A NEW HEAVY-DUTY VEHICLE VISUAL CLASSIFICATION AND ACTIVITY ESTIMATION METHOD FOR REGIONAL MOBILE SOURCE EMISSIONS MODELING

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ABBREVIATIONS

13-County Area	Atlanta 13-County 1-hr Ozone Nonattainment Area
20-County Area	Atlanta 20-County 8-hr Ozone Nonattainment Designated Area
21-County Area	Atlanta Heavy-Duty Vehicle and Equipment Inventory and Emissions Study Area
AADT	Annual Average Daily Traffic
AAMA	American Automotive Manufacturers Association
BSFC	Brake-Specific Fuel Consumption
CAA	Clean Air Act
CO	Carbon Monoxide
FTP	Federal Test Procedure
g/bhp-hr	Grams per Brake Horsepower - Hour
g/mi	Grams per Mile
g/sec	Grams per Second
GCWR	Gross Combination Weight Rating
GIS	Geographic Information System
GPS	Global Positioning System
GVW	Gross Vehicle Weight
GVWR	Gross Vehicle Wight Rating
HDDV-MEM	Heavy-Duty Diesel Vehicle Modal Emissions Model

HDV	Heavy-Duty Vehicles
HPMS	Highway Performance Monitoring System
lbs	Pounds
LDV	Light-Duty Vehicle
MATES-II	Multiple Air Toxics Exposures Study -II
MEASURE	Mobile Emission Assessment System for Urban and Regional Evaluation
MOVES	Motor Vehicle Emission Simulator
mph	Miles Per Hour
NAAQS	National Ambient Air Quality Standards
NO_2	Nitrogen Dioxide
NO_X	Oxides of Nitrogen
O_3	Ozone
PM	Particulate Matters
SIP	State Implementation Plan
SO_X	Sulfur Oxides
tonne	Mass in metric units, i.e., 1tonne equals to 1.102ton
UDDS	Urban Dynamometer Driving Schedule
VIUS	Vehicle Inventory and Use Survey
VMT	Vehicle Miles Traveled
VSP	Vehicle Specific Power

SUMMARY

For Heavy-duty vehicles (HDVs), the distribution of vehicle miles traveled (VMT) by vehicle type is the most significant parameters for onroad mobile source emissions modeling used in the development of air quality management and regional transportation plans. There are two approaches for the development of the HDV VMT distribution. The first approach uses HDV registration data and annual mileage accumulation rates. The second approach uses HDV VMT counts/observations collected with the Federal Highway Administration (FHWA) truck classification.

For the purpose of emissions modeling, the FHWA truck classes are converted to those used by the MOBILE6.2 emissions rate model by using either the U.S. Environmental Protection Agency (EPA) guidance or the National Research Council (NRC) conversion factors. However, both these approaches have uncertainties in the development of onroad HDV VMT distributions that can lead to large unknowns in the modeled HDV emissions. Uncertainties in HDV VMT distributions can be associated with the aggregated FHWA truck activities and the lack of proper region-wide activity simulation methods for each truck or HDV. Three questions associated with the uncertainties are:

- Are registered HDV data properly classified to EPA HDV classes?
- Do HDV registration distributions developed from registered HDV data properly represent onroad HDV fleet compositions?
- Do current HDV conversion methods or guides properly map FHWA truck classes into EPA HDV classes without losing the fine resolution of original vehicle characteristics?

This dissertation reports a new heavy-duty vehicle visual classification and activity estimation method that minimizes uncertainties in current HDV conversion methods and the vehicle registration based HDV VMT estimation guidance. The HDV visual classification scheme called the X-scheme, which classifies HDV/truck classes by vehicle physical characteristics such as the number of axles, the number of tires, gross vehicle weight ratings, horsepower ranges, vehicle activity characteristics, and tractor-trailer configuration, converts FHWA truck classes into EPA HDV classes without losing the original resolution of HDV/truck activity and emission characteristics. The new HDV VMT estimation method, developed with the combination of the X-scheme, publicly available HDV activity databases, and the 2003 Georgia Tech HDV/BUS database, minimizes uncertainties in the vehicle registration based VMT estimation method suggested by EPA. Specifically, the new HDV VMT estimation method minimizes the VMT allocation from heavy HDVs to light and medium HDVs. The analysis of emissions impact with the new HDV visual classification and VMT estimation method indicates that emissions with the EPA HDV VMT estimation guidance are underestimated by 22.9% and 25.0% for oxides of nitrogen (NO_X)and fine particulate matter ($PM_{2.5}$) respectively within the 20-county Atlanta 8-hr ozone nonattainment area. The new heavy-duty vehicle visual classification and activity estimation method can be used for the development of HDV/truck activity databases without losing the fine resolution of vehicle characteristics, and can be used for the facility-specific HDV VMT estimation for the development of onroad emissions inventories. Because the new heavy-duty vehicle visual classification and activity estimation method has the ability to provide accurate HDV activity and emissions estimates, this method has the potential to significantly influence policymaking processes in regional air quality management and transportation planning. In addition, the ability to estimate link-specific emissions benefits Federal and local agencies in the development of project (microscale), regional (mesoscale), and national (macroscale) level air quality management and transportation plans.

CHAPTER 1

INTRODUCTION

Over the last several decades, both government and private industry to regulate and control the emissions of wide range of pollutants into the atmosphere from a variety of sources have made extensive efforts. While these efforts have met with substantial success, problems persist and management of air quality remains an important public priority and influences numerous public and private decisions. Management of emissions from a source requires knowledge of both quantity of activity from a source (e.g., in the case of motor vehicles the vehicle miles traveled (VMT)) and the rate of emissions per unit of activity (emission rates).

Heavy-duty vehicles (HDVs) are major air pollutant emission sources, especially for oxides of nitrogen (NO_X) and fine particulate matter ($PM_{2.5}$). Although previous studies (see for example Lloyd, 2001; Gautam, 2003; Hill, 2003) have stressed the significance of emissions from HDVs, in urban nonattainment areas especially for ozone (for which nitrogen oxides are a precursor) and $PM_{2.5}$, current methods to estimate HDV activity have major deficiencies.

For example, the methods used to separate overall HDV activity into individual HDV classes are often inappropriately used or have high uncertainties (Guensler, 1991). Specifically, the U.S. Environmental Protection Agency (EPA) guidance, which provides a conversion method from axle and tractor-trailer configuration truck classes into gross vehicle weight rating (GVWR) HDV classes, can result in a loss of resolution of vehicle class information relative to field observations and misrepresent onroad HDV fleet VMT (Yoon, 2004a).

In addition, the EPA recommended HDV VMT estimation method used in conjunction with its current primary emissions model (MOBILE6.2) is based on vehicle registration and annual mileage accumulation rates that underestimate inter-region or inter-state operations because a greater portion of inter-region operating HDV activity occurs within urban areas than relative to their registration fractions.

1.1 NO_X and $PM_{2.5}$ Emission Rates from Heavy-Duty Vehicles

Baseline NO_X and $PM_{2.5}$ emissions rates used in the EPA MOBILE6.2 emission rate model to estimate emission rates from HDV are based on the laboratory test procedure (CFR, 2004c) of the emissions from HDV engines. In the test procedure (CFR, 2004c), an engine is removed from a HDV chassis, mounted on an engine dynamometer test stand, and operated through a defined test cycle. As the engine operates under the test procedure, measured emissions are combined with engine power measurements to produce the brake-specific emission rates (g/hp-hr) that are ultimately used in the MOBILE6.2 emission rate model as baseline emission rates. In HDV emissions inventory development, baseline emission rates are combined with estimates of vehicle fuel economy and vehicle activity parameters, such as annual mileage accumulation rates, registration distributions by age, and vehicle miles traveled (VMT) fractions (if VMT is not separated into vehicle classes) or HDV vehicle miles (if VMT estimates exist for each vehicle class), to estimate emission rates for a certain modeling year (USEPA, 2002a).

Individual HDV annual mileage accumulation rates are area specific and can be estimated not only by field data collection and survey methods, but also by VMT fractions and aggregated HDV VMT. Among onroad mobile emission sources, HDVs contribute only 7% of total onroad motor vehicle VMT (BTS, 2003)yet contribute more than 45% and 75% of total onroad motor vehicle emissions for NO_X and $PM_{2.5}$ respectively (USEPA, 2003). The estimated emission contributions from HDV can vary significantly from region to region or by the method chosen to assign overall HDV activity into individual vehicle classes (vehicle mapping) or VMT estimation methods, or both. Errors due to vehicle mapping arise since estimated emission rates vary substantially between different vehicle classes. For example, the estimated emission rates from the heaviest diesel HDV class are five and three times greater for NO_X and $PM_{2.5}$ than those from the lightest diesel HDV class. Figure 1.1 shows 2003 MOBILE6.2 NO_X and $PM_{2.5}$ emission rates from diesel and gasoline HDVs with modeling parameters (GDNR, 2005) used for the 13-county Atlanta metropolitan air quality planning area.

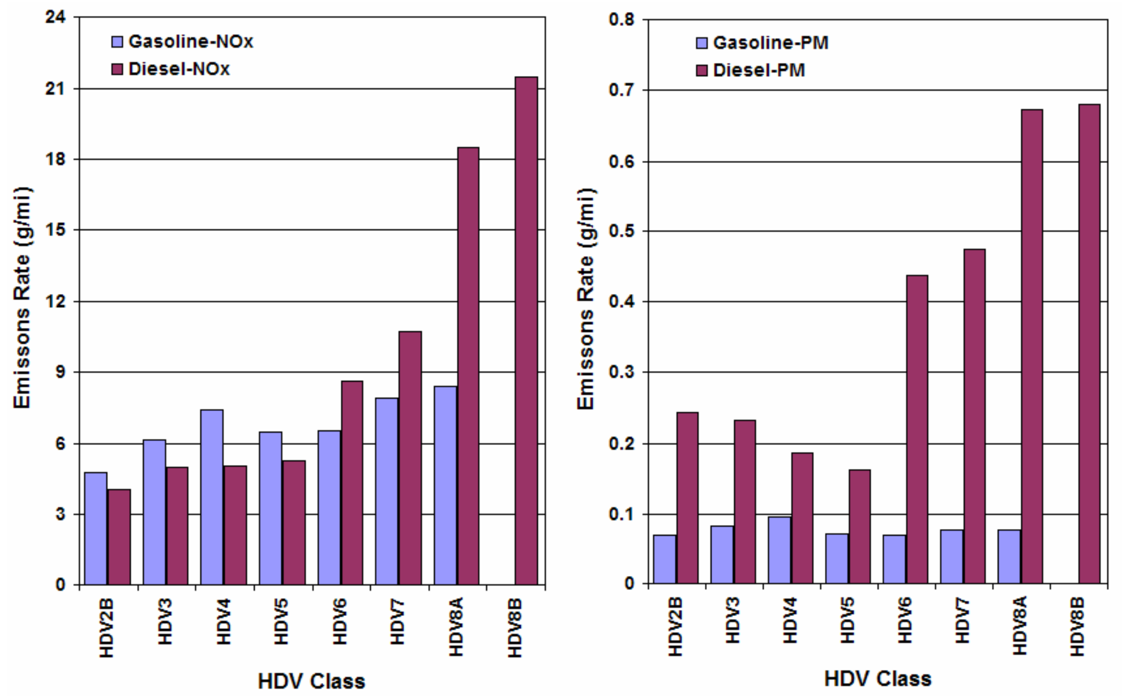

Figure 1.1: MOBILE6.2 NO_X and $PM_{2.5}$ Emission Rates for Freeways at 35mph of Average Speed and July 2003 within the 13-County Atlanta Metropolitan Area

1.2 Current Heavy-Duty Vehicle Conversion and VMT Estimation Methods

EPA defines heavy-duty vehicles as *"any motor vehicle rated at more than 8,500 pound of gross vehicle weight rating (GVWR)"* (CFR, 2004e). For emissions modeling purposes, HDVs are separated into eight subclasses for each gasoline and diesel vehicle by GVWR. While EPA defines HDV classes by their GVWR, FHWA defines truck classes by the number of axles, the number of tires, and tractor-trailer configuration (FHWA, 2001). Because Federal and state HDV vehicle activity measurements are referenced to FHWA truck classes (EPA classes which are based on GVWR cannot be directly observed), a EPA class to FHWA class conversion process or processes is required to estimate VMT for each EPA HDV class for input into the mobile source emissions model. To make this conversion, EPA suggests aggregating data for nine of the FHWA truck classes (5 to 13) and bus class (4) into an overall HDV VMT estimate and then disaggregating this estimate into the sixteen EPA HDV and two bus classes in accordance with their estimated VMT fractions for each class (USEPA, 2004c). However, this conversion guidance can bias in the estimation of light and medium HDV VMT and allocate heavy HDV VMT into light or medium HDV VMT, especially in urban areas (USEPA, 2004c; Yoon, 2004a). The VMT fraction estimation method, which is based on vehicle registration data with HDV classification and model year information used in the MOBILE6.2 emission rate model (USEPA, 2001a), misrepresents regional HDV VMT fractions for areas with higher than average heavy HDV traffic because inter-region operating HDVs, which are not registered within a specific study regional boundary, are not incorporated into the VMT fractions for the specific study region. For example, the Georgia Department of Natural Resources (GDNR) developed regional HDV VMT fractions and included only HDVs registered in the13-county Atlanta metropolitan area (GDNR, 2003). This can result in the overestimation of light and medium HDV VMT and the underestimation of heavy HDV VMT because Atlanta has a large volume heavy HDV traffic.

1.3 Research Approaches and Objectives

The major effort of this research is to develop a new heavy-duty vehicle visual classification and VMT estimation method that overcomes many of the limitations of existing methods and guides. The new method incorporates observed field data, regulatory criteria, and Federal and state HDV activity databases in a logical and consistent fashion. This effort consists of a number of specific objectives outlined below:

- Develop a method to convert observed FHWA truck classes into EPA HDV classes without losing the fine resolution of vehicle class information observed in the field and without misallocating heavy HDV VMT into light and medium HDV VMT and vise versa.
- Develop a method to extract HDV or truck activity data from publicly available databases with established criteria
- Incorporate the data extraction method into the new HDV classification scheme, and develop a new HDV activity estimation method to estimate HDV VMT for various roadway function classes, specifically freeways, arterials, and local roads.

To develop the information necessary for development of a new FHWA truck-to-EPA HDV conversion process, vehicle volume data were observed within the newly defined 21-county Atlanta metropolitan area (previously the Atlanta non-attainment area was comprised of 13 counties) using the Ahanotu truck classification scheme developed at Georgia Institute of Technology (Georgia Tech) (Ahanotu, 1999). The Ahanotu truck classification scheme is a visual classification scheme and was developed for use in collecting onroad truck activity data. The scheme regroups and aggregates various FHWA truck classes by the relationships between engine horsepower and truck weight distributions and ultimately employs only four truck classes. While this scheme offers lower resolution than a full FHWA classification scheme it is a rapid and easy to use scheme that offers the potential greatly improving truck activity estimates relative to the existing EPA guidance.

Because the observed vehicle volume data were partially aggregated with the Ahanotu truck classification scheme, new procedures were developed to relate the Ahanotu truck classes to EPA HDV classes and appropriate criteria were developed from truck GVWR and axle specifications from manufacturers' truck specification data and truck weight limitations from FHWA regulations (FHWA, 1994; FHWA, 2004). With these criteria and observed field volume data, a new FHWA truck-to-EPA HDV hybrid vehicle classification scheme called the X-scheme was developed to translate FHWA trucks into EPA HDV classes, or vice versa (Yoon, 2004a).

The field vehicle activity observations were expanded through the use of external public databases on truck and other HDV activity. These databases include the Highway Statistics from U.S. Department of Transportation, the Georgia Highway Performance Monitoring System (HPMS) from the Georgia Department of Transportation, the Vehicle Inventory and Use Survey (VIUS) from the U.S. Department of Transportation, and additional HDV and bus activity databases collected and maintained by a variety of agencies and groups. Using these databases the estimated truck VMT for the Atlanta metropolitan area was developed and processed through the new vehicle classification scheme to apportion VMT into EPA HDV, school bus, and urban bus classes for all but the lightest EPA HDV class (HDV2B) because these data were not directly available. Separate VMT estimates for the HDV2B class were estimated using AADT from HPMS and *"other 2-axle, 4-tire vehicle"* VMT percentages on various roadway facility types from Highway Statistics.

Through this process, HDV VMT was estimated for each roadway facility type within the 20-county Atlanta metropolitan area and used to estimate HDV emissions in this region using the EPA MOBILE6.2 emission rate model. This approach allows estimated HDV VMT to be directly connected to MOBILE6.2 emission rates without losing the fine resolution of observed field data, limits the misallocation of VMT from one HDV class to another, and thus provides more accurate emission estimates for regional emissions inventories and air quality impact analyses.

CHAPTER 2

HEAVY-DUTY VEHICLE EMISSIONS REGULATIONS AND EMISSIONS MODELING

In the United States, emissions from HDVs are regulated only indirectly by the imposition of emissions standards on the engines used to power these vehicles. While these emissions standards and associated testing requirements provide information regarding engine baseline emission rates (e.g., g/sec or g/bhp-hr) under a standard set of conditions, evaluating the overall vehicle emissions from HDV under realistic operating conditions required for air quality planning purposes requires the use of separate emission models. Emission models range from EPA’s MOBILE6.2 emission rate model that bases emissions estimates on typical operational speed cycles to HDV modal activity based emission models such as the Motor Vehicle Emission Simulator (MOVES), the Mobile Emission Assessment System for Urban and Regional Evaluation (MEASURE), or the Heavy-Duty Diesel Vehicle Modal Emission Model (HDDV-MEM).

2.1 Heavy-Duty Vehicle Emissions Regulations

Efforts to regulate tailpipe emissions from motor vehicles in the United States began in the mid-1960s. The Clean Air Act (CAA) of 1970 provided for the establishment of National Ambient Air Quality Standards (NAAQS) to protect the public health and the public welfare (Davis, 1998) and provided a mechanism for the regulation of emissions from a range of emissions sources including motor vehicles. Emissions from heavy-duty vehicles were not regulated until the mid-1970s, although tailpipe emission reduction efforts for light-duty vehicles started much earlier. In 1977, amendments to the CAA provided for the regulation of oxides of nitrogen (NO_X) and particulate matter (PM) from diesel vehicles effectively began regulations on heavy-duty vehicle emissions. The CAA of 1990 required the regional transportation plans to ensure the mobile source emissions inventories used for transportation planning conforming to the emission budgets presented in the corresponding state implementation plan used for regional air quality planning (FHWA, 1997). This requirement had the practical effect of coupling air quality and transportation planning.

2.1.1 National Ambient Air Quality Standards

The CAA of 1970 requires EPA to set NAAQS for six criteria pollutants, which are carbon monoxide (CO), nitrogen dioxide (NO_2), lead, particulate matter (PM), ozone (O_3), and sulfur oxides (SO_X). The NAAQS defines two types of air quality standards. The first are the primary standards designed to protect public health especially for sensitive populations such as asthmatics, children, and the elderly. The second set of standards is the secondary standards to protect public welfare including visibility, animals, vegetation, and buildings (CFR, 2004d). Table 2.1 illustrates the current NAAQS for ambient concentrations of various pollutants.

Table 2.1: National Ambient Air Quality Standards

Pollutant		Averaging Times	Primary Standards	Secondary Standards
Carbon Monoxide		8-hr	9ppm	None
		1-hr	35ppm	None
Lead		Quarterly	1.5μg/m^3	1.5μg/m^3
Nitrogen Dioxide		Annual	0.053ppm	0.053ppm
Particulate Matter[1]	PM$_{10}$	Annual	50μg/m^3	50μg/m^3
		24-hr	150μg/m^3	150μg/m^3
	PM$_{2.5}$	Annual	15μg/m^3	15μg/m^3
		24-hr	65μg/m^3	65μg/m^3
Ozone		8-hr	0.08ppm	0.08ppm
		1-hr	0.12ppm	0.12ppm
Sulfur Oxides		Annual	0.03ppm	None
		24-hr	0.14ppm	None
		3-hr	None	0.5ppm

Among the pollutants emitted from onroad motor vehicles, volatile organic compounds (VOC) and NO$_X$ are involved in atmospheric chemical processes that result in the

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[1] Particulate matter less than 10 μm or 2.5 μm in diameters

formation of ambient O_3 and in formation of secondary PM that in addition to the PM emitted by the motor vehicles themselves (Figure 2.1).

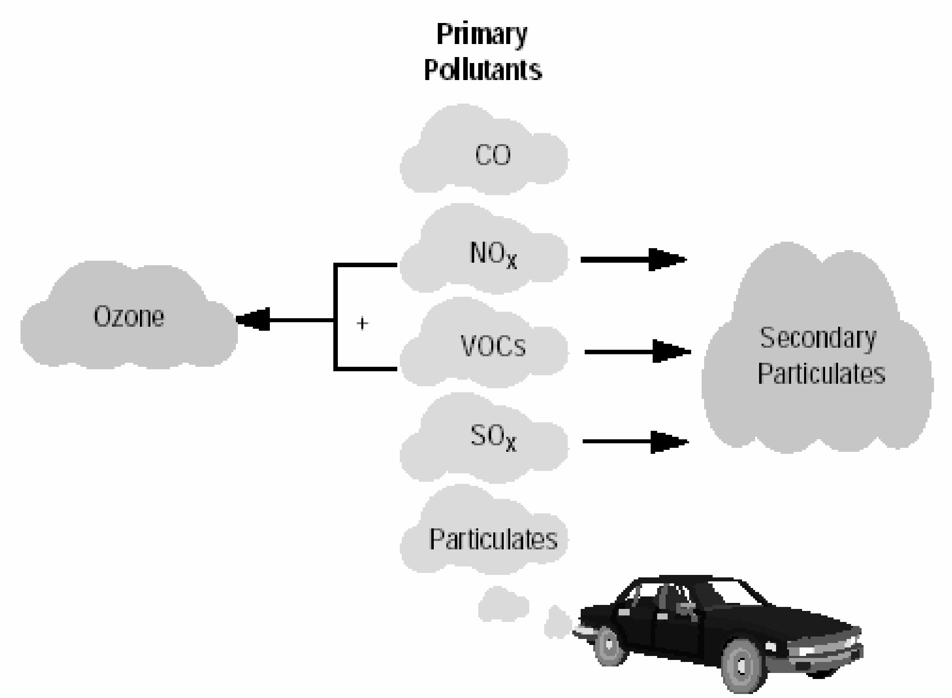


Figure 2.1: Air Pollutants Emitted from Onroad Motor Vehicles (Source: USEPA, 1996a)

2.1.1.1 Fine Particulate Matter ($PM_{2.5}$)

As illustrated above, both primary and secondarily fine particulate matter ($PM_{2.5}$) are directly emitted from emission sources and formed by chemical reaction processes in the air. $PM_{2.5}$ emitted from heavy-duty vehicles, which emit more than 75% of that from all onroad motor vehicles, can cause not only human health problems and property damage, but also adversely impact the environment through visibility reduction and retard plant growth (Davis, 1998). EPA promulgated the $PM_{2.5}$ standard in 1997 based on health studies showing that excessive fine particle concentrations are significantly associated with premature death from heart or lung diseases (Sheth, 2000). Fine particles from heavy-duty vehicles are mostly smaller than 0.1 μm in diameter and more than 90% of them are smaller than 1μm in diameter (Lloyd, 2001). These small particles penetrate deeply into the lungs and affect a larger surface area of lung tissue than an equivalent mass of larger particles. These small particles even cause more serious health problems when they grow larger through nucleation, condensation, and coagulation pathways with airborne toxic materials (Huffman, 2001). Sensitive populations including people with heart or lung disease, children whose lungs are still developing, and older people with reduced lung function are considered at greater risk than healthy adults (USEPA, 2004a) from these effects.

In addition, fine particles may be considered a critical airborne toxic itself and has been shown to cause double-digit increase in the relative risk of lung cancer to people in long-term occupational exposure to relatively high concentrations of these particles (HEI, 1995). These effects may also extend to the general population. For example, a major study (MATES-II) conducted in the south coast air basin of California has concluded that fine particulates from diesel vehicles (called diesel PM) contribute more than 70% of cancer risks among airborne toxic materials in this region (SCAQMD, 2000) although these results remain controversial.

2.1.1.2 Oxides of Nitrogen and Ozone Formation

Nitrogen contained in both fuel (40~500 ppm in diesel) and air (78% in volume) is converted into oxides of nitrogen through internal engine combustion processes. During combustion processes, NO_X ($NO+NO_2$), and nitrate (NO_3^-) is generated through a series of chemical reactions typically called Zeldovich mechanism (Stone, 1992). Chemical reaction processes generate more NO_X at higher temperatures (higher kinetic energy) and at lower flame speed (longer reaction time). After combustion, almost all (90% or more) of the NO_X is in the form of NO at the tailpipe (Heywood, 1998). After exhausting to the air, some of this NO is rapidly converted to NO_2 by reaction with atmospherics oxidants, principally ozone (Moran, 1994).

NO and NO_2 emitted from heavy-duty vehicles act as a precursor to ground level ozone formation. Ozone, which is not emitted directly from motor vehicles, secondarily forms by chemical reactions involving NO_X and volatile organic compounds (VOC) in the air through chained radical reactions in the presence of sunlight (Arya, 1999; Spedding, 1974).

- Internal combustion reactions (high temperature processes)

  $O + N_2 \leftrightarrow NO + N$

  $N + O_2 \leftrightarrow NO + O$

  $N + OH \leftrightarrow NO + H$

- Photochemical reaction (net reactions)

  $NO + HO_2 \leftrightarrow NO_2 + OH$

  $NO_2 + VOC + \text{sunlight (UV)} \rightarrow O_3 + \text{others}$

Ozone as a highly reactive oxidant gas and is the major constituent of the mixture of photochemical oxidants frequently referred to as smog. Ozone can cause eye irritation, lachrymation, and respiratory difficulties for people working outdoors. In terms of human health effects, a review of health studies conducted by the National Research Council (NRC) has concluded that exposure to long period with marginal ozone concentrations is potentially of greater concern than a short period with high ozone concentrations because some pollutants involved in ozone formation processes have longer reactive scales than others (NRC, 1999). For this and other reasons, EPA promulgated an 8-hour ozone standard in 1997 intended to replace the 1-hr ozone standard. However, industry groups led by the American Trucking Association challenged the $PM_{2.5}$ and the 8-hr ozone standards in federal court. Through the case review process, the U.S. Supreme Court upheld EPA's interpretation of CAA and let EPA move forward with the $PM_{2.5}$ and the 8-hr ozone designation processes (USSC, 2000). EPA is currently conducting the $PM_{2.5}$ and the 8-hr ozone nonattainment area designation processes (CRS, 2004; FR, 2004).

2.1.2 Heavy-Duty Vehicle Certification Standards

Heavy-duty vehicles classified by their GVWR are further characterized by EPA according to the engine size; light, medium, and heavy heavy-duty engines. Under the Federal Tier 2 regulation, light-duty vehicles of GVWR up to 10,000 lbs used for personal transportation (called medium-duty passenger vehicles) such as larger sport utility vehicle and passenger vans are subject to the light-duty vehicle regulations. That means that light heavy-duty vehicles in between 8,501 and 10,000lbs of GVWR can be certified to different standards; chassis dynamometer certification or engine dynamometer certification depending on the application (CFR, 2004e). Except Tier 2 vehicles, all heavy-duty vehicle emissions standards are defined with the engine dynamometer certification process.

2.1.2.1 Heavy-Duty Engine Test Cycles

Currently EPA requires that heavy-duty vehicles should be certified with their engine emission test results expressed in grams per brake horsepower-hour (g/bhp-hr) over the transient Federal Test Procedure (FTP) engine dynamometer cycle, which includes both engine cold and warm start operations (CFR, 2004f). For the engine dynamometer test, the engine is removed from the vehicles' chassis, mounted on the test stand, and operated with the transient FTP cycle. The transient test cycle consists of four segments combined in the order of "New York Non-freeway (NYNF)", "Los Angeles Freeway (LAF)", "Los Angeles Non-freeway (LANF)", and "New York Non-freeway (NYNF)" cycles. First two cycles for the cold start, and next two cycles for the hot start portions of the cycle (NRC, 1995). While the engine operates with the test cycle, composite emissions and cold-/hot-start time integrated engine revolution per minute (RPM) and torque are measured. From measured RPM and torque, actual torque is determined by applying performance percentages to the maximum torque curve at given maximum RPM (CFR, 2004f). Then, the actual torque is converted to the time integrated brake horsepower. Composite emissions associated with the brake horsepower are expressed as brake-specific emission rates in g/bhp-hr (CFR, 2004i). Because the engine dynamometer test procedure does not directly account for the impacts from load and grade changes, the chassis dynamometer test procedure, which adopted the urban dynamometer driving schedule (UDDS), was developed. The UDDS procedure does not require the removal of the engine from the vehicles' frame. The chassis dynamometer test procedure incorporated with second-by-second vehicle speed and emission produces emission rates in grams per mile (g/mi).

