EVALUATION OF DATA INPUTS AND SENSITIVITY ANALYSIS OF THE MOVES MOBILE EMISSION INVENTORY MODEL

by

Chuoran Wang

A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil Engineering

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ABSTRACT

MOVES is the current emission inventory model developed by the Environmental Protection Agency (EPA) for estimating mobile source emissions. This model is very data intensive compared to its predecessors and definitive guidance has not yet been provided for doing regional analyses. There is reliance, in many cases, on using national default data. The impact of the assumptions and pre-processing of input data have not been well studied or if they have, not well documented. New technologies and sensors now in use by many transportation agencies could be a rich source of regional data.

This research has compared the current conformity analysis for a county in Delaware and selected alternatives for five of the more significant inputs to the MOVES model. This work analyzed average speed distributions, vehicle miles travelled by road type distribution, temporal distribution of vehicle miles travelled, vehicle starts estimation, and future vehicle population and age distribution. For each input the current data and pre-processing methods were compared to an alternative based in easily obtainable data and the impact on the emissions inventory. Some of the alternative methods showed small changes on the inventory, while some provided a significant reduction.

This research will be useful to agencies that must utilize the MOVES model. It will be clear which inputs require precise, local data and which inputs where either default or simplified data is sufficient. The findings of this research could be used by EPA as guidelines for implementing the MOVES model.

Chapter 1

INTRODUCTION AND PURPOSE OF STUDY

With the passage of the Clean Air Act and its amendments, the US government took an active role in controlling sources of air pollution[1; 2]. When the ambient air quality in a state or region does not meet the standards required in the CAA, that state or region is designated as a non-attainment area. The federal Department of Transportation cannot fund, authorize or approve any project that cannot be shown to be aiding a non-attainment area in coming into compliance. Air quality and emissions models are used as part of these project assessments. The current model specified by the Federal Highway Administration and the Environmental Protection Agency for the estimation of emissions from motor vehicles is called Motor Vehicle Emission Simulator (MOVES). This research will examine the procedures specified for using the MOVES model and offer alternatives, including the preparation of input data; examine sources of better data; and evaluate the impact on emissions inventory estimates from these data sets.

Some academic analysis of the new MOVES model has been done but has generally been focused on project level studies [3-7]. Evaluating the change in emissions due to improvements on small networks of roads may be useful, but these changes are extremely small when compared to the emissions inventory of a metropolitan region or county. The defaults and general processes for the MOVES model are based on past data and research, but can be improved considering the larger volumes of data available to transportation agencies. This research will examine the current guidelines and data sources for using the MOVES model and demonstrate how using other available data might improve emission estimates.

Because transportation data resources vary from region to region, MOVES can not specify a single procedure to be followed. However, the data choices an agency makes when using MOVES could affect the model's output and the estimated emissions inventory. Also, this family of mobile emissions models, which have been in use for over 30 years, has led to processes, procedures and assumptions in using the models. Alternative data sources and methods for processing data may not have been explored.

The contribution and objective of this research is to 1) examine the existing practices in one state with regard to mobile emissions models; 2) examine the current data used and alternatives that are easily obtained from traffic studies and existing sensors; and 3) evaluate the differences between the inventories obtained with current and alternative data. The research presented here can be used by the Federal Highway Administration and the Environmental Protection Agency as guidelines for agencies to consider when using the MOVES model. Also, the findings of the research on the impact of real world data on emission inventory results from the model could direct agencies better distribute their resources in gathering intensive data for the model.

This dissertation will first present a more detailed background of emissions models and a review of the current literature. Chapter 3 will provide a comparison of MOVES and its predecessor, MOBILE 6 and will describe the MOVES model in more detail. Chapter 4 outlines the quantitative analysis plan. Chapter 4 also includes the analyses regarding speed distributions, road type classifications and temporal distribution. Chapter 5 contains the analyses relating to vehicle starting emissions. Chapter 6 covers vehicle populations and age distributions. Chapter 7 will present the conclusions of the research and opportunities for future work.

Chapter 2

BACKGROUND AND LITERATURE REVIEW

2.1 Problem Context

The first federal statute regarding air quality and air pollution control was the Clean Air Act of 1963[1]. This Act and its amendments in 1970, 1977 and 1990 were designed to protect the general public from exposure to airborne contaminants that are known to be hazardous to human health, and set up the basis for the legal authority for federal programs regarding air pollution control [1; 2; 8-11]. The 1963 Act established a basic research program for monitoring and controlling air pollution. The 1970 amendments established the first set of comprehensive state and federal regulations for stationary sources, such as industrial facilities, and mobile sources [8]. The 1990 Amendments mandated enhanced motor vehicle inspection and maintenance programs in heavily polluted areas, set up new regulations for re-formulated gasoline and when these re-formulated fuels could be sold as well as many requirements to limit emissions from vehicles. [2; 12].

The U.S Environment Protection Agency (EPA) was established in 1970 to provide oversight and regulatory enforcement. Under the Clean Air Act requirements for mobile sources, the EPA has established progressively more stringent emission standards for vehicles. Emissions standards set limits on the amount of pollutant a vehicle can emit. Vehicle manufacturers improved engine and vehicle technology in order to comply with these new standards. Inspection and maintenance programs have been established at the state level. On-board diagnostic systems can notify a driver that the emissions control system may not be functioning properly and that service may be needed.

2.1.1 National Ambient Air Quality Standards and State Implementation Plan

EPA established the National Ambient Air Quality Standards (NAAQS) for six principal air pollutants, usually referred to as the “criteria pollutants”, and four of them are related to mobile source emissions. These four are ozone (O_3), carbon monoxide (CO), particulate matter (PM) and nitrogen oxides (NO_x). The EPA establishes the maximum concentration of each pollutant above which there will be possible adverse effect on human health. The CAA provides that an area is designated as nonattainment for a pollutant if it doesn’t meet the air quality standard for that pollutant[13; 14]. When a region is designated a non-attainment region, the emission inventory of this pollutant and its precursors, which caused the production of this pollutant, need to be monitored.

Ozone is a highly reactive gas that is the main component of smog. Ozone in the lower atmosphere (troposphere) is considered to be a pollutant and is distinct from the ozone layer in the upper atmosphere (stratosphere) where it acts as a shield of the earth from ultraviolet radiation. Ozone is a strong respiratory irritant that affects healthy individuals as well as those with impaired respiratory systems. It can cause respiratory inflammation and reduce lung function. Ozone also adversely affects trees, crops (soybeans are a particularly sensitive species), and other vegetation. The national agricultural loss from ozone pollution is estimated by EPA to be several billion dollars annually. Since ozone is a secondary pollutant, which means the pollutant is formed in the atmosphere as a result of photochemical reactions, its precursors – NO_x and Volatile Organic Compounds (VOC) should be under control. Sources of nitrogen oxides include automobiles, power plants and other combustion activities. VOCs can come from automobiles, gasoline vapors, and a variety of large and small commercial and industrial sources that use chemical solvents, paint thinners, and other chemical compounds. These compounds or "precursors of ozone" can travel for miles before the chemical reactions in the atmosphere form ozone.

Carbon Monoxide (CO) is a colorless, odorless, poisonous gas and usually a product of incomplete combustion. Carbon monoxide reduces the blood's ability to carry oxygen; overexposure to CO may be fatal.

Particular matter (PM) is a mixture of tiny solid or liquid particles. PM, especially those with a diameter less than or equal to 2.5 µm (PM2.5), can be inhaled through the respiratory tract and cause adverse health impacts[15]. Epidemiological studies have revealed that long-term exposure to a high concentration of PM2.5 increases the risk of acute and chronic respiratory infection, lung cancer, arteriosclerosis, and other cardiovascular diseases, while short-term PM2.5 exposure exacerbates existing pulmonary and cardiovascular diseases[16-19]. PM2.5 is both primary and secondary pollutant, so both PM 2.5 itself and its precursor, NOx, needs to be controlled.

Oxides of Nitrogen (NO_x) are chemical compounds of nitrogen and oxygen, usually a mixture of NO and NO_2. NO_2 destroys resistance to respiratory infection. Heavy vehicles and delivery trucks blow hot exhaust containing life dangerous quantities of NO2 into the atmosphere [20]. NO_x is also responsible for ozone and PM 2.5 formation.

The State Implementation Plan (SIP) is the air quality planning tool for each state which identifies 1) how that state will eliminate or reduce violations of the NAAQS for the nonattainment areas, 2) how the state will come into compliance in an expeditious manner, and 3) if already in attainment, how to continue in compliance. Air quality goals made by the SIP are usually referred to as the “emission budgets”. The SIP budget must be adequate and approved by EPA before it can be used for a conformity determination [21].

2.1.2 Transportation Conformity Process

A written conformity determination is usually prepared by a Metropolitan Planning Organization (MPO). Conformity requirements apply in areas that do not meet national ambient air quality standards, for one or more of the pollutants mentioned before. For state’s long-range metropolitan transportation plans, shorter-term metropolitan transportation improvement programs (TIPs) and transportation projects funded or approved by Federal Highway Administration (FHWA) or Federal Transit Administration (FTA)[22], state transportation agencies should demonstrate that air pollutant emissions from these are consistent with the emission budget, which means these plans or projects will not cause new air quality violations, worsen existing violations or delay the attainment process.

The conformity statement for plans and TIPs should be based on an analysis of the most recent information available for the affected area regarding population, employment, travel and congestion. In nonattainment and maintenance areas, transportation conformity should be determined on the transportation plan at least every four years. For critical planning assumptions such as population, employment, and vehicle registration, areas are encouraged to update the information at least every five years. If states fail to do so, there are limitations in obtaining federal funding for state transportation projects. The roles and responsibilities in the conformity process are listed in Table 2.1[14].

Table 2.1: Roles and Responsibilities in the Transportation Conformity Process

Roles	Responsibilities
MPOs	Prepare the conformity determination for Transportation Plans and TIPs using current approved modeling program
State DOT and transit agencies	Prepare project-level conformity determination; Technical assistance to MPOs such and the travel demand model output
State and local air agencies	Develop the SIP budget; serve in a consultation role on conformity determinations
US DOT (FHWA/FTA)	Determine conformity on transportation plans, TIPs, and Projects
US EPA	Serve in a consultation role in the conformity process, conformity regulations and guidance; Approve SIP mobile budgets

2.2 Commonly Used Emission Models

Mobile emission impact is calculated as emission inventories. These inventories can be in the forms of total emissions for a region, usually as expressed in tons or as rates – per vehicle mile travelled or per vehicle hour of use. Conditions that affect these emission rates include ambient temperature, vehicle speed, age of the vehicle fleet, whether an area has an inspection and maintenance program, and types of fuels used. For conformity analyses purposes, emission models developed by EPA are used to calculate the emission inventory from motor vehicles now and in the future.

2.2.1 MOBILE Model

The MOBILE emissions model series has been used for conformity analysis since 1978. It was developed by the EPA Office of Transportation and Air Quality and was designed to provide estimates of current and future emissions from motor vehicles. Its development was supported by testing thousands of vehicles in the laboratory under controlled environmental and operating conditions.

Using recent vehicle-emission testing data collected by the EPA and automobile manufacturers, inspection and maintenance tests conducted in various states, and driving and testing vehicles under specific driving patterns and measuring their emissions, EPA developed a set of baseline emission rates. These tests were conducted under standardized conditions of temperature, fuel type, and driving cycle. A series of correction factors were developed and then are used to predict the emissions from these vehicles when they operate under conditions different from those observed in the laboratory. These correction factors include average operating speed vs. laboratory test speeds, usage of air conditioning systems, fuel characteristics, and details of a state's inspection/maintenance programs. EPA also assumed a pattern of deterioration in engine performance and emission control system performance over time. Past studies have concluded that two of the most important correction factors are the ambient temperature and the average vehicle speed[23].

Each new version of MOBILE has incorporated new emission test data based on engine performance, emission control systems and new fuels as well as changes to new regulations and standards. The models also take advantage of the latest research in factors that affect emission levels. MOBILE 6 was released in 2004. It included new modules for particulate matter emissions and mobile source air toxics and a simplified CO_2 emission estimator. Also, MOBILE 6 estimated the emission factors for the startup and running portions of the trip separately [24].

2.2.2 MOVES Model

Since 2005, the Federal Highway Administration has worked with EPA to develop a new emission model to replace the MOBILE models. This new model is the Motor Vehicle Emissions Simulator (MOVES). MOVES is EPA's state-of-the-art tool for estimating emissions from motor vehicles and will eventually include emissions from off-road sources (which will replace the current NONROAD model). In addition to SIP or conformity analysis, MOVES can now be used for smaller or larger scale analyses, such as project level or a national level emission analysis. MOVES calculates the emissions for an engine during startup and while running, the emissions for fuel evaporative processes, and particulate matter from brake wear or tire wear[25].

2.2.3 Other Emission Models

There are other emission estimation models which can operate on a scale large enough for conformity analysis. California uses their own emission model called EMission FACtors (EMFAC) model. The latest version of this model - EMFAC 2007 could cover most of the criteria pollutants and a variety of air toxics. Similar to MOBILE 6 and MOVES, emissions from motor vehicles are based on testing vehicles and standardized driving cycles and then a series of correction factors are applied to account for on-road vehicle usage. For the emission inventory, this model considers running, starting and different types of evaporative processes [26] which is similar to MOBILE 6 and MOVES.

The Comprehensive Modal Emission Models (CMEM) provides emission estimation at intervals as small as one second based on the dynamic behavior of vehicles in traffic. CMEM focuses more on microscopic modeling which allows second-by-second emission estimation but also requires detailed inputs representing the dynamic behavior of vehicles in traffic. CMEM was used extensively to model emission impact of specific traffic projects. When it comes to modeling an area, there is insufficient details of data for each vehicle in the whole region being modeled to support the CMEM model [27-29].

2.3 Emission Rates in Look-up Tables vs. Emission Inventory

As mentioned in section 2.2.1, MOBILE 6 produces emission rate tables tailored to describe analysis area. These tables were arranged by county, road type (arterial, etc.), vehicle class, and vehicle speed and emission rates for each emission of interest. This data could then be combined with results of planning models to produce inventories for any region of interest[30; 31]. An improvement with the deployment of MOVES is the direct calculation of the emission inventory. When performing a county level analysis, MOVES can produce either the complete emissions inventory or can generate emission rate tables similar to what were produced in MOBILE 6. This requires users to provide information such as total vehicle miles traveled (VMT) and vehicle population. Table 2.2 below [7] listed the common input sources for MOVES and different input requirement of rate mode and inventory mode. In Delaware's specific situation, the travel demand model is used by Delaware's Department of

Transportation (DelDOT) planning department for long term transportation planning, state implementation plan, and conformity analysis.

Table 2.2: MOVES Input Data Sources and Rate Mode vs. Inventory Mode Requirement

MOVES Input	**Common Sources**	**Rate Mode**	**Inventory Mode**
Average Speed Distribution, which is the VHT fraction in each 5 mph speed bin	Travel Demand Model		x
VMT fractions by weekday and weekends	National Default Statewide Fractions		x
Fuel supply market share and fuel formulations	State Environmental Protection Agency	x	x
VMT fractions for each hour of a day	Travel Demand Model National Default		x
The total VMT traveled by 6 HPMS vehicle types	Travel Demand Model Statewide Permanent Count Stations	x	x
Inspection/maintenance programs used in the area	State Environmental Protection Agency	x	x

Table 2.2 continued.

MOVES Input	**Common Sources**	**Rate Mode**	**Inventory Mode**
VMT fractions of each month of the analysis year	National Default Converted from AADT by EPA's method		x
VMT distributions among different road types	Travel Demand Model		x
Vehicle population distribution by different ages	DMV Registration Data EPA Defaults	x	x
Vehicle population for each MOVES vehicle type	DMV Registration Data MOVES default	x	x
Meteorology data such as temperature and humidity	State Environmental Protection Agency	x	x

EPA has reported that the MOVES model provides faster solutions by using the emission inventory mode when performing single county analyses. [32]. It has also been reported that Metropolitan Planning Organizations use the emission rate mode which generates one set of emission rates averaged over several counties and then applies these rates to specific counties Using the rate mode allows for easier evaluation of emissions with changes to the travel demand model without the need to re-run the entire MOVES model. Both options are available, produce similar results and the decision of mode to be used is up to the needs of the user. [33].

2.4 Sensitivity Analysis for Emission Inventory Development

In the field of modeling, sensitivity analysis analyzes how a model solution responds to changes in the input data. Sensitivity analysis can help guide the user's decision processes for which input data needs greater levels of precision and how assumptions in his data set might impact the model's solutions. There will never be a perfect data set and the time and cost required to collect more precise input data may not be worth the investment when considering the impact on the solution. For the MOBILE 6 model, EPA sponsored a sensitivity analysis to compare the relative impact of individual input parameters on emissions results[34].

By changing the inputs by 20% and calculating the corresponding changes in emission output, the study grouped inputs' impact on emissions into "major", "intermediate", and "minor" categories. Different pollutants demonstrated different sensitivities and detailed results and findings of the study can be found on EPA's website[34]. In general, average speed, min/max temperature and registration distribution were said to have major impact on all pollutants for light duty gasoline vehicles. Speed distribution by VMT had a significant impact only on hydrocarbons emissions.

EPA has funded some research into a sensitivity analysis for the MOVES model. Choi et.al. [35] analyzed the model's sensitivity to temperature and humidity. They concluded that the model's output is very sensitive to temperature, especially for gasoline fueled vehicles. The analysis for humidity was less conclusive due to its relation to temperature. They also concluded that vehicle emission control technology has made newer cars more sensitive to temperature. While this study provides useful information, temperature and humidity are not estimated values for the MOVES model. Temperature and humidity are parameters that state agencies cannot work to change - a study concentrating more on the transportation system related inputs would be more useful for conformity analysis.

In 2012, FHWA and the Volpe National Transportation Systems Center have prepared a more-detailed report covering more inputs of MOVES2010a[36]. Using a regional analysis perspective, this study found that the average speed distribution on roadways and vehicle age distributions have significant impact on emissions. Temperature and humidity are excluded because they were not controlled by local planning agencies. As a systematic sensitivity analysis on MOVES regional level modeling performance, this study has covered most of the common inputs. However, the speed distribution used by this study were converted from second by second data in MOVES default database's driving schedules. MOVES intended to use speed distribution to determine the driving schedules distribution, not the other way round. This misunderstanding of MOVES mechanism makes this part of the study less useful in reality.

On 2010, FHWA worked with the Eastern Research Group and generated a report which included sensitivity analysis on customized driving cycles[37]. This study has implementing real world testing data to drive cycles in MOVES. Because the data used in to generate customized driving cycles are much localized mostly based on urban driving data, it did not intend to provide general assessment of how speed distribution impact emissions calculation from MOVES. However, this study drilled into the core of the running exhaust emission by modifying the driving cycle so that it is of much value to consider how driving pattern which speed distributions are applied to, impact on emissions.

2.5 Current Studies on MOVES Model

Some current studies focused on utilizing field measured traffic data to help MOVES develop project level running operating mode distributions. MOVES running operating mode is determined by speed and vehicle specific power, which took the vehicle weight and engine power, acceleration, and roadway grade into consideration. The running operating mode directly affect which emission rates MOVES is going to use. Combining data using new technologies to obtain speed, acceleration or fleet composition data such as image recognition and GPS equipment, or using hypothetical traffic simulation software's output, people studied how MOVES' performance would be affected in terms of emission output and its impact on transportation projects emission evaluation[3-7]. Comparatively, project level's data change could result in a more significant change of emission, as of for regional level, when so many parameters work together, they tend to average out the emission changes in different directions. In regional level analysis, MOVES was used to help evaluating transportation planning strategy towards reducing emissions and agencies worked towards pre-aggregate MOVES input data to produce accurate yet time efficient results [38].

Chapter 3

COMPARISON OF MOBILE 6 AND MOVES EMISSION MODEL

According to the Clean Air Act's requirements, EPA needs to regularly update its mobile source emission model[2; 12]. For the MOBILE model series, EPA continuously collected new data and measured vehicle emissions and made minor changes in modeling methods. After MOBILE 6, the MOVES model came out not only representing EPA's most up-to-date assessment of on-road mobile source emissions, but also incorporating changes to the mobile source emission modeling approaches which are based on the National Academy of Science's recommendations.

