM + ECPM + Sulfate • CarbonPM (g/mi) = BER (g/bhp-hr) × CF (bhp-hr/mi)
EMFAC2000	• BEL (g/mi) determined by **chassis dynamometer test** results • BEL = *f*(model year, speed, temperature, off-cycle, etc.) • BEL = *f*(ZML, DETR[f]) • ER[h] (g/mi) = BEL × Corrections (model year, speed, temperature, off-cycle, etc) • Idling ER (g/hr)

[a] BER = basic emission rate.
[b] OCPM = organic carbon PM emissions.
[c] ECPM = elemental carbon PM emissions.
[d] CF = conversion factor.
[e] ER = emissions rate.
[f] BEL = diesel initial (baseline) PM emisions.
[g] DETR = deterioration rate..

Table F-2. NO_X Emissions Estimation—Primary Model Components.

Model	Core Components
EMFAC7G	• BEL[a] (g/bhp-hr) determined by **engine dynamometer test** results • BEL = *f*(model year, speed, temperature, off-cycle, etc.) • BEL = *f*(ZML, DETR[b]) • EL[c] = *f*(sales fraction, horsepower fraction, BEL) • ER[d] (g/mi) = EL (g/bhp-hr) × CF[e] (bhp-hr/mi)
MOBILE6	• BEL (g/bhp-hr) determined by **engine dynamometer test** results • BEL = *f*(model year, speed, temperature, off-cycle, etc.) • BEL = *f*(ZML, DETR) • EL = *f*(diesel sales fraction, horsepower fraction, BEL) • ER (g/mi) = EL (g/bhp-hr) × CF (bhp-hr/mi)
EMFAC2000	• BEL (g/mi) determined by **chassis dynamometer test** results • BEL = *f*(model year, speed, temperature, off-cycle, etc.) • BEL = *f*(ZML, DETR) • ER (g/mi) = BEL × Corrections (model year, speed, temperature, off-cycle, etc) • Idling ER (g/hr)

[a] BEL = diesel initial (baseline) PM emisions.
[b] DETR = deterioration rate.
[c] EL = average emission rate for each vehicle type.
[d] ER = emissions rate.
[e] CF = conversion factor.

PART5

PART5 emission model released by U.S. EPA in 1995 can estimate diesel PM emission rates from on-road HDDVs. Diesel PM emission rates, which are a function of vehicle model year, speed, speed cycle (transient and steady), the number of wheels, and so on, consist of carbon PM, direct sulfate, brake-wear, and tire-wear emissions. Carbon PM emissions include organic carbon and elemental carbon emissions from HDDVs. Because initial (base) carbon emissions are expressed in particulate grams per brake-horsepower-hour, they are converted in particulate grams per mile with the conversion factor in brake-horsepower-hour per mile. The expressions of elemental and organic carbon emissions follow.

$$ECPM_{m,v} = \left(BEL_{m,v} \times CF_{m,v} - DSF_{m,v}\right) \times FEC_{m,v} \qquad \text{(F-1)}$$

$$OCPM_{m,v} = BEL_{m,v} \times CF_{m,v} - DSF_{m,v} - ECPM_{m,v} \qquad \text{(F-2)}$$

$$CF_{m,v} = \frac{FD}{BSFC_{m,v} \times FE_{m,v}} \qquad \text{(F-3)}$$

where *ECPM* is the elemental carbon PM emissions in grams per mile,
BEL is the diesel initial (baseline) PM emissions in grams per brake-horsepower-hour,
CF is the conversion factor in brake-horsepower-hour per mile,
DSF is the direct sulfate emissions in grams per mile,
FEC is the elemental carbon fraction of the diesel exhaust emissions factor,
OCPM is the organic carbon PM emissions in grams per mile,
FD is the fuel density in pounds per gallon,
BSFC is the brake specific fuel consumption in pounds per brake-horsepower-hour,
FE is the fuel economy in miles per gallon,
m is model year, and
v is vehicle class.

Direct sulfate emissions are calculated with the assumption that all sulfur in diesel fuel is exhausted as sulfate or sulfate dioxide.

$$SUPM_{m,v} = 17.5 \times FD \times SWP \times DSCF / FE_{m,v} \qquad \text{(F-4)}$$

where *SUPM* is the direct diesel sulfate emissions in grams per mile,
SWP is the sulfur weight percent in diesel fuel, and
DSCF is the direct sulfur conversion percent to sulfate.

From the equations F-1 to F-4, base exhaust emission rates can be determined for each vehicle class and vehicle model year. In PART5, base exhaust diesel PM emissions can be determined with the zero mile emissions rate and deterioration rates, which were obtained from Federal Test Procedure (FTP) test results.

$$ExhPM_{m,v} = ZM_{m,v} + \left(CM_1 \times DTR_1\right)_{m,v} + \left(CM_2 \times DTR_2\right)_{m,v} \qquad \text{(F-5)}$$

where *ExhPM* is the exhaust base emissions rate in grams per mile,
ZM is the zero mile emissions rate in grams per mile,
CM_1 is the cumulative mileage less than useful life (mileage),
DTR_1 is the deterioration rate at CM_1,
CM_2 is the cumulative miles at useful life (mileage) minus CM_1, and
DTR_2 is the deterioration rate at CM_2.

Then, the base exhaust emissions rates are weighted with series of correction factors such as speed, temperature, high emitter correction factors, and so on for each vehicle type and vehicle model year. Brake-wear emissions rate is uniformly applied to all vehicle classes.

$$BrakePM = 0.0128 \times PSBRK \qquad \text{(F-6)}$$

where *BrakePM* is the brake-wear PM emissions in grams per mile and
PSBRK is the particle fraction to the particle size cutoff.