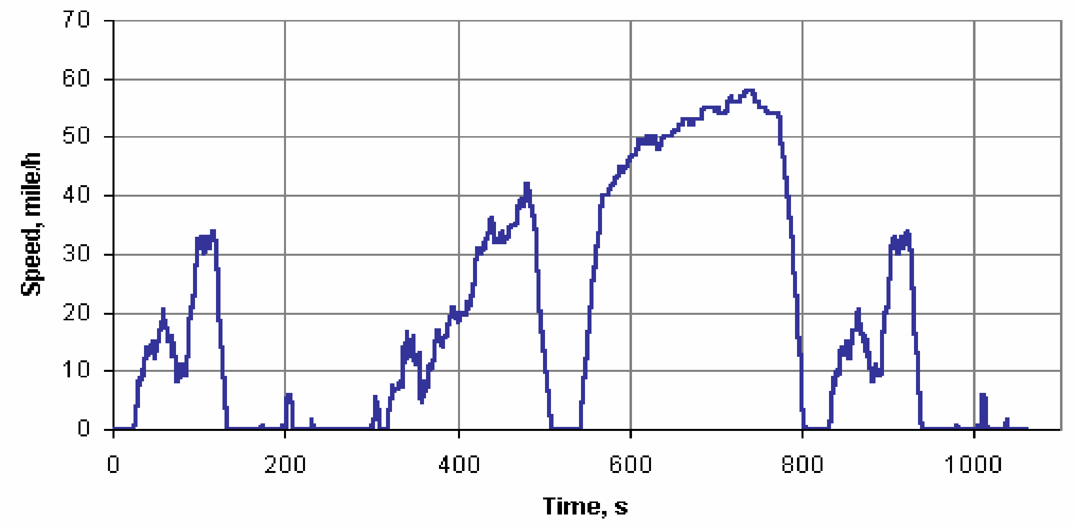


Figure 2.2: Urban Dynamometer Driving Schedule (UDDS)

2.1.2.2 Heavy-Duty Engine Emissions Regulations

EPA regulates heavy-duty vehicle emissions, complied with emissions standards, over the useful life of the engine. Useful life, which warrants zero-mile emission rates (g/bhp-hr), varies for each heavy-duty engine; 110,000, 185,000, and 290,000 miles for all heavy-duty gasoline and light heavy-duty diesel engines, medium heavy-duty diesel engines, and heavy heavy-duty diesel engines, respectively (CFR, 2004g). Certified engine emissions consist of a deterioration emission rate (g/bhp-hr) at the end of useful life and a zero-mile emission rate. However, the sum of the zero-mile emission rate and deterioration emission rates should not exceed certified emissions standards. Table 2.2 shows the changes of heavy-duty engine emissions standards for NO_X and PM by vehicle model year group (Lindhjem, 1999).

Table 2.2: Heavy-Duty Engine Emissions Standard Changes for NO_X and PM

Model Year Group	Heavy-Duty Engine Emissions Standard (g/bhp-hr)		
	Gasoline Engine	Diesel Engine	Diesel Bus Engine
1990	6.0 NO_X	6.0 NO_X	5.0 NO_X
1991-1992	5.0 NO_X	5.0 NO_X 0.25 PM	0.25 PM
1993			0.10 PM
1994-1995		0.10 PM	0.07 PM
1996-1997			0.05 PM
1998-2003	4.0 NO_X	4.0 NO_X	4.0 NO_X
2004-2006	2.5 HC + NO_X	2.5 HC + NO_X	2.5 HC+ NO_X
2007+	1.0 HC + NO_X	0.01 PM 0.2 NO_X	0.01 PM 0.2 NO_X

2.2 Onroad Mobile Source Emission Rate Model, MOBILE6.2

EPA developed the MOBILE6.2 onroad mobile source emission rate model for use in regional air quality planning such as the development of state implementation plans (SIP) by way of mobile source emissions inventory development to protect public health, welfare, and ecological resources (USEPA, 2004b). While forty-nine states use the MOBILE6.2 rate model for emission analyses, the state of California uses its own onroad mobile source emission rate model, the EMFAC2002 (CARB, 2002). Both MOBILE6.2 and EMFAC2002 models estimating HC, CO, NO_X, PM, SOx, CO_2 and Lead share similar core concepts to estimate emission rates. Emission rates in the models result from combining baseline emission rates, vehicle travel activity, and a series of correction factors such as speed, temperature, altitude, humidity, and so on.

A mobile source emission estimation process consists of two processing steps: the determination of modeling year baseline emission rates modified by a series of correction factors and the estimation of vehicle activity (Sawyer, 1998). With The MOBILE6.2 emission rate model, HDV modeling year baseline emission rates in grams per mile are obtained through the estimation of baseline emission rate, unit conversion processes, and weighting by a series of correction factors such as speed, temperature, altitude, etc. Then, the baseline emission rate for a modeling year can be multiplied by vehicle activity expressed as VMT for the estimation of emissions and for the development of year-specific mobile source emissions inventories.

2.2.1 Baseline Emission Rates

Baseline emission rates (g/bhp-hr) for heavy-duty vehicles are obtained from the engine dynamometer test results conducted during EPA's cooperative test program with engine manufacturers. Once a modeling year (i.e. the year for which emissions are to be predicted) is specified, modeling year baseline emission rates are estimated with the association of year-specific baseline emission rates, vehicle sales fractions, and horsepower ratings by age (individual categories for vehicles aged 1 to 24 years and an additional category for 25 years and older) for each HDV class (Lindhjem, 1999).

$$EL_v = \frac{\sum (Sales_{v,yr} * HP_{v,yr} * EL_{v,yr})}{\sum (Sales_{v,yr} * HP_{v,yr})} \qquad (2.1)$$

Where, EL_v is the modeling year baseline emission rate (g/bhp-hr)

$Sales$ is the vehicle sales fraction

HP is the engine horsepower rating (bhp)

$EL_{v,yr}$ is the year-specific baseline emission rate by age (g/bhp-hr)

v is the vehicle type

yr is the vehicle age from the modeling year

However, HDV emission rates (g/bhp-hr) can not be directly used to estimate modeling year HDV emission rates (g/mi), although light-duty vehicle (LDV) emission rates can be obtained from tailpipe emissions measurement and used directly to calculate modeling year emission rates. To convert g/bhp-hr emission rates into g/mi emission rates, the MOBILE6.2 uses conversion factors for each HDV class. Conversion factors are a function of fuel density, brake-specific fuel consumption (BSFC), and fuel economy for each HDV class (USEPA, 2002b; USEPA, 2002c). For the development of BSFC and fuel economy, EPA developed regression models with available data from 1987 to 1996 derived from Truck Inventory and Use Survey (TIUS) conducted by the U.S. Census Bureau. Due to the limit of data, post-1996 BSFC and fuel economy were set to the same as 1996 values. However, post-1996 BSFC and fuel economy may ultimately require extensive revision because engine horsepower ratings, vehicle weight, and other vehicle characteristics keep changing with time. For instance, Ahanotu and Yoon have recently concluded that overall heavy HDV fleet horsepower ratings are increasing (getting higher) and fleet age is decreasing (getting younger) (Ahanotu, 1999; Yoon, 2004b).

2.2.2 Speed Correction Factors

In MOBILE6.2, speed implies average speed over vehicle trips; that is the total trip distance divided by the total trip time that excludes extended idling time. For light-duty gasoline vehicles, EPA tested eighty five 1990s' model vehicles including 22 light-duty trucks under a variety laboratory driving test cycles representing level of service conditions on roadway types during the development of the model (USEPA, 2001b). Unlike light-duty vehicles, however, new speed correction factors were not developed for heavy-duty vehicles in the MOBILE6.2 model. Instead, speed correction factors used in the MOBILE5 model were used in the MOBILE6.2 without modification. The speed correction factors for HDVs originated from the publication of AP-42, Volume II (USEPA, 1995), which provided gasoline and diesel HDV speed correction factor models and coefficients for HC, CO, and NO_X. These speed correction factors were developed from each average speed of three segment cycles except the first NYNF cycle of the engine dynamometer test cycle, and expressed as polynomial equations for each pollutant. Because there are only three average speeds from three segments in the test cycle, speed correction factors rise steeply at low speeds, and become infinite at idle (zero speed). Therefore, speed correction factors at idle were not used (NRC, 1995). Instead, EPA developed idling emission rates (g/hr) for use in idle emissions estimation at vehicle speeds of less than 2.5 miles per hour (mph). These HDV speed correction factors, however, only apply for emission rate estimation on freeways and arterials. Thus, HC and CO emission rates for a certain HDV class at any given average speed are always same on freeways and arterials because same speed correction factors are applied to both freeways and arterials at average speeds over 30mph. However, NO_X emissions for diesel vehicles on freeways are greater than on arterials (Figure 2.3). This is not because of speed correction factors, but because of NO_X off-cycle emission effect on freeways (USEPA, 2002c).

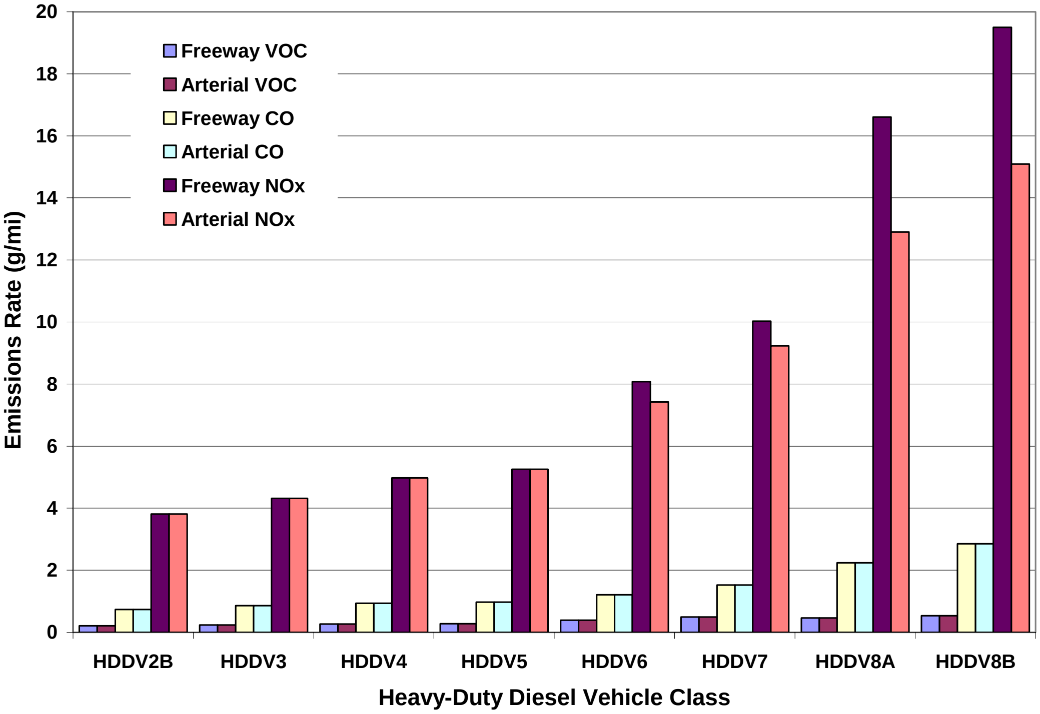


Figure 2.3: VOC, CO, NO_X Emission Rates on Freeways and Arterials at 41mph

For HDVs on locals and freeway ramps, speed correction factors are not applied. That is because MOBILE6.2 does not use speed correction factors for locals and freeway ramps, but instead, use single average speeds of 12.9mph and 34.6mph for locals and freeway ramps, respectively.

2.2.3 Vehicle Miles Traveled Estimation

The estimation of vehicle miles traveled (VMT) in the MOBILE6.2 model was based on EPA's fleet characterization study (USEPA, 1998). To characterize heavy-duty vehicle fleet VMT, they used vehicle registrations and annual mileage accumulation rates. Vehicle data registered in 1996 were obtained from R.L. Polk Company, which was a widely recognized source of vehicle registration data. Vehicle classes were identified by GVWR. However, because the class HDV8 vehicles were not separated into classes HDV8A and HDV8B, an average ratio of classes HDV8A to HDV8B obtained from 1992 Truck Inventory and Use Survey (TIUS) was used to separate them. In addition, light-duty diesel vehicle class 2 (defined as vehicles having 6,001 to 10,000 lbs of GVWR) was not separated into the light-duty truck (LDT) and the light heavy-duty class, HDV2B. Through the consultation with EPA staffs and industry published market data books, 10% of light-duty diesel class 2 vehicles were assigned to be the light heavy-duty vehicles of HDV2B. After screening registration data, EPA developed statistical models to estimate vehicle registration distributions by age (USEPA, 2001a).

Annual mileage accumulation rates were determined with annual average miles obtained from 1992 TIUS data (USEPA, 1998). Because 1992 TIUS data provided annual average miles only from 1983 to 1992 and aggregated miles for the pre-1983 model years, EPA developed statistical models by age to estimate annual mileage accumulate rates with the 10 year (1983-1992) annual average miles. To apportion the aggregated miles for the pre-1983 into each model year, they used the R.L. Polk registration data. With these average annual miles, EPA developed statistical equations to estimate annual mileage accumulation rates by vehicle age (USEPA, 2001a). Statistical models for vehicle registration distributions and annual mileage accumulate rates were used to estimate vehicle activity expressed as VMT or VMT fractions.

2.3 Modal Activity Based Emission Models

EPA's MOBILE series models have significantly improved through the series of model revisions from 1970's. However, MOBILE models still have major modeling defects for the heavy-duty components, which have been widely recognized for more than 10 years (Guensler, 1991). One of the most frequently stated defects is that fleet average speed, which aggregates other vehicle activity factors that may address significant bias in emissions characterization, characterizes vehicle emission rates.

Studies (USEAP, 2001d; Bachman, 2000; Ramamurthy, 1998) indicate that vehicle individual modal activities including idle, motoring, cruse, acceleration, and deceleration can be better indicators to properly reflect vehicle emissions resulting from various vehicle activities and to characterize relationships between vehicle emissions and activities, rather than with only vehicle average speed. With the consideration of vehicle modal activity, EPA and various research communities have been developing modal activity based emission models. The report published by Nation Research Council (NRC,

2000) comprehensively reviewed the modeling of mobile source emissions and provided recommendations for the improvement of future mobile source emission models.

2.3.1 MOVES

U.S. Environmental Protection Agency has developed a new modal activity based mobile source emission model called the Motor Vehicle Emission Simulator (MOVES), intended to follow NRC recommendations. MOVES estimates emissions of onroad and nonroad sources for multiple scale analysis, from fine-scale analysis to national emissions inventory estimation (EPA, 2001d). The basic concept of MOVES starts with the characterization of vehicle activity and the development of relationships between characterized vehicle activity and energy consumption, and between energy consumption and vehicle emissions (EPA, 2005). To estimate energy consumption by vehicle modal activity, vehicle specific power (VSP), which is a function of speed, acceleration, road grade, etc., is first estimated, and then VSP is converted to energy consumption rates in energy per vehicle weight (kW/tonne) (NAM, 2003).

$$VSP = v*(a*(1+\varepsilon)+g*grade+g*C_R)+0.5\rho*C_D*A*v^3/m \qquad (2.2)$$

Where, v is the vehicle speed (assuming no headwind) (m/s)

a is the vehicle acceleration (m/s^2)

ε is the mass factor accounting for the rotational masses (~0.1)

g is the acceleration due to gravity

$grade$ is the road grade

C_R is the rolling resistance (~0.0135)

ρ is the air density (1.2)

C_D is the aerodynamic drag coefficient

A is the frontal area (m^2)

m is the vehicle mass (tonne)

To characterize the relationship between vehicle activity and energy consumption, EPA establishes a binning approach, which allows the use of laboratory emission test results associated with VSP (USEPA, 2002e). VSP estimated with the equation 2.2 is originally separated into 14 VSP bins by VSP ranges, which generalize vehicle modal activity into 14 VSP bins (USEPA, 2001d). However, because VSP associated with vehicle average speed produces bias at low and high speeds, EPA refines the VSP binning approach by the association of second-by-second speed, engine rpm, and acceleration rates (Koupal, 2004). The original 14 VSP binning approach are revised with the combination of five different speed operating modes and redirected to a total of 37 VSP bins. If a vehicle activity mode is characterized from vehicle activity data, 17 VSP bins, which represent the vehicle activity mode, are selected and used to estimate vehicle specific power demand.

2.3.2 MEASURE

Since 1995, the Georgia Institute of Technology (Georgia Tech) has developed the Mobile Emission Assessment System for Urban and Regional Evaluation (MEASURE) model, which estimates onroad mobile source emissions as a function of vehicle technology groups and vehicle modal activity under a geographic information system (GIS) framework. Vehicle technology groups, which were combinations of vehicle characteristics and operating conditions, were identified in regression tree analysis by analyzing laboratory emission test data on various driving cycles. Vehicle modal activity such as acceleration, deceleration, cruse, and idle were identified with speed and acceleration distributions (Grant, 1996) as a function of facility type, level of service, and other parameters in the Highway Capacity Manual. Because MEASURE has been developed under the GIS platform, it provides following benefits (Bachman, 2000).

- Manages topographical parameters that affect emissions
- Calculates emissions from vehicle modal activities
- Allows a ‘layered’ approach to individual vehicles activity estimation
- Aggregates emission estimates into grid cells for use in photochemical air quality models

In the MEASURE model, to estimate emission rates, baseline emission rates for a given engine load were multiplied by instantaneous engine loads, which were estimated with variables including vehicle weight, speed, acceleration, and road grade.

2.3.3 HDDV-MEM

Georgia Tech has developed a beta version of the heavy-duty diesel vehicle modal emissions model (HDDV-MEM), which is based on vehicle technology groups, engine emission characteristics, and vehicles modal activity (Guensler, 2005a). A new heavy-duty vehicle visual classification scheme, which is an EPA and FHWA hybrid vehicle classification scheme developed by Yoon et al. (Yoon, 2004b), classified vehicle technology groups by engine horsepower ratings, vehicles GVWR, vehicle configurations, and vehicle travel characteristics (see CHAPTER 6). Currently, engine emission characteristics are under the review and development process with chassis dynamometer test results obtained from public and university research communities. In the beta HDDV-MEM version, engine emissions by age and by vehicle class have same characteristics with the vehicle emissions, which were developed with engine dynamometer test results and currently used in the MOBILE6.2.

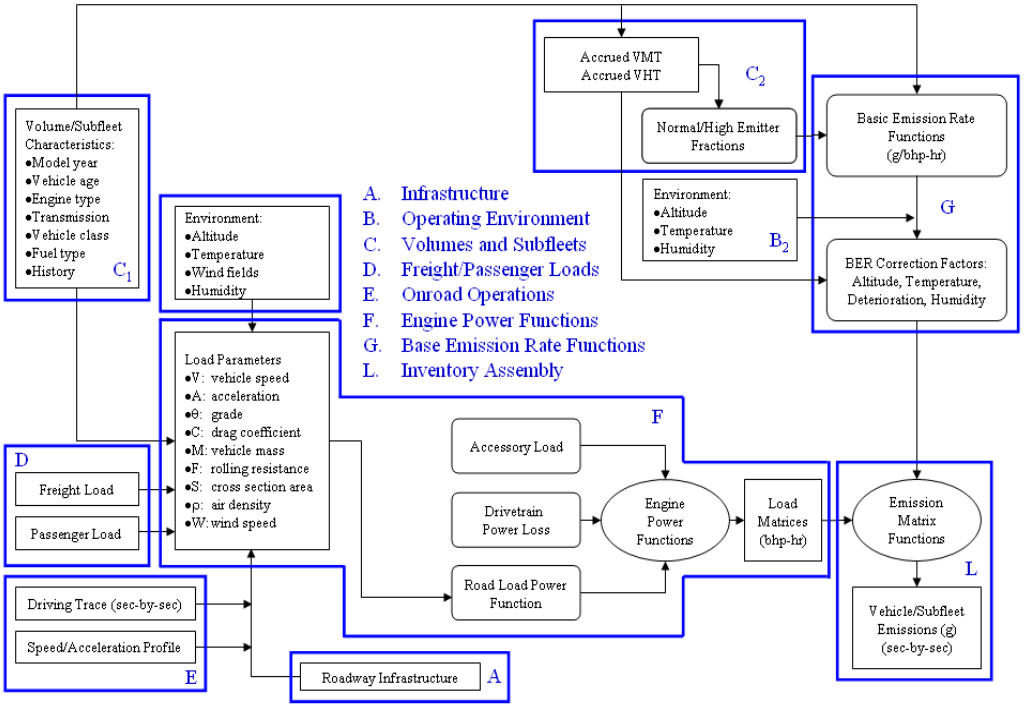


Figure 2.4: A Framework of Heavy-Duty Diesel Vehicle Modal Emission Model (Source: Guensler et al., 2005a)

2.3.3.1 Model Development Approaches

The HDDV-MEM first predicts second-by-second engine power demand as a function of onroad vehicle operating conditions and then applies brake-specific emission rates to these activity predictions (Guensler, 2005a; Yoon, 2005a).

$$P_{V,a,W,l} = [(\frac{V}{550})*((\frac{W}{g} \times a) + F_R + F_W + F_D + F_I)]_{V,a,W,l} + AP \qquad (2.3)$$

Where: P is the total engine power demand (bhp)

V is the vehicle speed (ft/s)

a is the vehicle acceleration (ft/s^2)

W is the actual vehicle weight (lb$_f$)

l is the road grade (degree)

g is the gravitational acceleration (32.2 ft/s^2)

F_R is the rolling resistance force (lb$_f$)

F_W is the gravitational weight force (lb$_f$)

F_D is the aerodynamic drag force (lb$_f$)

F_I is the drivetrain rotational inertial loss (lb$_f$)

AP is the auxiliary power demand (bhp)

550 is the conversion factor to bhp

Onroad operating modes (cruise, acceleration, deceleration, and motoring/idle) are integral in the power demand functions with other relevant factors such as vehicle weight, road grade, road surface type, etc. (Guensler, 2005a; Feng, 2005). The HDDV-MEM consists of three modules: a vehicle activity module (with vehicle activity tracked by vehicle technology group), an engine power module, and an emission rate module. Each module performs a series of routines designed to estimate onroad vehicle activity and operating conditions for each vehicle technology group, estimate engine horsepower demand for each technology group and roadway link, and then calculate resulting emissions from these onroad activities. The three modules are initiated with modeling parameters defined in model input command lines. Once modeling parameters are defined in the command window, each module processes in parallel and serial to predict HDDV emissions on each roadway link (Figure 2.5).

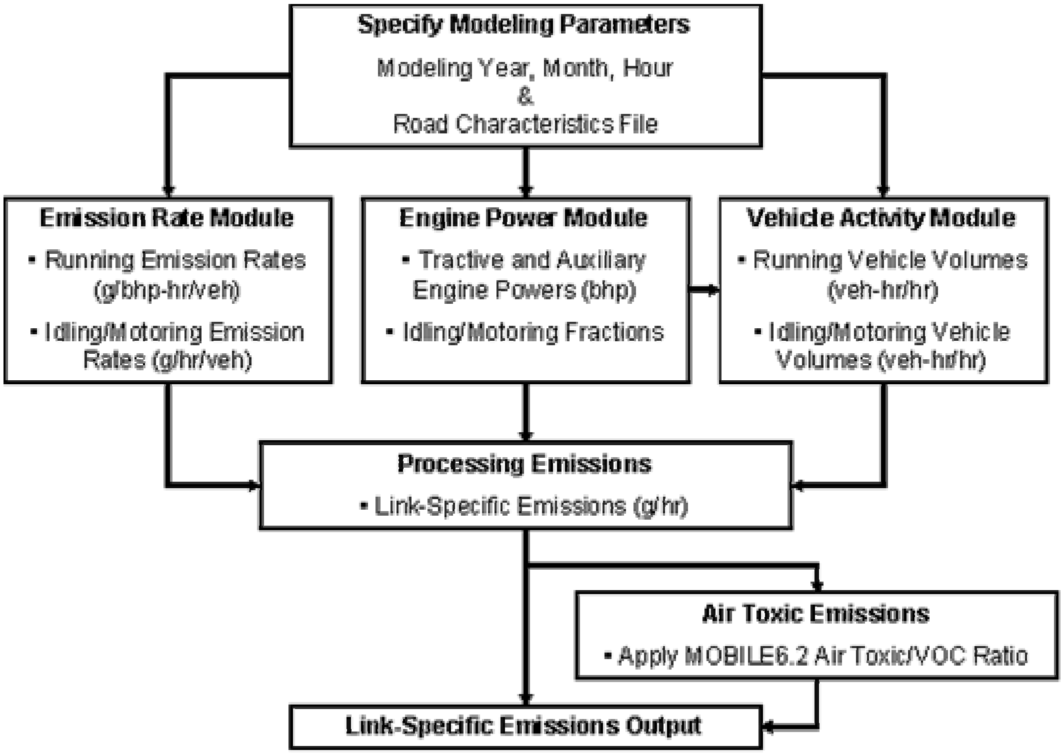


Figure 2.5: Heavy-Duty Diesel Vehicle Modal Emissions Modeling Process (Source: Guensler et al., 2005a)

2.3.3.2 Vehicle Activity Module

The vehicle activity module provides hourly vehicle volumes for each vehicle technology group on each transportation link in the modeled transportation system. The annual average daily traffic (AADT) estimate for each road link is processed to yield vehicle-hours of operation per hour for each technology group (using truck percentages, VMT fraction by vehicle technology group, diesel fraction, hourly volume apportionment of daily travel, link length, and average vehicle speed).

$$VA_{v,h,s|f} = (AADT_s * (NL_s / TNL) * HVF_{v,h} * VF_v * DF_v) * (SL_s / AS_v) \qquad (2.4)$$

Where, *VA* is the estimated vehicle activity (veh-hr/hr):

v is the vehicle technology group

h is the hour of day

s is the transportation link

f is the facility type for the link

AADT is the annual average daily traffic for the link

NL is the number of lanes in the specific link direction

TNL is the total number of lanes on the link

HVF is the hourly vehicle fraction

VF is the VMT fraction for each vehicle technology group

DF is the diesel vehicle fraction for each technology group

SL is the link length (miles)

AS is the link average speed of the technology group (mph)

To estimate onroad running emissions from each link, two sets of calculations are performed. Onroad vehicle activity (vehicle-hr) for each hour is multiplied by engine power demand for observed link operations (positive tractive power demand plus auxiliary power demand), and then by baseline emission rates (g/bhp-hr). As discussed in the engine power module section, these calculations are processed separately for each speed/acceleration matrix cell (Yoon, 2005c). Emissions from motoring/idling activity are calculated by the determination of the vehicle-hours of motoring/idling activity on each link for each hour and the multiplication of the baseline idle emission rate (g/hr).

2.3.3.3 Engine Power Model

In the engine power module, the engine horsepower demand (bhp) for each roadway link is calculated for each technology group. Power demand is predicted by applying speed-acceleration matrices (Yoon, 2005c), vehicle weight distributions, auxiliary power requirement estimates, environmental conditions, roadway link characteristics, and a variety of applicable parameters associated with vehicle physical characteristics. Power demand includes tractive power demand plus auxiliary power demand, associated with running refrigeration units and other equipment onboard the heavy-duty vehicles. Onroad activity with positive tractive power demand (and all activity with auxiliary power demand) is linked directly to work-related emission rates (g/bhp-hr). Activity for which tractive power demand is less than or equal to zero (motoring) is linked to idle emission rates (g/hr/veh).

$$P_{v,h,f,s} = \sum_i \sum_j [(V * AFF * ((\frac{W}{g} \times a) + F_R + F_W + F_D + F_I))_{i,j|v,h,f,s} + AP_{i,j|v,h}] \quad (2.5)$$

Where, P is the engine power demand (bhp)

v is the vehicle technology group

h is the hour of day

s is the transportation link

f is the facility type for the link

i is the speed bin from the applicable speed-acceleration matrix

j is the acceleration bin from the applicable speed-acceleration matrix

V is the vehicle speed for each speed/acceleration bin (mph)

AFF is the acceleration frequency fraction for each speed/acceleration bin

W is the actual vehicle weight (lb_f)

g is the gravitational force (32.2 ft/s^2)

a is the vehicle acceleration (ft/s^2)

F_R is the rolling resistance (lb_f)

F_W is the gravitational force (lb_f)

F_D is the aerodynamic drag (lb_f)

F_I is the drivetrain rotational inertial loss (lb_f)

AP is the auxiliary power requirement (bhp equivalent)

Speed/acceleration matrices implied to the beta HDDV-MEM has been improved to speed/acceleration/grade matrices (Yoon, 2005a), and further improvement undergoes with parameters, such as vehicle weight, drivers' driving behavior, etc.

2.3.3.4 Emission Rate Module

The emission rate module provides work-related emission rates (g/bhp-hr) and idle emission rates (g/hr) for each technology group. Work-related emission rates are derived from EPA's baseline running emission rate data, and idle emission rates are derived from EMFAC2002 idling emission rate test data. Diesel vehicle registration fractions and annual mileage accumulation rates are employed to develop calendar year emission rates for each technology group. Baseline diesel emission rates for each engine certification group are aggregated according to diesel registration fractions and annual mileage accumulation rates by vehicle age. Each zero-mile emission rate is multiplied by diesel registration fraction by vehicle age, and each deterioration emission rate is multiplied by diesel registration fraction and by annual mileage accumulation rate by vehicle age. Twenty-five weighted zero-mile emission rates and deterioration emission rates are aggregated to a calendar year emission rate.

$$ER_v = \sum_{y=0}^{24} [(ZML_{v,y} * DRF_{v,y}) + (DET_{v,y} * DRF_{v,y} * AMR_{v,y})] \quad (2.6)$$

Where, *ER* is the emission rate (g/bhp-hr)

v is the vehicle technology group

y is the vehicle age

ZML is the baseline zero-mile emission rate (g/bhp-hr)

DRF is the diesel vehicle registration fraction by vehicle age

DET is the baseline deterioration emission rate (g/bhp-hr)

AMR is the annual mileage accumulation rate (miles)

2.3.3.5 Emissions Outputs

HDDV-MEM outputs link-specific emissions in grams per hour (g/hr) for volatile organic compound (VOC), carbon monoxide (CO), oxides of nitrogen (NO_X), and particular matter (PM) for each vehicle type. Toxic air contaminant emissions rates (benzene, 1, 3-butadiene, formaldehyde, acetaldehyde, and acrolein) are also estimated in grams/hour for each vehicle type using the MOBILE6.2-modeled ratios of air toxics to VOC for each calendar year. HDDV-MEM provides not only hourly emissions, but also aggregated total daily emissions (in accordance with input command options). The structure of output files, which provide link specific hourly emissions, can be directly incorporated with roadway network features in a GIS environment for use in interactive air quality analysis in various spatial scales, i.e., national, regional, and local scales.