When MOVES first came out, there are many general comparisons of the two models to introduce people to what MOVES was capable of doing and how it had improved from MOBILE's model structure[25; 39; 40]. Comparisons on model structure and data updates are shown in Table 3.1.

Other than mentioned above, the two models were fundamentally different in terms of how vehicle activities were counted for. In the MOBILE series models, VMT which is the distance a vehicle traveled has been the main count for vehicle running activity. In MOVES, instead of distance, the model uses the time a vehicle operated to count for running activities. the VMT and Vehicle Hour Traveled (VHT) could be converted to each other as long as the speed is known. In extreme cases such as running at very low speed or when the engine is idling, vehicle hours is a better way to describe the amount of activity spent at these modes. For evaporative emissions, the vehicle hours operating and hours parking are both taken into account. When counting the operating modes in hours, the time spend on parking could be provided.

Table 3.1: General Differences between MOVES and MOBILE 6

MOBILE 6	**MOVES**
GENERAL	
Emission Rate Only	Emission Rate & Inventory
Limited user-provided emission data	Easier to corporate in-use data
User coding input	Friendly GUI
County to national level	Project, county, multi-county, national level
DATA IMPROVEMENT	
In-Use data for only pre-1994 vehicles	Larger data set
PM data with no temperature effects	In-use PM data for light duty vehicles with temperature effects
Heavy duty vehicles' data no speed effects, no crankcase, start and extended idle emissions	In-use data with speed effects and other processes

Also, both MOVES and MOBILE 6 calculate emissions by multiplying emission rates by emission activity and applying correction factors as needed. However, the emission rates and activity in MOVES are distinguished at much finer level than in MOBILE 6. For example, most running emissions are categorized into one of 25 operating modes, depending on vehicle speed and vehicle specific power (VSP). Vehicles are categorized into narrow subtypes or "source bins" with similar fuels, engine sizes and other emission-related characteristics. Especially, MOVES has taken into account the impact of activity level to start and evaporative emission. Start emissions are now distinguished based on the time a vehicle has been idle prior to start for all vehicles, compared to previously, only light duty passenger car, light duty truck and motorcycle vehicle's start emissions can be estimated separately in MOBILE 6. Evaporative emissions modes are defined based on whether the vehicle is operating or has recently been operating, and in MOVES this has been expanded to cover more vehicle types and more pollutants.

Even though the MOBILE model is no longer in use, its general framework is the same as the MOVES model. This research focused on the MOVES model, but there will be discussions on MOBILE 6 to help understand the comparison between the two models in terms of critical inputs.

3.1 Emission Models' Critical Inputs

The inputs for the MOBILE 6 and MOVES have similarities. The inputs that MOBILE 6 and MOVES use can be categorized into these groups: 1) external conditions, such as temperature and humidity; 2) programs, regulations and control measures that affect emissions such as state vehicle inspection frequency; 3) fuel characteristics; 4) fleet characteristics, including vehicle age and fuel they use; 5) activities of the vehicles and 6) the distribution of these activities. This section will describe these inputs and their interactions and interdependencies.

3.1.1 External Conditions

External condition inputs include the selection of modeling period and modeling area, the meteorological conditions such as temperature, relative humidity, and barometric pressure as they relate to the area and time frame to be modeled. MOVES can model at a wide variety of geographic scales from national level, to a multi-county regional level, a county level, or even at the project level.

MOBILE 6 is capable of modeling any year from 1952-2050 and users select if they want the model to generate emission rates for July 1 or Jan 1. Other months can be estimated by mathematical interpolation between these two results. MOVES can model calendar years of 1990 and 1999-2050 and can model multiple months. However, for one MOVES run, some inputs could be entered one set of values for all the modeling months. Users need to consider if they would like to conduct multiple runs to better describe the scenarios for different months or using one representative set of data. Similarly, MOVES can model weekdays and weekends within a single run also, but if users wanted certain inputs vary by day type, they will need to conduct multiple run.

Meteorological data are used by emission models for two main purposes: they determine the usage of air conditioner which will impact the emission rate adjustment for criteria pollutants' running and idling emissions as well as total energy consumption; they also affect the NO_x running emission and extended idle emission. The main inputs for meteorological data are the ambient temperature and humidity data for each hour that are to be modeled. If users have only min/max temperature, EPA has provided a tool to create an hourly temperature profile based on typical patterns, which assumes the lowest temperature occurs at 6 am and the highest at 3 pm.

3.1.2 Fuel Characteristics

Fuel formulation defines the basic attributes of chemical components that affect emissions for each fuel. Emission models calculate emission adjustments based on these specific attributes. In the MOBILE 6 model, users are required to specify representative gasoline fuel properties for areas being modeled, but doesn't include options to assign diesel fuel properties.

In the MOVES model, users input different fuel formulation properties separately and use the fuel supply table to identify which fuel formulations are used in the area and what is their market share. This is used by MOVES to weigh the adjustments for fuel formulations.

3.1.3 Inspection/Maintenance Programs

Inspection and maintenance programs (I/M programs) are the emission control programs implemented at different levels of government to improve mobile source emission issues. The MOVES inputs of inspection/maintenance programs are a list of these programs and their association with specific pollutant, emission processes, vehicle type, and fuel type, so that they will be taken into consideration when calculating emission rate or inventory for these pollutants, processes, vehicles and fuel types. They also indicate the inspection frequency and test standards for a specific time span. If MOVES' analysis year is covered by certain programs, the compliance factor and waiver rates for the analysis area in the analysis year reflects the amount of adjustments needed to account for.

3.1.4 Vehicle Fleet Characteristics

Because different vehicle type, vehicle age and fuel/engine type tend to have distinctively different emission properties, the fleet characteristics input of emission models provides a reasonable representation of the vehicle fleet mix for emission calculation. MOBILE 6 requires the age distribution for each vehicle type, the amount of distance these types of vehicles of this age usually travel for a year, and the fractions of the vehicle population using gas, diesel and natural gas. In addition to the three inputs in MOBILE 6, MOVES requires vehicle population for each vehicle type. For the fuel fractions, instead of gas, diesel and natural gas option in MOBILE 6, MOVES allows users to develop a more sophisticated fuel/engine technology distribution, which included 6 fuel types and 2 engine types. This provided better options of modeling future scenarios with advanced fuel engine technology.

MOBILE 6 classifies vehicles into 16 different types mostly by the weight. Data from transportation planning or projects are usually using Highway Performance Monitoring System (HPMS)'s vehicle classifications, and MOVES groups vehicles into 13 categories, which are the subsets of 6 main HPMS vehicle types as shown in Table 3.2. This way of classification makes it easier to map the transportation related data such as VMT to MOVES input.

Table 3.2: MOBILE 6, HPMS and MOVES Vehicle Classification Matching Scheme

<table>
<tr><th>MOBILE 6 Vehicle Classes</th><th>6 HPMS Vehicle Classes</th><th>MOVES Vehicle Classes</th></tr>
<tr><td>Motorcycles</td><td>Motorcycles</td><td>Motorcycle</td></tr>
<tr><td>Light-Duty Vehicles (Passenger Cars)</td><td>Passenger cars</td><td>Passenger car</td></tr>
<tr><td>Light-Duty Trucks 1 (0-6000 lbs. gross weight, 0-3750 lbs. loaded weight)</td><td rowspan="4">Other 2-axle/4-tire vehicles</td><td rowspan="2">Passenger truck</td></tr>
<tr><td>Light Duty Trucks 2 (0-6000 lbs. gross weight, 3751-5750 lbs. loaded weight)</td></tr>
<tr><td>Light Duty Trucks 3 (6001-8500 lbs. gross weight, 0-5750 lbs. loaded weight)</td><td rowspan="2">Light commercial truck</td></tr>
<tr><td>Light Duty Trucks 4 (6001-8500 lbs. gross weight, >5750 lbs. loaded weight)</td></tr>
<tr><td rowspan="2">School Buses</td><td rowspan="4">Buses</td><td>Intercity bus</td></tr>
<tr><td rowspan="2">Transit bus</td></tr>
<tr><td rowspan="2">HDBT Transit and Urban Buses</td></tr>
<tr><td>School bus</td></tr>
</table>

Table 3.2 continued.

MOBILE 6 Vehicle Classes	**6 HPMS Vehicle Classes**	**MOVES Vehicle Classes**
Class 2b Heavy Duty Vehicles (8501-10000 lbs.)		Refuse truck
Class 3 Heavy Duty Vehicles (10001-14000 lbs.)		Single-unit short-haul truck
Class 4 Heavy Duty Vehicles (14001-16000 lbs.)		Single-unit long-haul truck
Class 5 Heavy Duty Vehicles (16001-19500 lbs.)	Single unit and combination trucks	Motor home
Class 6 Heavy Duty Vehicles (19501-26000 lbs.)		Combination short-haul truck
Class 7 Heavy Duty Vehicles (26,001-33,000 lbs.)		
Class 8a Heavy Duty Vehicles (33001-60000 lbs.)		Combination long-haul truck
Class 8b Heavy Duty Vehicles (>60,000 lbs.)		

As mentioned, MOVES requires vehicle population by each vehicle type. MOVES need the vehicle type population information to calculate the time vehicles spend on parking vs. running, so to calculate start and evaporative emissions inventory. Compared to MOBILE 6, which calculated start and non-running evaporative emission by VMT, this is more logical and realistic.

3.1.5 Vehicle Activity

Vehicle activity is the indicator of how much total activity is happening that is ultimately responsible for producing emissions; and its distributions among different vehicle type, on different road type, at different time and on different operating modes is taken into account how to weigh the emission rates among these groups. Vehicle activities are measured by different units according to what they are describing: for example, for running emissions, the distance a vehicle traveled or the time a vehicle spent on running would be both reasonable, but for starting emissions, it is really more relevant on how many start actions a vehicle has performed rather than how much a vehicle traveled after it started. For evaporative processes such as fuel vapor venting or permeation from the fuel system, it would make more sense to measure the time a vehicle sits at different environment to evaluate its emission. As mentioned at the beginning of the chapter, MOVES model uses the time based activity measurement for running and evaporative emission calculation and this is one improvement from MOBILE 6.

3.1.6 Vehicle Activity Distributions

3.1.6.1 VMT Fractions by Time and Roadway Type

In MOVES, VMT fractions by month and hour are used to select different adjustments for fuel used in different months, temperature and air conditioning usage in different months and hour of day, to apply to emission rates. VMT fractions by different days, that is, weekday or weekend, are used mainly because the operating mode distributions tend to be significantly different. VMT fractions by hour of the day are the only temporal distribution of VMT in MOBILE 6 and it has little effect on overall daily emissions.

It is considered that on different road types such as an urban local road versus a rural freeway, vehicles will have distinctively different driving behavior, which has a significant impact on emissions. Emission models use several different driving cycles to describe the driving behavior for certain different groups of vehicles on different roads. MOVES has four road types and one “off network” road type, indicating parking facilities where vehicles are not considered running. The matching schemes of roadway types of MOBILE 6 and MOVES to FHWA highway functional classes are shown in Table 3.3 [41; 42].

Table 3.3: Matching FHWA Roadway Types with MOBILE 6 and MOVES Roadways types

FHWA Highway Functional System	**MOBILE 6**	**MOVES**
Rural interstate	Freeway and freeway ramp	Rural Restricted
Rural other principle arterial	Freeway and freeway ramp	Rural Unrestricted
Rural minor arterial	Arterial/collector	Rural Unrestricted
Rural major collector	Arterial/collector	Rural Unrestricted
Rural minor collector	Arterial/collector	Rural Unrestricted
Rural local	Arterial/collector	Rural Unrestricted
Urban interstate	Freeway and freeway ramp	Urban Restricted
Urban other freeways	Freeway and freeway ramp	Urban Restricted
Urban other principle arterial	Arterial/collector	Urban Unrestricted

Table 3.3 continued.

FHWA Highway Functional System	**MOBILE 6**	**MOVES**
Urban minor arterial	Arterial/collector	Urban Unrestricted
Urban collector	Arterial/collector	Urban Unrestricted
Urban local	Local roadway	Urban Unrestricted

Because of the impact of these VMT fractions, states are expected develop the VMT fractions by month, day, hour and road types for each vehicle type. A problem with different distributions of VMT is that they require far more data in details than it would be reasonable to acquire for agencies. In MOVES model, there are 29952 entries of fractions to be entered. Figure 3.1 below shows levels of distribution of VMT MOVES model requires. National average values are available in both models but for SIP related analysis EPA expected states to develop local data on these inputs.

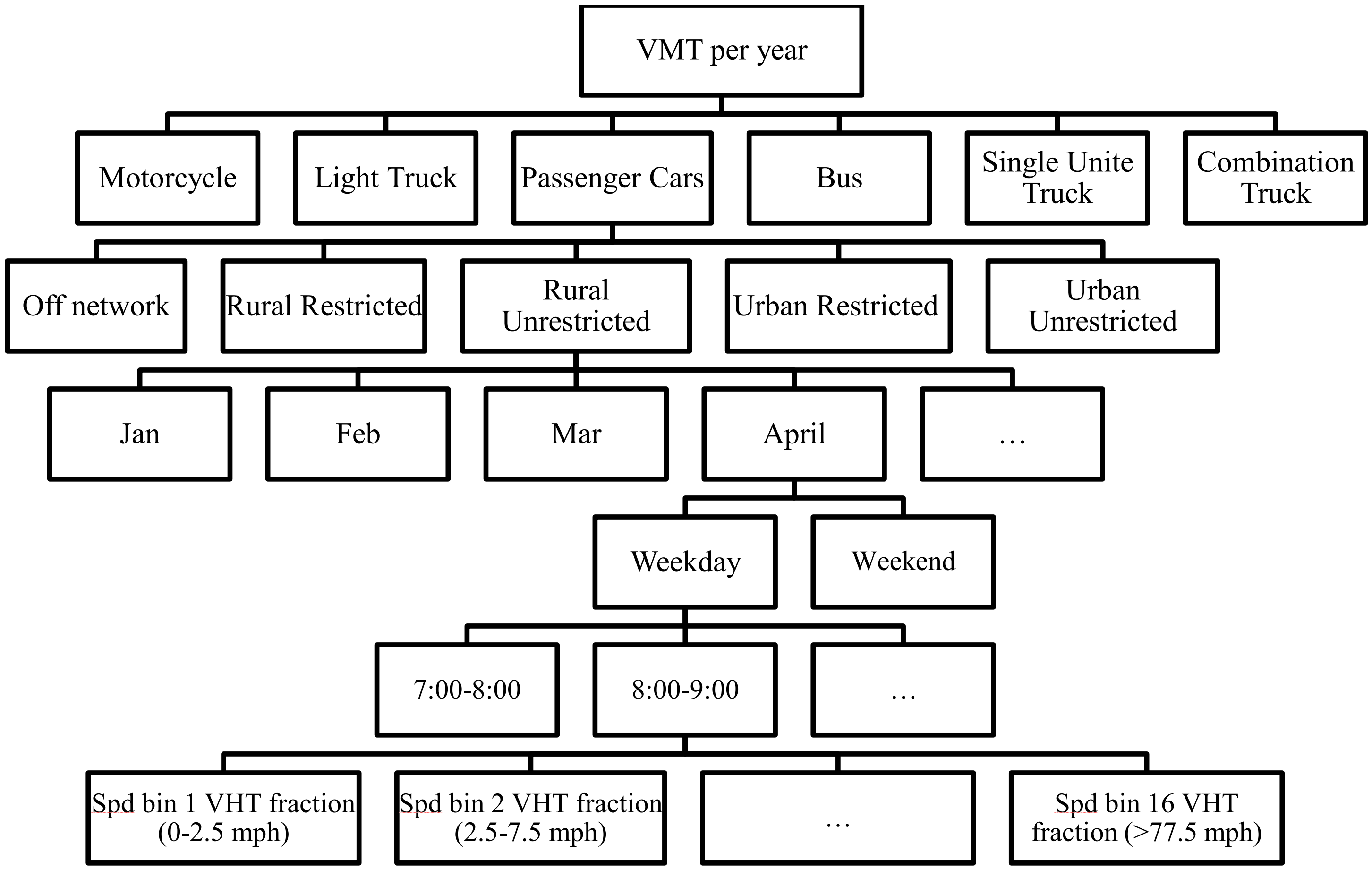

Figure 3.1: VMT Distributions MOVES Model Required

3.1.6.2 Activity Fraction by Average Speed

The distribution of vehicle running activity, either vehicle miles traveled or vehicle hours traveled by average speed has a significant effect on overall daily emissions from highway mobile sources. This input reflects the transient behavior of vehicle as they travel. For SIP and conformity related emission inventory analysis, EPA requires states to develop and use local estimation of VMT or VHT by average speed.

Average speed used in emission models is not the same as instantaneous velocity of vehicles or the posted speed limit on the roadway link. It takes into consideration the delays traveling along each road. These delays include intersection stopping, acceleration, deceleration, idling, etc. The speed distribution is usually from local travel demand network model with post-processing.

MOBILE 6 can estimate emissions separately by average speed and roadway type, and a post-processing procedure outside the model is needed. The process of finding the emission rate for each link according to speed is shown in Figure 3.2 and Equation 3.1.

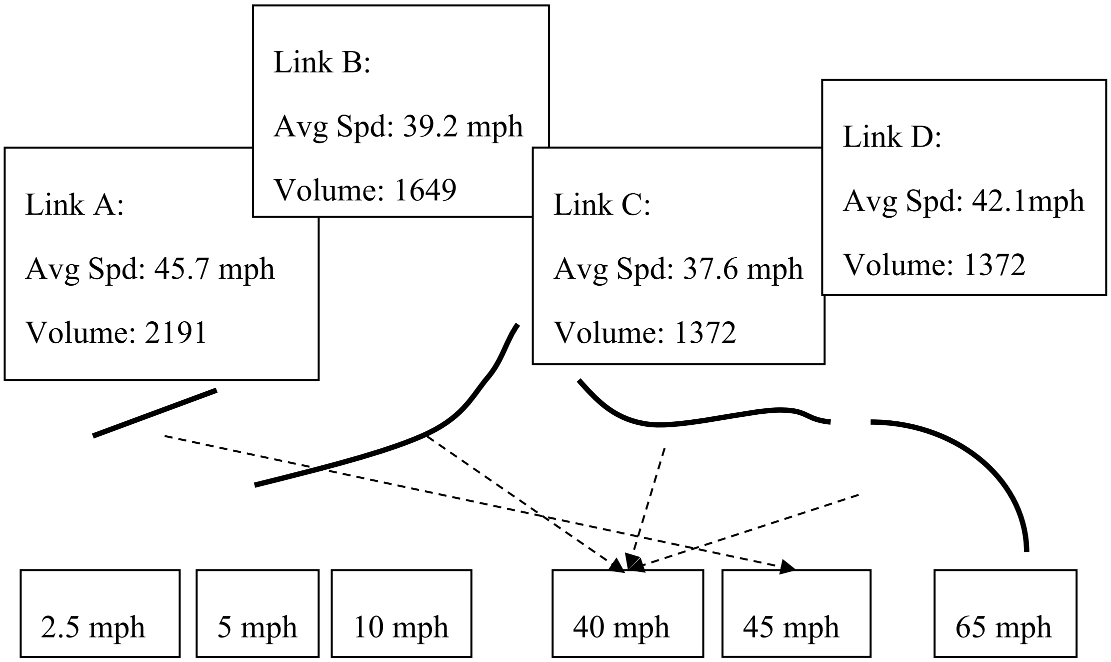

Figure 3.2: Matching Emission Rates with Appropriate Roadway Links

Equation 3.1

$$VMT_{spd\ x} = \sum_{Link\ i=1,}^{Link\ i=n} Length * Volume, \qquad link\ i's\ avg\ spd\ \in (x-2.5, x+2.5)$$

3.2 MOVES Emission Calculation

MOVES has been designed with improved understanding of some emission modules, yet it keeps the basic ideas of "basic rate multiples correction factor" from MOBILE series models. However, for MOVES to produce emission inventory inside the model, rather than just generate emission rate to post process later like the way MOBILE 6 uses, activity data will directly impact the emission inventory output. This chapter introduces MOVES' key calculations algorithms and it's similarity to or difference from MOBILE 6, in order to help understanding unexpected MOVES modeling results from conformity analysis.