Tire-wear emissions are a direct function of the average number of wheels (tires) for the vehicle type.

$$TirePM_v = 0.002 \times PSBRK \times ANW_v \qquad \text{(F-7)}$$

where *TirePM* is the tire-wear PM emissions in grams per mile and
ANW is the average number of wheels.

In addition, PART5 displays diesel HDDV idle emissions rates in grams per hour, which were collected from vehicle manufacturers. Idle emissions rates, however, only varies by vehicle year group, but not by vehicle type.

EMFAC7G

EMFAC7G (a model in MVEI7G package) estimates diesel PM emissions from on-road HDDVs, using an approach almost identical to PART5, except for tire-wear particle size cut-off fraction for PM_{10}. The particle size cut-off fraction used in EMFAC7G was 0.4 for PM_{10} out of total suspended particulate (TSP), while PART5 used 1.0 for the particle size cut-off fraction.

NO_X emissions from HDDVs in EMFAC7G can be calculated with average emissions levels and correction factors for each vehicle type and vehicle model year. The concept to estimate NO_X emissions with EMFAC7G is same with MOBILE5 and MOBILE6.

MOBILE6

MOBILE6 also used the same estimation approach that PART5 used to calculate diesel PM emissions. However, the linear relationship between zero mile emissions rate and mileage in MOBLE6 may differ from that in PART5 because MOBILE6 uses some modified correction factors from original PART5 correction factors.

NO_X emissions from HDDVs in MOBILE6 can be calculated with average emissions levels and correction factors for each vehicle type and vehicle model year. Baseline NO_X emissions can be determined with Equation F-5. Base emission rates for each vehicle model year can be averaged among each vehicle type.

$$EL_v = \frac{\sum \left(Sales_{v,yr} \times HP_{v,yr} \times EL_{v,yr} \right)}{\sum \left(Sales_{v,yr} \times HP_{v,tr} \right)} \qquad \text{(F-8)}$$

where EL_v is the average emissions rate for each vehicle type,
$Sales$ is the diesel sales fraction,
HP is the engine horsepower, and
$EL_{v,yr}$ is the base emissions rate for each vehicle type and vehicle model year.

Then, the average emission rates in NO_X grams per brake-horsepower-hour can be converted by the conversion factor expressed in the Equation F-3. In MOBILE6, the fuel economy and the brake specific fuel consumption are expressed with curve fit equations for vehicle model year using Truck Inventory and Use Survey data and truck manufacturers' brake specific fuel consumption test results.

EMFAC2000

In diesel PM and NO_X emissions estimation from on-road HDDVs, EMFAC2000 uses a completely different approach from other emissions models. EMFAC2000 uses chassis dynamometer test results to estimate base emissions rate for diesel PM and NO_X emissions, whereas other models use engine dynamometer test results. Because EMFAC2000 uses base emissions rate in pollutant grams per mile, it does not need to use conversion factors to change emission rate units. To develop diesel PM and NO_X curve fit equations for vehicle model year, EMFAC2000 uses chassis dynamometer test results (tested with urban dynamometer test schedule—UDDS) collected from U.S. EPA, NYSDEC, and WVU. Then, the base emissions rate can be weighted with series of correction factors. Because U.S. EPA, NYSDEC, and WVU only provide the UDDS results of medium and heavy HDDVs, EMFAC2000 uses the FTP test results done by CE-CERT (UC Riverside) for light HDDVs. EMFAC2000 also recalculate zero mile emissions rate and deterioration rate to reflect tampering and maintenance component effect on the collected data.

$$ZM = ER \Big/ \left[1 + \left(EL_1 + EL_2 \right) / 2 \right] \qquad \text{(F-9)}$$

$$DR = \left(ER - ZM \right) \Big/ \left(Odometer / 10000 \right) \qquad \text{(F-10)}$$

where ZM is the zero mile emissions rate,
ER is the average emissions rate of the chassis dynamometer data,
EI_1 is the emissions impact prediction of the Radian model (HDDV I/M study by Radian Corporation) assuming the effect of both tampering and mal-maintenance,
EI_2 is the emissions impact prediction of the Radian model assuming the effect of only tampering, and
DR is the deterioration rate.

For the first time in EMFAC models, EMFAC2000 introduced idling emissions rates (grams per hour), which are for HDDVs running with speeds of less than 5 mph and a trip length of less than 5 miles.

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16. ABSTRACT
The report outlines research of a proposed heavy-duty Diesel vehicle modal emission modeling framework (HDDV-MEMF) for heavy-duty diesel-powered trucks and buses. Although the heavy-duty vehicle modal modules being developed under this research are different from the motor vehicle emissions simulator (MOVES) model, the HDDV-MEMF modules should be compatible with MOVES. In the proposed HDDV-MEMF, emissions from heavy-duty vehicles are predicted as a function of hours of on-road operation at specific engine horsepower loads. Hence, the basic algorithms and matrix calculations in the new heavy-duty diesel vehicle modeling framework should be transferable to MOVES. The specific implementation approach employed by the research team to test the model in Atlanta is somewhat different from other approaches in that an existing geographic information system (GIS) based modeling tool is being adapted to the task. The new model implementation is similar in general structure to the previous modal emission rate model known as the mobile assessment system for urban and regional evaluation (MEASURE) model. This exploratory framework is designed to be applied to a variety of policy assessments, including those aimed at reducing the emission rates from heavy-duty vehicles and those designed to change the on-road operating characteristics to reduce emissions.

17. KEY WORDS AND DOCUMENT ANALYSIS		
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