CHAPTER 3

TRUCK/HEAVY-DUTY VEHICLE CLASSIFICATIONS

A truck defined by FHWA means a motor vehicle with a power unit not including trailer, and a truck-tractor means a truck designed primarily for drawing loads such as other power units or trailers (CFR, 2004b). In view of GVWR, all FHWA trucks correspond to heavy-duty vehicles defined by EPA. EPA uses the term, “trucks” but only for light-duty vehicles, i.e., light-duty trucks (LDTs). Meanwhile, California Air Resources Board (CARB) uses both “trucks” and “vehicles” to differentiate heavy-duty vehicle classes (CARB, 2002).

For various purposes in transportation and air quality management, vehicle classification schemes have been developed with typical vehicle characteristics, which include the number of axles, total vehicle length, body or trailer types, gross vehicle weight ratings, engine types, etc. However, any vehicle classification scheme does not directly match to other classification schemes for all analytical purposes because of the lack of detailed vehicle characteristics information (Hallenbeck, 2004). For instance, FHWA classifies vehicles with the number of axles and truck-trailer combinations, while EPA classifies vehicles with gross vehicle weight ratings.

3.1 Gross Vehicle Weight Rating Based Vehicle Classification

American Automotive Manufacturers Association (AAMA) divides motor vehicles into eight classes (1 to 8) in regards to applications and vehicle configurations (Merrion, 1994). Among these eight classes, parts of the class 2 and all of classes 3 to 8 are corresponding to EPA heavy-duty vehicles (heavier than 8,500 pounds of GVWR). Until late 1990’s, EPA had only two HDV classes (heavy-duty gasoline vehicle (HDGV) and heavy-duty diesel vehicle (HDDV)) including three heavy-duty engine types that were light, medium, and heavy heavy-duty engines for exhaust emissions certification purposes. In late 1990’s, the two EPA HDV classes were separated into eight classes from classes HDV2B to HDV8B, which numeric numbers in class description correspond to AAMA truck classes, for use in the MOBILE6 emission rate model. Current EPA HDV classes are mostly comparable to HDV defined by California Air Resource Board (CARB) for use in series of EMFAC emission rate models. AAMA vehicle classes based on the GVWR are comparable to EPA HDV classes and to CARB truck classes. However, vehicle classes on AAMA, EPA, and CARB do not clearly match one-by-one, and some classes crossover two or more classes in other classification schemes (Table 3.1).

Table 3.1: Heavy-Duty Vehicle Classes Classified by AAMA, EPA, and CARB

	GVWR (x 1,000 pounds)								
	6	**8.5**	**10**	**14**	**16**	**19.5**	**26**	**33**	**60+**
AAMA	2 (LDT)		3 (LDT)	4 (MDT)	5 (MDT)	6 (MDT)	7 (HDT)	8 (HDT)	
EPA		HDV2B	HDV3	HDV4	HDV5	HDV6	HDV7	HDV8A	HDV8B
CARB		LHDT1	LHDT2	MHDT				HHDT	LHV

3.1.1 EPA Heavy-Duty Vehicle Classification

EPA defines heavy-duty vehicles by gross vehicle weight rating (GVWR), vehicle curb weight, or vehicle frontal area as,

> "*any motor vehicle rated at more than 8,500 pounds of GVWR or that has a vehicle curb weight of more than 6,000 pounds or that has a basic vehicle frontal area in excess of 45 square feet*" (CFR, 2004e).

Although a HDV can be defined by one of the three criteria, the GVWR criterion is considered first because a vehicle defined by the curb weight and frontal area criteria generally satisfies the GVWR criterion as well. However, Code of Federal Regulations (CFR) does not define the GVWR separating HDV classes that are used in the MOBILE6 model. Instead, heavy-duty vehicles are grouped by three primary heavy-duty engine types. These three engine types are determined by factors such as vehicle GVWR, vehicle usage and operating patterns, vehicle design characteristics, engine horsepower, and engine design and operating characteristics, which characterizes similar exhaust emissions certification (CFR, 2004h).

- Light heavy-duty diesel engines are generally designed with 70 to 170 rated horsepower. Vehicle body types with this engine type might include vans trucks, recreational vehicles, and some single axle straight trucks. The application of these vehicles would include personal transportation, light-load commercial haul, and construction, and the GVWR of them is usually less than 19,500 pounds (lbs) (40CFR86.085-2(a)(1)).
- Medium heavy-duty diesel engines are generally designed with 170 to 250 rated horsepower. Vehicle body types include buses, tandem axle trucks, city tractors, dump trucks, and trash compactor trucks. The application of these vehicles would include commercial short haul and intra-city delivery and pickup. The GVWR of these vehicles usually ranges from 19,500 to 33,000 lbs (40CFR86.085-2(a)(2)).

- Heavy heavy-duty diesel engines are generally over 250 rated horsepower. Typical vehicle body types are tractors, trucks, and buses used in inter-city long haul applications. The GVWR of these vehicles usually exceeds 33,000 lbs (40CFR86.085-2(a)(3)).

EPA reclassifies HDVs and buses into eight HDV classes and two bus classes, which were eight classes in conjunction with the three engine types, school bus, and transit/urban bus, for use in the MOBILE6 emission rate model. The EPA HDV classification is almost the same as the AAMA classification except vehicle classes 2 and 8. AAMA vehicle class 2 is a mixture of LDT (rated at less than or equal to 8,500lbs of GVWR) and EPA's lightest HDV or HDV2B (8,501 to 10,000lbs of GVWR). AAMA vehicle class 8 includes all vehicles rated at greater than 33,000lbs of GVWR, while EPA separated AAMA vehicle class 8 into classes HDV8A (33,001 to 60,000lbs of GVWR) and HDV8B (more than 60,000lbs of GVWR).

3.1.2 CARB Truck/Vehicle Classification

California Air Resources Board classifies heavy-duty vehicles into five truck/vehicle classes by GVWR, which represents vehicle common emissions characteristics such as emission standards, technologies, or in-use emissions (CARB, 2002).

Table 3.2: Heavy-Duty Truck/Vehicle Types Used in the EMFAC2002 Emission Rate Model

Class	Fuel Type	Description	GVWR (lbs)
LHDT1	Gasoline, Diesel	Light Heavy-Duty Trucks	8,501 ~ 10,000
LHDT2	Gasoline, Diesel	Light Heavy-Duty Trucks	10,001 ~ 14,000
MHDT	Gasoline, Diesel	Medium Heavy-Duty Trucks	14,001 ~ 33,000
HHDT	Gasoline, Diesel	Heavy Heavy-Duty Trucks	33,001 ~ 60,000
LHV	Gasoline, Diesel	Line-Haul Vehicles	60,001+

CARB truck/vehicle classes LHDT1, LHDT2, HHDT, and LHV correspond to EPA classes HDV2B, HDV3, HDV8A, and HDV8B, respectively. However, class MHDT corresponds to the aggregation of EPA classes HDV4 to HDV7. Emissions characteristics of the class MHDT conflicts with those of EPA classes HDV4 to HDV7 because EPA classes HDV4 and HDV5 fall into different engine horsepower groups (See Section 6.3) from EPA classes HDV6 and HDV7, which leads different emissions characteristics.

3.2 Axle and Configuration Based Vehicle Classification

For traffic data analysis related to a variety of transportation policy issues, in the 1980s FHWA developed a nationally consistent vehicle classification, which classifies motor vehicles into 13 vehicle classes. This vehicle classification scheme, usually called an axle and vehicle configuration based classification, classifies vehicles according to the number of axles, the axle spacing, and tractor-trailer configurations (FHWA, 2001). For simple and easy application in transportation and air quality analysis, Ahanotu grouped FHWA truck classes into four truck classes based on similarities of engine horsepower ratings and vehicle weights (Ahanotu, 1999). Table 3.3 compares the FHWA truck and Ahanotu truck classes.

Table 3.3: Axle and Configuration Based Truck Classes by FHWA and Ahanotu

Truck Type	FHWA	Ahanotu
Other Two-Axle, Four-Tire Single Unit Vehicles	3	N/A
Two-Axle, Six-Tire, Single-Unit Trucks	5	A
Three-Axle, Single-Unit Trucks	6	B
Four or More Axle Single-Unit Trucks	7	
Four or Fewer Axle Two-Unit Trucks	8	C
Five-Axle Two-Unit Trucks	9	D
Six or More Axle Two-Unit Trucks	10	
Six or More Axle Two-Unit Trucks	11	
Six-Axle Multi-Unit Trucks	12	
Seven or More Axle Multi-Unit Trucks	13	

3.2.1 FHWA Vehicle Classification

The FHWA axle and configuration based truck classification scheme is used for the development of a variety of transportation data products including HPMS, Highway Statistics and VIUS by both Federal and state transportation agencies. FHWA vehicles can be easily identified visually because they rely on the number of axles and combinations. However, state transportation agencies are required to develop algorithms to classify vehicles from the number of axles and axle space information obtained axle-sensor-based field measurements such as pneumatic detectors that measure time intervals between two consecutive tire sets on axles, when they develop HPMS data (Wyman, 1985). Due to the overlapping axle-space ranges between vehicle classes and the complexity of fine-tuning algorithms, many state transportation agencies aggregate 13 vehicle classes into two vehicle groups; a group of classes 1 to 3 and another group of classes 4 to 13. Among the 13 FHWA vehicle classes, class 3 and classes 5 to 13 include trucks corresponding to the EPA HDV classes and CARB truck/vehicle classes. However, FHWA class 3, other 2-axle, 4-tire single unit vehicles, includes both light-duty trucks and heavy-duty vehicles. For emissions estimation purposes, vehicle activity data collected with the FHWA scheme, FHWA class 3 must be properly separated into EPA LDT and HDV2B classes.

Federal and state HDV activity databases such as VIUS (TIUS before 1997) and HPMS, built with the axle-based vehicle classification scheme, provide extensive HDV activity data. Due to that reason, EPA recommends those data sources for use in regional emissions inventory development and in local air quality studies. However, the axle and configuration based vehicles can not be directly translated into EPA or CARB vehicle classes because of the lack of similarity between axle and configuration based and GVWR based classifications.

3.2.2 Ahanotu Truck Classification

For use in collecting onroad heavy-duty vehicle activity data, Ahanotu developed a visual truck classification scheme by modifying FHWA truck classes based upon relationships between engine horsepower and truck weight distributions (Ahanotu, 1999). Relationships between engine horsepower and truck weight distributions were developed through surveying FHWA truck weights and engine horsepower ratings at weight stations in Atlanta, Georgia in 1996 and 1997. Figure 3.3 shows the horsepower-to-weight relationship that the bigger and heavier vehicles generally had the higher horsepower ratings.

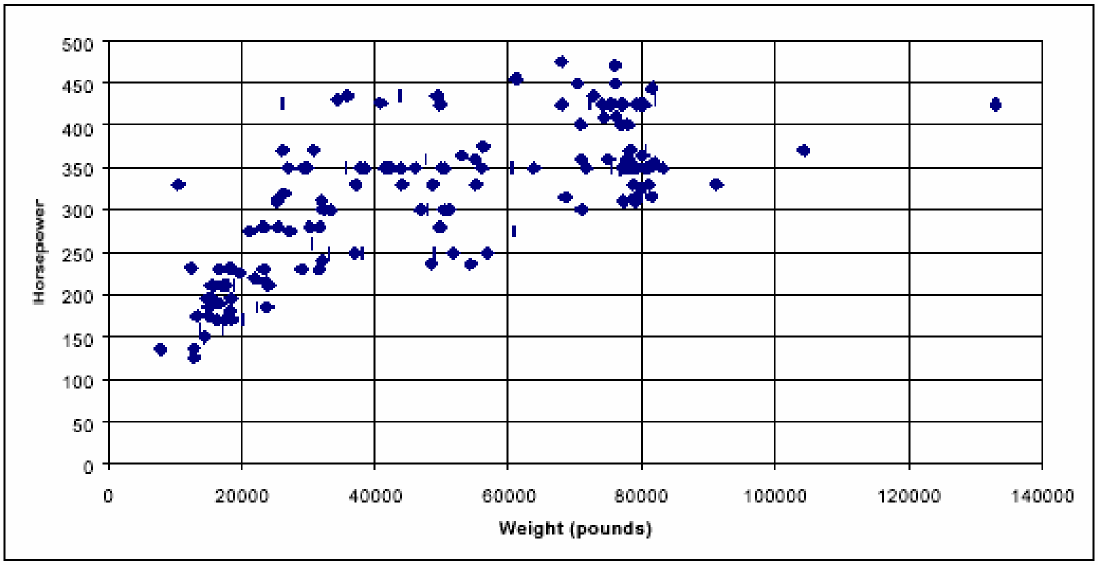


Figure 3.1: Relationships between Truck Engine Horsepower Ratings and Truck Weights (Source: Ahanotu, 1999)

Engine horsepower-to-weight cross tabulation statistical analyses revealed that certain groups of FHWA trucks had the different engine horsepower characteristics from other groups of trucks. Thus, Ahanotu grouped the nine FHWA truck classes into four truck classes and found that engine horsepower within each of four truck groups was independent of truck weight within each of four truck groups. For instance, 5-axle trucks (mostly tractor-trailer combinations) had the same engine horsepower distribution as more than 5-axle trucks, and their engine horsepower were independent from their weights, so that they grouped as a unique vehicle group.

CHAPTER 4

HEAVY-DUTY VEHICLE ACTIVITY DATA COLLECTION METHODS AND DATA SOURCES

Collecting heavy-duty vehicle activity data with vehicle characteristics is resource intensive both in terms of cost and time required relative to collecting light-duty vehicle activity data (FWHW, 1996). This is because HDV travel is mostly for commercial purposes and completely different from LDV travel for private and/or commute purposes. Because HDV travel varies by industry, travel patterns can not be readily characterized. In addition, the distrust between the government/research community and trucking industry makes it more difficult to collect HDV activity and characteristics data (Lloyd, 2001).

Heavy-duty vehicle characteristics are generally associated with a wider variability and more varied set of factors than those for LDVs. For instance, engine power ranges for heavy HDVs are more than two times greater than light HDVs (Ahanotu, 1999), and load carrying capacity for heavy HDVs is up to eight times heavier than light HDVs. The wide ranges of variations result in the wide range of emission rates among HDV classes. Therefore, collecting activity data with the fine resolution of HDV characteristics should be a prime concern in the application of HDV emissions analysis.

4.1 Heavy-Duty Vehicle Activity Data Collection Methods

Heavy-duty vehicle activity data with their activity characteristics can be collected with one of four typical methods: vehicle classification counts, roadside intercept surveys, mail/fax surveys, and travel diary surveys. These four methods can be used individually, or combined with other data collection methods for particular data uses.

4.1.1 Vehicle Classification Counts

Vehicle classification counts, which include both manual and automatic vehicle classification counts, are the most commonly used method for the collection of HDV activity data. The primary advantage of vehicle classification counting is that HDV activity data can be collected along with temporal and spatial information. Manual classification counts can be conducted by direct HDV observations in the field or video taped vehicle counts. Manual classification counts can minimize the ambiguity of HDV classification, which automatic vehicle classification method often faces. For instance, manual classification counts readily classify HDV classes by the number of axles, vehicle configuration, and body type (Fischer, 2001). However, manual classification counts require extensive time and cost and risk surveyors' safety in the field. In addition, manual classification counts should be conducted only after educating observers regarding the HDV data collection purposes such as transportation planning, emissions analysis, highway maintenance, etc. This is because observer errors in vehicle classification can yield errors in the estimation of emissions (Yoon, 2004a). Automated vehicle classification counts, which can be accomplished with pneumatic tube counters or loop detectors, provide large and continuous HDV activity data. However, the ability to accurately capture vehicle class characteristics influences the accuracy of the classification from automated vehicle classification counts (Fischer, 2001).

4.1.2 Roadside Intercept Surveys

Roadside intercept surveys can be conducted at interstate weight stations, warehouse/distribution centers, truck stops/terminals, mode change ports, etc (ODOT, 2004). Roadside intercept surveys include questions on HDV vehicle characteristics (vehicle model year, engine power ratings, current gross vehicle weight, and tractor-trailer configurations), trip origins and destinations, trip purposes (puck-up, delivery, or both), etc. Roadside intercept surveys generally have high response rates, provide temporal and spatial information, and enable interviewers to respond immediately to any question from respondents, which can possibly used for the response correction (Meyer, 2000). As an example, a truck stop survey conducted by Yoon et al. (Yoon, 2004b) showed that over 90% of truck drivers willingly participated in the survey and answered for survey questions, and surveyed data readily allocated truck trips into spatial locations and time of day. However, disadvantages of roadside intercept surveys include potential disruption to traffic flow, safety hazards for interviewers, and less ability to follow up with respondents (FWHW, 1996). In addition, roadside intercept surveys have potential disadvantaging parameters such as weather, time of day, restricted sampling locations (rather than an entire region), etc., which may cause interview results to be skewed from the representation of an entire study region.

4.1.3 Mail/Fax Surveys

Mail/Fax surveys generally focus on the information of vehicle characteristics, commodity types, origins and destinations, shipping frequencies, vehicle weight, average VMT (annually, monthly, or daily VMT), etc. If response rates are high enough, mail/fax surveys are more efficient to collect representative HDV activity data in an entire study region than roadside intercept surveys. However, mail/fax surveys are not effective in collecting temporal activity distributions (i.e., activity by time of day) and making immediate responses to respondents. In addition, mail/fax surveys can easily biased when they sample HDVs among registered HDVs in a region. In fact, much of the business activities for inter-region operating HDVs occur in locations other than where they are registered. In general, mail/fax surveys return low response rates. Response rates to a mail/fax survey conducted by Oregon Department of Transportation (ODOT) ranged from 9% to 55% depending on the amount of follow-up (ODOT, 2004). As the follow-up of mail/fax surveys for the increase of response rates, telephones and postcard reminders or web-based online survey substitution can be used. The combination of mail/fax surveys and telephone surveys yields a higher response rate than mail/fax only surveys. However, this combination is likely to be more expensive and time consuming.

4.1.4 Travel Diary Surveys

As one of common methods for collecting HDV trip data, travel diary surveys randomly select representative samples from a HDV activity study region and ask them to manually record the characteristics of each trip that they make in a standard paper diary. Travel diary surveys are composed of vehicle characteristics, trip origins and destinations, the purposes of vehicle activity, vehicle routes, land use at trips, etc. Trip data collected with travel diary surveys are used to estimate and characterize HDV travel activity (the number of engine starts, travel miles, travel duration, and travel time of day) for use in regional emissions estimation. Sampling among vehicle population in a study region is commonly accomplished by contacting registered vehicle owners. However, this can result in significant errors because HDV trips made by samples in the study region may not include non-registered HDV trips, which are not registered in the study region (Fischer, 2001; Yoon, 2004b). Because travel diary surveys use paper-based travel diaries, however, collected travel activity data also have potential errors such as uncompleted survey items, inaccurate trip information, etc. In addition, response rates of travel diary surveys for HDVs are not as high as for typical household travel diary surveys for LDVs. Phoenix and Atlanta HDV travel diary surveys conducted in 1992 and

1998 show that the response rates from their surveys were 17% for Phoenix region (Ruiter, 1992) and 19% for Atlanta region (Thornton, 1998), while the response rates of travel diary surveys for LDVs were much higher. For instance, the response rate for a LDV travel diary survey conducted in Pennsylvania reached up to 41% (Patten, 2004), and the response rate of the National Personal Transportation Survey (NPTS) reached over 50% (NPTS, 1995). The biggest problem in travel diary data collection is that drivers are generally not surveyed directly. They often have to receive approval from their management and vehicle owners who are often concerned about the impact of surveys on driver productivity and the potential disclosure of confidential business information.

To minimize and overcome potential errors and low response rates in paper-based travel diaries, automated travel diary survey methods are introduced in transportation research field such as Global Positioning Systems (GPS) technologies and instrumented vehicle studies. Wolf et al. comprehensively discussed current GPS and instrumented vehicle application in vehicle trip data collection (Wolf, 2000). However, automated travel diary survey methods require extensive cost and time to collect as many samples as paper-based travel diary surveys.

4.2 Public Heavy-Duty Vehicle Activity Data Sources

Heavy-duty vehicle activity data are available from publications by Federal and state government agencies including FHWA, Bureau of Transportation Statistics (BTS), Census Bureau, and state transportation agencies (e.g., Georgia Department of Transportation, GDOT). For the propose of vehicle emissions analysis, vehicle activity data are often extracted from Highway Statistics annually published by FHWA from the Vehicle Inventory and Use Survey (VIUS) published by Census Bureau every five years, or from the Highway Performance Monitoring System (HPMS) biennially published by FHWA and the various state transportation departments.

4.2.1 Highway Statistics

FHWA annually collects highway related statistics from state and local governments and publishes Highway Statistics for administering the highway network of the Nation, providing funds for its continued improvement and maintenance, and regulating its use. Highway Statistics contain statewide summary data of analyzed statistics on highway finance, highway mileage, fuel use, driver license, registered vehicles, and highway-user taxation. In Highway Statistics, the highway mileage is expressed as statewide annual total VMT by facility type and by vehicle class originated from FHWA vehicle classes, which configure vehicles by the number of axles and tractor-trailer configuration (FHWA, 2001).

Although statistics in Highway Statistics provide extensive information of vehicle activity, vehicle activity data in Highway Statistics can not be directly used for emissions analysis because FHWA vehicle classes do not exactly match EPA vehicle classes. This vehicle mismatch may cause overestimation or underestimation of regional emissions. For instance, 2-axle, 4-tire trucks correspond to the mixture of EPA classes LDT and HDV2B. However, Highway Statistics do not provide any information regarding how to separate this mixture into LDT and HDV2B classes. Until 1999, Highway Statistics had provided "*other 2-axle, 4-tire vehicle*" VMT percentages out of total vehicle VMT for each facility type except collectors and locals (CFR, 2004j). However, these data for other 2-axle, 4-tire vehicle VMT percentage by facility type has not been provided in Highway Statistics since the year 2000. Due to the lack of information in the estimation of other 2-axle, 4-tire vehicle VMT percentage from the latest Highway Statistics, other 2-axle, 4-tire vehicle VMT percentages from 1993 to 1999 Highway Statistics can be used for the LDT/HDV separation process. Seven year mean VMT percentages of other 2-axle, 4-tire vehicle VMT percentages for each facility type are statistically significant at the 5% significant level. Therefore, mean values of other 2-axle, 4-tire vehicle VMT percentages can be used to separate HDV2B VMT out of the mixture of LDT and HDV2B classes by associating of daily vehicle miles and the number of vehicle registered (see Section 7.3.2).

4.2.2 Highway Performance Monitoring System

FHWA biennially publishes data from the Highway Performance Monitoring System, which state departments of transportation provide. HPMS contains data on the extent, conditions, performance, use, and operating characteristics of the Nation's highways. As the principal source of highway system information, HPMS provides extensive information for the analysis of highway system conditions, performance, and investment, which support a data driven decision-making process with FHWA, USDOT, and the Congress (FHWA, 2005). The analysis results (published to annual Highway Statistics) are reported the Congress, who authorizes legislations that determine the scope and size of the Federal-aid highway program and the level of Federal highway taxation.

HPMS provides roadway segment lengths, annual average daily traffics (AADT), and truck percentages from which total VMT and truck VMT can be calculated for each facility type. For the estimation of truck percentage and AADT, 48-hour continuous vehicle counts with permanent (i.e., loop detectors) or temporary (i.e., pneumatic tube detectors) automated vehicle counters on week days are used (FHWA, 2001). The total vehicle count is then adjusted with series of adjustment factors, such as seasonal (month), day-of-week, axle, and growth factors. Studies show that truck counts or percentages can be significantly improved by factoring seasonal and day-of-week factors (Sharma, 1998; Weinblatt, 1996). Because HPMS provides extensive vehicle activity information, EPA recommends use of the vehicle activity data from HPMS when state agencies do emissions analyses and develop emissions inventories in regional air quality planning processes (EPA, 2004j). In HPMS, however, truck percentages do not count 2-axle, 4-tire HDVs by definition since trucks according to FHWA include only those with at least two axles and six tires. This means that EPA class HDV2B VMT is not included in the truck VMT estimated from HPMS. Using the VMT percentage of other 2-axle, 4-tire vehicles from Highway Statistics and the LDT/HDV2B VMT ratio from vehicle daily miles and the number of vehicle registered, HDV2B VMT can be estimated with total VMT from HPMS.

4.2.3 Vehicle and Truck Inventory and Use Survey

U.S. Census Bureau conducts the Vehicle Inventory and Use Survey as a part of the economic census every fifth year specifically those ending in "2" and "7". The primary goal of VIUS is to provide measures of the Nation's economy, i.e., gross domestic product, production and price indices, and the short-term changes in economic conditions. Private and commercial trucks registered as of July 1 of the survey year are sampled, and a questionnaire is mailed to registered vehicle samples. The questionnaire is designed to obtain information on two truck information groups, i.e., truck physical characteristics such as weight, the number of axles, length, and body type, and truck operational characteristics such as gas mileage, mileage driven, hauling commodity type, and month of operation (Census Bureau, 2004). However, the survey does not include public vehicles owned by governments, buses, motor homes, farm tractors, etc.. Because the VIUS provides statewide annual vehicle miles with vehicle GVWR ranges, annual vehicle miles can be estimated for vehicle types for emissions analysis purposes.

4.3 Georgia Tech Heavy-Duty Vehicle and Bus Database

The Georgia Institute of Technology recently developed a heavy-duty vehicle activity and characteristics database, including trucks, school buses, and urban buses (including transit, charter, church, and intercity buses) within the 21-county Atlanta metropolitan area (Figure 4.1) (Rodgers, 2005).

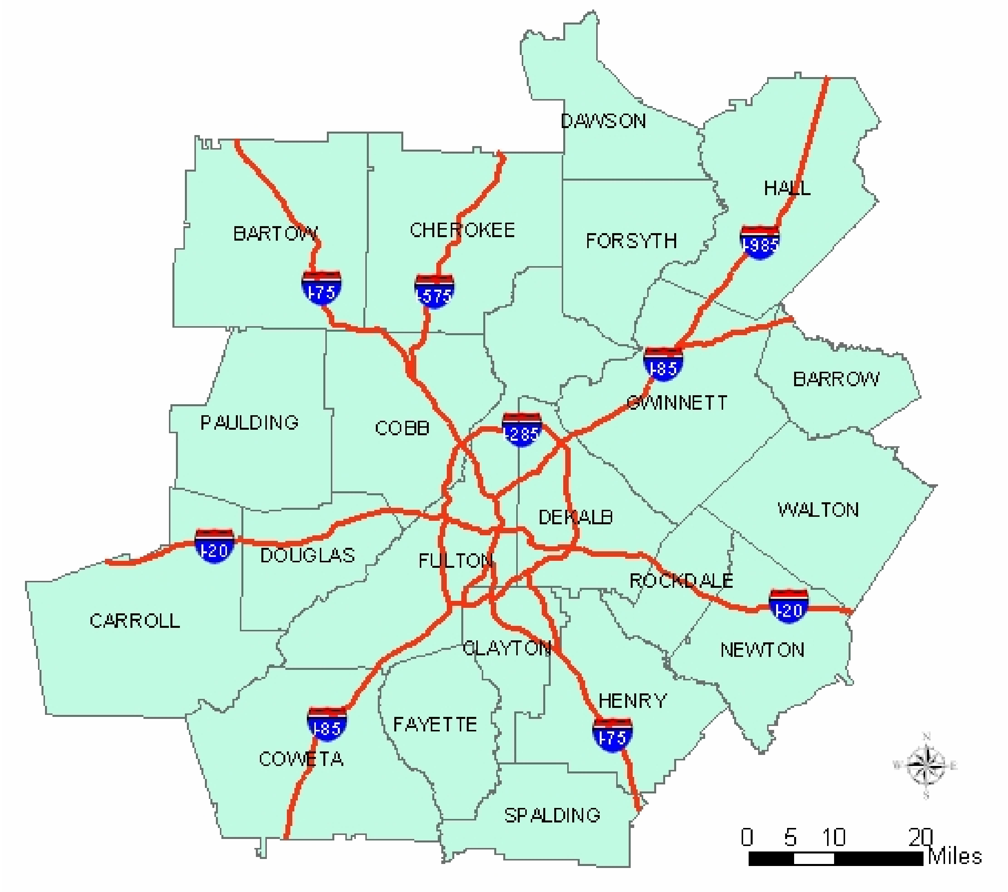


Figure 4.1: The 21-County Atlanta Metropolitan Area in the Development of Georgia Institute of Technology Heavy-Duty Vehicle and Bus Databases

To develop the database, HDV activity data were collected by the vehicle classification count method on a selected highway network, and bus activity and characteristics were collected by telephone, mail surveys, and on-site interviews. For the emission analysis in this research, HDV activity data from Dawson County was not included because the

Dawson County was not included in the Atlanta 8-hr ozone nonattainment designated area.

4.3.1 Heavy-Duty Vehicle Activity Data Collection

Heavy-duty vehicle volumes were counted on a developed highway network including freeways and arterials within the 21-county Atlanta metropolitan area. Using a geographic information system (GIS), a highway network to collect HDV activity was developed, composed of 90 freeway and 202 arterial links falling within one mile of the region's major warehouses (greater than 100,000ft^2 of area) and truck stops (Figure 4.2). The 292 links on the highway network were aggregated into 59 link groups by roadway geometry changes, such as lane merges and separations, interchanges, and ramps. The goal of link grouping was to minimize the number of data collection sites without losing the characteristics of original highway network, so that one link from each 59 link group can be randomly selected as the representative of each group. Vehicle volumes collected on a selected link in a link group were used for all links in a link group.