3.2.1 MOVES Running Emissions Calculation

MOVES defines a set of operating modes and distribute the amount of activities spend to each of those operating modes. The two modules in MOVES that perform these procedures are the total activity generator and the operating mode distribution generator. Different pollutants and processes may have different categories of operating modes. For running emissions, operating modes are defined by vehicle specific power (VSP) and instantaneous speed, and activities are defined as the source hour operated (SHO).

In the running operating mode distribution generator, the first step is to match each one average speed with two bracketing driving schedules. Next, based on the vehicle characteristics such as drag terms, vehicle mass and the speed from each second of each driving schedule, the module will calculate the VSP and acceleration of that type of vehicle in that particular second of that particular driving schedule. The VSP value and the speed are then used to locate the corresponding operating mode bins. For all the seconds of all the driving schedules taken through those steps, the fractions of operating modes can be determined. Further explanation on VSP, driving schedules, and MOVES running operating mode distribution will be discussed in section 4.2. Since the operating modes are calculated second by second, the distribution results would be time based also. This is another reason why it is good for MOVES to count driving activities by source hour operated (SHO).

3.2.2 MOVES Start Emissions Calculations

Start emission is the additional energy consumed or the tailpipe exhaust emissions produced while the vehicle just started and it comprised an important part in the total mobile source emissions. Based on MOBILE 6 model default, in 2001 summertime scenario, for light duty passenger car and truck, plus motorcycle, start emissions is estimated to take 28% of total on-road VOC , 31% CO and 20% NOx ; in wintertime conditions, start emissions could take 50% of total CO exhaust emissions[43].

The operating modes for calculating vehicle start emission are bounded with the length of time the engine was off prior to starting. Instead of simply characterizing starts as just hot and cold like in earlier emission models, MOVES groups the starts by soak time distribution – the length of time that the vehicle was parked prior to start. MOVES uses the start operating mode generator, assign a start operating mode to the trip by comparing its soak length with the low soak length and high soak length values stored in the model.

Based on these rates, adjustments were made according to modeling areas' local condition. The amount of activities for starting are counted in MOVES by the number of starts by each modeling hour and vehicle type.

3.2.3 MOVES Evaporative Emissions Calculations

Evaporative emission takes a significant amount of the total mobile source emissions, especially the gaseous hydrocarbon inventory. Both source hours parked and source hour operated are taken into account for evaporative emissions. The hours parked can be split into "cold soak" and "hot soak" modes, and its distribution were calculated via simple trip data by MOVES. Some commute and parking patterns are affected by geographic allocation also.

Like in MOBILE 6, for a long time evaporative emissions were quantified in three distinct modes: running loss, diurnal/resting loss, and hot soak. But when considering factors such as ambient temperature and fuel type, they act upon emission processes more noticeably than the three modes[44]. There are three emission processes to consider for evaporative emissions in MOVES- permeation, tank vapor venting and liquid leaks. Permeation is the migration of hydrocarbons through elastomers in a vehicle's fuel system. Tank vapor venting refers to expulsion into the atmosphere of fuel vapor generated from evaporation of fuel in the fuel system. It includes the canister breakthrough, the vapor leaks, and other non-liquid fuel vapor losses. Liquid leaks means fuel, in liquid form, leaking from the fuel tank or fuel system, which then evaporates into the atmosphere.

Among all the factors, fuel tank temperature is the most critical one, especially for permeation and vapor venting emissions. This factor is mostly depending on day-to-day vehicle operating pattern and when in cold soak, it relates to the environmental temperature as well. MOVES estimates the real world fuel tank temperature based on sample trips and it was used in the format of hourly averages by different modes (cold soak, hot soak, operating).

In permeation, the three modes are assumed to have the same base emission rate at the standard temperature of 72 degrees F. With temperature changing the permeating rate changes exponentially[45]. Different from permeation, fuel vapor venting is only related to temperature in cold soak mode.

The evaporative emission rates are multiplied with source hour parked and source hour operated to get the total emission. Evaporative failure frequencies are highly related to vehicle age and whether the vehicle is equipped with I/M standards, and liquid leak frequencies depends on vehicle age largely.

3.3 The Issue of Inconsistence between the Two Models

Even though MOVES is generally considered a more advanced model, during the transition from MOBILE 6 to MOVES, many agencies reported issues with the process. One prevailing issue is that MOVES generating higher emissions than MOBILE and many states could not achieve conformity with MOVES's calculation. Table 3.4 below shows the difference in emission inventory forecasts from the two emission models in New Castle County, Delaware[46]. As mentioned in section 3.2, MOVES also requires more data compared with MOBILE 6, which are not readily available or need more processing or with many assumptions. As a result, the deadline of changing to MOVES is extended from 2012 to 2013.

Table 3.4: New Castle County's Emission Estimation Difference between MOVES and MOBILE 6

	2008	2020	2030	2040
NOx	+89%	+57%	+35%	+34%
VOC	+11%	-27%	-84%	-92%
PM 2.5	+253%	+62%	+39%	+38%

The resulted emission output may reflect the impact of one or many differences mentioned above, and it needs more in-depth analysis from many aspects. The performance difference of the two models is the key motivation driving this dissertation, because it brings controversial arguments not only in the conformity processed for government, but also for greenhouse gas emissions, air toxic emissions and other project level concerns and regulation. However, with the fact that MOBILE 6 is no longer used for conformity analysis, this dissertation will mostly focus on the impacts of MOVES model characteristics on conformity analysis. The purpose of this dissertation on studying the emission models is not only in finding the reason of higher emission with one model than the other, but also in understanding the challenges of the ever more sophisticated modeling methods and yet ever more intensive data requirement.

Chapter 4

QUANTITATIVE ANALYSIS

4.1 Analysis Plan

As mentioned in section 2.4, past research have performed some sensitivity analyses on the inputs for MOBILE 6 and MOVES [34-36]. These studies included analyses for data inputs like temperature and barometric pressure. While it is useful to understand how a particular emission is affected by temperature, a sensitivity analysis is generally considered to be a measurement of the uncertainty in a model's output based on uncertainty with its inputs. Excluding negligible errors in temperature sensing and recording, there are nearly no uncertainties with inputs like temperature, humidity and barometric pressure. The input uncertainties arise from those inputs that this research can only estimate from samples or the outputs of other models.

The quantitative analysis plan for this research is to examine the data sources recommended for the MOVES model, the assumptions or errors in that input data, and other data sources that are available and could be used. In some cases, the best data available will be the defaults established by MOVES, but in several cases, it will be shown that alternatives exist. For each alternative, the impact on the emissions inventory will also be shown.

4.2 Average Speed Distribution Analysis

For each MOVES roadway type and vehicle type at each hour of a day, a VHT based average speed distribution across 16 pre-defined speed bins with 5 mph interval is required. The speed bin 1 covers the speed range of 0-2.5 mph, speed bin 2 is 2.5-7.5 mph, speed bin 3 is 7.5-12.5 and the same for other speed bins until speed bin 15. The speed bin 16 is 72.5 mph and greater. The average speed distributions are usually obtained from travel demand models that serve for transportation planning purposes.

Running operating modes for most pollutants are defined by vehicle specific power (VSP) and instantaneous speed. VSP is the instantaneous power demand of the vehicle divided by its mass[47; 48]. It represents the sum of the engine loads resulting from aerodynamic drag, acceleration, rolling resistance, and hill climbing, all divided by the mass of the vehicle[47]. Typically the parameters needed to calculate VSP are vehicle weight, several dragging properties of the engine, acceleration and speed at the time, and roadway grade. Conventionally, it is reported in kilowatts per tonne[47; 48]. These two values change on every second for each vehicle. Because it is impossible to these two values in a county area for every vehicle at every second, MOVES uses a set of driving schedules that simulate typical driving behaviors on different roadways for different vehicle types. For each driving schedule, the operating mode for each second could be determined as shown in Table 4.1. A list of example driving schedules could be found in Table 4.2. Schedule ID 1017 to schedule ID 1021 are associated with same road types and vehicle types, but representing different driving behavior under different average speed. The instantaneous speed for each second of these driving schedules is shown in Figure 4.1.

Table 4.1: Operating Mode Defined by VSP and Speed for Hydrocarbons, CO, and NO_x

VSP/Instantaneous Speed	**0-25 mph**	**25-50 mph**	**>50 mph**
<0 kW/tonne	Mode 11	Mode 21	
0 to 3	Mode 12	Mode 22	
3 to 6	Mode 13	Mode 23	
6 to 9	Mode 14	Mode 24	
9 to 12	Mode 15	Mode 25	
12 and greater	Mode 16		
12 to 18		Mode 27	Mode 37
18 to 24		Mode 28	Mode 38
24 to 30		Mode 29	Mode 39
30 and greater		Mode 30	Mode 40
6 to 12			Mode 35
<6			Mode 33

Table 4.2: MOVES Build-in Driving Schedules of Different Average Speeds

Schedule ID	**Average Speed**	**Schedule Name**
101	2.5	LD Low Speed 1
153	30.5	LD LOS E Freeway
158	76	LD High Speed Freeway 3
1009	73.7991	Final FC01LOSAF Cycle
1011	49.0722	Final FC02LOSDF Cycle
1017	66.3632	Final FC11LOSB Cycle
1018	64.3993	Final FC11LOSC Cycle

Table 4.2 continued.

Schedule ID	Average Speed	Schedule Name
1019	58.7949	Final FC11LOSD Cycle
1020	46.132	Final FC11LOSE Cycle
1021	20.6006	Final FC11LOSF Cycle
1024	63.66	Final FC12LOSC Cycle
1025	52.8263	Final FC12LOSD Cycle
1026	43.2662	Final FC12LOSE Cycle
1029	31.0232	Final FC14LOSB Cycle
1030	25.379	Final FC14LOSC Cycle
1033	8.71909	Final FC14LOSF Cycle
1041	18.5781	Final FC17LOSD Cycle
1043	15.733	Final FC19LOSAC Cycle

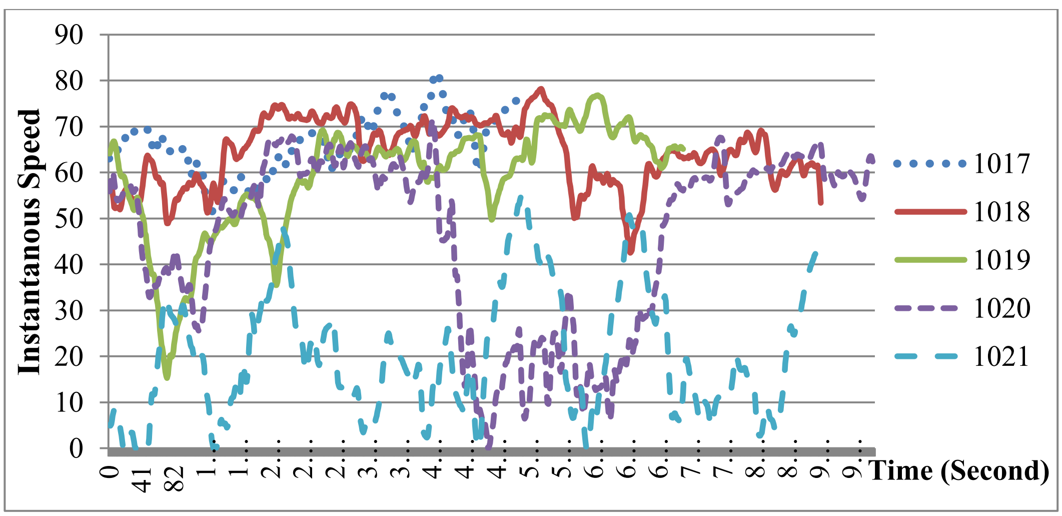

Figure 4.1: MOVES Driving Schedule with Different Average Speed on Restricted Road Types

For each speed bin of the average speed distribution, MOVES uses the median speed value of that speed bin to look for driving schedules of similar average speed. For example, for vehicles driving at average speed in speed bin 12 on certain roadway types, which refers to speed of 52.5-57.5 mph, MOVES uses it's middle speed value, 55 mph, to look for driving schedules that are associated with the same vehicle type and roadway type, and whose average speeds are just below and above 55. In this example, the driving schedule of 1019 with an average speed of 58.8 and 1020 with an average speed of 46.1 would be selected. MOVES gives the amount of vehicle activities in this speed bin to these two driving schedules proportionally, and then further distribute these activities into each operating mode in these driving schedules.

4.2.1 Speed Distribution from Travel Demand Model

Travel demand models are designed to forecast long-term traffic network performance based on current or projected demographic. The speed on each link computed by the model and is based on free flow speed and adjusted for the calculated volume / capacity ratio. In the model, the travel time on each roadway section is calculated as follows:

$$Tc = T_0 * (1 + TC_{COEFF} * (V/C)^\wedge TC_{EXP})$$

In this equation, Tc is the congested travel time which will be used by MOVES, T_0 is the free flow travel time, V is the traffic volume on the roadway link, and C is the capacity of the roadway. TC_{COEFF} and TC_{EXP} are adjustments by the modeler for number of traffic lights, the length of the link, the roadway class, and posted speed limit. However, this method bases an emission inventory contribution from a road section based on all the volume moving at a single speed.

Figure 4.2, Figure 4.3 and Figure 4.4 below show speed distributions generated from a travel demand model which are used for conformity analysis for the 3 road types in Delaware's current conformity analysis: Rural Unrestricted, Urban Restricted, and Urban Unrestricted. Each figure showed four speed distributions for off peak hours, morning peak hours, mid-day hours, and afternoon peak hours of weekdays during spring time.

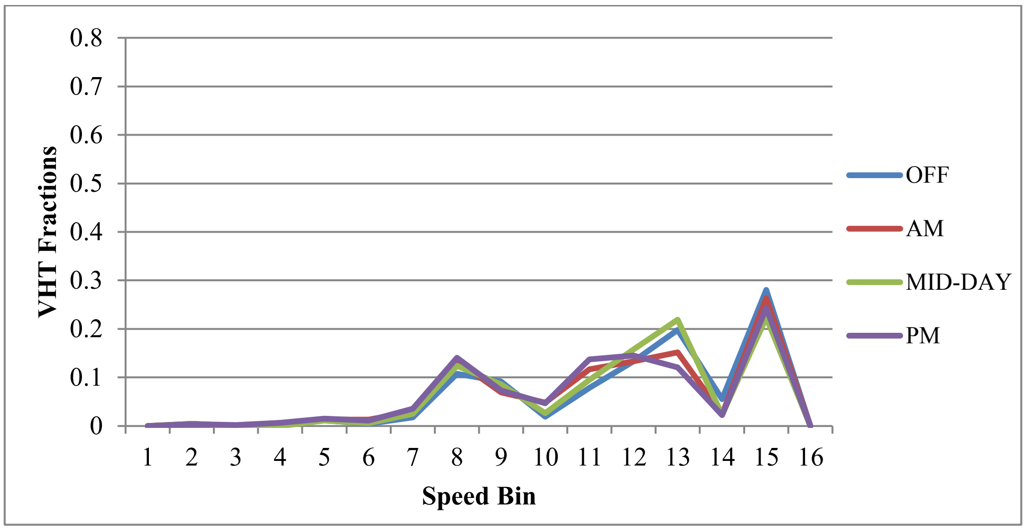

Figure 4.2: Speed Distribution Input of New Castle County, DE Conformity Analysis – Rural Unrestricted Highway

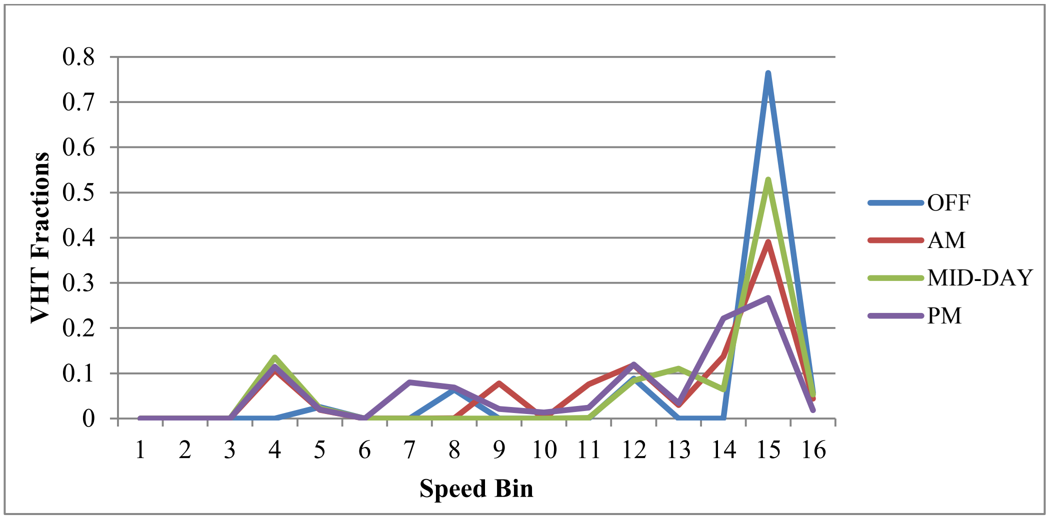

Figure 4.3: Speed Distribution Input of New Castle County, DE Conformity Analysis –Urban Restricted Highway

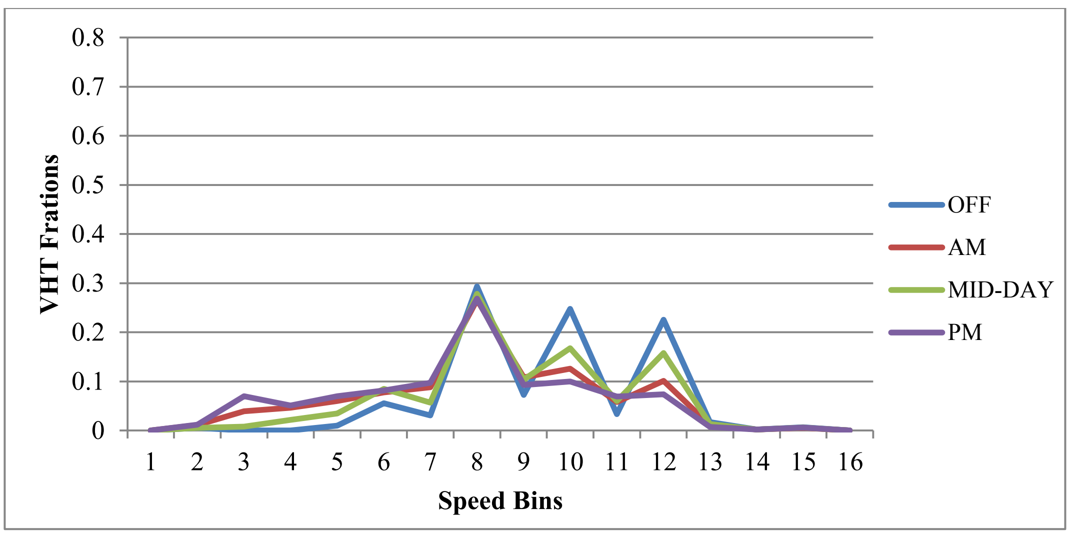

Figure 4.4: Speed Distribution Input of New Castle County, DE Conformity Analysis –Urban Unrestricted Highway

4.2.2 Speed Distribution from Field Measured Data

There exists another data source to be used as speed input to an emission model. Traffic studies and field detectors generate roadway speed profiles which could serve as an alternative to single point speeds based on travel demand models. Speed and volume data from 33 links in New Castle County, DE was processed based on MOVES roadway classifications and posted speed limits. Speed distribution curves were developed and applied to each network link. The revised results are shown in Figure 4.5, Figure 4.6 and Figure 4.7.

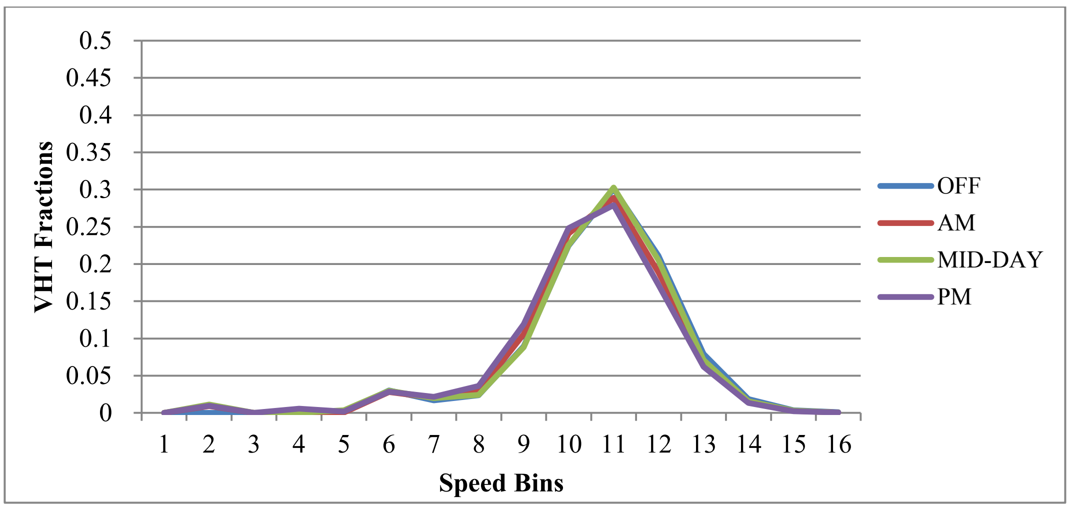

Figure 4.5: Speed Distribution from Field Measured Data – Profile of Rural Unrestricted Highway during spring on weekdays

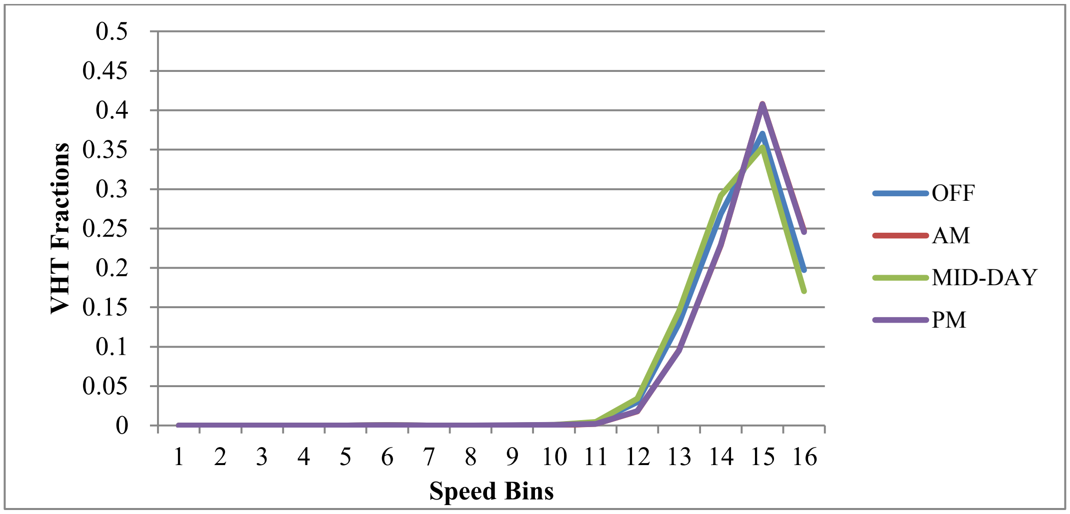

Figure 4.6: Speed Distribution from Field Measured Data – Profile of Urban Restricted Highway during spring on weekdays

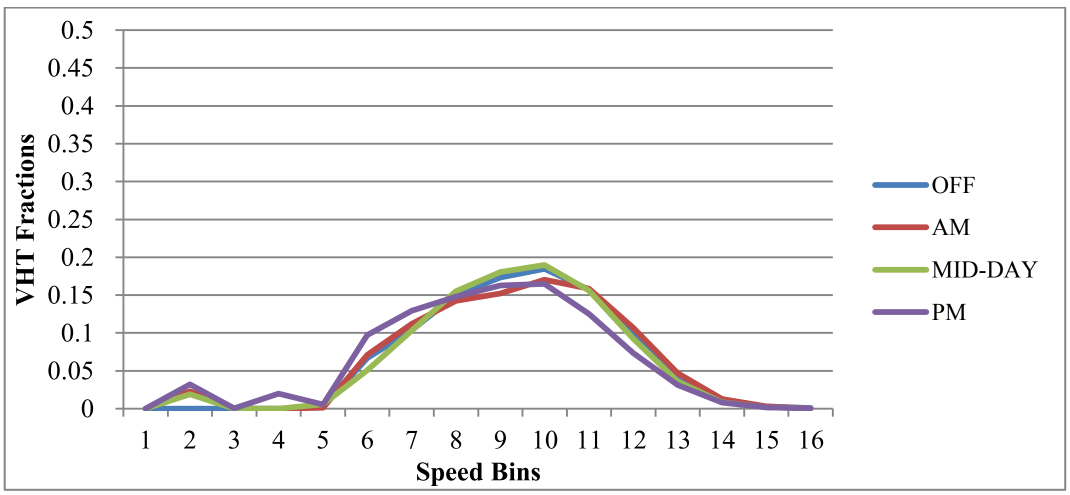

Figure 4.7: Speed Distribution from Field Measured Data – Profile of Urban Unrestricted Highway during spring on weekdays

Table 4.3 shows the comparison of the emission results for the two sets of speed distributions. As discussed in section 2.4, emissions are sensitive to speed distribution according to many studies. However, the results of this research do not support that claim. Even though the speed distribution is distinctively different for the two sets of data, the total emissions are only slightly affected. The emission output were further broken down by processes in Table 4.4 and the emission changes occurred only for running exhaust, extended idle and brake wear, meaning that average speed distributions affect only these three emission processes. The running activities changed by using these drastically different speed distributions were only around 3%. Running exhaust emissions changed less than 2% and was less responsive to activity changes than brake wear emission, which changed nearly 8%.

Table 4.3: Total Emission Change of MOVES Using Travel Demand Model's Speed Distribution vs. Field Measured Speed Distribution

	Travel Demand Model	**Field Measured**	**Difference (ton)**	**Difference %**
HC Gaseous	1031.184	1023.78	-7.4	-0.718%
CO	11909.71	11862.23	-47.49	-0.399%
NO_x	2537.234	2519.4	-17.84	-0.703%
Non Methane HC	984.58	977.42	-7.16	-0.727%
PM 10 Total	68.78	68.17	-0.62	-0.899%
Brake Wear PM 10	16.18	14.90	-1.28	-7.943%
PM 2.5 Total	65.55	64.95	-0.59	-0.906%
Brake Wear PM 2.5	4.24	3.90	-0.33	-7.943%

Table 4.4: Speed Related Process' Emission and Activity Change MOVES Using Travel Demand Model's Speed Distribution vs. Field Measured Speed Distribution

Process	**Pollutant**	**Emission Change**	**Corresponding Activity**	**Activity Change**
Running Exhaust		-1.036%	Source Hour Operating	-3.19%
	Total Gaseous Hydrocarbons	-1.874%		
	Carbon Monoxide	-0.769%		
	Oxides of Nitrogen	-0.788%		
	Non-Methane Hydrocarbons	-1.873%		
	Total Energy Consumption	-1.037%		
	Primary Exhaust PM10	-0.957%		
	Primary Exhaust PM2.5	-0.963%		
Brake Wear	PM10, PM2.5	-7.943%	Source Hour Operating	-3.19%
Extended Idle Exhaust		-3.190%	Extended Idle Hours	-3.19%

Field measured data could capture the different average speed for vehicles on same road links rather than assuming them driving at one single speed as used in travel demand model as mentioned before, yet its disadvantages should not be overlooked. The biggest concern of field measured data is the sample size. Thirty three roadway links of field measured speed are far less than the thousands of roadway links covering the whole county modeled by travel demand model. The 33 links were selected at where traffic tended to be congested for assessment purposes. They were not selected by the proportion of real world road functional classes to a representative miniscule network for area emission impact study. For example, there might be two local roads and five busy collectors, and in reality local roads could be much more than 2/5 of collector roadway links. In this case the sample links will overestimate the impact of traffic on collector roads. In summary, travel demand model is more representative for a wide range, yet field measured data captures the details happened on each road link.

4.2.3 Combination of Travel Demand Model and Field Measured Speed Distribution

To utilize the advantages of both sets of data and to avoid their disadvantages, the following methods were developed to create speed distributions using both data sources. The method used could be summarized in two steps: taking the travel demand model's VHT fraction of each speed bin to preserve the regional level bases; convert each single fraction into a distribution generated from field measured speeds on links with its 85% speed matching this speed bin, to add the details of difference among each individual vehicle. A detailed examination on processing the speed distribution from these two data sources is listed below:

Step 1. Calculate the 85% speed for each link over the observing time period (typically 7 days), and see which of the MOVES speed bin does the 85% speed fit into and lable the link with the speed bin number.

Step 2. Calculate the VHT fraction in each speed bin for each roadway link. Calculation was carried for each of the four periods of a day.

Step 3. Group the links together by MOVES roadway type. Under each of the roadway type groups, further group links with their 85% speed bin.

Step 4. Average the VHT fractions for each speed bin over all the grouped links and generate a speed distribution for each group of links.

Step 5. Picking out the VHT fraction of speed bin n from travel demand model, then picking out the distribution with the 85% speed bin same as bin n generated from step 4 to this fraction. Then instead of one fraction in one bin, now there are some smaller fractions distributed in several bins around bin n. Do this from bin 1 to bin 16.

Step 6. Adding the distributed fractions for each bin to generate a new distribution across 16 speed bins.

For speed bins that don't have the field measured data with its 85% speed falling into the speed range, VHT fractions of that speed bin were directly applied as they were without being spread out into neighboring speed bins. Also, even that the method could be applied to all four roadtypes in MOVES, there are too few links of restricted roads that can be used. So this method was applied only to urban and rural unrestricted roads. The two graphs in Figure 4.8 show the speed distribution curves generated. The speed distribution of travel demand model originally concentrated around the common speed limits due to the algorithm used in these models, and with the field measured data, the peaks around speed limits were reformed to smoother curves.

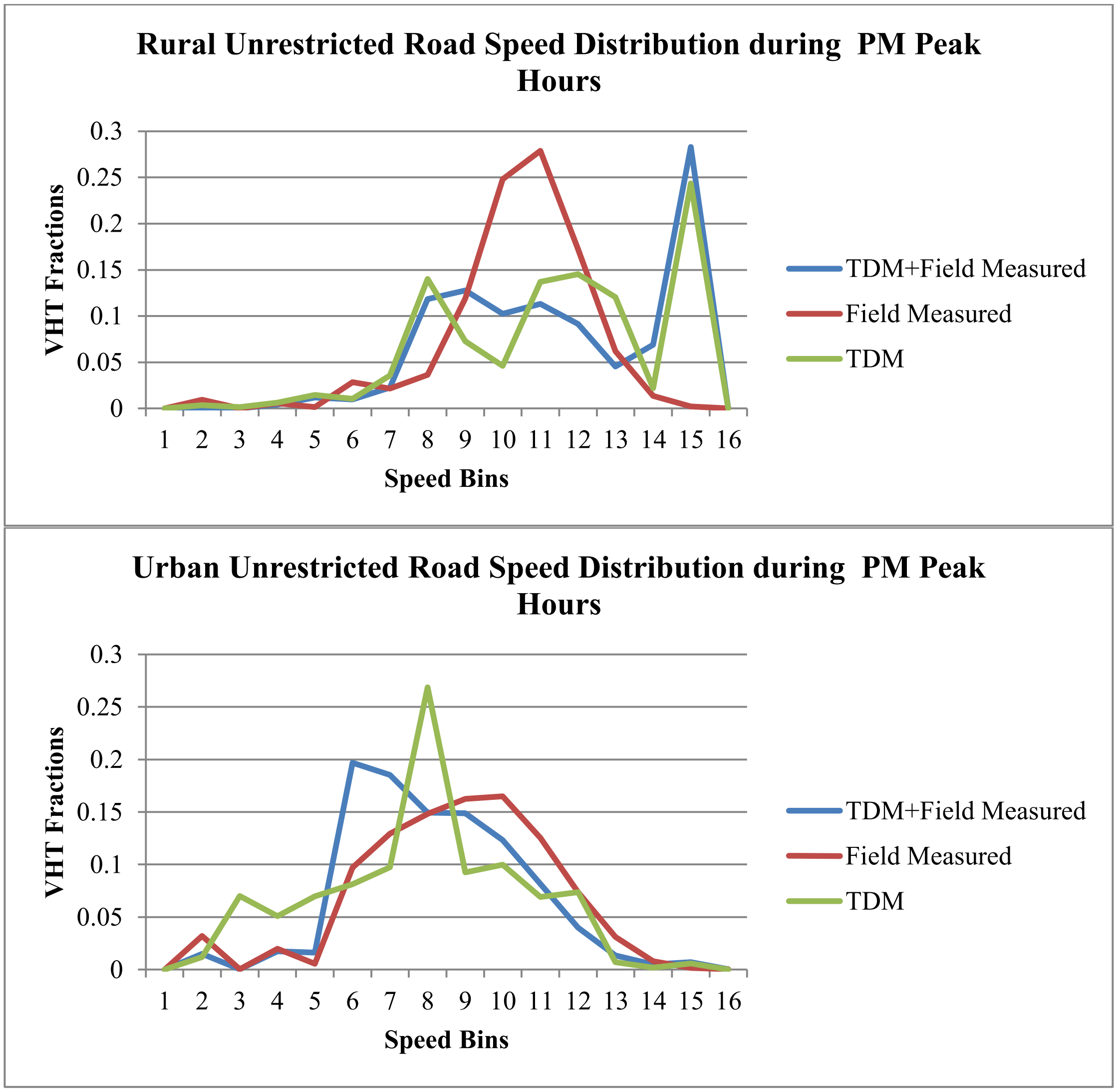

Figure 4.8: Comparison of Speed Distribution Profile from Travel Demand Model, Field Measured Speed, and the Combination of These Two

Table 4.5 below shows the amount of emission changes. The speed distributions from combined data source caused 2% to 4% changes in total emissions for all pollutants other than PM. Table 4.6 shows break down of emission changes for speed related processes. The result shows 16.9% of change in running activities, 2% to 9% change in running emission, and 44% drastic change in brake wear particulate matters.

Table 4.5: Total Emission Change of MOVES Using Travel Demand Model's Speed Distribution vs. Field Measured Speed Distribution

	Travel Demand Model	**TDM + Field Measured Data**	**Difference %**
HC Gaseous	1031.184	1067.29	3.501%
CO	11909.71	12148.05	2.001%
NO_x	2537.234	2596.64	2.341%
Non-Methane HC	984.58	1019.55	3.551%
PM 10 Total	68.78	74.72	8.629%
Brake Wear PM 10	16.18	23.41	44.655%
PM 2.5 Total	65.55	71.28	8.744%
Brake Wear PM 2.5	4.24	6.13	44.655%

Table 4.6: Speed Related Processes' Emission and Activity Change of MOVES Using Travel Demand Model's Speed Distribution vs. Field Measured Speed Distribution

Process	Pollutant	Emission Change	Corresponding Activity	Activity Change
Running Exhaust		4.33%	Source Hour Operating	16.674%
	Total Gaseous Hydrocarbons	8.90%		
	Carbon Monoxide	3.86%		
	Oxides of Nitrogen	2.48%		
	Non-Methane Hydrocarbons	8.91%		
	Primary Exhaust PM10	9.20%		
	Primary Exhaust PM2.5	9.31%		
Brake Wear	PM10, PM2.5	44.66%	Source Hour Operating	16.674%
Extended Idle Exhaust		16.67%	Extended Idle Hours	16.674%

4.2.4 Summary of Speed Distribution Analysis

As demonstrated in this chapter, the processing of the speed distribution plays important role in the emission output. The field measured speed distribution used in analysis did not impact emission output significantly. Using the field measured speed curve to interpolate the travel demand model's speed distribution resulted in distinctive changes in running activities, and some amount of emission changes.

Different from past sensitivity analysis studies on MOVES or MOBILE 6, speed distributions do not impact emissions output significantly for many pollutants other than particulate matters. Looking back into the model's algorithm, MOVES does not directly select operating modes using user supplied speed distribution. The speed distributions are actually used for driving schedule distribution. Each driving schedule was pre-defined in MOVES so its operating mode distribution is actually fixed. If other emission rates weighing factors were same, emission rates integrated across all operating modes for each driving schedule would be fixed also. For each vehicle type on each road type, there are only a few driving schedules for MOVES to choose from. This significantly brings the level of detail of the speed information down and caused the emissions to be less responsive to speed distribution change.

The speed distribution is important as a key measurement to vehicle running status, and the mechanism of the model's use of the speed information is sophisticated. However, from the analysis, it has been figured out that the ultimate goal of inputting the speed distribution of the area is to determine the operating modes distribution, not the driving schedules distribution. If for conformity analysis, guidance on generating the driving schedules is provided since some areas already experimented[37]; it could describe the local situation better than just using the speed distributions.

4.3 VMT Distribution by Roadway Type

In the case study in New Castle County, Delaware, current MOVES input included only three road types: rural unrestricted, urban restricted and urban unrestricted. Missing roadway type "rural restricted" in the study area, this study found alternative data sources to add this road type and compare the impact on emission output. The road type distributions dictates the driving cycles used for speed distribution, and thus affect the final running operating mode distribution, as shown in Figure 3.1. To match with the newly added rural restricted roadway VMT portion, speed distributions on restricted roads were also developed. Delaware's roadway centerlines ArcGIS file with urban/rural properties were used to identify the rural and urban restricted roads. Figure 4.9 below shows in New Castle County part of RT 1 is rural restricted highway. The distance proportion of rural and urban restricted roadways was used to determine the rural/urban split fraction. In New Castle County, Delaware, the proportion of rural restricted highway in all restricted roadways in 29.93%. The original 28% urban restricted VMT fractions were divided into 19.7% urban restricted and 8.5% rural restricted like shown in Table 4.7.

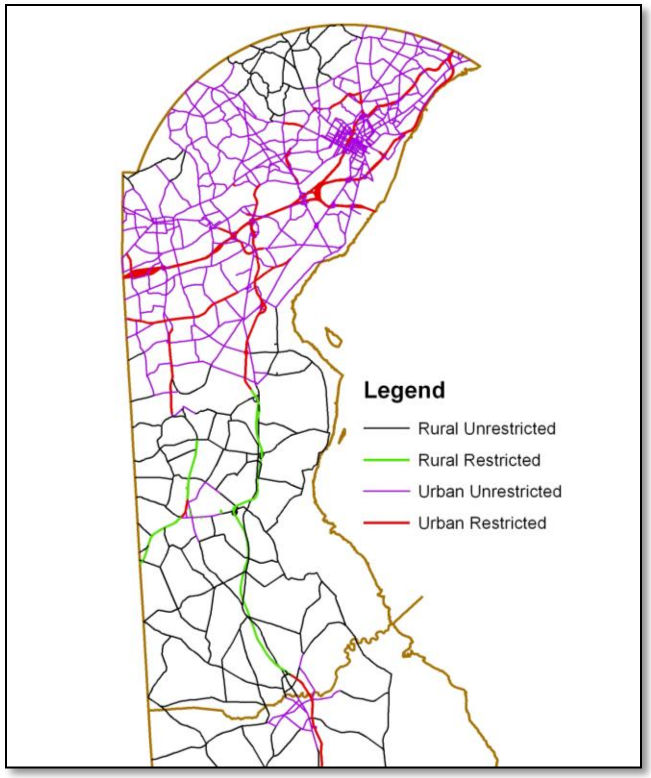

Figure 4.9: Roadway Classification in New Castle County, DE

Table 4.7: Road Type VMT Distribution Input Comparison

Road Type	Without Rural Restricted	With Rural Restricted
Off Network	0	0
Rural Restricted	0	0.084
Rural Unrestricted	0.128	0.127
Urban Restricted	0.281	0.197
Urban Unrestricted	0.591	0.591

The speed distributions for rural restricted roads, both urban and rural, are developed from the ATR counts. For each day, vehicle counts and average speed for each lane at each direction at every 5 minutes were recorded in representing ATR locations. These data were converted to vehicle counts by each MOVES speed bin for each hour, combining all the lanes in both directions for all the 5 minutes data.