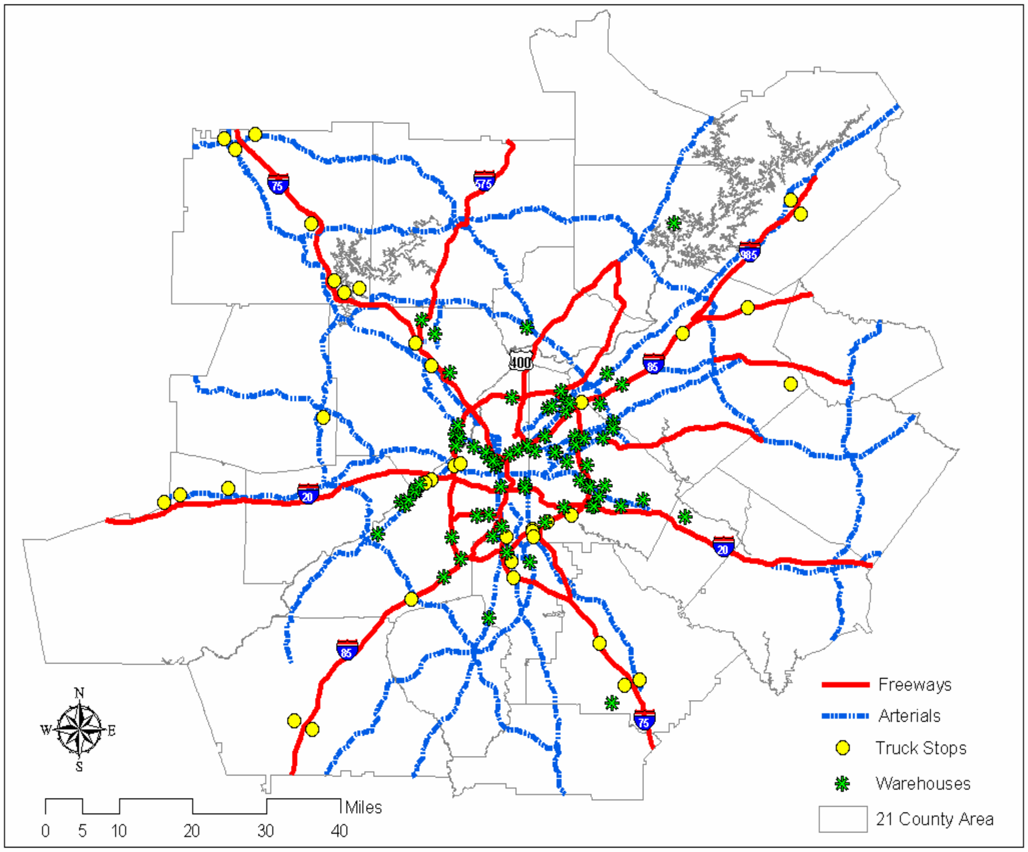


Figure 4.2: A Developed Highway Network to Collect Heavy-Duty Vehicle Activity within the 21-County Atlanta Metropolitan Area

Vehicle volumes for 15 links out of 59 were counted from video tapes captured by video detection system (VDS) cameras operated by Transportation Management Center (TMC) of Georgia DOT. Vehicle volumes for the last 44 links were manually counted at sites using traffic data collectors (Model TDC-8, JAMAR Technologies, Inc.). As vehicle volumes were counted in the field and on video tapes for consecutive 2 hours with 15 minute intervals, the Ahanotu truck classification scheme was used. Since vehicle volumes for each link were observed only for 2 hours, a scale-up method was developed to scale up 2-hour vehicle volumes to 24-hour vehicle volumes with representative 24-hour vehicle volume profiles (Figure 4.3a; Figure 4.3b) for each of Ahanotu truck classes. Three representative roadway links (two freeway links on I-285 and I-20 and one arterial segment on US-41) were selected and counted vehicle volumes for consecutive 24 hours on a weekday.

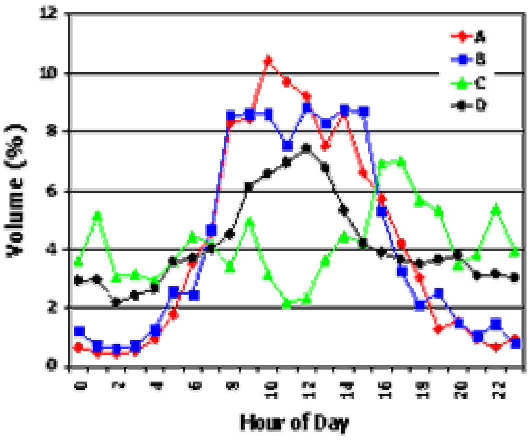


Figure 4.3a: Freeway 24-hr Volume Profiles for Ahanotu Truck Classes (Rodgers et al., 2005)

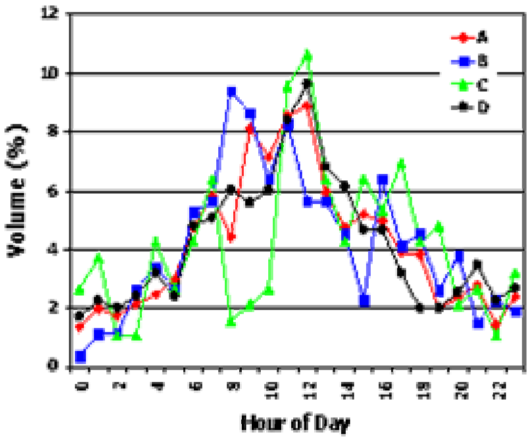


Figure 4.3b: Arterial 24-hr Volume Profiles for Ahanotu Truck Classes (Rodgers et al., 2005)

24-hour vehicle volume profiles for each of Ahanotu truck classes on I-285, I-20, and US-41 scaled up 2-hour truck volumes into 24-hour truck volumes. After the scale-up, the VMT for each truck class on each link was estimated. Among total HDV VMT estimated, over 75% of the VMT was generated from Ahanotu truck classes B, C, and D, which corresponded to EPA classes HDV8A and HDV8B (Yoon, 2004a). That implies that heavy HDVs were dominant on these freeways and arterials within the Atlanta metropolitan area.

4.3.2 Bus Activity Data Collection

Bus activity data were also counted on the highway network when HDV volumes were counted. However, observed bus activity data may underestimate regional total bus activity because a significantly high portion of bus (especially school buses) activity comes from lower roadway functional classes such as minor arterials, collectors, and local roads. Therefore, Georgia Tech researchers developed a bus activity database by way of mail survey, telephone survey, GIS spatial analysis, and onsite direct interviews. Buses included in the bus activity database were school, urban transit, church, charter, and intercity buses. Table 4.1 shows daily total bus miles for each bus class in the Georgia Tech bus activity database within the 20-county Atlanta metropolitan area.

Table 4.1: Daily Total Bus Miles within the 20-County Atlanta Metropolitan Area

Bus Class	Daily Total Bus Miles Per Day
School Bus	433,304
Urban Transit Bus	126,550
Church Bus	19,034
Charter Bus	17,880
Intercity Bus	9,587

4.3.2.1 School Buses

A school bus characteristics and activity database was developed by telephone calls and site visits. The database describes bus model years, chassis manufacturers, body manufacturers, average passenger rates, bus types, daily travel miles, engine types, and fuel types. Within the 20-county Atlanta metropolitan area, total estimated school bus VMT was 433,304 miles per day in 2003. Meanwhile, daily total school bus VMT from the observed school bus volume on the highway network was estimated by the same VMT estimation method used for HDVs for each county within the 20-county Atlanta metropolitan area. Estimated daily total school bus VMT was 13.8% lower than the daily VMT from the bus database. Therefore, school bus VMT estimated on the highway network were scaled up to the school bus VMT from the database. From the estimation of school bus VMT, school bus VMT distributed 13%, 19%, and 68% to freeways, arterials, and locals, respectively (see Section 7.2.3.1).

4.3.2.2 Urban Transit Buses

Urban transit bus VMT was estimated by GIS spatial analysis with transit bus routes and schedules, which were obtained from regional transit operators, including Cobb County Transit (CCT), Clayton County Transit (C-TRAN), Metropolitan Atlanta Rapid Transit Authority (MARTA), and Gwinnett County Transit (GCT). For the estimation of daily bus travel miles, a bus route map including all bus routes in a GIS feature format was developed with transit bus routes and schedules (the number of runs per day) from operators' websites (CCT, 2004; C-TRAN, 2004, MARTA, 2004; GCT,2004). By GIS spatial analysis tool, lengths of bus routes were estimated and multiplied by the number of runs per day to estimate daily transit bus VMT for each bus route. Figure 4.4 shows all bus service routes developed in a GIS feature format.

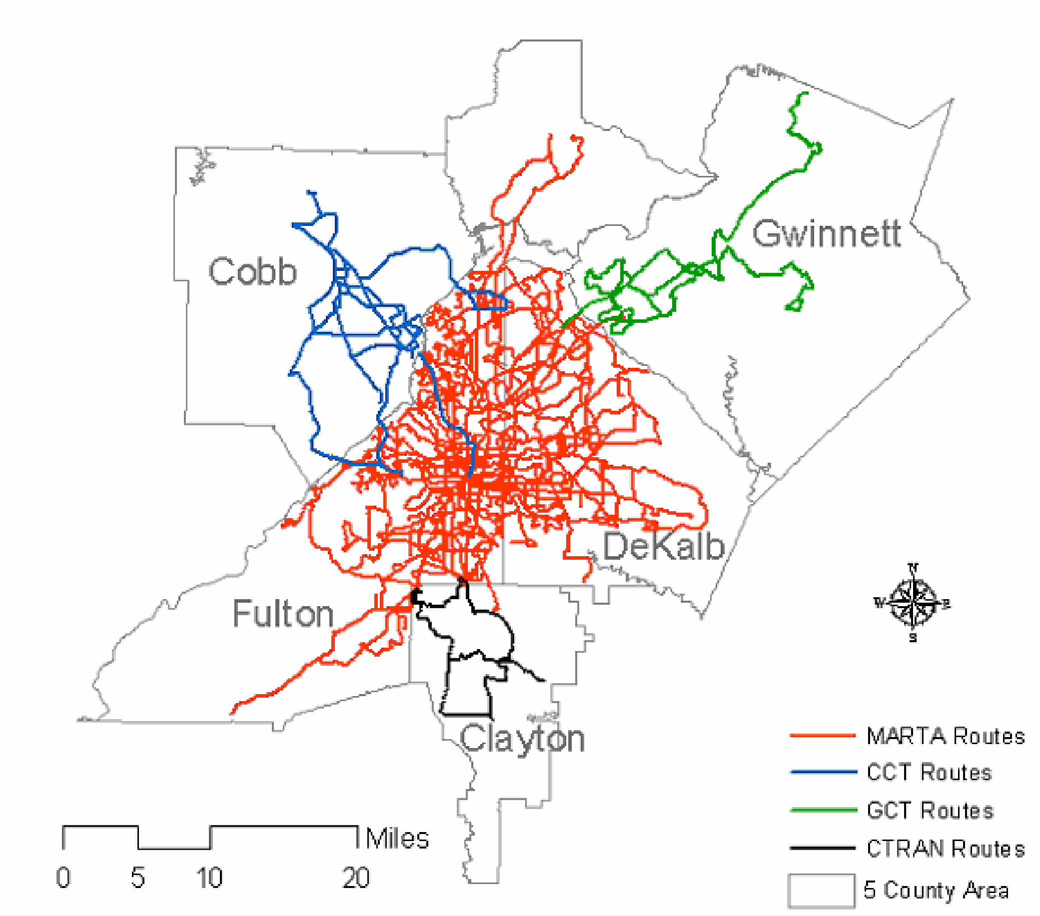


Figure 4.4: Urban Transit Bus Routes Operated by MARA, CCT, C-TRAN, and GCT in the Atlanta Metropolitan Area

Total urban transit bus daily VMT was estimated at 104,927 miles per day. However, estimated daily transit bus miles did not include bus miles traveled "out of bus service" routes including approaches to and from bus service routes. From transit bus speed and location data collected with Georgia Tech Trip Data Collectors on two transit buses operated by MARTA for eight months (July 2004 to March 2005), transit bus miles out of bus service routes were estimated (Yoon, 2005b). Two buses on routes 55 and 66 created 17% of total bus miles for service approaches and leaves. Therefore, the estimated total miles per day was scaled up by 17% for the total transit bus daily VMT.

In addition, transit bus characteristics were incorporated in the bus database by direct contacts and telephone calls to transit bus operators. Transit bus characteristics include model years, manufacturers, engine types, fuel types, and daily travel miles. Transit buses powered by compressed natural gas contributed about 46% of the total daily VMT estimated.

4.3.2.3 Church Buses

The number of church buses for each county was extracted from the 2003 Dun & Bradstreet database. Due to the lack of church bus VMT estimates, daily total church bus VMT was calculated using the school bus daily VMT. It was assumed that a church bus ran 50% of a school bus daily travel. The calculated total daily church bus VMT was 19, 034 miles.

4.3.2.4 Charter Buses

An average charter bus daily VMT was estimated with mail survey responses from charter companies in the Atlanta region. Survey responses accounted for which showed the yearly total VMT of 1,760,000 miles and 30 buses. The yearly total VMT was divided by 365 for the average daily charter bus VMT, which was 160 miles per day. The average daily charter bus VMT was close to the national average charter bus daily VMT (ABA, 2000). The number of charter buses for each charter operator not responded to the survey was estimated with their sales revenues and employee numbers, which were obtained from the 2003 Dun & Bradstreet database. The estimated total number of charter buses was 277 buses, and total charter bus daily VMT was estimated at 17,880 miles per day.

4.3.2.5 Intercity Bus VMT

Intercity bus VMT was estimated with the total number of departures a day at the Atlanta Greyhound terminal, which were 71 departures per day. The number of departures per day was assumed to be the same as the number of arrivals per day, so that the number of departures was doubled for the estimation of the total number of buses operated within the 20 counties. Total Greyhound bus VMT was estimated with the estimated total number of buses by multiplying the average freeway mile of six travel directions with an assumption that intercity bus VMT would be evenly distributed to six freeway directions, which were I-75 and I-85 north, and south, and I-20 east and west, connecting the Atlanta metropolitan area. The average freeway miles per direction of 67.5 miles, which was estimated with the total freeway miles of 405 miles in 20 counties divided by 6, was multiplied by the total number of buses of 142, so that the total intercity bus VMT was estimated to be 9,587 miles per day.

CHAPTER 5

UNCERTAINTIES IN THE CHARACTERIZATION OF HEAVY-DUTY VEHICLE VMT DISTRIBUTIONS

All states except California use the MOBILE6.2 as their regulatory mobile source emission rate model in developing state implementation and regional transportation plans. In MOBILE6.2 emission rate modeling, characterizing VMT distributions are the most significant influential parameter for accurate emissions estimation. Currently, VMT distributions are characterized by two approaches; one with registered HDV data combined with annual mileage accumulation rates and another with HDV VMT collected with FHWA truck classes. In use of registered HDV data, EPA suggests that vehicle fleet should be characterized by registered HDV distributions and annual mileage accumulation rates by vehicle age and fuel type for HDV classes (USEPA, 2001a). By linking HDV registration distributions and annual mileage accumulation rates, a HDV VMT distribution can be developed. For use of HDV activity data collected with FHWA truck classes, EPA and NRC recommend that the collected HDV VMT be aggregated and then disaggregated by VMT fractions or by conversion factors into EPA HDV classes. In regional emissions inventory development, however, HDV VMT distributions from HDV registration data and conversion guides can lead to the underestimation or overestimation of HDV emissions. Uncertainties in HDV VMT distributions can be associated with the aggregated FHWA truck or HDV activities and the lack of proper region-wide VMT simulation methods for each truck and HDV activity (Guensler, 1991). The following questions relate to the uncertainties in registration based HDV VMT distributions.

- Are registered HDV data properly classified to EPA HDV classes?
- Do HDV registration distributions developed from registered HDV data properly represent onroad HDV fleet compositions?
- Do vehicle class conversion guides properly map FHWA truck classes into EPA HDV classes without losing the fine resolution of original vehicle activity and emission characteristics?

5.1 Heavy-Duty Vehicle Registration Distributions in MOBILE6.2

Heavy-duty vehicle registration distributions can be developed from registered HDV data and annual mileage accumulation rates by vehicle class, fuel type, and model year. R.L. Polk compiles motor vehicle registration information from each state into their databases in a quarterly basis (RLP, 2005). As the only centralized vehicle registration data source, the R.L. Polk registration database provides vehicle information describing total vehicle population characterized by model year, gross vehicle weighting (GVWR), fuel type, vehicle type, the number of wheels, and registered county and state. As EPA developed vehicle registration distributions for use in the MOBILE6, they used vehicle registration data as of July 1, 1996. Because vehicle registration reflected only past year registration trends, EPA realized that the vehicle registration data of 1996 should be modified for the future emissions applications. That was because vehicle registration distributions in 1996 could be changed by any legislative and economical factor, which would lead different vehicle registration distributions in future years (USEPA, 1998). Therefore, EPA developed generic vehicle registration distributions by age for emissions modeling purposes. Because the registered vehicle population in 1996 significantly varied for each GVWR and fuel category, EPA decided to create most representative registration distribution curves only by aggregated vehicle category without considering fuel types. EPA aggregated 16 HDVs and three buses into four categories, which were EPA classes HDV2B to HDV3 (8,501 ~ 14,000lbs of GVWR), HDV4 to 8B (greater than 14,000lbs of GVWR), school buses, and urban transit buses. For each aggregated vehicle category, EPA developed a general curve fit HDV registration age distributions. Because the vehicle sales year begins three month earlier than a given calendar year, EPA assumed that only 75% of the total vehicle population of the newest vehicle age (the age of 1) would occur by the July 1 of a given modeling year, so that 0.75 was multiplied to the total vehicle population of the vehicle age of 1. Figure 5.1 shows EPA's actual registered vehicle age distribution and curve fit distribution for EPA classes HDV4 to HDV8B. The curve fit distribution can cause bias in emission rate estimation by differences from actual registered vehicle age distributions by year. This is because baseline emission rates differ by year, i.e., the newer vehicles have the lower baseline emission rates.

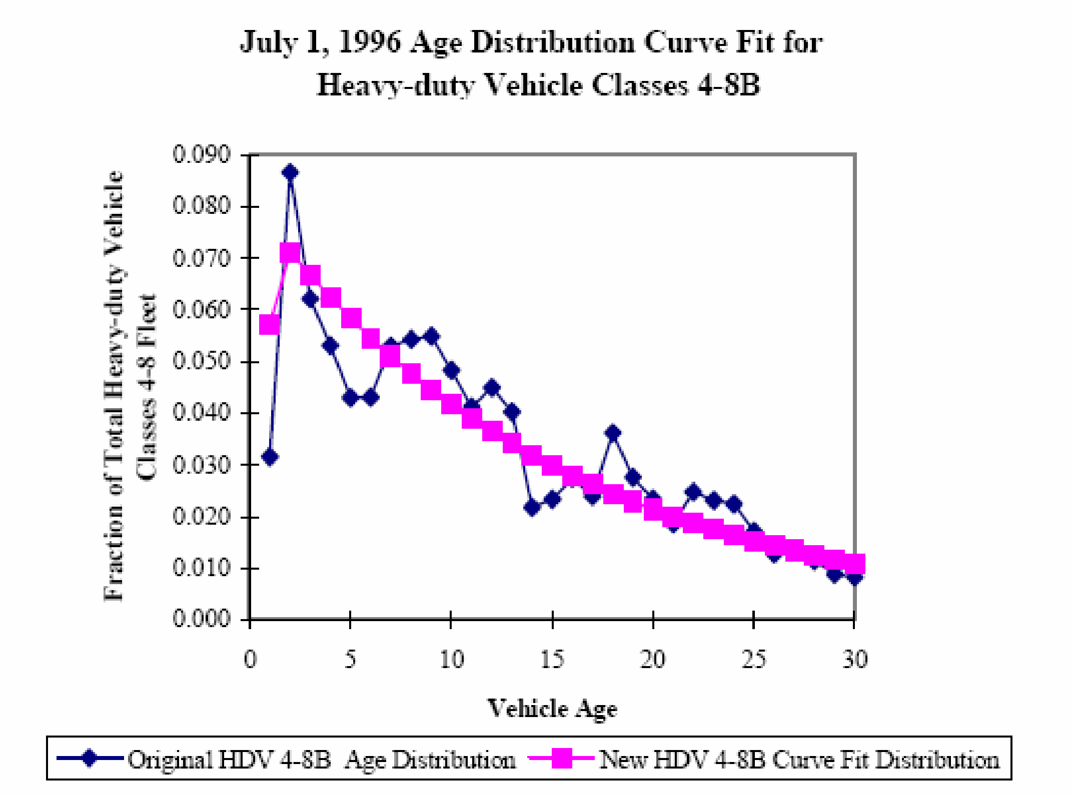


Figure 5.1: EPA's Registered Vehicle Age Distribution for Classes HDV4 to HDV8B (Source: USEPA, 2001a)

For the development of a VMT distribution, HDV registration age distributions for vehicle classes were associated with annual VMT estimates from curve fit annual mileage accumulation rates for corresponding ages of vehicles. VMT (the sum of VMT of all ages) for a HDV class at a given modeling calendar year is divided by total HDV VMT (the sum of VMT of all ages and HDV classes) to estimate the VMT fraction of the HDV class.

For nationwide mobile source emissions inventory purposes, EPA's approach to develop curve fit vehicle registration age distributions with vehicle registration database may be applicable. This is because long range (over 200 miles per day) and medium range (100 to 200 miles per day) vehicle travel will be captured within Nation's boundaries. However, EPA's approach with registration data may not properly capture vehicle activities within county or regional boundaries. EPA shows that more than 68% of HDDV8A and 84% of HDDV8B VMT are generated from long and medium range vehicle operations (USEPA, 2002b). This implies that entire heavy HDV VMT may be captured within county or regional boundaries. To explain this, HDV registration distributions were developed for the 13-county and the 20-county Atlanta metropolitan areas and Georgia statewide (Figure 5.2).

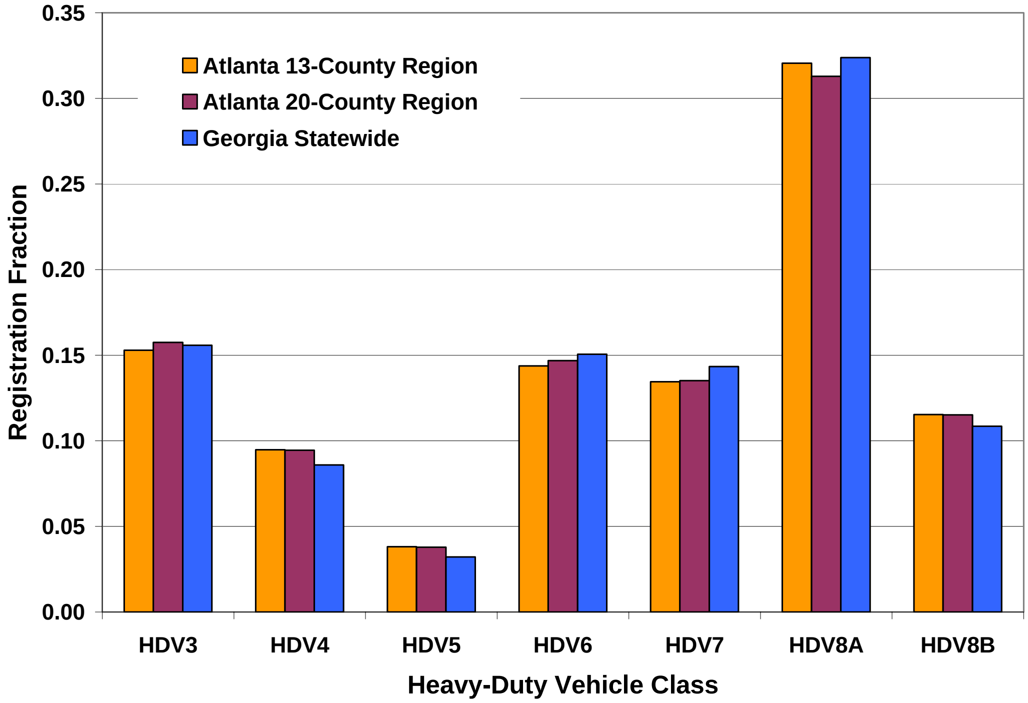


Figure 5.2: HDV Registration Distributions for the 13-County and the 20-County Atlanta Metropolitan Areas and Georgia Statewide

HDV registration fractions among three spatial boundaries are almost similar for each HDV class. For classes HDV4 and HDV5, Georgia statewide registration fractions are 10% and 18% less for the 13-county and the 20-county Atlanta metropolitan areas, respectively. The other HDV registration fractions for Georgia statewide fall within ±6% of the 13-county and the 20-county Atlanta metropolitan areas. These narrow differences of registration distributions among spatial boundaries do not significantly affect to emission rate changes. Registration fractions weighted emission rates (g/mi) change very little and are 0.02% and 0.56% greater for the 13-County and the 20-county regions respectively than Georgia statewide. This implies that HDV emissions estimation for the 20-county Atlanta metropolitan area will not be changed with any one of three registration distributions. Therefore, emissions estimated with VMT distributions created with registration database may be underestimated in the Atlanta metropolitan area because the significantly high percentage of inter-state or inter-region operating HDVs (Yoon, 2004c), which are not registered in the region, will not be reflected in the generation of a HDV VMT distribution.

5.2 Uncertainties in HDV Registration Data

In mobile source emissions modeling, the use of the registration data from the R.L. Polk database causes two major uncertainties in the estimation of VMT distributions and vehicle registration age distributions. The first uncertainty in VMT distributions is associated with gross vehicle weight rating (GVWR), and the uncertainty in registered vehicle age distributions is associated with vehicles that are not registered within a study area boundary.

5.2.1 Gross Vehicle Weight Rating

R.L. Polk applies 28 EPA vehicle codes to each vehicle types on their registration database. In the R.L. Polk registration database, it is expected that heavy HDVs, such as straight tucks and tractors (generally combined with non-motorized trailers), are classified into heaver HDV classes such as class HDV8A or HDV8B. However, any single tractor was not classified as the HDV8B class in the 20-county Atlanta metropolitan area in the R.L. Polk vehicle registration database (Table 5.1). This is because the R.L. Polk only counts the power unit weight for HDV classification (Kimbrough, 2004). However, manufacturers genetically design tractors to be articulated with one or more trailers and define their GVWR or gross combination weight rating (GCWR), or both.

Table 5.1: Registered Heavy-Duty Vehicle Fractions by Registered Vehicle Type and EPA HDV Class in the 20-County Atlanta Metropolitan Area

Registered Vehicle Type	EPA HDV Class							
	2B	3	4	5	6	7	8A	8B
Cab Chassis	0.054	0.064	0.000	0.000	0.000	0.000	0.000	N/A
Incomplete Pick-up	0.007	0.000	N/A	N/A	N/A	N/A	N/A	N/A
Incomplete Vehicle	0.039	0.037	0.016	0.002	0.006	0.000	N/A	N/A
Straight Truck	0.000	0.042	0.069	0.032	0.126	0.098	0.013	0.102
Tractor	N/A	N/A	N/A	0.000	0.000	0.024	0.269	N/A

Truck manufacturers define GCWR as total combined weight of tractors combined with one or more non-motorized trailers (USEPA, 2004e). In fact, in emissions modeling application, EPA uses GCWR for the classification of heavier HDVs because GCWR is always greater than or equal to GVWR. If R.L. Polk used GCWR in their vehicle registration databases, they would classify most tractors into class HDV8B. With the assumption that tractors can be classified to class HDV8B, Yoon et al. found that NO_X and $PM_{2.5}$ emissions increased by more than 30% in the Atlanta metropolitan area (Yoon, 2004c). To minimize this uncertainty before emissions inventory development, local air quality agencies reconsider HDV classes ranked by the R.L. Polk. For example, the Georgia Department of Natural Resource (GDNR) allocates all tractors in the R.L. Polk database into class HDV8B before developing mobile source emissions inventories for state air quality planning purposes (GDNR, 2005). However, this allocation can create another uncertainty that three-axle tractor-trailers, which may be not allowed to carry over 60,000lbs of GCWR on highways, can be classified to class HDV8B. In fact, the GCWR of three-axle tractor-trailers is defined up to 60,000lbs according to the FHWA truck weight regulation and manufacturers' truck specification data (see Section 6.1.2). This over-weight classification can cause the overestimation of emissions, especially NO_X and $PM_{2.5}$. Luckily, the population of three-axle tractor-trailers is not significant in the field (Yoon, 2004a), so that emissions overestimation by Georgia State's over-weight classification will not be significant.

Another uncertainty remaining in the R.L. Polk database is that they classify more than 97% of three-axle straight trucks into the class HDV8B. However, manufactures generally define that three-axle straight trucks can carry up to 54,000 lbs of GVWR. Straight trucks classified to the class HDV8B can cause the overestimation of NO_X and $PM_{2.5}$ emissions in mobile source emissions analysis.

5.2.2 Vehicles Not Registered in a Regional Study Boundary

Unlike light-duty vehicles making their most trips within a regional boundary where they are registered, heavy-duty vehicles, especially heavy HDVs, make significant portion of their trips outside of the region in which they are registered. This is because significant amount of freight movement relies on HDVs running between regions and states frequently. The registration also depends upon locations of corporate offices and the registration fee structure of states (Ahanotu, 1999). Yoon et al. conducted a screen-line cordon survey to investigate the fraction of pass-through heavy HDVs to the Atlanta region at truck stops on the border of the 21-county Atlanta metropolitan area boundary (Yoon, 2004b). About 50% out of 974 surveys (96% of surveys for HDV8B class) reported that their vehicle did not make any business stops on the day surveyed within the 21-county Atlanta metropolitan area (Figure 5.3).

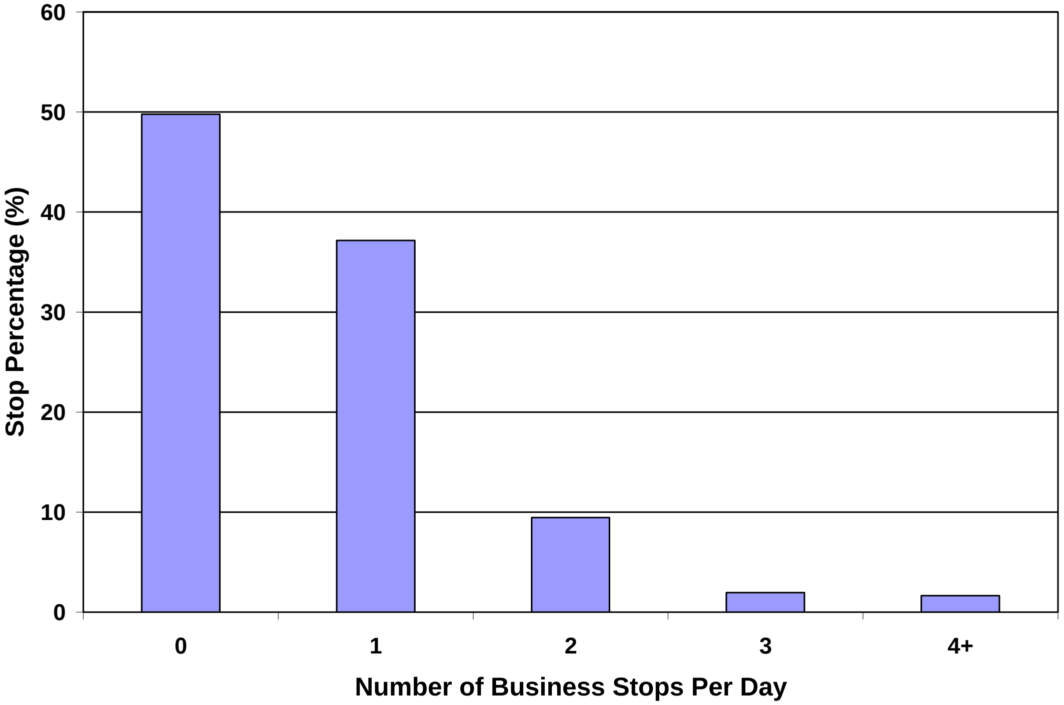


Figure 5.3: Number of Business Stops per Day for the Class HDV8B Surveyed at Truck Stops on the Cordon of the 21-County Atlanta Metropolitan Area

This implies that 50% of HDV8B vehicles running between regions may not be registered in the 21-county Atlanta metropolitan area. Hence, the total VMT of class HDV8B estimated with registration data will be underestimated, which causes the underestimation of regional NO_X and $PM_{2.5}$ emissions. In addition, vehicle age distributions from registration data may not properly represent the fleet age distributions in the field. In general, vehicles traveling longer distance beyond regional boundaries tend to younger than the vehicles traveling in local areas. The younger vehicles tend to emit the less pollutants. The truck stop survey shows that the engine average age of surveyed HDVs is 4.5 years with the assumption that vehicle model years are the same as engine model years (Figure 5.4).

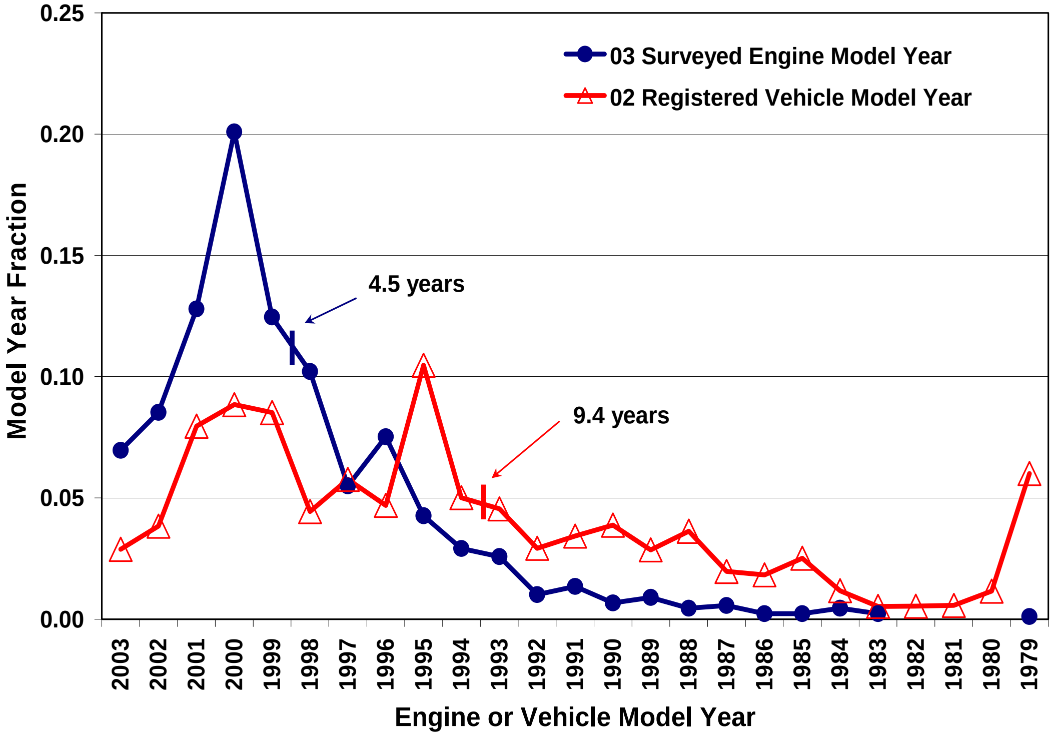


Figure 5.4: Surveyed Engine Model Year and Registered Vehicle Model Year Distributions for EPA Class HDDV8b by the Cordon Survey at the 21-County Atlanta Metropolitan Area Boundary

If non-registered HDV8B vehicles are incorporated for fleet age distributions in a region, fleet average age will be younger than currently registered average age of 9.4 years for class HDDV8B (Yoon, 2004b; GDNR, 2005). Ahanotu also showed that the trend of long-range traveling heavy HDV is getting younger (Ahanotu, 1999). Younger fleet age distributions including non-registered HDVs result in reduced emissions estimates in the region. However, this emission reduction effect depends on the vehicle travel miles by model year with younger vehicles traveling the more miles.

5.3 Heavy-Duty Vehicle Conversion Guides

5.3.1 EPA Conversion Guidance and Uncertainties

EPA classifies heavy-duty vehicles to eight HDV and two bus classes from HDV2B to HDV8b for both gasoline and diesel fuel, school bus, and urban bus. For emissions modeling, collecting HDV activity data with the EPA HDV classification scheme is almost impossible because the EPA HDV classification scheme has too many HDV classes to count separately. Although several HDV classes can be roughly identified by their typical figures such as pick-ups and vans for HDV2B or HDV3 and articulated trucks for HDV8A or HDV8B, the other HDV classes can not be easily identified due to the wide ranges of GVWR with similar vehicle figures. In addition, state and nationwide HDV activity databases such as HPMS and VIUS are not built with

GVWR, so that it is a challenge to obtain HDV activity data with the high resolution of HDV classes either from the field or from existing databases.

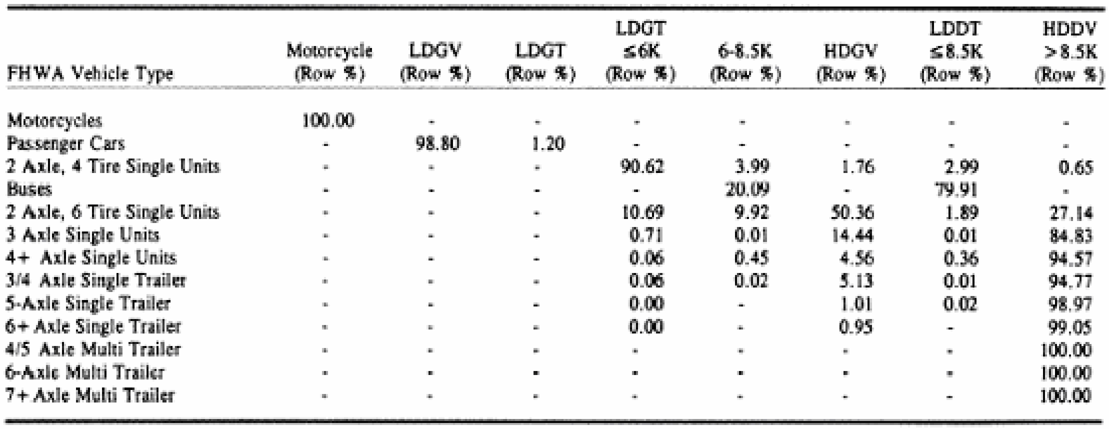
To obtain fleet VMT in regional air quality planning, EPA recommends that local agencies use vehicle activity data in HPMS. This federally mandated traffic-monitoring program provides estimates of vehicle activity by location and vehicle class, using a network of permanent and temporary ground count monitors. However, before using HPMS vehicle activity data, agencies must reclassify the data to EPA HDV classes. There is a mismatch between the FHWA and EPA vehicle classes, primarily because the EPA uses GVWR based classification scheme, while FHWA uses axle and configuration based classification scheme. To reclassify FHWA trucks to EPA HDV classes, the EPA conversion guidance suggests that nine FHWA truck classes 5 to 13 should be aggregated and then disaggregated to eight EPA HDV classes in accordance with their VMT fractions (USEPA, 2004c). However, this conversion guidance can bias by the VMT allocation for light and medium FHWA truck classes such as 2-axle, 4-tire trucks. For instance, FHWA defines trucks as more than or equal to 2-axle, 6-tire trucks, which have GVWRs over 10,000lbs. Meanwhile, the GVWR of EPA class HDV2B having two axles and four tires is falling in between 6,001 and 10,000lbs. This implies that HDV activity data provided by HPMS may not include EPA HDV2B activity data. In addition, any high-resolution vehicle class information contained in observed field HDV data can be lost when the data are aggregated and then disaggregated to EPA HDV classes.

Specifically, a significant portion of heavy FHWA trucks obtained in the field can be misallocated into light or medium trucks by the EPA conversion guidance.

5.3.2 Conversion Factors and Uncertainties

To facilitate the use of the FHWA truck classification scheme in emissions modeling with the MOBILE5 model, the National Research Council developed conversion factors, which translate FHWA trucks to EPA HDV classes and vice versa, with the VMT from the 1987 TIUS (NRC, 1997). VMT for each FHWA truck was assigned to EPA MOBILE5 vehicle classes by gross vehicle weight (GVW), axle configuration, and fuel type. Because the TUIS VMT for FHWA truck class 5 or heavier trucks was estimated lower than from Highway Statistics and HPMS, the TIUS VMT was adjusted by VMT factors of 1.36 (Highway Statistics VMT/ TIUS VMT) for single units and 1.41 for combinations (NRC, 1997).

Table 5.2: National Research Council FHWA VMT Conversion Factors to EPA Vehicle Classes (Source: NRC, 1997)



FHWA Vehicle Type	Motorcycle (Row %)	LDGV (Row %)	LDGT (Row %)	LDGT ≤6K (Row %)	6-8.5K (Row %)	HDGV (Row %)	LDDT ≤8.5K (Row %)	HDDV >8.5K (Row %)
Motorcycles	100.00	-	-	-	-	-	-	-
Passenger Cars	-	98.80	1.20	-	-	-	-	-
2 Axle, 4 Tire Single Units	-	-	-	90.62	3.99	1.76	2.99	0.65
Buses	-	-	-	-	20.09	-	79.91	-
2 Axle, 6 Tire Single Units	-	-	-	10.69	9.92	50.36	1.89	27.14
3 Axle Single Units	-	-	-	0.71	0.01	14.44	0.01	84.83
4+ Axle Single Units	-	-	-	0.06	0.45	4.56	0.36	94.57
3/4 Axle Single Trailer	-	-	-	0.06	0.02	5.13	0.01	94.77
5-Axle Single Trailer	-	-	-	0.00	-	1.01	0.02	98.97
6+ Axle Single Trailer	-	-	-	0.00	-	0.95	-	99.05
4/5 Axle Multi Trailer	-	-	-	-	-	-	-	100.00
6-Axle Multi Trailer	-	-	-	-	-	-	-	100.00
7+ Axle Multi Trailer	-	-	-	-	-	-	-	100.00

Because NRC developed conversion factors for nationwide, regional air quality agencies should not use conversion factors directly to their regions. In addition, conversion factors originally developed for the MOBILE5 emission rate model having only two HDV classes (HDGV and HDDV) are not applicable to the MOBILE6 emission rate model having 16 HDV classes without modification. In addition, FHWA truck mapping into EPA HDVs by NRC was based on GVW, not GVWR. Because GVW can not exceed GVWR, NRC conversion factors may underestimate HDV VMT fractions but overestimate LDV VMT fractions.

Starting with conversion factors developed by NRC, Williamson and Yao (Williamson, 2003) generated MOBILE6 conversion factors by multiplying national default MOBILE6 HDV VMT fractions to each HDV MOBILE5 conversion factors. If conversion factors are applied in region level emission estimation, conversion factors for HDVs by Williamson have the same uncertainties as the EPA conversion guidance has. This is because Williamson disaggregated conversion factors for HDVs with the VMT distribution developed with vehicle registration data.

CHAPTER 6

A NEW HEAVY-DUTY VEHICLE VISUAL CLASSIFICATION SCHEME

Heavy-duty vehicle classification methods suggested by EPA and National Research Council can cause losing the high resolution of onroad HDV activity information and misallocating fleet activity from one HDV class into another (see Section 5.3.1 and 5.3.2). Given the differences in the FHWA and EPA HDV classification schemes discussed in CHAPTER 5, the development of an improved HDV classification method can significantly improve HDV VMT and emissions estimation. To develop a new heavy-duty vehicle visual classification scheme, criteria obtained from the FHWA truck weight limitation, the FHWA truck classification, the EPA HDV classification, and manufacturers' truck specification data were used. Criteria counted the number of axles, GVWR, GCWR, and vehicle configurations. With the criteria, three prototype HDV classes were created, which is called the X-scheme (Yoon, 2004a), and the three prototype HDV classes were further sub-classified into six X classes by engine horsepower characteristics, vehicle travel characteristics, the number of tires, and tractor-trailer configurations (Yoon, 2005d; Guensler, 2005b). This new heavy-duty vehicle visual classification scheme keeps the original resolution of onroad fleet activity and properly assigns FHWA truck activity into EPA HDV activity for mobile source emissions modeling.

6.1 Onroad Heavy-Duty Vehicle Characteristics

Onroad heavy-duty vehicles are characterized and regulated by their carrying capacity (weight) permitted by the FHWA truck weight limitation rule. To meet truck weight limitations, truck manufacturers mechanically design vehicle engines and bodies, so that trucks can properly carry limited loads on the road.

6.1.1 Truck Weight Limitations

FHWA limits truck weights on highways to protect roadway facilities, especially bridges, and to support expected truck loads (FHWA, 1994) with the maximum gross vehicle weight (GVW) that is the maximum load a truck allowed to carry according to the number of axles and space between axles (CFR, 2004j). The maximum GVW (W), which is the maximum weight in pounds that can be carried on a group of two or more axles to the nearest 500 pounds, can be calculated with an equation called the bridge formula (Equation 6.1) that associates with the axle space (LN) and the number of axles (N) (FHWA, 1994).

$$W = 500 * (\frac{LN}{N-1} + 12N + 36) \tag{6.1}$$

A single-axle or a tandem-axle with maximum 40-inch space between two consecutive axles can carry a maximum load of 20,000lbs, and a tandem-axle (more than 40 inches, but not more than 96 inches between two or more consecutive axles) can carry a maximum load of 34,000lbs. With the bridge formula, FHWA tabulated the maximum GVW of 40,000, 60,000, and 80,000lbs for two, three, and more than three axle vehicles, respectively. Under the FHWA truck weight limitation rule, a single unit truck with two axles, which corresponds to the FHWA class 5, can carry loads up to 40,000lbs; a single or a two unit truck with three axles, which correspond to the FHWA class 6 or 8, can carry loads up to 60,000 lbs; and a single unit or a tractor-trailer combination truck with more than three axles, which correspond to FHWA classes 7, or 8 to 13, can carry loads up to 80,000 lbs.

6.1.2 Manufacturers' Truck Specifications

EPA classifies heavy-duty vehicles by vehicle gross vehicle weight rating specified by manufacturers (EPA, 2004e). Truck manufacturers annually publish truck specification data, which include truck types (pick-ups, vans, cutaways, chassis-cabs, straight trucks, tractor, etc.), the number of axles, axle types (single, tandem, etc.), the number of tires, fuel types, GVWR, GCWR, etc. (Truck Index, 1997a; Truck Index, 1997b; Ford, 2004; GMC, 2004; DC, 2004). For HDVs, the definition of GVWR is the maximum vehicle weight of the sum of vehicle curb (empty), fluid, a driver, and maximum payload weights. Vehicle manufacturers may also specify allowable maximum vehicle plus trailer weight as GCWR. However, the GCWR is allowed only for tractor-trailer articulated motor vehicles over 10,000 lbs of GVWR, and the GVWR is not allowed to exceed the GCWR (CFR, 2004a).

Through the review of truck specification data, truck types are separated into a light truck group I, a light truck group II, a medium truck group, and a heavy truck group. The light truck group I, which has two axles and four tires, includes pick-ups and vans. The light truck group II, which has two axles and six tires, includes chassis-cabs and cutaways. The medium truck group, which has two axles and six tires, includes straight trucks. The heavy truck group, which has more than two axles and more than five tires, includes straight trucks and tractors. GVWR of gasoline-powered trucks are approximately 15,000, 34,000, and 54,000lbs for light, medium, and heavy truck groups, respectively. Light group I trucks can carry up to 12,000lbs of GVWR, while light group II trucks can carry up to 15,000lbs of GVWR. Although a few light group I trucks, such as Ford *F-350* trucks and Dodge *Ram-3500*, can carry over 10,000lbs of GVWR, the other light group I trucks did not exceed 10,000lbs of GVWR. Gasoline-powered medium and heavy trucks have specified not only by GVWR, but also by GCWR, which are 60,000lbs for the both medium and heavy trucks. Table 6.1 shows GVWR, GCWR, the number of axles, and the number of tires for gasoline-powered trucks by truck group.

Table 6.1: Gasoline-Powered Truck Specifications

Truck Group	GVWR (lbs)	GCWR (lbs)	Axles	Tires
Light I (pick-ups/vans)	12,000	N/A	2	4
Light II (chassis-cabs/ cutaways)	15,000	N/A	2	6
Medium	34,000	60,000	2	6
Heavy	54,000	60,000	≥3	≥6

For diesel-powered trucks, the GVWR of light group I, light group II, and medium group trucks are the same as the GVWR of gasoline-powered trucks. However, the GVWR of 64,000lbs for heavy trucks is much heavier than that of gasoline-powered heavy trucks. In addition, the GCWR of 80,000lbs for heavy trucks is much heavier than that of gasoline-powered heavy trucks. Table 6.2 shows GVWR, GCWR, the number of axles, and the number of tires for diesel-powered trucks.

Table 6.2: Diesel-Powered Truck Specifications

Trucks	GVWR (lbs)	GCWR (lbs)	Axles	Tires
Light I (pick-ups/vans)	11,000	N/A	2	4
Light II (chassis-cabs/ cutaways)	15,000	N/A	2	6
Medium	34,000	60,000	2	6
Heavy	64,000[2]	80,000[2]	≥3	≥6

6.2 Three Prototype Heavy-Duty Vehicle Classes

The X-scheme, which is a new HDV visual classification scheme designed to bridge FHWA truck and EPA HDV classification schemes, employs three HDV classes. The three X classes are relatively simple and easy to identify in the field, i.e., 2-axle HDVs (the class X1), 3-axle HDVs (the class X2), and more than 3-axle HDVs (the class X3). The X classes interactively map among FHWA truck, Ahanotu truck, and EPA HDV classes.

Class X1 corresponds to Ahanotu truck class A (2-axle, 6-tire, single unit HDVs) and maps into FHWA truck class 5, or EPA classes HDV3 to HDV7. FHWA weight limitations and truck specifications support the mapping; that is that 2-axle, 6-tire single

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[2] Some specialty heavy trucks have much heavier GVWR or GCWR with more than three axles

unit HDVs can carry loads up to 34,000lbs of GVWR. Although 2-axle, 4-tire vehicles, corresponding to EPA class HDV2B, are not included in Ahanotu truck class A, they are included in class X1.

Because truck manufacturers specify few 2-axle, 4-tire vehicles with over 10,000 lbs of GVWR, they can be classified to EPA class HDV3. In addition, because 2-axle, 6-tire vehicles can be classified to a heavier class than HDV7, i.e., over 33,000lbs of GVWR, some of 2-axle, 6-tire vehicles can be classified to EPA class HDV8A. However, the classification to HDV3 for 2-axle, 4-tire vehicles or HDV8A for 2-axle, 6-tire vehicles does not significantly influence overall mobile source emissions inventory development. This is because VMT fractions of HDV3 with two axles and four tires and HDV8A with two axles and six tires portion only small parts of total HDV VMT. In fact, the HDV3 and the HDV8A take 3% and 10% out of overall HDV VMT from MOBILE6.2 default VMT fractions in 2004. In addition, only 2.4% of 2-axle, 6-tire HDV VMT are apportioned to class HDV8A (see Section 7.2.2).

Class X2 corresponds to parts of Ahanotu truck classes B (3-axle, single unit) and C (3-axle, two units). If a single unit or a tractor-trailer combination truck has three axles in total, the truck can carry loads up to 60,000lbs in conjunction with the FHWA weight limitations and truck specifications. As a field evidence, comprehensive truck size and weight study (FHWA, 2000) indicates that truck carrying capacity with three axles does not exceed 60,000lbs on the road. Therefore, class X2 includes 3-axle single unit and tractor-trailer combination trucks, which correspond to FHWA truck classes 6 and 8, and directly maps into EPA class HDV8A by definition.

Class X3 corresponds to remaining portions of Ahanotu truck classes B (4-axle, single unit) and C (4-axle, two units) and all of class D (more than 4-axle, multi units), which are FHWA truck classes 7, 8, and 9 to 13. Class X3 directly maps into EPA class HDV8B. The X-scheme as a hybrid HDV classification scheme between EPA HDV and FHWA truck classification schemes properly converts FHWA truck or Ahanotu truck classes into EPA HDV classes for the purpose of emissions modeling. Table 6.3 shows a map interactively mapping among X, EPA HDV, FHWA truck, and Ahanotu truck classes.

Table 6.3: Heavy-Duty Vehicle Reclassification Map Amongst X, EPA HDV, FHWA Truck, and Ahanotu Truck Classes

X Class	EPA Class	FHWA Class	Ahanotu Class	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	≥4

6.2.1 Typical X Class Vehicle Types

Class X1 typically includes pick-ups, vans, and straight delivery trucks (Figure 6.1). Although those HDVs are articulated with one or two small trailers, they should be still considered as 2-axle HDVs because their GVWRs will not be changed by articulated small trailers.

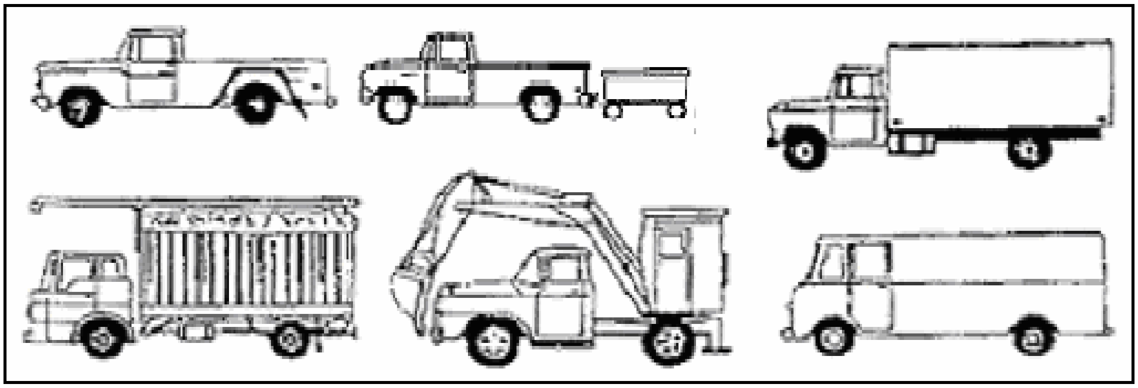

Figure 6.1: Class X1: 2-Axle HDVs, 8,501 to 33,000lbs of GVWRs

Class X2 includes dump trucks and articulated delivery trucks having three axles (Figure 6.2). Although X2 HDVs are articulated with a small trailer(s) as shown in Figure 6.3, those HDVs should be considered as 3-axle HDVs because their GVWRs will not be changed by articulated small trailers.

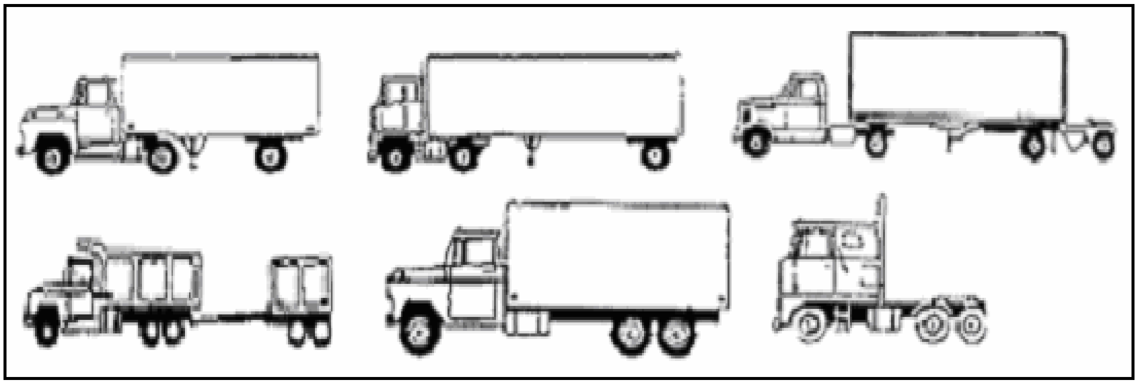

Figure 6.2: Class X2: 3-Axle HDVs, 33,001 to 60,000lbs of GVWRs

Figure 6.3 shows class X3 including all more than three-axle, articulated or single HDVs. Class X3 HDVs typically consists of a tractor and a trailer or multi-trailers for long range inter-region transports.

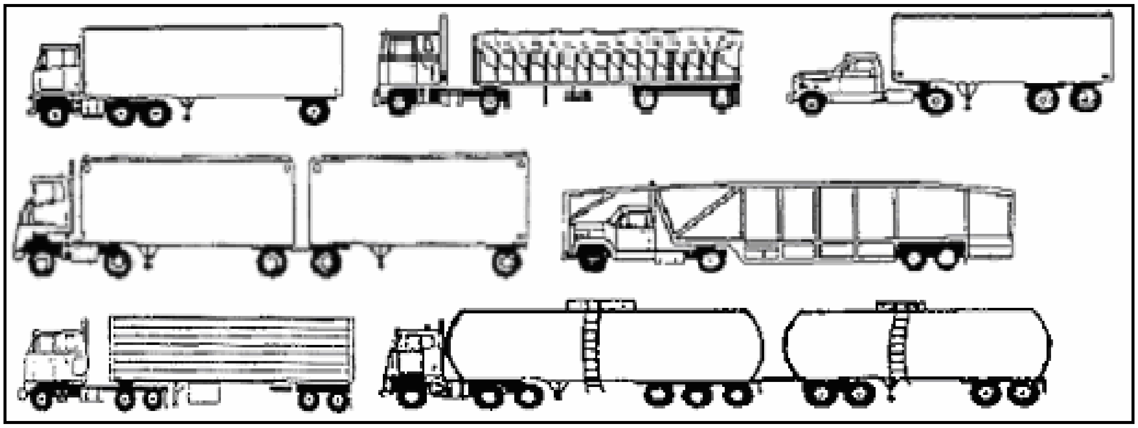

Figure 6.3: Class X3: more than 3-Axle HDVs, over 60,000lbs of GVWRs

6.2.2 Split of 3-axle and 4-axle Vehicle from Ahanotu Trucks B and C

Because Ahanotu truck classes B and C include 3-axle and 4-axle single and two unit trucks, they should be separated into 3-axle and 4-axle trucks and mapped into classes X2 and X3 for use of emissions modeling. The split of 3-axle and 4-axle vehicles from Ahanotu truck classes B and C was conducted by the observation of 3-axle and 4-axle trucks on the road. A field observation was conducted on a freeway segment of I-285 for 6 hours from 8 a.m. to 6 p.m. on a weekday. Only 3-axle and 4-axle single unit and tractor-trailer combination trucks were counted on the freeway segment. From the observed Ahanotu truck class B, more than 94% of single unit trucks had 3-axles, and less than 6% of them had 4-axles. From the observed Ahanotu truck class C, more than 89% of tractor-trailer combination trucks had 4-axles, and less than 11% of them had 3-axles. From the observation, majority of the mixture of 3-axle and 4-axle single unit trucks had 3-axles, while majority of 3-alxe and 4-axle tractor-trailers had 4-axles. Percentages of split 3-axle and 4-axle vehicles from the field observation were similar to values estimated from 2002 VIUS statistics. From the mixture of 3-axle and 4-axle single unit truck annual miles for Georgia statewide in the VIUS, 96% of single unit truck annual miles was contributed by 3-axles trucks, and 4% of single unit truck annual miles was contributed by 4-axle trucks. Among the mixture of 3-axle and 4-axle tractor-trailer combination truck annual miles, more than 84% and less than 16% of miles came from 4-axle and 3-axle trucks. Therefore, the percentages to split 3-axle and 4-axle trucks from the filed observation could be applicable to Ahanotu truck classes B and C.