4.3.1 Result and Summary

With the ATR speed data on restricted roads, field measured speed data on unrestricted roads and adding rural restricted roads VMT proportion, the emission has changed by around one percent as shown in Table 4.8. This one percent is not very significant and it included the speed distribution change's impact.

Table 4.8: Total Emission Change of MOVES from Using 3 Road Types to 4 Road Types with Field Measured and ATR Speed Distribution

	Differences %
HC Gaseous	-1.15%
CO	-1.07%
NOx	-1.52%
Non Methane HC	-1.16%
Energy Consumption	-1.59%
PM 10 Total	-1.29%
Brake Wear PM 10	-12.79%
PM 2.5 Total	-1.33%
Brake Wear PM 2.5	-12.79%

As mentioned in section 4.2, MOVES' build in driving schedules are associated with different road type and vehicle type combinations. From the emission result, it was concluded that the driving schedules used in urban and rural restricted roadways are not different by much. From the "drivingscheduleassoc" table in MOVES default database it could be confirmed that the driving schedule used on these two road types are exactly the same, which means that the running operating mode distribution will be the same for rural and urban unrestricted roads calculated by MOVES if speed distribution inputs on these two road types are the same.

4.4 VMT Temporal Distribution

In addition to the speed distributions and VMT distributions discussed in the prior two sections, MOVES also needs to know the temporal distribution of VMT. VMT distributions by month, day and hour provide information for grouping transportation activity and their operating modes and for determining hourly adjustments for temperature. For example, in Delaware's conformity analysis case, there are four speed distribution inputs in each year, representing each season. The monthly VMT fractions will help MOVES determine the proportion of activities applied by these four sets of speed distributions. One might ask why this level of detail is required. The reader is reminded that MOVES is a VHT based model, accounting for the emissions of the vehicle over each 24 hour period, so a strong understanding of the temporal distributions of activity and temperature is important.

4.4.1 Monthly Fraction

In Delaware's current conformity analysis, the monthly VMT fractions are from taken from the HPMS data. This data also assumes that these fractions apply to all vehicle types. Using data from fixed detectors that includes volumes and vehicle classification, another set of temporal VMT fractions were calculated.

The data from the detectors includes fifteen classes of vehicles. The first thirteen classes directly correspond to the FHWA's HPMS program classes, while classes fourteen and fifteen are vehicles that the counting station could not classify. These thirteen classes correspond to six vehicle classification in MOVES and are shown in Table 4.9.

Table 4.9: HPMS and MOVES Vehicle Classification Matching Scheme

HPMS 13 classes	**HPMS 6 classes**	**MOVES vehicle class**
Motorcycles	Motorcycles	Motorcycle
All cars and w/1 or 2-axle trailer	Passenger cars	Passenger car
Pickups and vans 1&2 axle trailer	Other 2-axle/4-tire vehicles	Passenger truck
		Light commercial truck
Buses	Buses	Intercity bus
		Transit bus
		School bus
2-axle single unit	Single unit trucks	Refuse truck
3-axle single unit		Single-unit short-haul truck
4-axle single unit		Single-unit long-haul truck
		Motor home
Tractor with single or multiple trailers (class 8,9,10,11,12,13)	Combination trucks	Combination short-haul truck
		Combination long-haul truck

Once this detector data was reviewed, cleaned and aggregated in the MOVES classes, a new set of VMT fractions by month, day type and hour were developed. The monthly fractions developed by this study are showed in Table 4.10. There is no valid data for rural restricted roadways and for motorcycle vehicle type. VMT temporal fractions of current conformity analysis were used for motorcycles and rural restricted road types for all vehicle types. For comparison, HPMS-based VMT fractions currently used for conformity analysis and the MOVES default data table in Table 4.11 and Figure 4.10.

Table 4.10: VMT Monthly Fractions by Vehicle Type from ATR Counts

Month	**Passenger Cars**	**Other 2-axle / 4-tire Vehicles**	**Buses**	**Single Unit Trucks**	**Combination Trucks**
1	6.10%	7.05%	6.20%	7.12%	6.44%
2	6.50%	7.36%	6.88%	7.39%	6.81%
3	6.12%	6.95%	7.24%	6.79%	6.59%
4	7.71%	9.05%	10.28%	8.18%	9.68%
5	8.04%	9.73%	9.24%	8.52%	10.17%
6	7.93%	9.35%	8.36%	8.93%	10.26%
7	7.86%	9.19%	7.17%	8.44%	8.96%
8	7.74%	9.12%	7.46%	9.36%	8.36%
9	8.70%	8.49%	9.13%	10.75%	7.84%
10	14.17%	8.45%	12.31%	9.10%	9.10%
11	10.71%	7.79%	8.68%	8.07%	8.14%
12	8.43%	7.47%	7.05%	7.36%	7.64%

Table 4.11: VMT Monthly Fractions by Vehicle Type from HPMS Data and MOVES Default

Month	HPMS	MOVES Default	Month	HPMS	MOVES Default
1	7.95%	7.29%	7	8.77%	9.21%
2	7.35%	7.20%	8	9.05%	9.32%
3	8.34%	8.15%	9	8.19%	8.45%
4	8.59%	8.21%	10	7.95%	8.63%
5	9.01%	8.73%	11	7.84%	8.00%
6	8.60%	8.81%	12	8.36%	8.00%

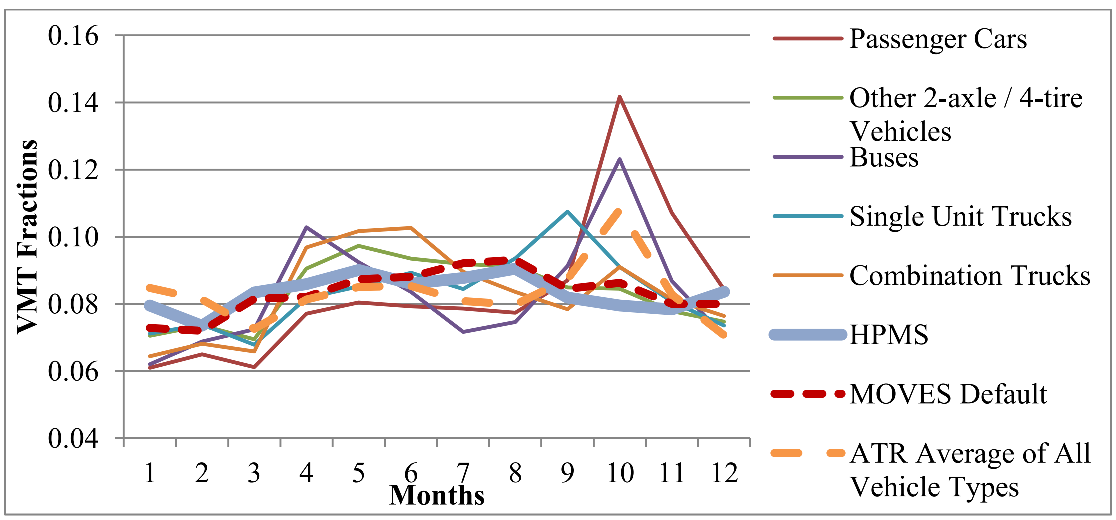

Figure 4.10: Comparison of ATR Generated VMT Fractions with HPMS VMT Fractions and MOVES Default

4.4.2 Daily and Hourly VMT Fraction

MOVES daily VMT fractions are used to account for activity variations between weekdays and weekends. MOVES hourly VMT fractions further divide the activities into each hour of the day. Different from monthly fractions, at these two levels, these two fractions also include road type. Current local conformity analysis does not have VMT fractions of this level of details so MOVES default was used. The results of the processed VMT fractions by day and hour are in Appendix B and Appendix C.

4.4.3 Result and Summary

The emission results using the VMT fractions processed from ATR data versus the current conformity analysis using HPMS monthly fraction and MOVES default daily/hourly fractions are showed in Table 4.12. Since VMT temporal fractions don't directly change the amount of total activity or the operating mode distribution, the output of the emission changed by this input relatively small. However, it defines the group for which operating modes distributions are calculated and treated with temperature effect separately. In this sense, for temperature sensitive areas and for areas with significant traffic pattern change during different time, this input needs to be carefully measured and processed to ensure the accuracy of the emission result.

Table 4.12: Total Emission Result Comparison Using Different VMT Temporal Fractions

	HPMS + MOVES Default	**ATR VMT Fractions**	**Difference %**
HC Gaseous	1031.184	1006	-2.43%
CO	11909.71	11484	-3.57%
NO_x	2537.234	2462	-2.96%
Non-Methane HC	984.58	960	-2.46%
Energy Consumption	8489706	8017061	-5.57%
PM 10 Total	68.78	67	-2.38%
Brake Wear PM 10	16.18	15	-8.31%
PM 2.5 Total	65.55	64	-2.31%
Brake Wear PM 2.5	4.24	4	-8.31%

Chapter 5

VEHICLE STARTS

The previous section analyzed emissions from running vehicles. These running emissions are the focus of many studies and research reports, due to their perceived importance in the emissions inventory. However, comparing the sources of the emissions with the vehicle activities, there are several pollutants of interest that running represents the minority source. This is shown in Table 5.1. Emissions during starts and due to evaporation could be the majority contributors.

Table 5.1: Emissions Output Break Down by Emission Processes and Pollutant

	Running	Start	Evaporative	Extended Idle	Refueling
Gaseous Hydrocarbons	25%	54%	19%	1%	2%
Carbon Monoxide	51%	49%	0%	0%	0%
Oxides of Nitrogen	81%	17%	0%	2%	0%
Non-Methane Hydrocarbons	25%	53%	20%	1%	2%
VOC	25%	52%	20%	1%	2%
Exhaust PM10	88%	10%	0%	1%	0%
Exhaust PM 2.5	89%	10%	0%	1%	0%

5.1 Start Activity Calculations and Start Operating Mode Distribution

As talked about in section 3.2.2, MOVES calculates start emissions using the average number of starts per vehicle per hour and a determination of fractions of each type of start. These two parameters are needed for each vehicle type, at each hour.

Similar to the driving schedules MOVES used for running emissions, MOVES contains a set of built-in sample vehicle trips which describe start operating modes. Each of the sample vehicle trips has been associated with a vehicle type, a day type, a start and finish time, and the ID of the trip prior to this trip for this same vehicle. The information in this dataset enables MOVES to calculate the number of starts for each type of vehicle at different time. These sample trips used by MOVES were developed from past studies. Table 5.2 [49] shows data sources used for starts for different vehicle types and their sample sizes. For some vehicle types, there has been no relevant study. These vehicles use trips from similar vehicle types which are shown in Table 5.3 [49].

Table 5.2: Source Data for Sample Vehicle Trip Information

Study	Study Area	Study Years	Vehicle Type	Sample Size
3-City	Atlanta, GA; Baltimore, MD; Spokane, WA	1992	Passenger cars & trucks	321
Minneapolis	Minneapolis/St. Paul, MN	2004-2005	Passenger cars & trucks	133
Knoxville	Knoxville, TN	2000-2001	Passenger cars & trucks	377
Las Vegas	Las Vegas, NV	2004-2005	Passenger cars & trucks	350
Battelle	California, statewide	1997-1998	Heavy duty trucks	120
TXDOT	Houston, TX	2002	Heavy duty diesel dump trucks	4

Table 5.3: Synthesis of Sample Vehicles for Vehicle types Lacking Data

Vehicle type	Direct Data?	Synthesized From
Motorcycles	No	Passenger Cars
Passenger Cars	Yes	
Passenger Trucks	Yes	
Light Commercial Trucks	No	Passenger Trucks
Intercity Buses	No	Combination long-haul trucks
Transit Buses	No	Single-unit short-haul trucks
School Buses	No	Single-unit short-haul trucks
Refuse Trucks	No	Combination short-haul trucks
Single-unit short-haul trucks	Yes	
Single-unit long-haul trucks	No	Combination long-haul trucks
Motor homes	No	Passenger Cars
Combination short-haul trucks	Yes	
Combination long-haul trucks	Yes	

The average starts calculated from the provided MOVES default database are shown below in Table 5.4. MOVES has distributed these starts into different hours of the day and the starts by each hour could be found in Appendix C.

Table 5.4: MOVES Build-in Vehicle Starts

Vehicle Type	Weekend	Weekdays
Motorcycle	1.497	0.445
Passenger Car	5.038	5.871
Passenger Truck	4.701	5.771
Light Commercial Truck	5.055	6.017
Intercity Bus	0.875	2.767
Transit Bus	3.461	4.578
School Bus	1.259	5.748
Refuse Truck	0.922	3.750
Single Unit Short-haul Truck	1.281	6.991
Single Unit Long-haul Truck	1.285	4.287
Motor Home	0.561	0.566
Combination Short-haul Truck	1.157	5.930
Combination Long-haul Truck	1.285	4.287

MOVES differentiate starts by the time they spend parking before the vehicle is started, which is referred to as the soak time. A starting operating mode is assigned for each trip by measuring the time between the end of the last trip and the start of this trip as shown in Table 5.5 [50]. Table 5.6 below shows the operating mode distribution for passenger cars for a weekday over 24 hours.

Table 5.5: Operating Mode Criteria in MOVES

Mode ID	Definition
101	Soak Time < 6 minutes
102	6 minutes <= Soak Time < 30 minutes
103	30 minutes <= Soak Time < 60 minutes
104	60 minutes <= Soak Time < 90 minutes
105	90 minutes <= Soak Time < 120 minutes
106	120 minutes <= Soak Time < 360 minutes
107	360 minutes <= Soak Time < 720 minutes
108	720 minutes <= Soak Time

Table 5.6: Weekday 24 hrs. Start Mode Distribution for Passenger Car

Hr	<6min	6-30min	30-60min	60-90min	90-120min	120-360min	360-720min	> 720min
1	31.82%	9.09%	18.18%	9.09%	0.00%	22.73%	9.09%	0.00%
2	8.33%	16.67%	12.50%	4.17%	4.17%	25.00%	29.17%	0.00%
3	0.00%	0.00%	0.00%	33.33%	33.33%	33.33%	0.00%	0.00%
4	38.46%	15.38%	0.00%	7.69%	15.38%	0.00%	23.08%	0.00%
5	10.00%	0.00%	0.00%	0.00%	0.00%	10.00%	80.00%	0.00%
6	15.38%	0.00%	2.56%	0.00%	2.56%	2.56%	46.15%	30.77%
7	18.18%	1.14%	4.55%	0.00%	0.00%	0.00%	44.32%	31.82%
8	12.71%	5.93%	2.97%	1.69%	0.00%	2.12%	29.66%	44.92%

Table 5.6 continued.

Hr	<6min	6-30min	30-60min	60-90min	90-120min	120-360min	360-720min	> 720min
9	22.91%	17.09%	4.73%	2.18%	0.00%	0.73%	13.82%	38.55%
10	20.33%	28.02%	9.89%	4.40%	3.30%	3.30%	6.04%	24.73%
11	26.98%	21.40%	11.16%	7.44%	0.93%	11.16%	3.72%	17.21%
12	23.57%	25.71%	10.71%	4.29%	4.29%	16.43%	2.14%	12.86%
13	26.56%	24.66%	13.28%	4.88%	3.25%	17.89%	1.63%	7.86%
14	23.60%	32.58%	10.86%	5.62%	5.62%	10.86%	3.75%	7.12%
15	19.75%	23.46%	12.65%	8.02%	5.56%	15.74%	9.57%	5.25%
16	26.75%	29.48%	8.51%	4.86%	5.47%	10.03%	11.25%	3.65%
17	20.16%	26.16%	8.17%	9.81%	4.36%	14.44%	13.35%	3.54%
18	22.89%	21.53%	10.63%	4.09%	5.72%	17.17%	15.80%	2.18%
19	21.90%	20.59%	11.44%	11.76%	4.58%	16.34%	11.11%	2.29%
20	17.07%	21.95%	18.29%	10.98%	7.72%	14.23%	8.54%	1.22%
21	15.89%	20.53%	12.58%	12.58%	9.93%	20.53%	6.62%	1.32%
22	23.81%	13.49%	11.90%	7.94%	8.73%	30.16%	3.97%	0.00%
23	12.90%	30.11%	2.15%	7.53%	3.23%	34.41%	6.45%	3.23%
24	12.31%	16.92%	9.23%	0.00%	6.15%	29.23%	21.54%	4.62%

5.2 Developing Local Data

A travel demand model generates trips from one transportation analysis zone to another in the study area based on land use type and demographic properties. The trips were generated for each type of vehicle separately. From description the vehicle types covered by the travel demand model and the required vehicle classifications from

MOVES, passenger cars and light trucks are the only vehicle types that have a separate trips data. Trips for trucks or buses are grouped together across many MOVES truck types and there is no available information to single out each MOVES vehicle type's trip data. So this study would be targeting on customized starts for passenger car and light trucks only. Since no data on how many stops and re-starts happened during each trip, another assumption made here is that each trip equals to one start.

The study area in this analysis would be New Castle County, Delaware, but the travel demand model includes trips to and from all three counties in Delaware as well as neighboring states. A GIS file of all transportation analysis zones was used to identify the zones in New Castle County, and processed the trips to keep only the trips starting from New Castle County, which would be 355169 in total (Table 5.7).

Table 5.7: Origin and Destinations of Trips from Travel Demand Model

From\To	**New Castle County**	**Other**	**Grand Total**
New Castle County	213560	141608	355168
Other	150808	406030	556838
Grand Total	364369	547638	912007

The temporal distribution of the starts from the travel demand model is one of four periods: off peak, morning peak, mid-day, and afternoon peak. The fractions used to distribute the starts are shown in Table 5.8. Within each time period, the starts were uniformly distributed since no better data was available. The starts per hour per vehicle for New Castle County Delaware are shown in Table 5.9.

Table 5.8: Distribution of Trips in the four Periods of a Day

Period	**%**	**Covered Hours**	**Passenger Car**	**Light Truck**
AM Peak	22%	3 hours, 6:30AM to 9:30AM	491816	78137.18
Mid-Day	16%	3 hours, 10:00AM to 1:00PM	364606	56827.04
PM Peak	23%	3 hours, 3:00PM to 6:00PM	525307	81688.87
Off Peak	39%	All other 15 hours	904186	142067.6

Table 5.9: Starts per Vehicle in 24 Hours of a Day

Hour	**Passenger Car**	**Light Truck**	**Hour**	**Passenger Car**	**Light Truck**
1	0.494022456	0.09505163	13	0.996053641	0.19010326
2	0.494022456	0.09505163	14	0.494022456	0.09505163
3	0.494022456	0.09505163	15	0.494022456	0.09505163
4	0.494022456	0.09505163	16	1.435066757	0.273273436
5	0.494022456	0.09505163	17	1.435066757	0.273273436
6	0.494022456	0.09505163	18	1.435066757	0.273273436
7	0.918798194	0.178221806	19	0.494022456	0.09505163
8	1.343573933	0.261391983	20	0.494022456	0.09505163
9	1.343573933	0.261391983	21	0.494022456	0.09505163

Table 5.9 continued.

Hour	Passenger Car	Light Truck	Hour	Passenger Car	Light Truck
10	0.918798194	0.178221806	22	0.494022456	0.09505163
11	0.996053641	0.19010326	23	0.494022456	0.09505163
12	0.996053641	0.19010326	24	0.494022456	0.09505163

5.3 Difference in Number of Starts and the Impact on MOVES Emission Output

Using the local travel demand model as a source of start data estimated twice as many starts as the national average shown in Figure 5.1 and the light trucks starts were about half of the national average as seen in Figure 5.2 and Figure 5.3. These differences in input data for starts generated a significant change in emissions inventory for both start emission showing in Table 5.10 or total emissions showing in Table 5.11. The responsible agency for emissions inventories would have to decide which data set better represents the condition in the county and use that data set.