6.3 Sub X Classes from the Three Prototype X Classes

The three prototype X classes, which are classes X1, X2, and X3, can be sub-classified into six classes by the number of axles, the number of tires, GVWR, GCWR, tractor-trailer combinations, and engine horsepower ranges without losing the fine resolution of original observed vehicle activity data. Class X1 can be sub-classified into two classes of X1A and X1B by the number of axles and tires. Class X1A represents 2-axle, 4-tire HDVs, which corresponding to EPA class HDV2B. From truck specification (see Section 6.1.2), the GVWR of majority of 2-axle, 4-tire HDVs is under 10,000lbs. Although some of 2-axle, 4-tire HDVs are classified to the EPA class HDV3, their impact in emissions inventories will be small and ignorable. For example, the baseline NO_X emission rate of HDV3 is 11% greater than HDV2B, and the MOBILE6.2 default VMT fraction of HDV3 is 3.4% of total HDV VMT. Therefore, HDV total emissions impact by 2-axle, 4-tire HDVs classified to HDV3 will be far less than 0.02% (= (11%*3.4%*10%)/2, assumed that 10% of HDV3 VMT from 2-axle, 4-tire vehicles and average HDV baseline emission rate is 2 times greater than HDV3). Class X1B represents EPA classes HDV3 to HDV8A. Although some of 2-axle, 6-tire HDVs are classified into class HDV8A, its impact in emissions inventories will be also ignorable. This is because only 2.4% (see Section 7.2.2) of 2-axle, 6-tire vehicle (HDV3 to HDV7) VMT (23% of the MOBLE6.2 default HDV VMT distribution) will be apportioned into HDV8A (10% of the MOBILE6.2 default HDV VMT distribution).

By vehicle types (single unit or tractor-trailer combination), class X2 can be separated into classes X2A and X2B for singe unit trucks and tractor-trailer combinations. Although classes X2A and X2B are classified to the same EPA class HDV8A, their travel characteristics are different, especially travel origins and destinations. For instance, class X2A typically representing dump trucks, cement mixers, and local delivery trucks involves in local and nonroad trips and travels shorter miles than class X2B. Class X2B involves in warehouse-to-retail center trips and travels 2.5 times greater annual miles than class X2A from the 2002 VIUS.

EPA classifies heavy-duty vehicle engines into three engine classes (light, medium, and heavy engines) by typical horsepower ranges (see Section 3.1.1). These engine classes closely represent light (HDV2B to HDV5), medium (HDV6 and HDV7) and heavy HDVs (HDV8A and HDV8B), respectively. Light and medium engine classes can be specified to class X1, and the heavy engine class can be specified to classes X2 and X3. However, Ahanotu found that horsepower ranges for three engine classes were much higher on the road than EPA defined. Onraod fleet horsepower ranges were 126hp to 231hp, 237hp to 350hp, and 210hp to 475hp for light, medium, and heavy engines, respectively. Mean horsepowers were 188hp, 279hp, and 360hp for light, medium, and heavy engines, respectively.

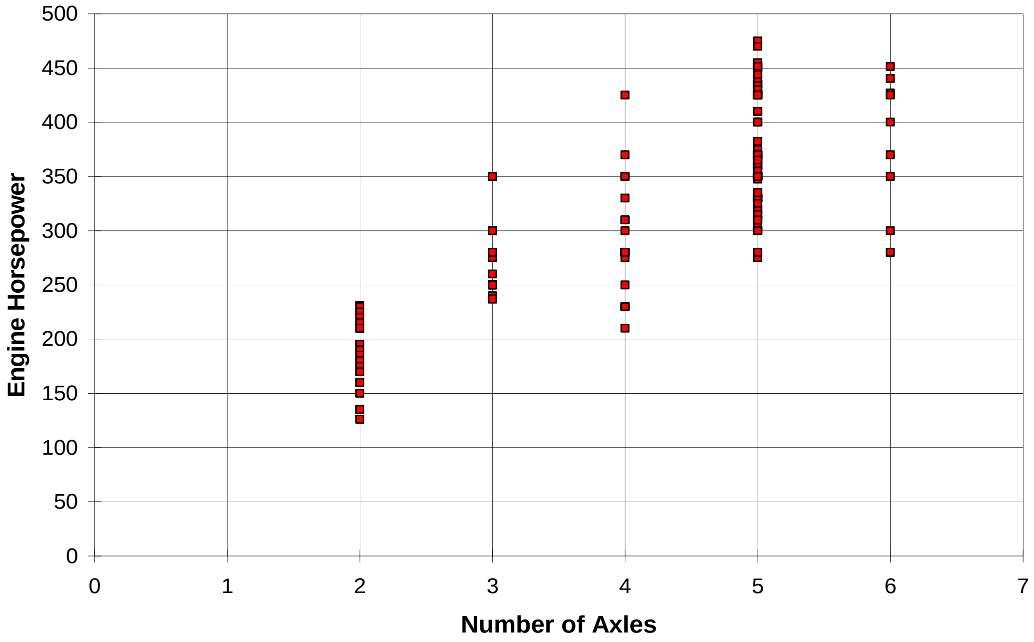

Figure 6.4: Horsepower Distributions by The number of Axles (Ahanotu, 1999)

Among heavy engines, horsepower distributions were quite different by the number of axles. For instance, mean horspowers were 293hp and 372hp for 4-axle trucks and 5+axle trucks. Mean engine horsepower for 5+axle trucks was 30% greater than for 4-axle trucks (Figure 6.5).

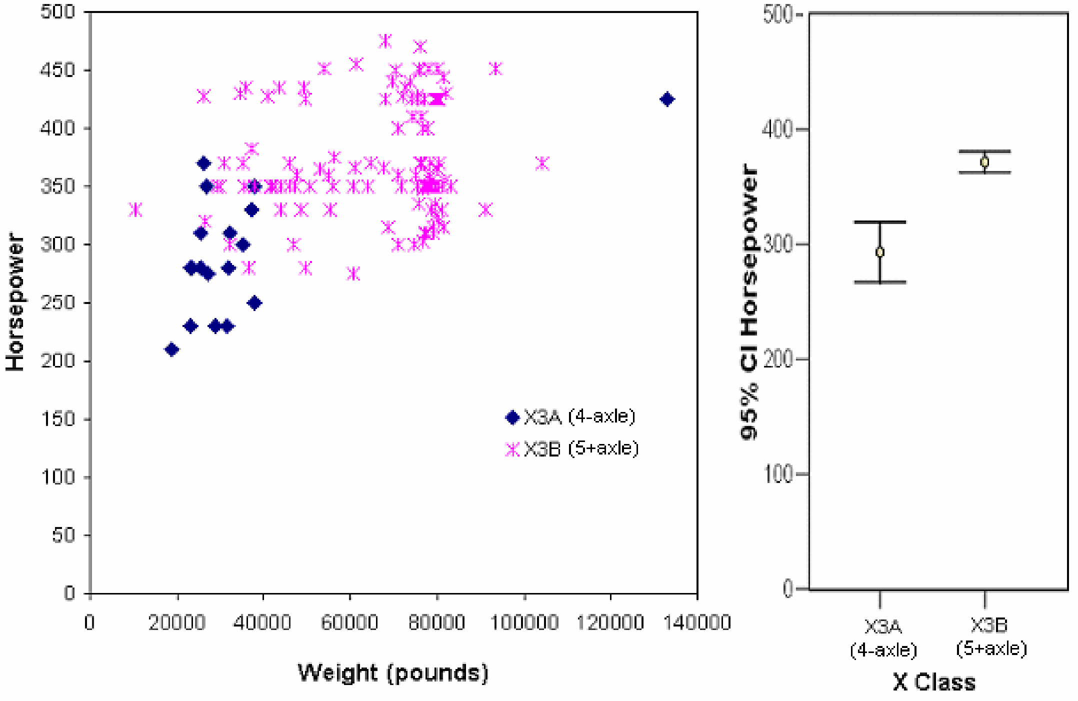

Figure 6.5: Horsepower Distributions and Mean Horsepower for 4-Axle (X3A) and 5+Axle (X3B) trucks

In addition, Chi-square tests indicated that horsepower distributions between 4-axle and 5+axle vehicles were independent each other. Because horsepower means and distributions between 4-axle and 5+axle trucks were significantly different, X3 class could be separated into classes X3A and X3B for 4-axle and 5+axle trucks, respectively.

To six sub-X classes, school and urban buses were added and directly classified to classes X4 and X5. FHWA class 4, the mixture of school and urban buses, should be properly separated into each bus class before conducting emissions modeling. This is because baseline emission rates between two bus classes are significantly different, i.e., the NO_X emission rate of urban diesel buses is about 25% greater than school buses. With typical vehicle types and detail definitions for each X classes, the three prototype X classes can be re-expressed into eight X classes.

Table 6.4: Eight X Classes with Their Vehicle Types and Definitions

X Class	Vehicle Type	Definition
X1A	Single Unit Truck	2-axle, 4-tire single trucks with or without trailers
X1B	Single Unit Truck	2-axle, 6-tire single trucks with or without trailers
X2A	Single Unit Truck	3-axle single trucks with or without trailers
X2B	Tractor Trailer	3-axle tractor-trailers (only total number of axles)
X3A	Single Unit Truck	4-axle single trucks with or without trailers
	Tractor Trailer	4-axle tractor-trailers (only total number of axles)
X3B	Single Unit Truc	5+ axle single trucks
	Tractor Trailer	5+ axle tractor-trailers (only total number of axles)
X4	School Bus	School buses
X5	Urban Bus	Urban buses

Table 6.5: Interactive Vehicle Mapping Among X, FHWA Truck, Ahanotu Truck, and EPA HDV Classes

X Class	FHWA Class	Ahanotu Class	Engine Size (EPA Power, hp) [Onroad Power, hp]	EPA HDV Class	Tires & Axles
X1A	3 (HDV)		Light (70 ~ 170) [126 ~ 231][3]	HDV2B	2 axles & 4 tires
				HDV3	
X1B	5	A		HDV3	2 axles & 6 tires
				HDV4	
				HDV5	
			Medium (170 ~ 250) [237 ~ 350][3]	HDV6	
				HDV7	
				HDV8A	
X2A	6	B (FHWA Classes 6 & 7) C (FHWA Class 8)	Heavy (> 250) [210 ~ 475][3]	HDV8A	3 axles
X2B	8 (3 axles)			HDV8A	3 axles
X3A	7 (4 axles) 8 (4 axles)			HDV8B	4 axles
X3B	7 (5 axles)[4], 9 to 13	D		HDV8B	5+ axles
X4	4		Heavy (> 250)	School Bus	
X5				Urban Bus	

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[3] Onroad fleet power distributions (Ahanotu, 1999)

[4] Ignorable due to extremely low frequency of this type of trucks on the road

X classes directly convert FHWA truck classes into EPA HDV classes and vise versa. However, the conversion of FHWA classes 3 and 4 into X classes or EPA HDV classes, a proper split guide is required such as annual vehicle miles or daily vehicle miles weighted by the number of registered vehicles of light-duty trucks (LDT1 to LDT4), HDV2B, school buses, and urban buses. Then, split ratios of LDTs to HDV2Bs for FHWA class 3 and of school to urban buses for FHWA class 4 can be developed.

6.4 Emissions Impact from the New Heavy-Duty Vehicle Visual Classification Scheme

Emissions estimates with the new heavy-duty vehicles visual classification scheme were compared to emissions with the EPA guidance for the development of HDV emissions inventories. Truck volumes observed on the highway network (see CHAPTER 4) were assigned into each X class. Observed truck volumes, which contain FHWA truck classes from 5 to 13, were aggregated into Ahanotu truck classes A, B, C, and D. Ahanotu class A was assigned into X1B class and apportioned into each EPA HDV classes from HDV3 to HDV8A using VMT fractions obtained from 2002 VIUS (see Section 7.2.2). 3-axle and 4-axle HDVs from Ahanotu classes B and C were split by observed 3-axle and 4-axle HDV percentages for single unit trucks and tractor-trailer combination trucks. After splitting the HDVs by the number of axles, 3-axle and 4-axle HDVs were assigned into HDV8A and HDV8B, respectively. Because Ahanotu class D corresponds to FHWA truck classes 9 to 13, all Ahanotu class D trucks were assigned into EPA HDV8B class. Figure 6.6 shows VMT fractions estimated and assigned into EPA HDV classes through the X-scheme from observed HDV volumes with the Ahanotu truck classes. Estimated HDV VMT fractions were compared to MOBILE6.2 default HDV VMT fractions.

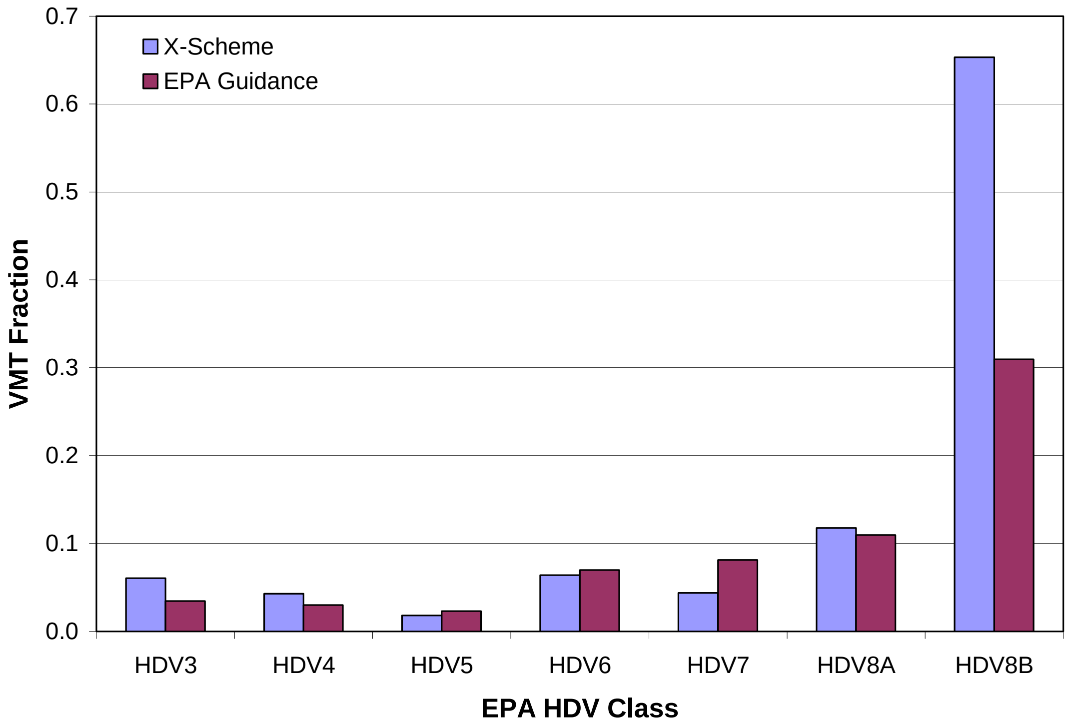

Figure 6.6: Heavy-Duty Vehicle VMT Fractions Assigned into EPA HDV Classes by the X-Scheme and the EPA Guidance

With the X-scheme, the estimated HDV8B VMT fraction was much higher than the MOBILE6.2 default HDV8B VMT fraction, while lighter HDV VMT fraction differences were rather small. Because the X-scheme avoided the aggregation and desegregation process used in the EPA guidance, observed heavier HDV activity was not misallocated into light and medium HDV activity. Therefore, HDV VMT fractions by the X-scheme kept the original fine resolution of onroad vehicles characteristics information.

For the evaluation of emissions impact by the X-scheme, the MOBILE6.2 model was run with input parameters used to develop air quality plans for the 13-county Atlanta 1-hr ozone nonattainment area. Input parameters were 2002 vehicle registration distributions in Atlanta, GDNR hourly temperatures, a fuel RVP of 7psi, the refueling program, and the fuel program. The MOBILE6.2 ran with the scenario for the month of July and the year of 2003. Emission rates (g/mi) for HDV classes from the MOBILE6.2 model were multiplied by each HDV VMT obtained with the X-scheme and MOBILE6.2 default VMT fractions. In comparing emissions with the EPA guidance, emissions of NO_X and $PM_{2.5}$ with the X-scheme significantly increased. With the X-scheme, NO_X and $PM_{2.5}$ emissions of HDVs observed on the highway network were greater by 35% and 32% respectively than estimates with the EPA guidance.

CHAPTER 7

A NEW HEAVY-DUTY VEHICLE VMT ESTIMATION METHOD

As has been discuss earlier, many existing methods for evaluating HDV VMT have major limitations and it is desirable to developing improved methods for estimating VMT from these vehicle classes. Presented here is such a method. This new heavy-duty vehicle VMT estimation method consists of two major processes; one is to estimate VMT from those HDV vehicle classes that can be derived from HPMS data (i.e., EPA HDV3 to 8 and Busses that are labeled as HDV3 to Bus VMT), and the second is to estimate HDV2B VMT as a fraction of travel for all trucks having two axle and four tires. For each process, heavy-duty vehicle data sources discussed in CHAPTER 4 are integrated to estimate HDV VMT for EPA facility types and EPA HDV classes within the 20-county Atlanta metropolitan area. Because EPA facility-specific HDV activity is required in emissions modeling, all HDV activity data, originated from HDV data sources and classified by FHWA facility types, are converted into EPA facility types using the facility conversion guidance developed by Guensler, et al. (Guensler, 2004).

For the estimation of HDV3 to bus VMT distributions, HDV VMT, which was observed with the Ahanotu truck classification scheme in the development of the 2003 Georgia Tech HDV/BUS database, was translated into X classes. Then, class X1 VMT was separated into each HDV3 to HDV8A class using mean annual mileage accumulation rates derived from the 2002 VIUS and the registration fractions of 2-axle, 6-tire HDVs. In addition, classes X4 and X5 VMT were corrected using school bus and urban transit bus activity data from the 2003 Georgia Tech HDV/BUS database. For the estimation of HDV2B VMT fractions on EPA facility types, "*other 2-axle, 4-tire vehicle*" VMT percentages on FHWA facility types from Highway Statistics were associated with MOBILE6.2 daily mileage accumulation rates and vehicle registration fractions for LDT1 to 4 and HDV2B classes.

For the estimation of HDV VMT by EPA HDV class and EPA facility type, HDV3 to bus VMT distributions and HDV2B VMT fractions were applied to total truck miles and total vehicle miles obtained from the Georgia DOT HPMS within the 20-county Atlanta metropolitan area. Figure 7.1 shows the overall HDV VMT estimation process schematically. Finally, emissions estimates from this new scheme were compared to emissions estimates using the EPA MOBILE6.2 default VMT fractions.

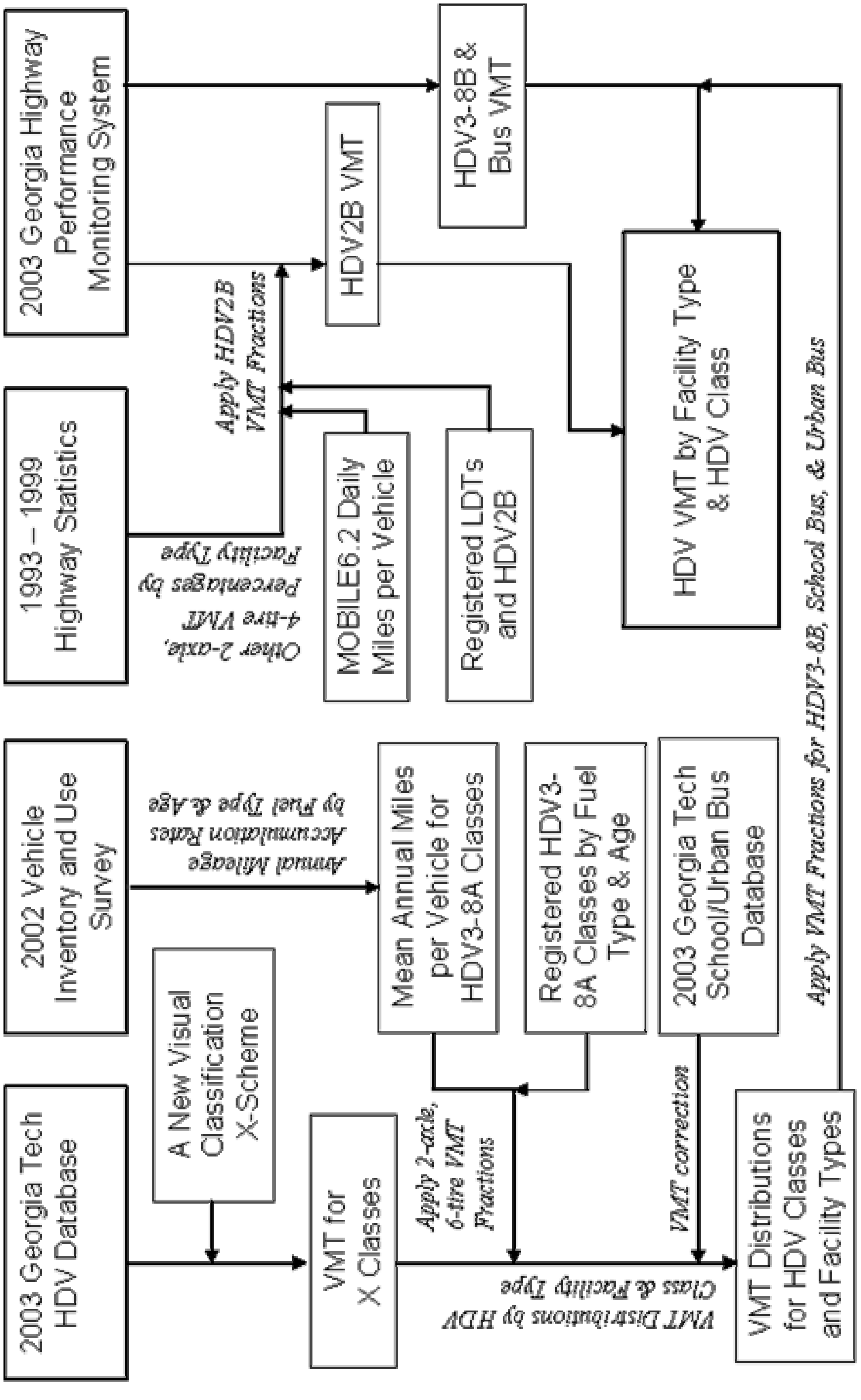

Figure 7.1: Heavy-Duty Vehicle VMT Estimation Process for the 20-County Atlanta Metropolitan Area

7.1 FHWA Facility Conversion into EPA Facility Types

The MOBILE6.2 emission rate model requires EPA facility-specific (freeway, arterial, local, and freeway ramp) heavy-duty vehicle activity data. However, HDV activity data including VIUS, HPMS, Highway Statistics, and Georgia Tech HDV/BUS database are classified by FHWA facility type. Therefore, all FHWA facility types must be converted into the four EPA facility types before applying in emissions modeling. EPA suggests a facility conversion method according to genetic facility functional characteristics (USEPA, 2004c).

However, Guensler, et al found that FHWA facility types should be characterized not only by functional characteristics, but also by traffic parameters. For instance, FHWA minor collectors and locals with high speed limits (i.e., over 40mph) have the same functional characteristics as FHWA minor arterials or major collectors. FHWA minor collectors and locals should be converted into EPA locals by the EPA facility conversion guidance, however, Guensler, et al converted FHWA minor collectors and locals with high speed limits into EPA arterials (Guensler, 2004). Using the Guensler's facility conversion method, HDV activity data with FHWA facility types can be converted into EPA facility types for air quality analysis purposes.

Table 7.1: Mapping of Functional Road Classifications for MOBILE-Matrix in Air Quality Analysis (Source: Guensler et al., 2004)

MOBILE6.2 Categories	FHWA Corresponding Categories	Georgia MTPT [5] 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	• 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 > 40mph (FHWA Class 8) • Collector Urban (FHWA Class 17) • Non-Ramp Local Rural, Local Urban with speed limit > 40mph (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 ≤ 40mph (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

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[5] Multimodal Transportation Planning Tool (MTPT)

7.2 HDV3 to Bus VMT Distributions

To develop HDV3 to Bus VMT distributions for EPA facility types, three serial steps should be followed. Theese are HDV class translation into X classes, the development of a 2-axle, 6-tire HDV VMT distribution, and bus VMT correction.

7.2.1 HDV VMT with Ahanotu Truck Classes into X Classes

From the 2003 Georgia Tech HDV/BUS database, observed heavy-duty vehicle VMT with Ahanotu truck classes A to D, school bus, and urban bus was translated into each X class for freeways and arterials. VMT from classes A, D, school bus, and urban bus were directly assigned into classes X1B, X3B, X4, and X5, respectively. Because Ahanotu truck classes B and C were mixtures of 3-axle and 4-axle single units and tractor-trailer combinations, they were separated by 3-axle and 4-axle HDV percentages observed in the field (see Section 6.2.1). Percentages of 3-axle and 4-axle HDVs observed in the field were applied to the Ahanotu truck classes B and C to split them into classes X2A, X2B, and X3A.

7.2.2 Two-Axle and Six-Tire HDV VMT Distribution

Because class X1B corresponds to EPA classes HDV3 to HDV7 and a part of HDV8A, aggregated HDV VMT must be separated into each EPA HDV class. From the 2002 VIUS, annual mileage accumulation rates of 2-axle, 6-tire HDVs were estimated by fuel type (gasoline and diesel) and vehicle model year for EPA classes HDV3, HDV4, HDV5, HDV6, HDV7, and HDV8A. Vehicle model years were categorized by year from 2002 to 1987 and all pre-1987. Due to the small sample size of classes HDV4, HDV5, HDV6, and HDV7 in the VIUS, they were combined into two HDV classes (classes HDV4 and HDV5, and classes HDV6 and HDV7) based on their engine horsepower similarities (see Section 6.3). For HDV classes, fuel types, and ages, mean annual mileage accumulation rates were estimated. As HDVs age, their annual mileage accumulation rates decrease, and for vehicles of the same age heavier HDVs travel more miles than lighter HDVs (Figure 7.2).

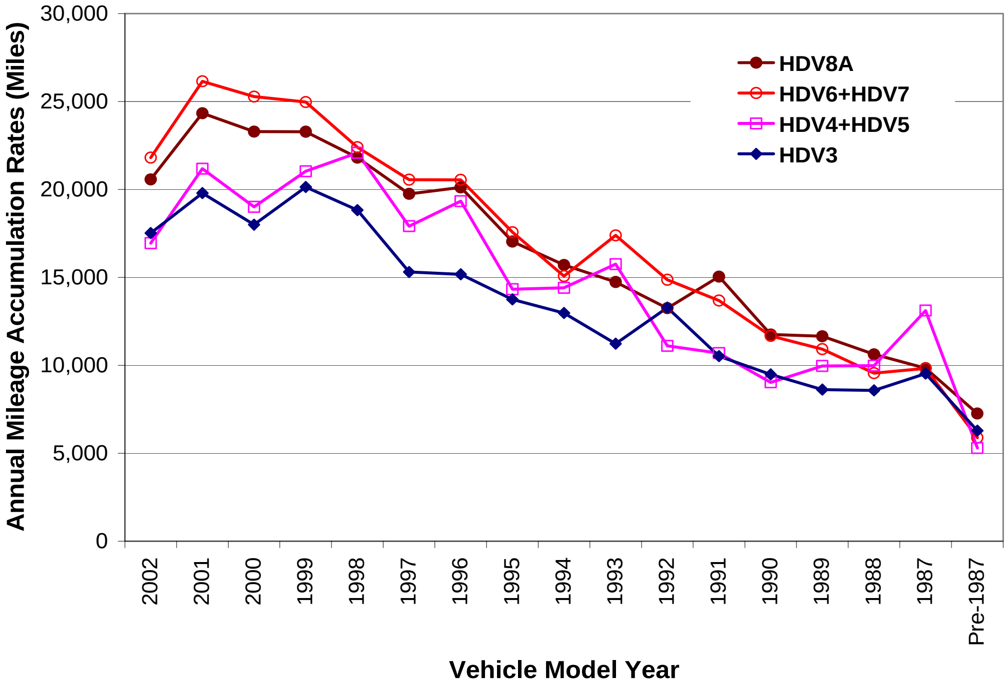

Figure 7.2: Annual Accumulated Vehicle Miles for 2-Axle, 6-Tire Single Unit Heavy-Duty Vehicles

To develop VMT distributions for 2-axle, 6-tire single unit HDVs, annual mileage accumulation rates were multiplied by the number of vehicles registered in the 20-county metropolitan area for only 2-axle, 6-tire HDV classes 3 to 8A. Since 2-axle, 6-tire single unit HDVs predominantly operate on the local network, the use of registration data is acceptable without generating large uncertainties. To estimate VMT fractions for each 2-axle, 6-tire single unit HDV class, annual mileage accumulation rates for each HDV class were divided by aggregated total annual mileage accumulation rates using equation 7.1.

$$VF_{v,f} = \frac{\sum_{y=0}^{16} AM_{v,y} * RF_{v,y} * RD_{v,y,f}}{\sum_{v=HDGV3}^{HDDV8} \sum_{y=0}^{16} AM_{v,y} * RF_{v,y} * RD_{v,y,f}} \qquad (7.1)$$

Where, *VF* is the HDV VMT fraction of 2-axle, 6-tire single unit HDVs

v is the EPA HDV class (3 to 8A)

f is the fuel type (gasoline or diesel)

y is the vehicle age from 0 to 16

AM is the annual mileage accumulation rates

RF is the registered vehicle fraction for a vehicle class

RD is the registered vehicle fraction for a fuel type

From the VMT fractions estimated with the equation 7.1, more than 82% of 2-axle, 6-tire single unit HDVs was generated from diesel HDVs, and more than 45% of 2-axle, 6-tire single unit HDVs was generated from medium HDV classes (HDV6 and HDV7) (Figure 7.3). This VMT distribution was used to split the aggregated VMT of 2-axle, 6-tire single unit HDV or Ahanotu trucks class A into EPA HDV3 to HDV8A VMT.