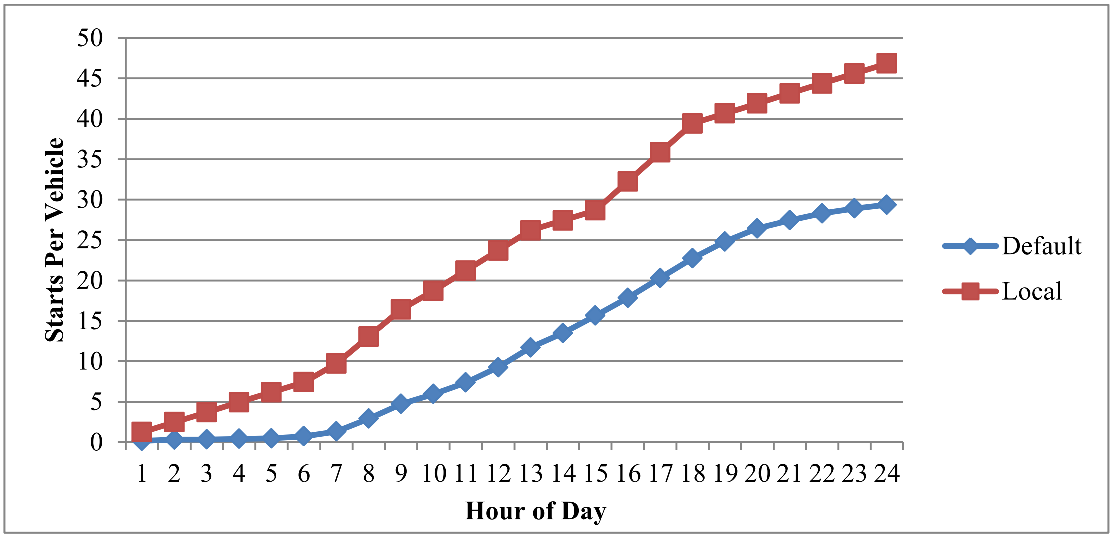

Figure 5.1: Number of Starts Comparison of Default MOVES data and Local data from Travel Demand Model for Passenger Car

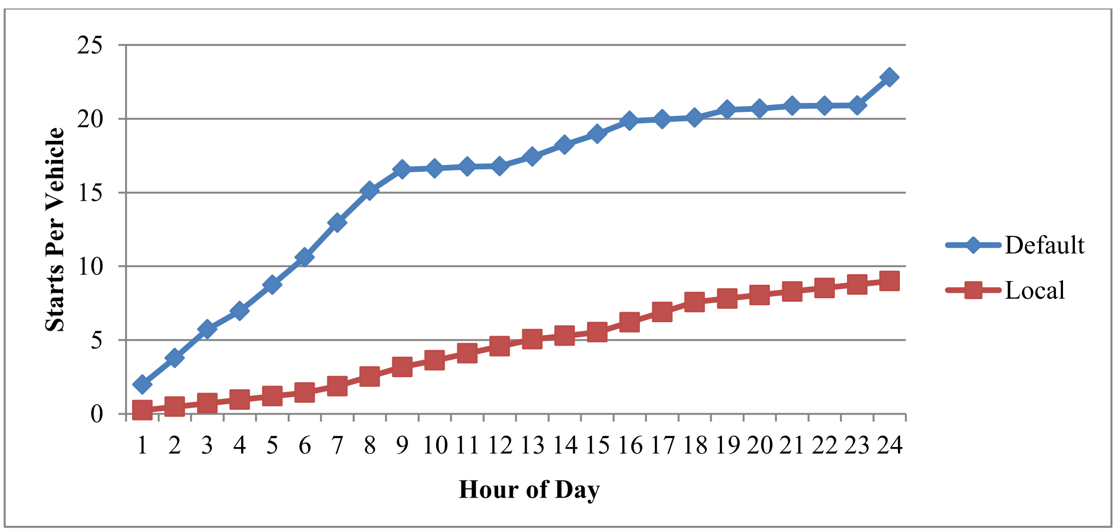

Figure 5.2: Number of Starts Comparison of Default MOVES data and Local data from Travel Demand Model for Passenger Truck

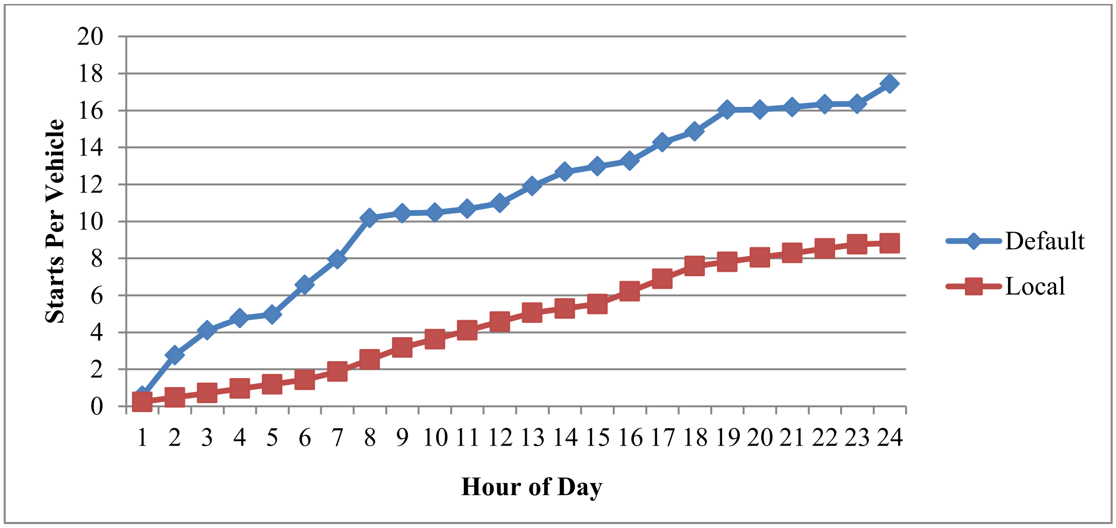

Figure 5.3: Number of Starts Comparison of Default MOVES data and Local data from Travel Demand Model for Light Commercial Truck

Table 5.10: Start Emission in Current NCC Conformity Analysis and the Change by Using Population/Age Distribution Forecasted by This Research for Passenger Car and Light Trucks

Pollutant	**Current Start Emissions**	**Study Forecasted Passenger Cars**	**Study Forecasted Light Trucks**
Total Gaseous Hydrocarbons	545.32	5.95%	-32.29%
Carbon Monoxide	5794.65	5.79%	-33.17%
Oxides of Nitrogen	428.91	-1.03%	-35.82%
Non-Methane Hydrocarbons	511.39	5.94%	-32.12%
Total Energy Consumption	361158.84	7.35%	-29.58%
Exhaust PM10 Total	6.99	10.31%	-27.32%
Exhaust PM2.5 Total	4.64	10.26%	-27.36%

Table 5.11: Total Emission from All Processes in Current NCC Conformity Analysis and the Change by Using Population/Age Distribution Forecasted by This Research for Passenger Car and Light Trucks

Pollutant	Current Conformity	This Study
Total Gaseous Hydrocarbons	1031.184	-14.14%
Carbon Monoxide	11909.71	-13.32%
Oxides of Nitrogen	2537.234	-6.23%
Non-Methane Hydrocarbons	984.58	-13.80%
Total Energy Consumption	8489706	-0.95%
Exhaust PM10 Total	68.78	-1.80%
Exhaust PM2.5 Total	65.54	-1.75%

Chapter 6

VEHICLE POPULATION AND AGE DISTRIBUTION

6.1 Age Distribution Algorithm

The last inputs to MOVES that will be examined in this research are vehicle population and vehicle age distribution. Vehicle age determines the emissions reduction technology installed in the vehicles and its deterioration in performance over time. These age factors are part of the running, start and evaporative emission calculations. The data source for population and age would come from the state's motor vehicle registration records. This data is suitable for current year analyses but since MOVES is used for future projections, some way to project this data into the future must be developed. Methods are provided for national analyses, but little detail is provided for model users about how to project population and age into the future for more regional analyses. For national level analysis, MOVES uses sales, migration, and survival to predict for changes in vehicle population and age distribution in future years. Sales growth is based on the current annual energy outlook report of the Energy Information Institute and is also included in EPA reports regarding using MOVES [49; 51; 52]. For each year beyond the base year, a new vehicle sales population can be estimated. The annual energy outlook reports are also produced on a regional level and it was this regional report that was used for this research and should be used by local agencies. The MOVES model uses a migration rate and a survival rate to account for changes in population over time. Migration is the percentage of vehicles moving in or out of the region, which for national level analyses is assumed to be 1. Survival is the percentage of vehicles from year 0 that are still on the road in year 1, year 1 to year 2, and so on. This national survival data is based on sources including R.L.Polk reports and is also found in EPA reports on using MOVES[49; 53] [52] [54]. A schematic representation of this process is found in Figure 6.1below. This method is similar to the Cohort Survival Projection method which is commonly used for human population forecasting.

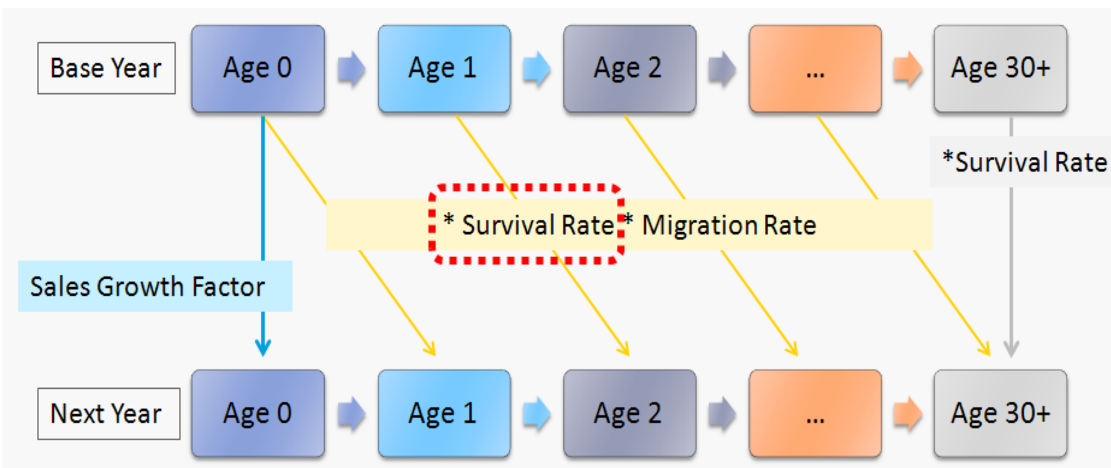

Figure 6.1: Vehicle Population and Age Distribution Forecasting in MOVES

6.2 Developing Local Vehicle Population and Age Distribution for Future Years

In this section a procedure of developing more locally tailored vehicle population and age distribution would be explained.

6.2.1 Developing Population Change Rate for Different Ages

Nine years of registration data was obtained from the Delaware Department of Motor Vehicles for calendar years 2002, 2004, 2005, 2007, 2008, 2009, 2010, 2011 and 2012. The vehicle population data was sorted and re-grouped by model year as shown inAppendix E. For example, for model year 2001, the data set would provide us with population data for years 1 (2002 data set), year 3 (2004 data set), year 4 (2005 data set), etc. The trends for population change are shown in Figure 6.2 below.

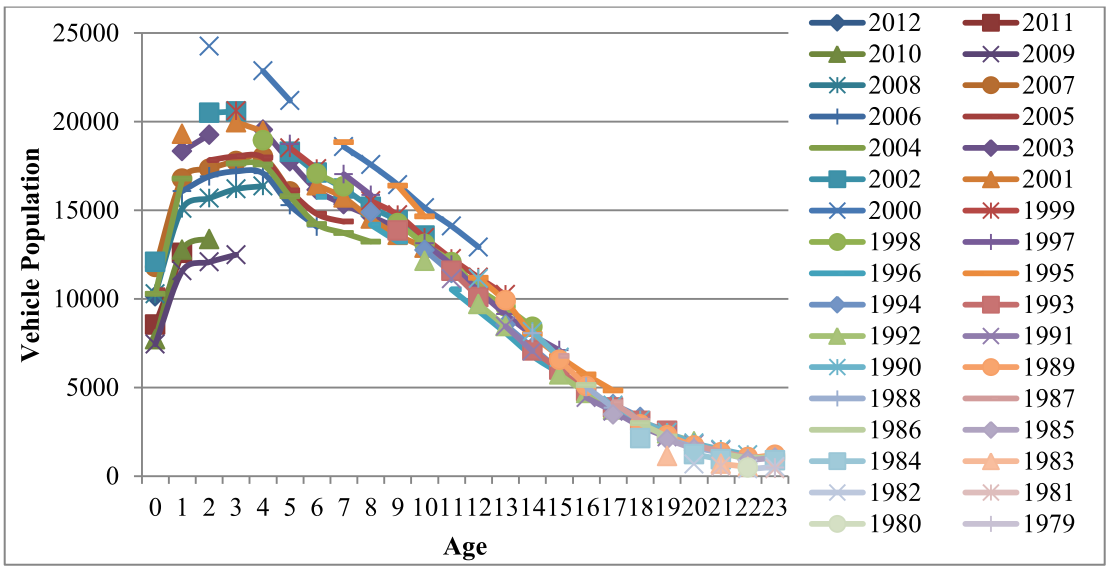

Figure 6.2: Population Change for Passenger Cars of Different Model Years

The figure above shows a similar trend for each model year. The total population rises until about year 4 and then decreases at a varying rate over time. Using the three factors MOVES uses for population and age distribution, the shape of this graph represents the combined effects of migration and survival. The term migration will include all increases in a model year population and survival will be the decreases. Migration would include individuals that move into the area and register their cars for the first time in Delaware or individuals purchasing used cars. The MOVES national level assumption of migration equaling 1 is no longer applicable. Without a far more detailed data set, it is impossible to calculate separate migration and survival rates. However, a combined rate was calculated based on the limited registration data that was available. Four curves and their associated formulas were developed for use with passenger vehicles and light trucks and for the time periods of 0-4 years and beyond 4 years. Sufficient data for heavier and multi-axle trucks did not exist with the registration data. In many cases these vehicles are registered in one state and operate in many. Buses and heavy vehicles used in state fleets would also not be part of DMV data, MOVES defaults would be used for these classes. The four curves are shown in Figure 6.3,Figure 6.4,Figure 6.5 and Figure 6.6. The population change rates were calculated from the functions of the trend line and are shown in Table 6.1.

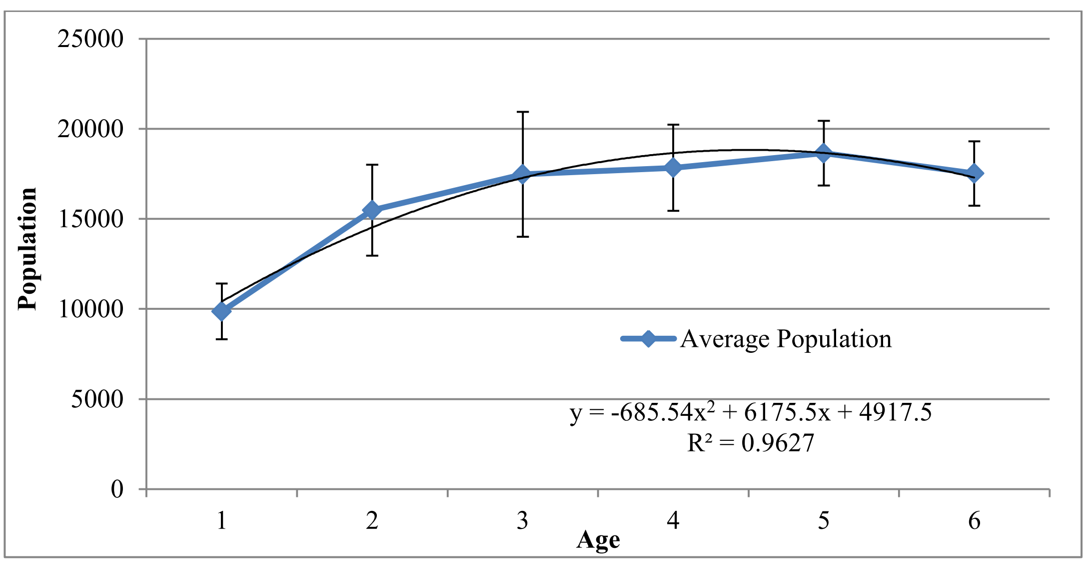

Figure 6.3: Function of Age to Population for Age 0-5 for Passenger Cars

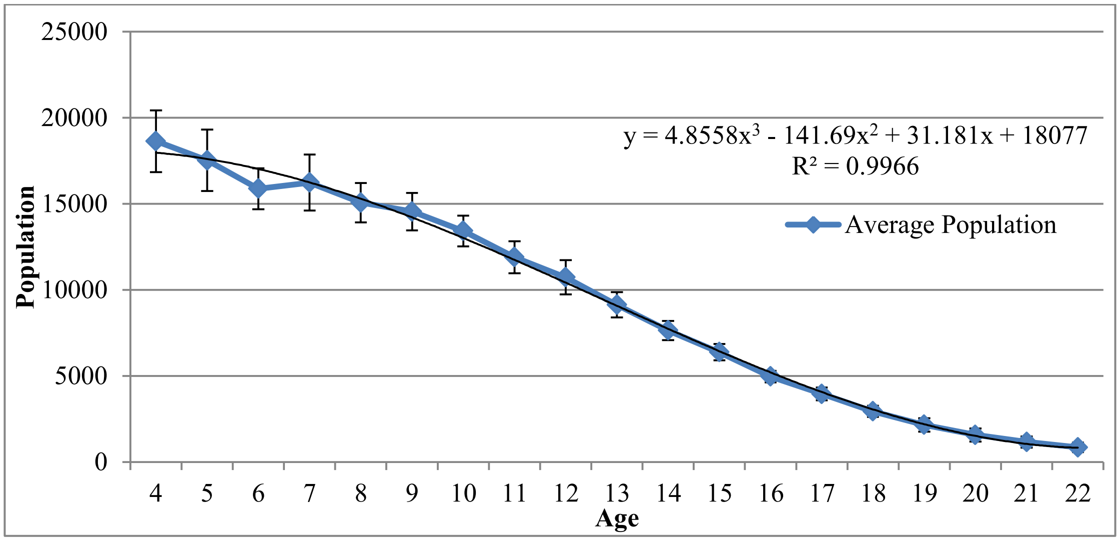

Figure 6.4: Function of Age to Population for Age 4-22 for Passenger Cars

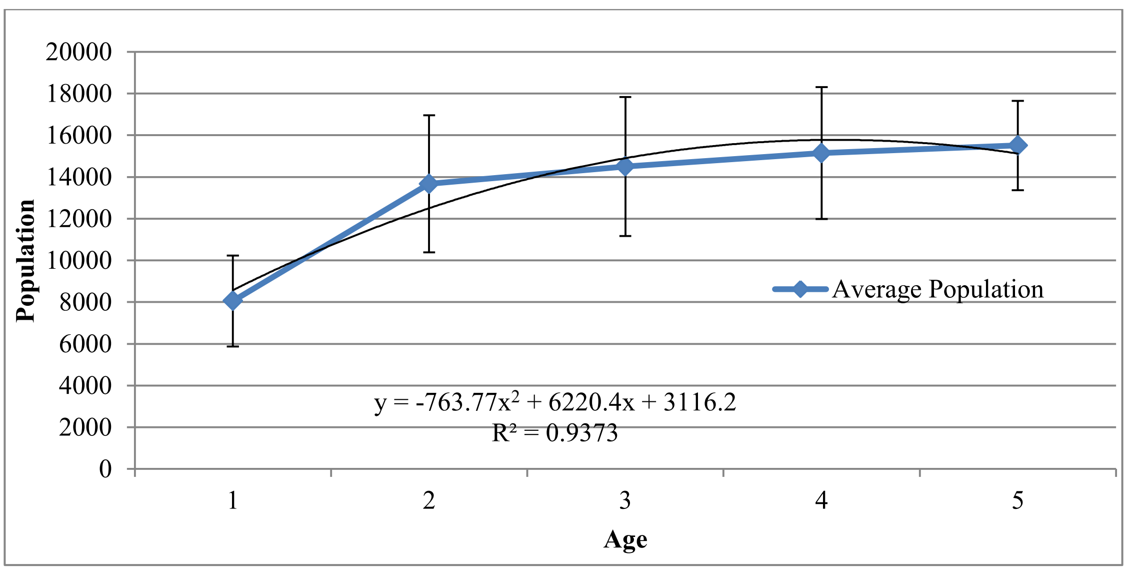

Figure 6.5: Function of Age and Population for Age 0-4 for Light Trucks

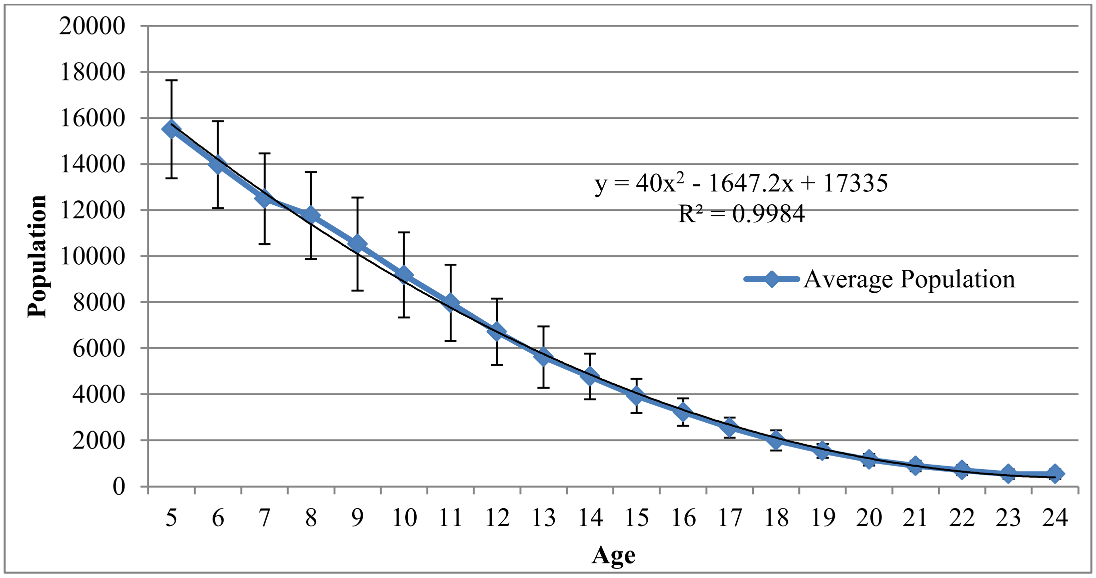

Figure 6.6: Function of Age and Population for Age 4-22 for Light Trucks

Table 6.1: Population Change Rate for Different Ages in New Castle County, DE

Age	Car	Truck	Age	Car	Truck	Age	Car	Truck
0 - 1	1.396	1.458	10 - 11	0.902	0.865	20 - 21	0.693	0.723
1 - 2	1.189	1.192	11 - 12	0.887	0.856	21 - 22	0.786	0.741
2 - 3	1.080	1.059	12 - 13	0.871	0.846	22 - 23	0.786	0.741
3 - 4	1.000	0.959	13 - 14	0.853	0.834	23 - 24	0.786	0.741
4 - 5	0.927	0.903	14 - 15	0.832	0.821	24 - 25	0.786	0.741
5 - 6	0.967	0.898	15 - 16	0.808	0.806	25 - 26	0.786	0.741
6 - 7	0.954	0.893	16 - 17	0.781	0.788	26 - 27	0.786	0.741
7 - 8	0.942	0.887	17 - 18	0.751	0.770	27 - 28	0.786	0.741
8 - 9	0.929	0.880	18 - 19	0.718	0.750	28 - 29	0.786	0.741
9 - 10	0.916	0.873	19 - 20	0.691	0.732	29 - 30	0.786	0.741

6.2.2 Sales Growth Factor

As discussed earlier, MOVES uses the 2009 Annual Energy Outlook report to develop sales growth factors for 2008 through 2030. The national sales trends are found in Table 57. Table 49 is the mid-Atlantic region data, which was used for Delaware's specific sales growth Also, the 2012 report, was used as part of this analysis. The sales growth factors are listed in Table 6.2.

Table 6.2: Sales Growth Factors Derived for Mid-Atlantic Area

Year	Car	Light Truck	Year	Car	Light Truck
2009 - 2010	1.087475	1.08454	2022 - 2023	1.015637	0.990356
2010 - 2011	1.176029	1.054407	2023 - 2024	1.009575	0.99558
2011 - 2012	1.021234	1.022772	2024 - 2025	1.005265	0.989104
2012 - 2013	1.120999	1.113146	2025 - 2026	1.003763	0.996547
2013 - 2014	1.074592	1.022227	2026 - 2027	1.000831	0.998862
2014 - 2015	1.049696	1.008842	2027 - 2028	0.993178	0.994615
2015 - 2016	1.031855	1.002567	2028 - 2029	0.994325	0.98263
2016 - 2017	0.976107	1.016184	2029 - 2030	0.999889	0.984367
2017 - 2018	0.989981	0.947367	2030 - 2031	1.000575	0.980448
2018 - 2019	1.01296	0.983173	2031 - 2032	0.991815	0.99643
2019 - 2020	1.014322	0.966575	2032 - 2033	0.998257	1.017291
2020 - 2021	1.018153	0.994086	2033 - 2034	1.003017	0.997646
2021 - 2022	1.034999	1.009793	2034 - 2035	0.999269	0.995583

6.3 Vehicle Population and Age Distribution Input Data Comparison

Using the 2012 vehicle population from DMV registration, the sales growth factors for the Mid-Atlantic area, the population change rate developed from historic DMV data a projection for year 2030 for passenger cars and light trucks was developed and compared to using the current conformity analysis' approach in New Castle County, DE[46]. The result is shown in Table 6.3, Figure 6.7 and Figure 6.8.

Table 6.3: Vehicle Population Result Compared with Current Conformity Analysis Assumption

Car	DelDOT Car	Difference	Light Truck	DelDOT Truck[46]	Difference
276487	286061	-3.35%	122167	175531	-30.40%

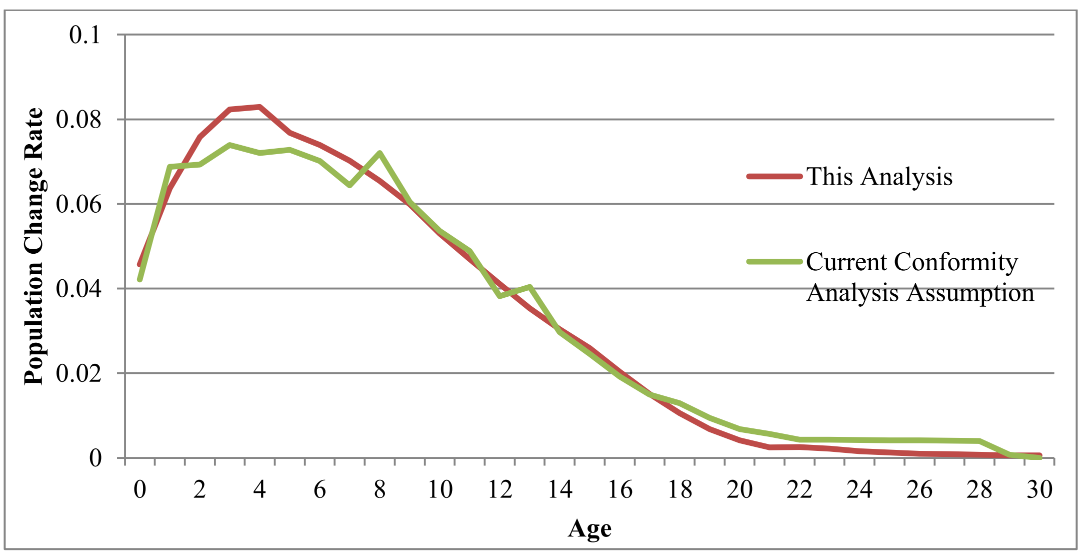

Figure 6.7: Passenger Car Age Distribution Comparison

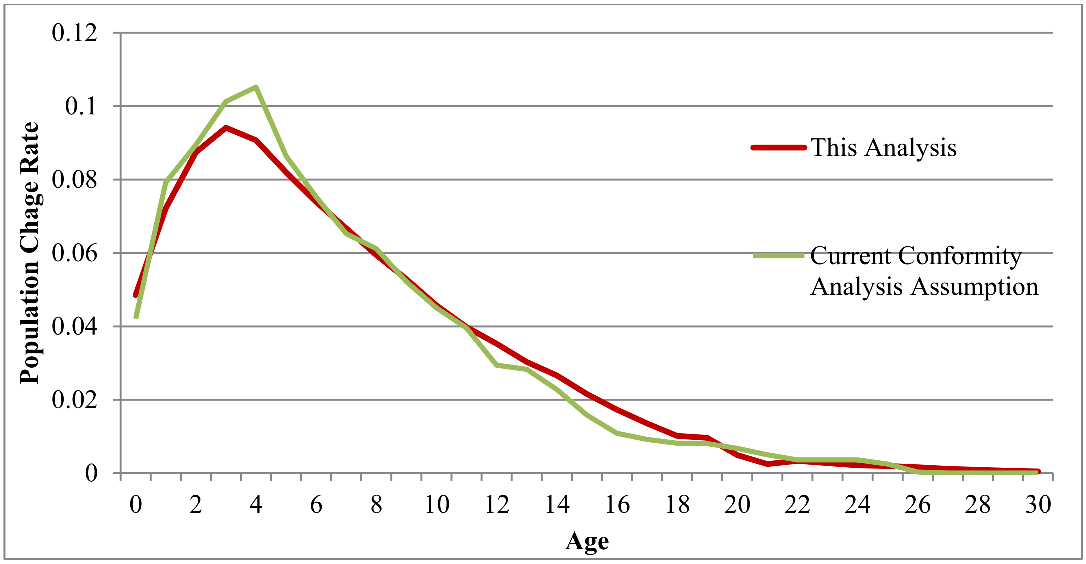

Figure 6.8: Light Truck Age Distribution Comparison

6.4 Emission Output Comparison

Comparing the emissions inventories of the populations, the impacts of the new data set are significant for hydrocarbon and VOC and is shown in Table 6.4. Emissions from the light trucks changed proportional to population input, but emissions from passenger cars changed more than the its population input.

Table 6.4: Emission Impact for Using Local Vehicle Population and Age Distribution Forecast Vs. Current Regional Conformity Analysis' Result

Pollutant	**Passenger Car**	**Light Passenger Truck**	**Light Commercial Truck**	**Total Emission**
Total Gaseous Hydrocarbons	-8.80%	-31.40%	-29.86%	-16.30%
Oxides of Nitrogen	-6.02%	-6.96%	-6.76%	-4.77%
Non-Methane Hydrocarbons	-9.31%	-30.00%	-28.24%	-15.91%
VOC	-9.41%	-29.99%	-28.27%	-15.91%
Energy Consumption	-0.64%	-1.74%	-1.62%	-1.04%
Exhaust PM2.5	-5.51%	-7.46%	-7.41%	-5.73%
PM2.5 - Break Wear	0.00%	-0.05%	0.16%	0.00%
PM2.5 - Tire Wear	0.00%	-0.05%	0.17%	0.00%

Chapter 7

CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

MOVES was created as the next generation in mobile source emissions modeling. MOVES represents a significant shift in thinking by EPA and FHWA because it is a model based on the 24 hour activity of a vehicle. It has better consideration with the emission calculation structure, yet it is data intensive. Many inputs for MOVES came from transportation planning models or field measured data. This data required preprocessing, during which assumptions were made and data were aggregated. At each step, there may be an impact on the emissions inventory.

This dissertation presented the motivation, comparison of the MOBILE and MOVES models, current and alternative sources of input data and the impacts of these alternative sources on emissions inventory estimates. Some of the current assumptions involving data sources have also been looked at as well as the strength or weaknesses of those assumptions. Most of the significant data inputs for MOVES have been analyzed in this research. These included speed distribution, road type distributions, temporal distributions; vehicle starts estimates and vehicle population and age distributions. The alternative data sources, pre-processing key points and section number are listed in the table below:

Table 7.1: Alternatives to Current Practices

Input	Current NCC Conformity	Alternative	Processing Keys	Section
Average speed distribution	Travel demand model forecast	Travel demand model+ field measured speed	Apply link distributions from field measured data to each speed bin fraction of the travel demand model	4.2.3
VMT road type distribution	Three road types fractions	Four road types fractions	GIS spatial analysis to determine road fraction of rural restricted road	4.3
VMT temporal distribution	Month – HPMS Day & hour – default	Field vehicle counts at multiple locations	Vehicle counts aggregated at each time level	4.4
Average number of starts	MOVES default	Travel demand model's trips generated	Vehicle trips starting in the analysis area / population	5.2
Future vehicle population / age distribution	Human population * vehicle ownership rates Current vehicle age distribution	DMV registration data of recent years Annual energy outlook	Sales growth factor using local value from annual energy outlook Population change trend from past registration data	6.2

In each case, a comparison was made between the emissions inventory obtained by using this new data source and the inventory currently calculated by DelDOT using their current practices. Some of the inventory estimate changes were small. Providing alternative inputs for speed distribution was a very processing intensive process compared to the current DelDOT practice and did not result in a significant shift in emission inventory. A similar small shift was seen for changing road type classifications and for new temporal distributions. However, a significant change in emissions inventory estimate was found with a new process for estimating starts and one for vehicle population and age. State agencies should give strong consideration for evaluating current practices and adopting the methods presented in this research. EPA could also consider providing the methods developed in this research to all MOVES users for estimating vehicle populations and ages, since no methods are provided in the current manuals. A summary table of the impacts of each input change is shown below. Each of these are using the current year vehicle emission inventory.

Table 7.2: Inventory Impacts Based on Proposed Methods

Pollutant	Current Conformity (U.S ton)	Start	Temporal VMT fraction	Adding Rural Restricted Road	Speed Distribution TDM+FM
Total Gaseous Hydrocarbons	1031.184	-14.14%	-2.43%	-1.15%	3.501%
Carbon Monoxide	11909.71	-13.32%	-3.57%	-1.07%	2.001%
Oxides of Nitrogen	2537.234	-6.23%	-2.96%	-1.52%	2.341%
Non-Methane Hydrocarbons	984.58	-13.80%	-2.46%	-1.16%	3.551%
Exhaust PM10 Total	68.78	-1.80%	-2.38%	-1.29%	8.629%
Exhaust PM2.5 Total	65.54	-1.75%	-2.31%	-1.33%	8.744%
Brake Wear PM 10			-8.31%	-12.79%	44.655%
Brake Wear PM 2.5			-8.31%	-12.79%	44.655%

For vehicle population analysis, the new method provided an alternative to determining the 2030 population and age distribution. The impact of the alternative method is shown below.

Table 7.3: Inventory Impacts Based on Proposed Methods for Age and Population

Emission 2030	Current Conformity Analysis	Change Based on Proposed Method
Total Gaseous Hydrocarbons	367.95	-16.30%
Oxides of Nitrogen	651.63	-4.77%
Non-Methane Hydrocarbons	321.37	-15.91%
Volatile Organic Compounds	331.14	-15.91%
Primary Exhaust PM2.5 Total	19.46	-5.73%
Primary PM2.5 – Brake wear Particulate	15.89	0.00%
Primary PM2.5 – Tire wear Particulate	3.20	0.00%

This research has looked at the model's properties to better understand these observed difference for these inputs. Based on a series of inputs including speed, vehicle and road type, MOVES selects a driving schedule to imitate the experience of a driver and vehicle during a trip. The driving schedule provides a speed profile as well as periods of acceleration, braking and idling. However, these driving schedules might be too generic to accurately capture behavior in regions. The driving patterns in large, congested metropolitan areas like Los Angeles, Boston and New York, might bear little resemblance to the patterns in smaller and less congested MPOs. Also, there are few driving schedules for MOVES to select from which may explain why three of the alternative methods resulted in only small changes in emissions inventory.

These research has provided new methods and simplified data requirements for agencies' emission analysis with MOVES. This work has also provided priorities for either updating the MOVES default database or for developing localized data for better assessments for conformity analysis.

7.2 Future Work

One portion of the MOVES model that might warrant more detailed review and analysis are the driving schedules. EPA might look for ways that regional users can select or develop the set of driving schedules that are the best fit to their region. Of course, the impacts of selecting the wrong set of schedules must also be considered and analyzed for.

Transportation agencies are collecting huge volumes of data regarding speed, volume and overall system performance. There could be on-going analysis of how this real time data can be utilized instead of travel demand model outputs. Other than developing the local vehicle starts, it would be worth looking into to develop the start mode distributions. This requires more trip data, and activity based travel demand model could be considered for this purpose.

Also, the vehicle population and age distribution methods presented in this research could be further analyzed and developed. In the development of the future vehicle population and age distribution, if migration of vehicles among surrounding states could be recorded, migration rate and survival rate could be studies separately. Sales growth rate and survival rate could be related to economic factors that can only be studied with more data.

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Appendix A

FIELD MEASURED SPEED DISTRIBUTION LOCATIONS

Name	Type	Area	MOVES Road Type
Rt. 72 South of Rt. 7	2-lane	Rural	RU
Rt. 896 West of Rt. 13	2-lane	Rural	RU
Rt. 301 South of Old School House Rd.	2-lane	Rural	RU
Route 41 Near PA State Line (North of McGovern Rd.)	2-lane	Rural	RU
Rt. 13 South of Rt. 1/13 Split	Multi	Rural	RU
Rt. 202 Outh of PA boader line	Multi	Urban	UU
Rt. 92 (Naamans Rd). Bet. Grubb Rd. & Bradywine Town Center	Multi	Urban	UU
Rt. 92 North of Woodlawn Rd.	2-lane	Urban	UU
Rt. 202 South of Naamans Rd.	Multi	Urban	UU
Grubb Rd. East of Foulk Rd.	2-lane	Urban	UU
Wilson Rd. East of Shipley Rd.	2-lane	Urban	UU
Rt. 261 (Foulk Rd.) North of Rt. 202	Multi	Urban	UU
Rt. 52 North of Hillside Rd.	2-lane	Urban	UU
Rt. 202 South of Foulk Rd.	Multi	Urban	UU
Rt. 48 East of Centerville Rd.	Multi	Urban	UU
Rt. 41 South of Hercules Rd.	2-lane	Urban	UU
Rt. 7 South of Rt. 72	Multi	Urban	UU

Name	Type	Area	MOVES Road Type
Rt. 273 between Red Mill Rd. & Ogletown Rd.	Multi	Urban	UU
Rt. 4 East of Harmony Rd.	Multi	Urban	UU
Rt. 141 South of I-95	Multi	Urban	UU
Rt. 4 East of Gender Rd.	Multi	Urban	UU
Rt. 273 between I-95 & Old Baltimore Pike	Multi	Urban	UU
Rt. 273 between Prangs Rd. & Pleasant Dr.	Multi	Urban	UU
Rt. 13 South of Route 13/40 Split	Multi	Urban	UU
Rt. 896 North of Rt. 40	Multi	Urban	UU
Rt. 72 North of Rt. 40	2-lane	Urban	UU
Rt. 71 West of Rt. 7	2-lane	Urban	UU
Rt. 299 East of Middletown	2-lane	Urban	UU
Rt. 2 (Kirkwood Hwy.) West of St. James Chruch Rd.	Multi	Urban	UU
Route 4 between Elkton Rd. and Rt. 896	Multi	Urban	UU
Rt. 141 South of Boxwood Rd.	Restricted	Urban	UR
Rt. 1 South of Rt. 1/13 Split	Restricted	Urban	UR

Appendix B

DAILY VMT FRACTIONS GENERATED FROM ATR COUNTS

Roadway Type	Month	Day	Motorcycles	Passenger Cars	Other 2-axle / 4-tire Vehicles	Single Unit Trucks	Buses	Combination Trucks
Rural Unrestricted	1	2	43.03%	41.89%	42.71%	23.17%	27.53%	28.73%
	2	2	42.92%	42.54%	42.06%	25.96%	26.18%	25.86%
	3	2	43.21%	47.44%	40.62%	21.99%	24.87%	23.98%
	4	2	43.37%	49.64%	44.31%	27.73%	29.79%	28.41%
	5	2	54.08%	50.47%	46.63%	30.81%	32.43%	29.69%
	6	2	50.91%	53.58%	47.39%	28.46%	31.88%	30.15%
	7	2	54.66%	57.21%	49.91%	29.52%	34.84%	30.97%
	8	2	39.24%	50.24%	45.82%	27.65%	32.60%	27.76%
	9	2	57.84%	50.54%	47.80%	32.93%	41.53%	31.28%
	10	2	48.66%	50.50%	47. 88%	31.27%	34.97%	29.65%
	11	2	44.41%	50.41%	46.07%	29.79%	31.87%	29.64%
	12	2	22.08%	46.66%	41.90%	25.65%	28.59%	27.46%