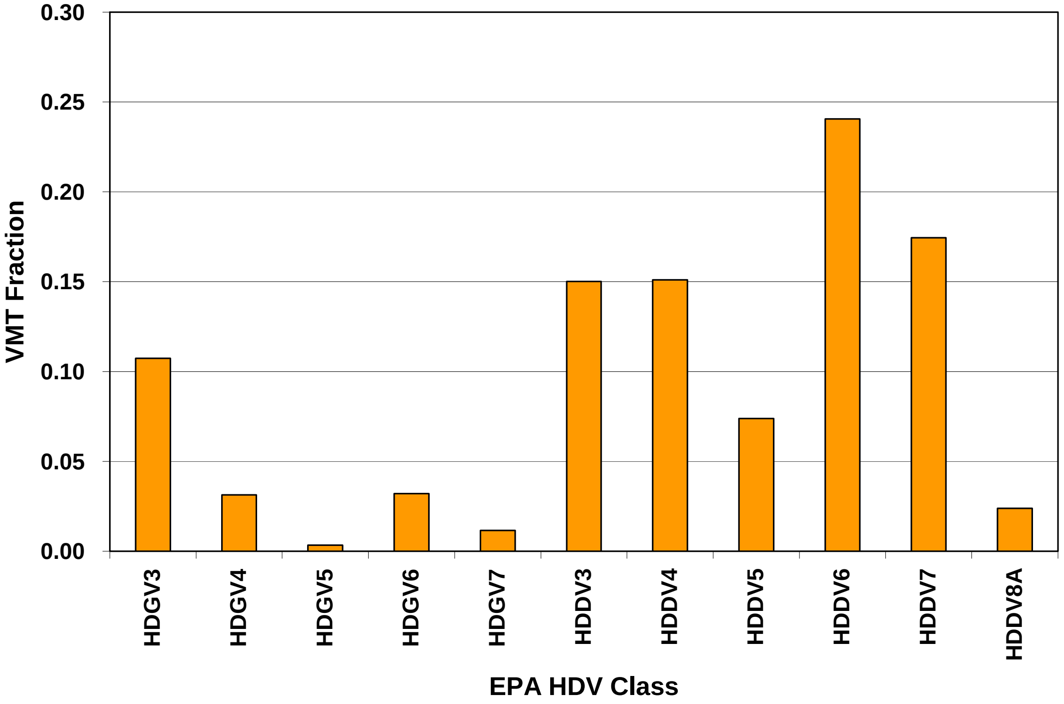

Figure 7.3: Heavy-Duty Vehicle VMT Distribution for 2-Axle, 6-Tire Single Unit HDVs

7.2.3 Bus VMT Correction

As described earlier, school buses and urban buses (including urban transit, church bus, charter, and intercity buses) were observed on the highway network (see CHAPTER 4). Buses observed on freeways and arterials were directly used to estimate bus VMT fractions on freeways and arterials. Because bus activity on collectors and local roads was not observed in the development of the HDV/BUS database, bus VMT fractions observed on minor arterials was used to estimate bus VMT fractions on EPA defined local roads.

However, school bus VMT fractions observed on minor arterials could underestimate school bus VMT fractions on local roads because school buses generate significant amount of their activity on collectors and local roads. In the 2003 Georgia Tech HDV/BUS database, urban transit bus VMT, which was 73% of total urban bus VMT in counties operating urban transit buses, only included urban transit bus activity on regular service routes without including out of service urban transit bus activity (i.e., travel to and from regular service routes). Therefore, school and urban transit bus VMT fractions observed on the network needed to be corrected.

7.2.3.1 School Bus VMT Correction

Daily school bus miles from the bus activity database were 14% greater than that estimated with school bus VMT fractions developed with the observed school bus activity on minor arterials. This implied that school bus VMT fractions developed with the highway network underestimated school bus VMT on local roads. Therefore, school bus VMT on local roads was scaled up by 14%. Estimated school bus VMT fractions within the 20-county region were thus 13%, 19%, and 68% for freeways, arterials, and local roads, respectively.

7.2.3.2 Urban Transit Bus VMT Correction

Because the 2003 Georgia Tech HDV/BUS activity database included only urban transit bus VMT on regular service routes, without including “out of service” activity, urban transit bus VMT also needed to be corrected. To correct urban transit bus VMT, transit bus activity data obtained with Georgia Tech Trip Data Collectors installed on two MARTA buses for routes 55 and 66 from July 2004 to February 2005 (Yoon, 2005b) were used. Yoon et al. (Yoon, 2005b) found that 17% of transit bus VMT was “out of service” bus activity. Therefore, bus VMT from the 2003 Georgia Tech HDV/BUS database increased by 17%. The corrected urban transit bus VMT was combined with other bus VMT including church, intercity, and charter buses. Estimated total urban bus VMT fractions were 47%, 39%, and 13% for freeways, arterials, and local roads, respectively.

7.2.4 HDV3 to Bus VMT Distributions for EPA Facility Types

Since class X1B was the mixture of EPA HDV classes 3 to 8A, the X1B VMT was disaggregated into each HDV class by the 2-axle, 6-tire single unit HDV VMT distribution (see Section 7.2.2). Because vehicles were observed on freeways and arterials, VMT distributions of EPA HDV classes 3 to 8B, school bus, and urban bus could be created for freeways and arterials. If VMT distribution on freeways or arterials was not available for a county, the 20-county average freeway or arterial VMT distributions were used for the county. However, because HDV VMT was not collected on EPA defined local roads, HDV and corrected bus VMT collected on rural and urban minor arterials were used to develop VMT distributions for EPA local roads. If VMT on either rural or urban minor arterials, or both, was not available for a county, the 20-county average local VMT distribution was used for the county (see APPENDIX A). However, this approach could cause the overestimation of emissions on local roads greater than with the MOBILE6.2 default VMT distribution because VMT fractions for heavier HDVs on locals are possibly lower than on the minor arterials. On the contrary, an EPA study (USEPA, 1999) showed that commercial tractor-trailer combination vehicle VMT on collectors was 10% greater than on minor arterials in metropolitan areas over 1,000,000 of population.

7.3 HDV2B VMT Fractions

The VMT fraction of the lightest heavy-duty vehicle of HDV2B, which corresponds to class X1A, can be estimated with the statewide "*other 2-axle, 4-tire vehicle*" VMT percentages provided by FHWA Highway Statistics and the number of vehicles registered as LDT1, 2, 3, and 4 and HDV2B in the 20-county Atlanta metropolitan area.

7.3.1 Other 2-Axle and 4-Tire Vehicle VMT Percentages

Highway Statistics defines "*other 2-axle, 4-tire vehicles*" as single unit vehicles including vans, pick-ups, and SUVs, but excluding passenger cars (FHWA, 1999). Before 2000, Highway Statistics had provided the other 2-axle, 4-tire truck VMT percentages in the table of the "*VM-4*" for FHWA facility types of rural/urban interstates, principal arterials, minor arterials, and urban expressways. Since 2000, Highway Statistics have not provided other 2-axle, 4-tire truck VMT percentages by facility type. Therefore, other 2-axle, 4-tire truck VMT percentages from available Highway Statistics (from 1993 to 1999) were used to estimate HDV2B VMT fractions. Seven-year mean VMT percentages, which were statistically significant at the 95% confidence level, were used to estimate HDV2B VMT for facility types. Table 7.2 shows mean VMT percentages of other 2-axle, 4-tire vehicles by facility type in Georgia.

Table 7.2: Georgia Statewide Mean VMT Percentages of "other 2-axle, 4-tire vehicles" from Highway Statistics

FHWA Facility Type		Mean VMT Percentage of the Other 2-Axle, 4-Tire Vehicles
1	Rural Interstates	20.5
2	Rural Other Principal Arterials	13.3
6	Rural Minor Arterials	15.2
11	Urban Interstates	26.1
12	Urban Other Freeways and Expressways	25.9
14	Urban Principal Arterials	23.0
16	Urban Minor Arterials	21.6

7.3.2 Separation of HDV2B VMT from Other2-Axle and 4-Tire Vehicle VMT

The category of *"other 2-axle, 4-tire vehicles"* was the mixture of light-duty trucks (LDTs) and HDV2Bs. To separate HDV2B VMT, other 2-axle, 4-tire vehicle VMT percentages were multiplied by MOBILE6.2 default daily VMT and the number of vehicles registered for LDT and HDV2B classes. To estimate HDV2B VMT fractions among the mixture of LDT and HDV2B classes, the HDV2B daily VMT was divided by the sum of HDV2B and LDT VMT. Then, the HDV2B VMT fraction was multiplied by VMT percentages of other 2-axle, 4-tire vehicles to estimate the HDV2B VMT fraction for each facility type in a county (Equation 7.2). APPENDIX B provides HDV2B VMT fractions for counties in the 20-county Atlanta metropolitan area.

$$FHDV2B_{F,v} = \left(\frac{P2A4V_{F,v}}{100} \right) * \left(\frac{\sum_{v=HDGV2B}^{HDDV2B} \sum_{f=gasoline}^{diesel} DM_{v,f} * NR_{v,f}}{\sum_{v=LDGV1}^{HDDV2B} \sum_{f=gasoline}^{diesel} DM_{v,f} * NR_{v,f}} \right) \qquad (7.2)$$

Where, *FHDV2B* is the VMT fraction of HDV2B out of all vehicle classes

P2A4V is the mean VMT percentage of other 2-axle, 4-tire vehicles

F is the FHWA facility type

f is the fuel type (gasoline or diesel)

v is the LDGT1/2/3/4, LDDT12/34, HDGV2B, and HDDV2B

DM is the MOBILE6.2 default daily VMT

NR is the number of vehicles registered in the 20-county Atlanta metropolitan area

By applying HDV2B VMT fractions to total VMT for all vehicle classes on each facility type, HDV2B VMT for facility types could be estimated.

7.4 HDV VMT Estimation for Facility Types

Heavy-duty vehicle VMT by HDV class for EPA facility types was estimated with link-specific transportation characteristics in Georgia HPMS and HDV VMT fractions developed in Sections 7.2 and 7.3. A link-specific aggregated truck VMT was estimated with a start and an end mile points, an annual average daily traffic (AADT), and a truck percentage. A set of start and end mile points indicated a homogeneous road link characteristics in geometry as start and end mile points defined changes in road geometry such as lane merge/split, bridges, intersections, and ramp changes. The difference of an end mile point and a start mile point was used to define the link length in miles.

Truck percentages in HPMS include all vehicle having at least two axles and six tires. This includes FHWA truck classes 5 to 13 and buses, EPA HDV3 to HDV8B and buses, and X classes X1B to X5. To estimate total truck VMT for each EPA facility type, link-specific truck percentages were multiplied by AADT and link length (the subtraction of an end mile point to a start mile point). Then, the total truck VMT was multiplied by estimated HDV VMT distributions and separated into each EPA HDV VMT for each facility type. Because HDV2B VMT was not included in truck percentages, HDV2B VMT fractions developed in the previous section (see Section 7.3) were used.

Overall, HDV VMT (including HDV2B and HDV3 to Bus VMT) distributions can be developed for EPA facility types for use in HDV emissions inventory development (see APPENDIX A). Within the 20-county Atlanta metropolitan area, the estimated regional HDV VMT distribution was significantly different from the MOBILE6.2 default VMT distribution.

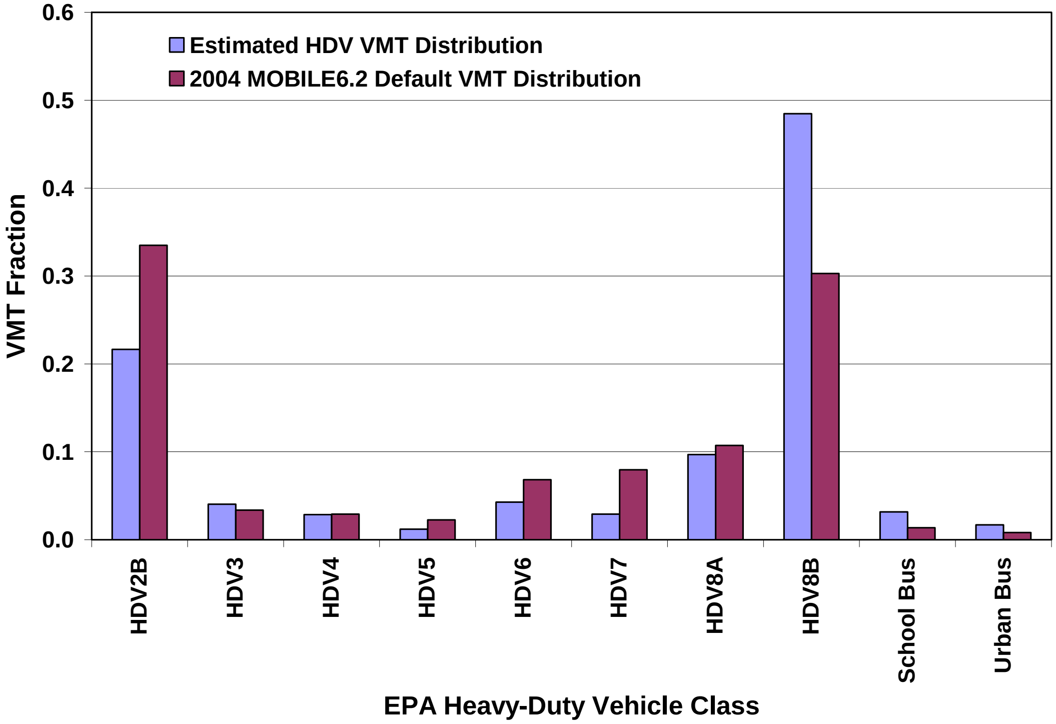

Figure 7.4: Heavy-Duty Vehicle VMT Distributions Estimated with the HDV VMT Estimation Method and the 2004 MOBILE6.2 Default VMT Distribution

Estimated VMT fractions for HDV8B, school bus, and urban bus classes were 61%, 107%, and 88% respectively greater than MOBILE6.2 default values. However, estimated VMT fractions for HDV2B, HDV5, HDV6, and HDV7 classes were 65%, 53%, 62%, and 36% respectively of MOBILE6.2 default VMT fractions. Estimated VMT fractions were generated from vehicle activity in the highly populated Atlanta urban area, while MOBILE6.2 default VMT fractions were developed nationwide including urban and rural areas. In urban areas, VMT fractions for heavy HDVs and buses were greater than in rural areas because of goods movement and the existence of public transportation systems. Table 7.3 shows estimated HDV VMT distributions for freeways, arterials, and locals in the 20-county Atlanta metropolitan area.

Table 7.3: Estimated HDV VMT Distributions for Freeways, Arterials, and Locals

EPA Facility	HDV VMT Fraction									
	2B	3	4	5	6	7	8A	8B	School BUS	Urban BUS
Freeway	0.161	0.049	0.035	0.015	0.052	0.036	0.084	0.552	0.006	0.011
Arterial	0.249	0.033	0.023	0.010	0.035	0.024	0.126	0.457	0.019	0.024
Local	0.339	0.023	0.016	0.007	0.025	0.017	0.091	0.340	0.130	0.011

7.5 Emissions Impact Analysis with the New HDV VMT Estimation Method

The new heavy-duty vehicle VMT estimation method that incorporated the new heavy-duty vehicle visual classification scheme was applied to estimate regional HDV emissions in the Atlanta 8-hr ozone nonattainment designated area. For the estimation of emission rates in 2004, MOBILE6.2 was run with input parameters developed for the 13-county Atlanta 1-hr ozone nonattainment area. Input parameters included; 2002 vehicle registration distributions for Atlanta, GDNR hourly temperatures, a fuel RVP of 7psi, the refueling program, and the fuel program. In emissions modeling, FHWA facility types were assigned into EPA facility types by the Guensler's (Guensler, 2004) facility conversion guide, and FHWA facility-specific average speeds (see Table 7.4), which were posted to the Atlanta Regional Commission (ARC) travel demand modeling network used for the development of Georgia State Implementation Plans (GDNR, 2001), were applied for the modeling month of July and the modeling year of 2004. APPENDIX C shows MOBILE6.2 inputs and outputs.

Table 7.4: FHWA Facility-Specific Average Speed Posted on ARC Travel Demand Modeling Network

Facility Type		Facility Code	Average Speed (mph)
Rural	Interstate	1	59
	Principal Arterial	2	53
	Minor Arterial	6	47
	Major Collector	7	44
	Minor Collector	8	43
	Local	9	40
Urban	Interstate	11	55
	Freeway/Expressway	12	54
	Principal Arterial	14	43
	Minor Arterial	16	38
	Collector	17	35
	Local	19	35

FHWA facility-specific emission rates were multiplied by HDV VMT estimated with EPA facility-specific VMT distributions corresponding to FHWA facility types (See Section 7.1). Then, road link-specific emissions were aggregated into each EPA facility types (freeways, arterials, locals) within the 20-county Atlanta metropolitan area using equation 7.3.

$$E_{f,i} = \sum_{j} ER_{f,i,j} * VMT_{f,j} \qquad (7.3)$$

Where, E is the total daily emissions (tons/day)

f is the FHWA facility type

i is the pollutant type

j is the heavy-duty vehicle class

ER is the emission rate (g/mi) from the MOBILE6.2

VMT is the vehicle miles traveled (miles/day)

7.5.1 NO_X and $PM_{2.5}$ Emissions by HDV Class and Facility Type

NO_X emissions estimated with the new HDV VMT estimation method were 27.2%, 18.5%, and 10.3% greater than estimates with the MOBILE6.2 default VMT fractions for EPA freeways, arterials, and locals, respectively. $PM_{2.5}$ emissions with the new HDV VMT estimation method were also 25.5%, 21.5%, and 31.2% greater than estimates with the MOBILE6.2 default VMT fractions for freeways, arterials, and locals, respectively. On freeways and arterials, the new HDV VMT estimation method, which minimized the misallocation of heavy HDV VMT into light and medium HDV VMT, resulted in greater emissions than the MOBILE6.2 default VMT fractions. On local roads, significant underestimation of school bus VMT with the MOBILE6.2 default VMT fractions caused lower emissions than the new HDV VMT estimation method.

Table 7.5: Emissions Increase with A New Heavy-Duty Vehicle Visual Classification and Activity Estimation Method from the Mobile6.2 Default VMT Fractions

Pollutant	Emissions Increase (%)			
	Freeway	Arterial	Local Road	Total
NO_X	27.2	18.5	10.3	22.9
$PM_{2.5}$	25.5	21.5	31.2	25.0

On freeways, the three largest NO_X emission contributors with the HDV VMT estimation method were classes HDV2B, HDV8A, and HDV8B by 5.1%, 8.8%, and 73.9%, respectively. With the MOBILE6.2 default VMT fractions, HDV2B, HDV6, HDV7, HDV8A, and HDV8B were major contributors by 12.9%, 5.2%, 7.8%, 14.4%, and 52.5%, respectively. Although emissions with the MOBILE6.2 default VMT fractions were greater for classes HDV2B, HDV6, HDV7, and HDV8A, the underestimation of HDV8b VMT by 44% caused a 27.2% underestimation of NO_X emissions on freeways. Figure 7.5 shows NO_X emission differences by vehicle class between the MOBILE6.2 default VMT fractions and estimated HDV VMT on freeways.

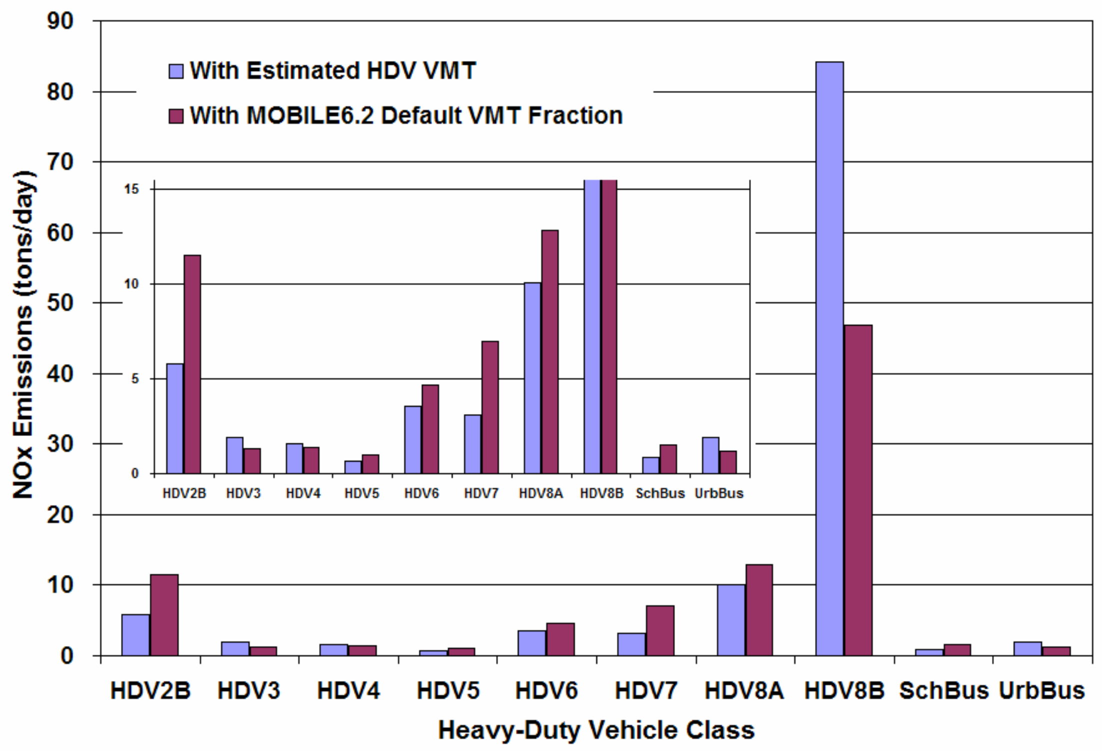

Figure 7.5: Heavy-Duty Vehicle NO_X Emissions on EPA Freeways

On arterials, classes HDV2B, HDV8A, and HDV8B contributed the largest NO_X emissions with the estimated HDV VMT by 9.4%, 13.4%, and 63.9%, respectively. With the MOBILE6.2 default VMT fractions, classes HDV2B, HDV6, HDV7, HDV8A, and HDV8B contributed most NO_X emissions by 12.9%, 5.2%, 7.8%, 14.4%, and 52.5%, respectively. Although emissions with the MOBILE6.2 default VMT fractions greater for classes HDV2B to HDV7, the underestimation of HDV8B VMT by 34.5% caused 18.5% underestimation of NO_X emissions on arterials. Figure 7.6 shows NO_X emission difference by vehicle class between the MOBILE6.2 default VMT fractions and the estimated HDV VMT on arterials.

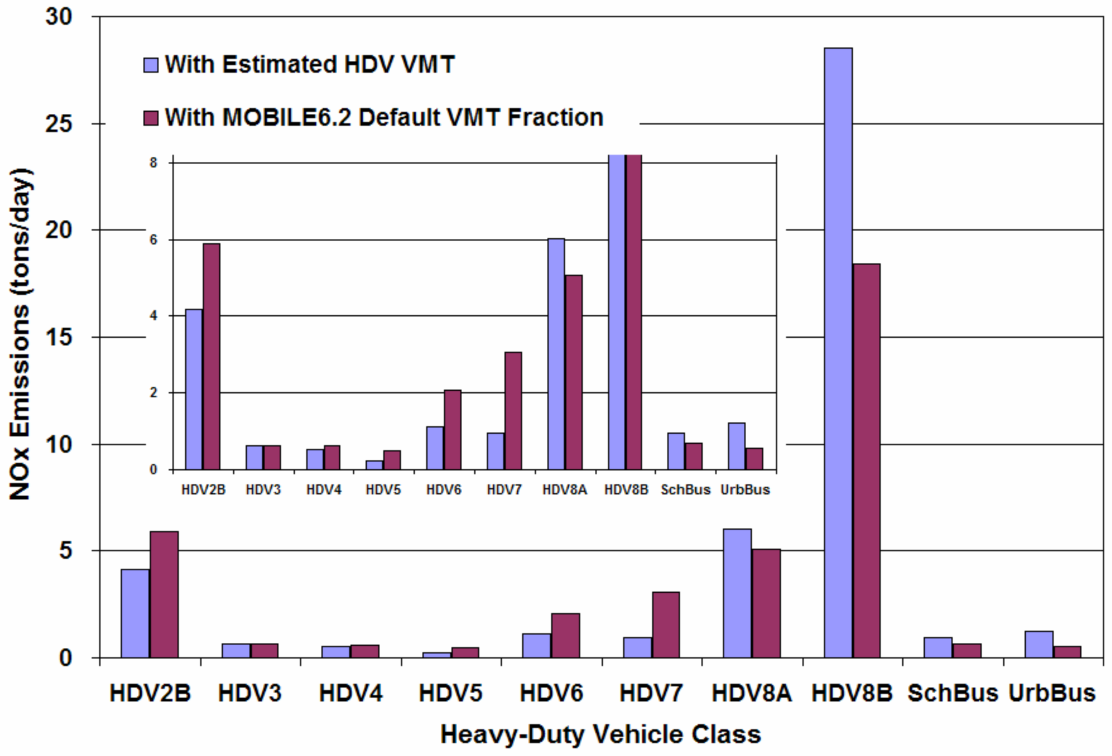

Figure 7.6: Heavy-Duty Vehicle NO_X Emissions on EPA Arterials

On local roads, classes HDV2B, HDV8A, HDV8B, and school bus contributed the largest NO_X emissions with the estimated HDV VMT by 11.9%, 10.2%, 47.5%, and

21.8%, respectively. With the MOBILE6.2 default VMT fractions, classes HDV2B, HDV6, HDV7, HDV8A, and HDV8B contributed most NO_X emissions by 13.0%, 5.9%, 9.2%, 14.1%, and 49.3%, respectively. NO_X emissions estimated with the two methods were close over all HDV classes except HDV6, HDV7, and school bus.

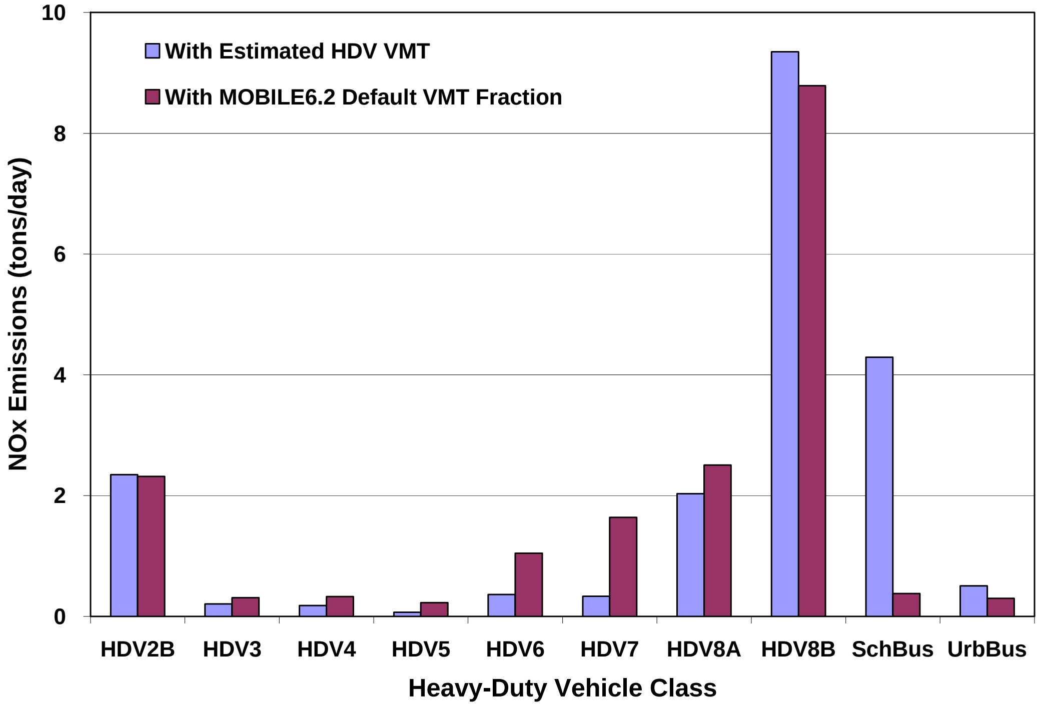

Figure 7.7: Heavy-Duty Vehicle NO_X Emissions on EPA Locals

Although the MOBILE6.2 default VMT fractions overestimate NO_X by 187% and 390% for classes HDV6 and HDV7, the underestimation of school bus VMT by 91% caused a 10.3% greater value with the estimated HDV VMT on locals.

CHAPTER 8

RESEARCH CONTRIBUTIONS, CONCLUSIONS, AND RECOMMENDED RESEARCH

The research community has long stressed the importance and significance of emissions from heavy-duty vehicle and developed methods for measuring engine and HDV emissions, collecting HDV activity data, reducing those emissions through new technologies, etc. However, applying those research results to professional practice is often challenging. The new heavy-duty vehicle visual classification and activity estimation method can provide a new protocol for developing HDV activity in “real-world” applications without losing the fine resolution of original vehicle activity and emissions characteristics.

This chapter will discuss how the new heavy-duty vehicle visual classification and activity estimation method can influence regional air quality management and transportation policymaking and next generation modal activity based emissions models.

8.1 Research Contributions

The new heavy-duty vehicle visual classification and activity estimation method provides planning and air quality management agencies with more specific information regarding the major NO_X and $PM_{2.5}$ emission contributors among HDVs. This, in turn, can lead to better policies to reduce regional emissions from these sources. Accurate heavy-duty vehicle activity and emissions information is therefore a key to success in regional air quality and transportation policymaking processes under the requirement of Clear Air Act and Transportation Equity Act for the 21st Century. This research has the potential to influence this process in the following ways:

- The new heavy-duty vehicle classification scheme, which can convert FHWA truck classes into EPA HDV classes or vice versa, and can be directly applied to HDV activity data collection in the field by providing more specific information and making better use of existing data than to current methods.
- The heavy-duty vehicle VMT estimation method, which can overcome uncertainties in HDV VMT estimation processes associated with HDV registration distributions, retains the resolution of HDV classes and activities observed in the filed, and improves the EPA HDV2B VMT estimation process.

In the research arena, the research results can contribute to the development of modal activity based emission models, which requires HDV vehicle technology groups having common emissions and engine characteristics, and roadway link level HDV activity.

8.1.1 Contributions to GVWR Based Vehicle Classification

Because EPA classifies heavy-duty vehicles by their gross vehicle weight ratings and certified engine emission characteristics, heavy-duty vehicles are not easily distinguished by visual observation, especially the eight EPA HDV classes for MOBILE6.2 emission rate modeling purposes. In the development of HDV activity databases, EPA HDV classes are rarely used and FHWA truck classes based on visually observable qualities (i.e. configuration and number of axles) are used instead. The new heavy-duty vehicle visual classification X-scheme as a hybrid scheme associating EPA heavy-duty vehicles and FHWA trucks without losing the original HDV activity and emissions characteristics. Although light and medium HDVs are aggregated into class X1B, however, class X1B still retains similarities in terms of certified engine emissions characteristics.

8.1.2 Contributions to Axle and Configuration Based Vehicle Classification

FHWA classifies trucks into nine truck classes by the number of axles and tractor-trailer configuration largely for purposes of infrastructure maintenance and protection. However, keeping nine truck classes is not necessary for the purpose of emissions analysis. Nine truck classes can be regrouped into the new classification that retain similar activity and emissions characteristics. Unlike the EPA method that focuses only of GVWR, the X-scheme regroups nine truck classes into five X classes (X1B to X3B) using criteria that include GVWR, truck weight limit, engine horsepower ratings, travel characteristics, and emissions characteristics.

8.1.3 Contributions to Heavy-Duty Vehicle Activity Database Development

Because the EPA guidance to estimate HDV VMT is based on HDV registration distributions, the guidance can cause severe bias in VMT estimation. Heavy HDV activity, especially that generated by inter-region operating HDVs, will be significantly underestimated in regions where they are not registered. Even though inter-region operating HDVs can create the high portion of heavy HDV activity in the regions, their activity will not be reflected in the estimation of VMT fractions if the EPA guidance is applied. This can cause heavy HDV VMT to be allocated into light and medium HDV VMT, and result in the underestimation of emissions for heavy HDV and the overestimation of emissions for light and medium HDV, especially in the case of NO_X and $PM_{2.5}$ emissions. The new HDV VMT estimation method presented in this research includes all vehicle activities with sufficient resolution of onroad vehicle classes to avoid significant misallocation of heavy HDV VMT into light and medium HDV VMT.

The new HDV VMT estimation method can also improve the estimation of the lightest HDV (HDV2B) VMT when HDV VMT is estimated from HPMS databases. By definition, a FHWA truck includes trucks having at least two axles and six tires that have over 10,000 lbs of GVWR. Vehicles with these characteristics belong to EPA HDV3 or heavier HDV classes and thus do not include vehicles from the lightest EPA HDV class (HDV2B) that includes two axle vehicles with four tires. EPA advises that FHWA truck VMT percentages in HPMS should be apportioned into EPA HDV2B to Urban Bus categories even though the FHWA truck definitions do not include the EPA HDV2B class. Therefore, the EPA guidance can cause lower HDV VMT estimation and higher LDT VMT estimation by misallocation of FHWA truck VMT into HDV2B VMT. Because the new HDV VMT estimation method separates HDV2B VMT estimation process from the HDV/BUS VMT estimation process, this problem is largely avoided in the procedure outlined in this research.

8.1.4 Contributions to Current Emissions Modeling

In developing mobile source emissions inventories, state air quality agencies estimate VMT via HDV databases or field HDV volume counts using the FHWA truck classification scheme. The X-scheme works as a hybrid HDV-to-truck classification scheme, which converts FHWA truck classes into EPA HDV classes and vise versa, without losing truck axle and configuration characteristics or HDV GVWR and emissions characteristics. HDV-to-truck conversion with the X-scheme can minimize the potential bias in VMT misallocation and provide more precise onroad fleet VMT distributions for emissions modeling proposes. The new heavy-duty vehicle VMT estimation method combined with the X-scheme also has the capability of estimating facility-specific emissions by the use of facility-specific HDV VMT distributions.

8.1.5 Contributions to Heavy-Duty Vehicle Modal Emissions Modeling

Road load-based modal emissions models estimate emissions from relationships between emission rates and engine power demand for vehicle technology groups having similar engine and emission characteristics. The X-scheme, which classifies HDVs by their physical configurations, can be a starting point for vehicle technology grouping since each X class has similar engine and emission characteristics. Modal emission models can use the X-scheme to guide data collection in the following areas:

- Emissions characteristics
- Weight distributions
- VMT distributions
- Speed and acceleration characteristics

The X-Scheme can be further subdivided by statistical analysis to account for detailed relationships between emission rates and engine power demand. This research effort is currently under development by researchers at Georgia Tech.

The new heavy-duty vehicle visual classification and activity estimation method also provides the ability to estimate road link level HDV VMT and VMT distributions that can be directly used in modal emission models incorporating link-specific speed/acceleration/grade matrices (Yoon, 2005a; Yoon, 2005b). The new heavy-duty vehicle visual classification and activity estimation method further associates with link-specific roadway characteristics (i.e., road characteristics, mile point, speed, the number of lanes, facility type, AADT, truck percent, etc.).

The combination of the new heavy-duty vehicle visual classification and activity estimation methods allows interconnection of modal activity variables and facility parameters and therefore provides the potential for link-specific emissions estimation in modal activity based emission models. Link-specific emissions estimates could significantly benefits agencies in all levels of government in the development of project (microscale), regional (mesoscale), and national (macroscale) scale air quality management and transportation plans.

8.2 Conclusions

In policymaking processes of regional air quality and transportation management, accurate emissions and vehicle activity information should be guaranteed. Given this, uncertainties in current HDV classification and VMT estimation methods, which are mostly developed with vehicle registration data, should be minimized. The new heavy-duty vehicle visual classification and VMT estimation method better reflects onroad HDV fleet VMT distributions. This has the impact of reducing uncertainties in emissions estimation processes that are currently derived from locally registered vehicle information. In addition, the new heavy-duty vehicle visual classification and VMT estimation method provides key protocols for developing modal activity based emission models.

8.2.1 A New Heavy-Duty Vehicle Visual Classification Scheme

Because the new heavy-duty vehicle visual classification X-scheme bridges the gap between the EPA HDV and FHWA truck classification schemes, it converts FHWA truck classes into EPA HDV classes and vise versa while keeping original fine resolution of vehicle activity and emissions characteristics. Emissions estimated for the Atlanta metropolitan area indicate that the new HDV visual classification scheme shows that NO_X and $PM_{2.5}$ emissions increase by 35% and 32% respectively more than emissions estimates based on the EPA VMT estimation guidance. This indicates that current methods may be severely underestimating emissions from HDVs. Benefits using the new heavy-duty vehicle visual classification X-scheme in emissions analyses follow:

- Mitigates uncertainties in current EPA and NRC HDV-to-truck conversion methods,

- Adopts three prototype X classes (six sub-X classes) and two bus classes with simple criteria for use in HDV and truck activity data collection in the filed,
- Keeps the original fine resolution of HDV or truck class characteristics such as certified engine emissions characteristics and vehicle activity characteristics throughout the HDV-to-truck conversion process, and
- Estimates emissions with regionally specific onroad fleet VMT distributions

8.2.2 A New Heavy-Duty Vehicle VMT Estimation Method

In the development of the new heavy-duty vehicle VMT estimation method, publicly available HDV databases, which are Vehicle Inventory and Use Survey, Highway Performance Monitoring System, and Highway Statistics, and Georgia Tech HDV/BUS activity database, incorporate to estimate HDV VMT for HDV classes, facilities types, and counties. With the combination of the new HDV visual classification scheme, the new HDV VMT estimation method mitigates uncertainties in the HDV registration based VMT estimation method suggested by EPA. For instance, HDV VMT distributions excluding non-registered HDV VMT in a specific regional boundary misallocates heavy HDV VMT into light and medium HDV VMT. The emissions impact analysis with the HDV VMT estimation method within the 20-county Atlanta 8-hr ozone nonattainment designated area shows that NO_X and $PM_{2.5}$ emissions are significantly underestimated with the MOBILE6.2 default VMT fractions developed with vehicle registration data. With the new HDV VMT estimation method, NO_X emissions estimate by 27.2%, 18.5%, and 10.3% for freeways, arterials, and locals, and $PM_{2.5}$ emissions by 25.5%, 21.5%, and 31.2% greater than estimates with the MOBILE6.2 default VMT fractions. Benefits using the new HDV visual classification scheme in emissions analyses follow:

- Mitigate uncertainties in the current EPA's registration based HDV VMT estimation guidance by the combination of the new HDV visual classification scheme,
- Easily obtains publicly available HDV activity databases,
- Minimizes heavy HDV VMT allocation into light and medium HDV VMT, and
- Estimate emissions for HDV classes, facility types, and counties.

The new HDV VMT estimation method can be applicable for the facility-specific HDV VMT estimation and for the development of onroad emissions inventory development for use in regional air quality and transportation planning processes.

8.3 Recommended Research

While the new heavy-duty vehicle visual classification scheme and activity estimation method has been developed and undergone limited validation testing, much additional work is needed to be done before the method is fully validated for widespread applications. Recommended future research includes the validation of the new heavy-duty vehicle visual classification scheme with engine characteristics and emissions data and the validation of the new HDV activity estimation method with regionally specific HDV activity data. In addition, methods of onroad HDV data collection should be reviewed in conjunction with emissions inventory development and modal emissions model development.

- The new HDV visual classification scheme explains HDV technology and emissions characteristics only by their physical characteristics. Emissions test data with engine physical characteristics should be collected and analyzed to validate and possibly refine physical characteristic based HDV classes, since emissions can be characterized with engine size, horsepower ratings, related engine technologies, etc.
- For the validation of the HDV activity estimation method, regional-specific HDV activity data should be collected and analyzed. These data should include daily travel miles, trip origins and destinations, spatial and temporal information, place of registration, etc. These HDV activity data can be collected with the combination of mail/fax surveys, roadside intercepts surveys, screen line cordon surveys, travel diary survey, etc.
- For modal activity emissions modeling applications, HDV activity data, which include spatial and temporal information, speed, acceleration, speed, weight, and etc., should be collected and associated into HDV technology grouping and VMT estimation processes. The effort required to collect these HDV activity data can

be substantially aided by increased reliance on more advanced technologies such as geographic information system (GIS), global positioning system (GPS), and onboard diagnostic system (OBD).

Research results from this recommended research will improve the proposed methods and potentially help identify major emission contributors and make regionally consistent and effective air quality management and transportation plans more efficiently.

APPENDIX A

ESTIMATED HEAVY-DUTY VEHICLE VMT DISTRIBUTIONS BY FACILITY TYPE AND COUNTY FOR THE ATLANTA METROPOLITAN AREA

Table A-1: Estimated Heavy-Duty Vehicle VMT Distributions for Facility Types and the Atlanta Metropolitan Counties

County *^{a}	Facility *^{b}	HDV Class								Bus	
		2B	3	4	5	6	7	8A	8B	School	Urban
13	1	0.080	0.019	0.014	0.006	0.021	0.014	0.156	0.677	0.012	0.000
13	2	0.149	0.033	0.023	0.010	0.034	0.024	0.078	0.609	0.034	0.006
13	3	0.233	0.028	0.020	0.008	0.030	0.020	0.068	0.529	0.059	0.004
15	1	0.106	0.078	0.055	0.023	0.083	0.057	0.081	0.515	0.001	0.001
15	2	0.176	0.023	0.016	0.007	0.025	0.017	0.147	0.554	0.028	0.007
15	3	0.337	0.019	0.013	0.006	0.020	0.014	0.094	0.442	0.052	0.003
45	1	0.091	0.034	0.024	0.010	0.036	0.024	0.075	0.697	0.005	0.005
45	2	0.180	0.044	0.031	0.013	0.047	0.032	0.157	0.456	0.035	0.003
45	3	0.325	0.036	0.025	0.011	0.038	0.026	0.126	0.366	0.041	0.008
57	1	0.132	0.100	0.071	0.030	0.106	0.073	0.108	0.366	0.006	0.008
57	2	0.185	0.044	0.031	0.013	0.047	0.032	0.138	0.501	0.007	0.001
57	3	0.291	0.027	0.019	0.008	0.029	0.020	0.109	0.343	0.147	0.006
63	1	0.172	0.044	0.031	0.013	0.047	0.032	0.081	0.568	0.001	0.009
63	2	0.349	0.044	0.031	0.013	0.047	0.032	0.121	0.323	0.022	0.016
63	3	0.361	0.045	0.032	0.013	0.047	0.032	0.070	0.233	0.154	0.012
67	1	0.286	0.063	0.045	0.019	0.067	0.046	0.064	0.404	0.001	0.004
67	2	0.358	0.037	0.026	0.011	0.039	0.027	0.082	0.374	0.014	0.031
67	3	0.348	0.026	0.018	0.008	0.027	0.019	0.059	0.256	0.220	0.019
77	1	0.103	0.026	0.018	0.008	0.027	0.019	0.054	0.733	0.008	0.003
77	2	0.163	0.038	0.027	0.011	0.040	0.028	0.224	0.447	0.015	0.006
77	3	0.341	0.013	0.010	0.004	0.014	0.010	0.157	0.303	0.146	0.002

Table A-1: Estimated Heavy-Duty Vehicle VMT Distributions for the Atlanta Metropolitan Area (Continued)

County *[a]	Facility *[b]	HDV Class								Bus	
		2B	3	4	5	6	7	8A	8B	School	Urban
89	1	0.168	0.034	0.024	0.010	0.036	0.025	0.106	0.583	0.009	0.004
89	2	0.373	0.034	0.024	0.010	0.036	0.025	0.071	0.403	0.010	0.014
89	3	0.341	0.021	0.015	0.006	0.023	0.015	0.046	0.263	0.263	0.006
97	1	0.147	0.031	0.022	0.009	0.033	0.023	0.069	0.647	0.013	0.006
97	2	0.293	0.036	0.026	0.011	0.038	0.026	0.130	0.411	0.025	0.004
97	3	0.370	0.031	0.022	0.009	0.033	0.022	0.114	0.364	0.029	0.004
113	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
113	2	0.207	0.048	0.034	0.014	0.050	0.034	0.165	0.431	0.010	0.005
113	3	0.312	0.024	0.017	0.007	0.025	0.017	0.091	0.327	0.158	0.022
117	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
117	2	0.131	0.048	0.034	0.014	0.051	0.035	0.171	0.504	0.010	0.004
117	3	0.269	0.021	0.015	0.006	0.022	0.015	0.118	0.397	0.131	0.005
121	1	0.212	0.062	0.044	0.018	0.065	0.044	0.085	0.418	0.009	0.043
121	2	0.367	0.018	0.013	0.005	0.019	0.013	0.126	0.325	0.006	0.108
121	3	0.403	0.016	0.011	0.005	0.017	0.012	0.128	0.297	0.071	0.041
135	1	0.157	0.043	0.031	0.013	0.046	0.031	0.077	0.577	0.015	0.010
135	2	0.275	0.015	0.010	0.004	0.016	0.011	0.113	0.513	0.030	0.014
135	3	0.325	0.011	0.008	0.003	0.011	0.008	0.071	0.346	0.203	0.014
139	1	0.221	0.039	0.028	0.012	0.042	0.028	0.071	0.543	0.010	0.007
139	2	0.200	0.022	0.016	0.007	0.023	0.016	0.089	0.591	0.030	0.007
139	3	0.280	0.019	0.013	0.006	0.020	0.014	0.077	0.512	0.056	0.003

Table A-1: Estimated Heavy-Duty Vehicle VMT Distributions for the Atlanta Metropolitan Area (Continued)

County *[a]	Facility *[b]	HDV Class								Bus	
		2B	3	4	5	6	7	8A	8B	School	Urban
151	1	0.102	0.017	0.012	0.005	0.018	0.012	0.054	0.776	0.002	0.003
151	2	0.166	0.071	0.050	0.021	0.075	0.051	0.124	0.419	0.015	0.006
151	3	0.306	0.051	0.036	0.015	0.054	0.037	0.068	0.256	0.176	0.001
217	1	0.094	0.036	0.025	0.011	0.038	0.026	0.110	0.656	0.003	0.002
217	2	0.156	0.034	0.024	0.010	0.036	0.024	0.070	0.598	0.038	0.010
217	3	0.297	0.021	0.015	0.006	0.023	0.015	0.047	0.388	0.186	0.001
223	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
223	2	0.125	0.040	0.028	0.012	0.042	0.029	0.117	0.590	0.008	0.009
223	3	0.294	0.022	0.016	0.007	0.024	0.016	0.086	0.307	0.227	0.001
247	1	0.212	0.028	0.020	0.008	0.030	0.020	0.092	0.578	0.006	0.006
247	2	0.385	0.026	0.019	0.008	0.028	0.019	0.105	0.388	0.015	0.007
247	3	0.402	0.019	0.014	0.006	0.020	0.014	0.083	0.316	0.122	0.004
255	1	0.116	0.016	0.012	0.005	0.017	0.012	0.052	0.761	0.002	0.007
255	2	0.188	0.034	0.024	0.010	0.035	0.024	0.170	0.483	0.025	0.008
255	3	0.320	0.024	0.017	0.007	0.026	0.017	0.105	0.396	0.085	0.003
297	1	0.142	0.040	0.029	0.012	0.043	0.029	0.122	0.573	0.004	0.006
297	2	0.139	0.044	0.031	0.013	0.046	0.032	0.137	0.519	0.034	0.005
297	3	0.307	0.035	0.025	0.011	0.037	0.025	0.119	0.400	0.036	0.005

*[a] County

13 = Barrow
15 = Bartow
45 = Carroll
57 = Cherokee
63 = Clayton
67 = Cobb
77 = Coweta
89 = DeKalb
97 = Douglas
113 = Fayette
117 = Forsyth
121 = Fulton
135 = Gwinnett
139 = Hall
151 = Henry
217 = Newton
223 = Paulding
247 = Rockdale
255 = Spalding
297 = Walton

*[b] Facility

1 = Freeway
2 = Arterial
3 = Local Road

APPENDIX B

HDV2B VMT FRACTIONS FOR THE ATLANTA METROPOLITAN COUNTIES

Table B-1: HDV2B VMT Fractions for Counties in the Atlanta Metropolitan Area

County Name	County Code	HDV2B VMT Fractions
Barrow	13	0.102
Bartow	15	0.102
Carroll	45	0.101
Cherokee	57	0.107
Clayton	63	0.089
Cobb	67	0.084
Coweta	77	0.106
DeKalb	89	0.077
Douglas	97	0.102
Fayette	113	0.097
Forsyth	117	0.116
Fulton	121	0.097
Gwinnett	135	0.094
Hall	139	0.100
Henry	151	0.098
Newton	217	0.104
Paulding	223	0.107
Rockdale	247	0.119
Spalding	255	0.101
Walton	297	0.121

APPENDIX C

MOBILE6.2 INPUTS AND OUTPUTS FOR THE ATLANTA METROPOLITAN AREA

C.1 MOBILE6.2 Inputs for the Atlanta Metropolitan Area

```
MOBILE6 INPUT FILE :

AGGREGATED OUTPUT  :
DATABASE EMISSIONS : 2111 1111 22
DATABASE FACILITIES: Freeway Arterial Local
DATABASE OUTPUT    :
DATABASE VEHICLES  : 22222 22222222 2 222 22222222 222
PARTICULATES       : SO4 OCARBON ECARBON GASPM LEAD BRAKE TIRE
POLLUTANTS         : HC CO NOX
WITH FIELDNAMES    :
REPORT FILE        : AtlVMTEM.txt


RUN DATA
HOURLY TEMPERATURES: 74 74 74 84 84 84 92 92 92 94 94 94
                     89 89 89 81 81 81 75 75 75 72 72 72
FUEL RVP           : 7.0
EXPRESS HC AS VOC  :
EXPAND EXHAUST     :
EXPAND EVAPORATIVE :
EXPAND LDT EFS     :
EXPAND HDGV EFS    :
EXPAND HDDV EFS    :
EXPAND BUS EFS     :

STAGE II REFUELING :
92 3 81. 81.

FUEL PROGRAM       : 4
  150.0  150.0  150.0   90.0   30.0   30.0   30.0   30.0
   30.0   30.0   30.0   30.0   30.0   30.0   30.0   30.0
 1000.0 1000.0 1000.0 1000.0  150.0  150.0   87.0   87.0
   80.0   80.0   80.0   80.0   80.0   80.0   80.0   80.0

REG DIST           : 02regis2.d

ANTI-TAMP PROG     :
82 75 97 22222 11111111 1 11 097. 12111111

I/M DESCRIPT FILE  : iminfo-p.d
I/M CREDIT FILE    : Tech12.d

SCENARIO REC       :  Freeway, Atlanta, 2004, 59mph

CALENDAR YEAR      : 2004
EVALUATION MONTH   : 7
ALTITUDE           : 1
RELATIVE HUMIDITY  : 68 68 68 50 50 50 37 37 37 32 32 32
```

```
                     40 40 40 56 56 56 64 64 64 70 70 70
BAROMETRIC PRES    : 28.98
PARTICLE SIZE      : 2.5
PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV
PMDDR1.CSV PMDDR2.CSV
DIESEL SULFUR      : 500.00
AVERAGE SPEED      : 59 Freeway 100.0 0.0 0.0 0.0

SCENARIO REC       : Freeway, Atlanta, 2004, 55mph

CALENDAR YEAR      : 2004
EVALUATION MONTH   : 7
ALTITUDE           : 1
RELATIVE HUMIDITY  : 68 68 68 50 50 50 37 37 37 32 32 32
                     40 40 40 56 56 56 64 64 64 70 70 70
BAROMETRIC PRES    : 28.98
PARTICLE SIZE      : 2.5
PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV
PMDDR1.CSV PMDDR2.CSV
DIESEL SULFUR      : 500.00
AVERAGE SPEED      : 55 Freeway 100.0 0.0 0.0 0.0

SCENARIO REC       : Freeway, Atlanta, 2004, 53mph

CALENDAR YEAR      : 2004
EVALUATION MONTH   : 7
ALTITUDE           : 1
RELATIVE HUMIDITY  : 68 68 68 50 50 50 37 37 37 32 32 32
                     40 40 40 56 56 56 64 64 64 70 70 70
BAROMETRIC PRES    : 28.98
PARTICLE SIZE      : 2.5
PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV
PMDDR1.CSV PMDDR2.CSV
DIESEL SULFUR      : 500.00
AVERAGE SPEED      : 53 Freeway 100.0 0.0 0.0 0.0

SCENARIO REC       : Arterial, Atlanta, 2004, 54mph

CALENDAR YEAR      : 2004
EVALUATION MONTH   : 7
ALTITUDE           : 1
RELATIVE HUMIDITY  : 68 68 68 50 50 50 37 37 37 32 32 32
                     40 40 40 56 56 56 64 64 64 70 70 70
BAROMETRIC PRES    : 28.98
PARTICLE SIZE      : 2.5
PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV
PMDDR1.CSV PMDDR2.CSV
DIESEL SULFUR      : 500.00
AVERAGE SPEED      : 54 Arterial

SCENARIO REC       : Arterial, Atlanta, 2004, 47mph
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CALENDAR YEAR      : 2004
EVALUATION MONTH   : 7
ALTITUDE           : 1
RELATIVE HUMIDITY  : 68 68 68 50 50 50 37 37 37 32 32 32
                     40 40 40 56 56 56 64 64 64 70 70 70
BAROMETRIC PRES    : 28.98
PARTICLE SIZE      : 2.5
PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV
PMDDR1.CSV PMDDR2.CSV
DIESEL SULFUR      : 500.00
AVERAGE SPEED      : 47 Arterial

SCENARIO REC       : Arterial, Atlanta, 2004, 44mph

CALENDAR YEAR      : 2004
EVALUATION MONTH   : 7
ALTITUDE           : 1
RELATIVE HUMIDITY  : 68 68 68 50 50 50 37 37 37 32 32 32
                     40 40 40 56 56 56 64 64 64 70 70 70
BAROMETRIC PRES    : 28.98
PARTICLE SIZE      : 2.5
PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV
PMDDR1.CSV PMDDR2.CSV
DIESEL SULFUR      : 500.00
AVERAGE SPEED      : 44 Arterial

SCENARIO REC       : Arterial, Atlanta, 2004, 43mph

CALENDAR YEAR      : 2004
EVALUATION MONTH   : 7
ALTITUDE           : 1
RELATIVE HUMIDITY  : 68 68 68 50 50 50 37 37 37 32 32 32
                     40 40 40 56 56 56 64 64 64 70 70 70
BAROMETRIC PRES    : 28.98
PARTICLE SIZE      : 2.5
PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV
PMDDR1.CSV PMDDR2.CSV
DIESEL SULFUR      : 500.00
AVERAGE SPEED      : 43 Arterial

SCENARIO REC       : Arterial, Atlanta, 2004, 38mph

CALENDAR YEAR      : 2004
EVALUATION MONTH   : 7
ALTITUDE           : 1
RELATIVE HUMIDITY  : 68 68 68 50 50 50 37 37 37 32 32 32
                     40 40 40 56 56 56 64 64 64 70 70 70
BAROMETRIC PRES    : 28.98
PARTICLE SIZE      : 2.5
PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV
PMDDR1.CSV PMDDR2.CSV
DIESEL SULFUR      : 500.00
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AVERAGE SPEED      : 38 Arterial

SCENARIO REC       : Local Road, Atlanta, 2004, 12.9mph

CALENDAR YEAR      : 2004
EVALUATION MONTH   : 7
ALTITUDE           : 1
RELATIVE HUMIDITY  : 68 68 68 50 50 50 37 37 37 32 32 32
                     40 40 40 56 56 56 64 64 64 70 70 70
BAROMETRIC PRES    : 28.98
PARTICLE SIZE      : 2.5
PARTICULATE EF     : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV PMDZML.CSV
PMDDR1.CSV PMDDR2.CSV
DIESEL SULFUR      : 500.00
AVERAGE SPEED      : 12.9 Local

END OF RUN
```

C.2 Summary of MOBILE6.2 Outputs of NO_X and $PM_{2.5}$ Emission Rates for the Atlanta Metropolitan Area

Table C-1: MOBILE6.2 NO_X and $PM_{2.5}$ Emission Rates (g/mi) for the Atlanta Metropolitan Area

Pollutant	Facility *[c]	Speed	HDV Class								Bus	
			2B	3	4	5	6	7	8A	8B	School	Urban
NO_X	1	59	4.81	5.73	6.83	6.52	10.03	13.03	17.59	22.61	16.81	21.87
NO_X	1	53	4.55	5.12	6.01	5.95	8.96	11.47	15.65	20.26	14.60	19.19
NO_X	1	55	4.45	4.93	5.74	5.76	8.62	10.97	15.04	19.53	13.91	18.33
NO_X	2	47	4.50	5.03	5.88	5.86	8.40	10.80	13.24	16.89	14.26	18.77
NO_X	2	44	4.18	4.40	5.04	5.24	7.30	9.24	11.32	14.56	12.07	16.07
NO_X	2	54	4.06	4.21	4.80	5.04	6.98	8.78	10.76	13.88	11.43	15.27
NO_X	2	43	4.03	4.17	4.74	4.99	6.90	8.68	10.65	13.74	11.30	15.10
NO_X	2	38	3.87	3.98	4.52	4.78	6.59	8.28	10.17	13.16	10.75	14.39
NO_X	3	12.9	3.56	4.72	5.80	5.19	7.91	10.63	12.05	14.96	14.47	18.55
$PM_{2.5}$	1	59	0.08	0.11	0.12	0.09	0.21	0.29	0.31	0.42	0.75	0.70
$PM_{2.5}$	1	53	0.08	0.11	0.12	0.09	0.21	0.29	0.31	0.42	0.75	0.70
$PM_{2.5}$	1	55	0.08	0.11	0.12	0.09	0.21	0.29	0.31	0.42	0.75	0.70
$PM_{2.5}$	2	47	0.08	0.11	0.12	0.09	0.21	0.29	0.31	0.42	0.75	0.70
$PM_{2.5}$	2	44	0.08	0.11	0.12	0.09	0.21	0.29	0.31	0.42	0.75	0.70
$PM_{2.5}$	2	54	0.08	0.11	0.12	0.09	0.21	0.29	0.31	0.42	0.75	0.70
$PM_{2.5}$	2	43	0.08	0.11	0.12	0.09	0.21	0.29	0.31	0.42	0.75	0.70
$PM_{2.5}$	2	38	0.08	0.11	0.12	0.09	0.21	0.29	0.31	0.42	0.75	0.70
$PM_{2.5}$	3	12.9	0.08	0.11	0.12	0.09	0.21	0.29	0.31	0.42	0.75	0.70

*[c] Facility 1 = Freeway; 2 = Arterial; 3 = Local Road

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