Roadway Type	Month	Day	Motorcycles	Passenger Cars	Other 2-axle / 4-tire Vehicles	Single Unit Trucks	Buses	Combination Trucks
Rural Unrestricted	1	5	56.97%	58.11%	57.29%	76.83%	72.47%	71.27%
	2	5	57.08%	57.46%	57.94%	74.04%	73.82%	74.14%
	3	5	56.79%	52.56%	59.38%	78.01%	75.13%	76.02%
	4	5	56.63%	50.36%	55.69%	72.27%	70.21%	71.59%
	5	5	45.92%	49.53%	53.37%	69.19%	67.57%	70.31%
	6	5	49.09%	46.42%	52.61%	71.54%	68.12%	69.85%
	7	5	45.34%	42.79%	50.09%	70.48%	65.16%	69.03%
	8	5	60.76%	49.76%	54.18%	72.35%	67.40%	72.24%
	9	5	42.16%	49.46%	52.20%	67.07%	58.47%	68.72%
	10	5	51.34%	49.50%	52.12%	68.73%	65.03%	70.35%
	11	5	55.59%	49.59%	53.93%	70.21%	68.13%	70.36%
	12	5	77.92%	53.34%	58.10%	74.35%	71.41%	72.54%
Urban Restricted	1	2	31.24%	49.41%	39.61%	26.62%	24.31%	24.19%
	2	2	25.94%	47.97%	38.89%	23.48%	24.62%	24.93%
	3	2	28.27%	49.15%	40.19%	23.81%	26.27%	24.93%
	4	2	41.15%	49.48%	39.87%	27.68%	26.50%	23.83%

Roadway Type	Month	Day	Motorcycles	Passenger Cars	Other 2-axle / 4-tire Vehicles	Single Unit Trucks	Buses	Combination Trucks
Urban Restricted	5	2	56.18%	50.77%	42.16%	29.85%	27.56%	25.66%
	6	2	50.41%	58.53%	43.08%	33.17%	28.07%	27.31%
	7	2	40.33%	48.32%	44.40%	29.32%	26.63%	26.14%
	8	2	33.40%	49.85%	40.74%	30.18%	25.54%	26.42%
	9	2	36.59%	40.87%	41.65%	27.87%	24.76%	25.85%
	10	2	34.61%	42.94%	41.11%	40.55%	29.53%	28.02%
	11	2	52.99%	34.50%	41.62%	35.53%	26.32%	26.27%
	12	2	45.21%	18.94%	39.94%	28.74%	23.28%	24.96%
Urban Restricted	1	5	68.76%	50.59%	60.39%	73.38%	75.69%	75.81%
	2	5	74.06%	52.03%	61.11%	76.52%	75.38%	75.07%
	3	5	71.73%	50.85%	59.81%	76.19%	73.73%	75.07%
	4	5	58.85%	50.52%	60.13%	72.32%	73.50%	76.17%
	5	5	43.82%	49.23%	57.84%	70.15%	72.44%	74.34%
	6	5	49.59%	41.47%	56.92%	66.83%	71.93%	72.69%
	7	5	59.67%	51.68%	55.60%	70.68%	73.37%	73.86%

Roadway Type	Month	Day	Motorcycles	Passenger Cars	Other 2-axle / 4-tire Vehicles	Single Unit Trucks	Buses	Combination Trucks
Urban Restricted	8	5	66.60%	50.15%	59.26%	69.82%	74.46%	73.58%
	9	5	63.41%	59.13%	58.35%	72.13%	75.24%	74.15%
	10	5	65.39%	57.06%	58.89%	59.45%	70.47%	71.98%
	11	5	47.01%	65.50%	58.38%	64.47%	73.68%	73.73%
	12	5	54.79%	81.06%	60.06%	71.26%	76.72%	75.04%
Urban Unrestricted	1	2	24.18%	46.12%	39.98%	19.74%	27.37%	29.98%
	2	2	33.49%	47.11%	41.37%	23.37%	29.09%	31.28%
	3	2	40.17%	46.99%	41.52%	24.17%	28.40%	30.76%
	4	2	50.14%	48.03%	41.38%	42.35%	31.01%	32.89%
	5	2	51.96%	48.53%	43.46%	26.47%	30.81%	31.48%
	6	2	50.35%	48.49%	43.41%	24.11%	30.67%	32.95%
	7	2	50.86%	51.36%	45.13%	26.73%	30.76%	31.01%
	8	2	41.25%	48.88%	44.18%	26.39%	29.52%	29.38%
	9	2	41.98%	47.39%	45.99%	24.72%	33.08%	30.27%
	10	2	49.25%	48.46%	44.64%	26.29%	31.17%	33.39%

Roadway Type	Month	Day	Motorcycles	Passenger Cars	Other 2-axle / 4-tire Vehicles	Single Unit Trucks	Buses	Combination Trucks
	11	2	43.57%	48.35%	43.94%	26.47%	30.57%	33.24%
	12	2	32.64%	46.81%	41.41%	23.64%	27.54%	30.88%
Urban Unrestricted	1	5	75.82%	53.88%	60.02%	80.26%	72.63%	70.02%
	2	5	66.51%	52.89%	58.63%	76.63%	70.91%	68.72%
	3	5	59.83%	53.01%	58.48%	75.83%	71.60%	69.24%
	4	5	49.86%	51.97%	58.62%	57.65%	68.99%	67.11%
	5	5	48.04%	51.47%	56.54%	73.53%	69.19%	68.52%
	6	5	49.65%	51.51%	56.59%	75.89%	69.33%	67.05%
	7	5	49.14%	48.64%	54.87%	73.27%	69.24%	68.99%
	8	5	58.75%	51.12%	55.82%	73.61%	70.48%	70.62%
	9	5	58.02%	52.61%	54.01%	75.28%	66.92%	69.73%
	10	5	50.75%	51.54%	55.36%	73.71%	68.83%	66.61%
	11	5	56.43%	51.65%	56.06%	73.53%	69.43%	66.76%
	12	5	67.36%	53.19%	58.59%	76.36%	72.46%	69.12%

Appendix C

HOURLY VMT FRACTIONS GENERATED FROM ATR COUNTS

Roadway Type	Day	Hour	Passenger Cars	Other 2-axle / 4-tire Vehicles	Single Unit Trucks	Buses	Combination Trucks
Rural Unrestricted	2	1	1.38%	1.14%	1.89%	1.52%	4.01%
	2	2	0.97%	0.74%	1.93%	1.05%	3.64%
	2	3	0.76%	0.52%	1.90%	0.85%	3.50%
	2	4	0.75%	0.52%	3.40%	1.01%	3.27%
	2	5	0.76%	0.83%	4.09%	1.37%	3.37%
	2	6	0.92%	1.46%	2.86%	2.13%	3.75%
	2	7	1.52%	2.32%	3.40%	3.07%	3.78%
	2	8	2.47%	3.38%	4.64%	4.17%	3.95%
	2	9	3.79%	4.52%	4.77%	5.13%	4.41%
	2	10	4.97%	5.49%	5.30%	5.49%	4.80%
	2	11	6.31%	6.68%	5.13%	6.46%	5.33%
	2	12	7.22%	7.30%	7.54%	7.77%	5.48%
	2	13	7.67%	7.78%	5.75%	6.92%	5.61%
	2	14	7.85%	7.68%	5.67%	7.04%	5.24%
	2	15	7.79%	7.43%	6.17%	7.76%	4.86%
	2	16	7.74%	7.43%	5.53%	6.43%	4.68%
	2	17	7.50%	6.98%	4.93%	5.83%	4.51%
	2	18	6.85%	6.33%	5.35%	5.79%	4.37%
	2	19	6.01%	5.73%	5.12%	5.14%	3.83%
	2	20	5.06%	4.88%	4.72%	4.61%	3.94%
	2	21	4.31%	4.08%	3.85%	3.42%	3.61%
	2	22	3.37%	3.22%	2.33%	3.16%	3.51%
	2	23	2.49%	2.19%	2.13%	2.29%	3.41%
	2	24	1.54%	1.36%	1.60%	1.57%	3.13%
	5	1	0.67%	0.59%	0.77%	0.62%	2.51%
	5	2	0.49%	0.37%	0.69%	0.61%	2.53%
	5	3	0.38%	0.29%	0.97%	0.65%	2.69%
	5	4	0.42%	0.40%	1.93%	1.09%	3.11%
	5	5	0.75%	0.88%	3.05%	1.67%	3.44%
	5	6	1.83%	2.96%	4.21%	3.83%	3.97%
	5	7	3.96%	5.91%	5.51%	5.77%	4.00%
	5	8	5.93%	5.84%	6.23%	6.87%	4.26%

Roadway Type	Day	Hour	Passenger Cars	Other 2-axle / 4-tire Vehicles	Single Unit Trucks	Buses	Combination Trucks
Rural Unrestricted	5	9	5.47%	5.65%	7.38%	7.23%	4.92%
	5	10	4.99%	5.49%	7.61%	7.10%	5.48%
	5	11	5.06%	5.66%	6.93%	6.89%	5.89%
	5	12	5.52%	5.98%	7.22%	6.92%	5.84%
	5	13	5.94%	6.14%	6.58%	6.98%	5.84%
	5	14	6.18%	6.36%	6.80%	7.14%	5.60%
	5	15	6.55%	6.87%	6.15%	6.86%	5.33%
	5	16	7.21%	8.07%	6.44%	6.79%	5.01%
	5	17	8.04%	7.89%	5.35%	6.08%	4.55%
	5	18	8.19%	6.64%	4.19%	4.83%	4.26%
	5	19	6.59%	5.35%	3.85%	3.61%	4.04%
	5	20	4.96%	4.07%	2.88%	2.56%	3.73%
	5	21	4.04%	3.37%	1.81%	2.17%	3.46%
	5	22	3.24%	2.52%	1.27%	1.74%	3.48%
	5	23	2.23%	1.65%	1.25%	1.16%	3.17%
	5	24	1.36%	1.06%	0.92%	0.84%	2.89%
Urban Restricted	2	1	2.98%	1.55%	3.42%	2.18%	3.38%
	2	2	2.82%	1.14%	3.27%	2.01%	3.51%
	2	3	2.61%	0.96%	3.44%	1.81%	3.59%
	2	4	2.44%	0.98%	3.11%	1.85%	3.61%
	2	5	2.48%	1.28%	3.12%	2.25%	4.10%
	2	6	2.50%	2.13%	3.01%	3.38%	4.20%
	2	7	2.77%	3.39%	4.35%	4.73%	4.38%
	2	8	3.32%	3.99%	4.39%	5.23%	4.79%
	2	9	3.83%	4.68%	5.65%	6.20%	5.15%
	2	10	4.52%	5.45%	5.60%	6.28%	5.65%
	2	11	5.21%	6.05%	5.32%	6.20%	5.77%
	2	12	5.57%	6.50%	5.05%	6.22%	5.50%
	2	13	5.79%	6.54%	5.29%	5.91%	5.11%
	2	14	5.75%	6.60%	5.01%	5.92%	4.91%
	2	15	5.60%	6.76%	4.87%	5.74%	4.27%
	2	16	5.67%	6.82%	4.71%	5.69%	4.06%
	2	17	5.60%	6.58%	4.29%	5.92%	4.07%
	2	18	4.98%	6.23%	4.42%	5.22%	3.76%
	2	19	5.11%	5.66%	4.55%	4.36%	3.63%
	2	20	4.76%	4.76%	4.23%	3.39%	3.50%
	2	21	4.47%	3.96%	3.72%	2.86%	3.39%
	2	22	4.24%	3.29%	3.44%	2.51%	3.30%
	2	23	3.77%	2.68%	2.93%	2.24%	3.42%
	2	24	3.21%	2.00%	2.80%	1.88%	2.96%

Roadway Type	Day	Hour	Passenger Cars	Other 2-axle / 4-tire Vehicles	Single Unit Trucks	Buses	Combination Trucks
Urban Restricted	5	1	2.86%	0.74%	1.72%	1.00%	2.28%
	5	2	2.72%	0.56%	1.77%	1.05%	2.40%
	5	3	2.62%	0.57%	1.92%	1.08%	2.57%
	5	4	2.72%	0.78%	2.18%	1.50%	3.19%
	5	5	3.05%	1.54%	3.03%	2.33%	4.12%
	5	6	3.71%	4.38%	3.37%	4.30%	4.78%
	5	7	4.93%	7.90%	6.68%	6.37%	4.92%
	5	8	5.87%	6.43%	6.16%	6.90%	4.62%
	5	9	5.39%	5.85%	7.27%	7.09%	5.27%
	5	10	4.84%	5.28%	6.71%	7.29%	6.34%
	5	11	4.85%	5.23%	6.32%	7.39%	6.70%
	5	12	4.90%	5.17%	6.48%	7.50%	6.76%
	5	13	4.80%	5.24%	6.35%	7.26%	6.38%
	5	14	4.63%	5.63%	6.28%	7.18%	5.95%
	5	15	4.59%	6.57%	6.00%	7.14%	5.65%
	5	16	4.86%	8.03%	5.24%	6.26%	4.70%
	5	17	5.04%	7.29%	4.61%	4.77%	3.79%
	5	18	5.12%	6.16%	3.30%	3.48%	3.22%
	5	19	4.58%	4.75%	3.10%	2.70%	3.00%
	5	20	4.16%	3.57%	2.82%	2.01%	2.85%
	5	21	3.72%	2.77%	2.66%	1.65%	2.80%
	5	22	3.52%	2.24%	2.30%	1.41%	2.70%
	5	23	3.39%	1.87%	1.84%	1.22%	2.56%
	5	24	3.13%	1.46%	1.91%	1.13%	2.43%
Urban Unrestricted	2	1	1.40%	1.16%	2.58%	1.52%	3.23%
	2	2	0.89%	0.77%	1.97%	1.13%	3.12%
	2	3	0.61%	0.54%	1.58%	0.91%	2.98%
	2	4	0.47%	0.53%	1.72%	1.05%	2.92%
	2	5	0.54%	0.78%	4.56%	1.57%	3.02%
	2	6	0.89%	1.57%	2.52%	2.45%	3.06%
	2	7	1.75%	2.63%	3.01%	3.37%	3.46%
	2	8	2.67%	3.54%	4.80%	4.37%	3.96%
	2	9	3.86%	4.59%	4.83%	5.19%	4.35%
	2	10	5.12%	5.68%	5.41%	5.98%	4.47%
	2	11	6.45%	6.75%	5.77%	6.83%	4.97%
	2	12	7.21%	7.45%	7.58%	7.39%	5.10%
	2	13	7.61%	7.61%	5.53%	7.26%	4.98%
	2	14	7.77%	7.52%	5.28%	6.96%	4.87%
	2	15	7.74%	7.42%	6.06%	6.76%	4.61%
	2	16	7.58%	7.21%	5.11%	6.59%	4.50%

Roadway Type	Day	Hour	Passenger Cars	Other 2-axle / 4-tire Vehicles	Single Unit Trucks	Buses	Combination Trucks
	2	17	7.32%	6.95%	4.95%	6.32%	4.55%
	2	18	6.79%	6.48%	5.65%	5.72%	4.67%
	2	19	6.10%	5.77%	5.15%	5.04%	4.67%
	2	20	5.09%	4.83%	4.79%	4.09%	4.65%
	2	21	4.25%	3.80%	3.59%	3.32%	4.62%
	2	22	3.42%	2.93%	3.06%	2.59%	4.58%
	2	23	2.67%	2.10%	2.47%	2.11%	4.59%
	2	24	1.79%	1.39%	2.03%	1.49%	4.06%
Urban Unrestricted	5	1	0.73%	0.53%	0.85%	0.70%	2.92%
	5	2	0.40%	0.34%	0.72%	0.67%	3.04%
	5	3	0.29%	0.30%	0.83%	0.68%	3.07%
	5	4	0.33%	0.46%	1.27%	1.10%	3.33%
	5	5	0.69%	1.07%	3.03%	1.93%	3.75%
	5	6	1.94%	3.59%	3.42%	4.29%	3.90%
	5	7	5.01%	7.65%	5.15%	6.43%	4.16%
	5	8	7.47%	6.69%	6.60%	6.50%	4.44%
	5	9	6.61%	5.76%	5.86%	6.63%	4.78%
	5	10	5.26%	5.48%	6.55%	6.84%	5.30%
	5	11	4.93%	5.39%	6.16%	6.72%	5.54%
	5	12	5.12%	5.46%	7.11%	6.83%	5.67%
	5	13	5.35%	5.56%	6.44%	6.84%	5.55%
	5	14	5.47%	5.73%	6.92%	6.86%	5.35%
	5	15	5.92%	6.32%	7.59%	6.88%	5.03%
	5	16	6.69%	7.90%	7.48%	7.20%	4.68%
	5	17	7.76%	8.18%	5.85%	6.40%	4.35%
	5	18	8.22%	6.93%	4.71%	4.94%	4.03%
	5	19	6.55%	5.30%	3.99%	3.65%	3.77%
	5	20	4.76%	3.83%	3.58%	2.60%	3.63%
	5	21	3.79%	2.87%	1.97%	1.85%	3.55%
	5	22	3.05%	2.16%	1.59%	1.44%	3.60%
	5	23	2.23%	1.51%	1.30%	1.12%	3.40%
	5	24	1.44%	0.97%	1.05%	0.90%	3.16%

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Appendix D

AVERAGE VEHICLE STARTS BY VEHICLE TYPE AND HOUR

Weekends

Hr	Passenger Car	Passenger Truck	Light Commercial Truck	Intercity Bus	Transit Bus	School Bus	Refuse Truck	Single Unit Short-haul Truck	Single Unit Long-haul Truck	Motor Home	Combination Short-haul Truck	Combination Long-haul Truck
1	0.0814	0.0377	0.0406	0.0694	0.0000	0.0000	0.1250	0.0000	0.1020	0.0101	0.1569	0.1020
2	0.0378	0.0108	0.0116	0.0278	0.0000	0.0000	0.0313	0.0000	0.0408	0.0055	0.0392	0.0408
3	0.0378	0.0081	0.0087	0.0139	0.0000	0.0000	0.0000	0.0000	0.0204	0.0041	0.0000	0.0204
4	0.0174	0.0054	0.0058	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0023	0.0000	0.0000
5	0.0058	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0009	0.0000	0.0000
6	0.0145	0.0054	0.0058	0.0278	0.0000	0.0000	0.0313	0.0000	0.0408	0.0018	0.0392	0.0408
7	0.0523	0.0566	0.0609	0.0000	0.0000	0.0000	0.0938	0.0000	0.0000	0.0041	0.1176	0.0000
8	0.0843	0.0728	0.0783	0.0000	0.0769	0.0345	0.1250	0.0351	0.0000	0.0129	0.1569	0.0000
9	0.1453	0.1429	0.1536	0.0556	0.0769	0.0517	0.0938	0.0526	0.0816	0.0175	0.1176	0.0816
10	0.2413	0.2722	0.2928	0.0278	1.1538	0.3276	0.0938	0.3333	0.0408	0.0309	0.1176	0.0408
11	0.3169	0.2722	0.2928	0.0556	0.7692	0.2414	0.1094	0.2456	0.0816	0.0332	0.1373	0.0816
12	0.3314	0.3208	0.3449	0.1111	0.3846	0.3103	0.0469	0.3158	0.1633	0.0406	0.0588	0.1633
13	0.4855	0.4340	0.4667	0.0556	0.0769	0.0172	0.0000	0.0175	0.0816	0.0507	0.0000	0.0816
14	0.3605	0.5445	0.5855	0.1389	0.0769	0.0172	0.0469	0.0175	0.2041	0.0401	0.0588	0.2041
15	0.4564	0.3558	0.3826	0.0000	0.0769	0.0172	0.0000	0.0175	0.0000	0.0470	0.0000	0.0000
16	0.4535	0.3612	0.3884	0.0278	0.1538	0.0690	0.0313	0.0702	0.0408	0.0475	0.0392	0.0408
17	0.3459	0.4690	0.5043	0.0833	0.3077	0.0690	0.0000	0.0702	0.1224	0.0420	0.0000	0.1224
18	0.3634	0.4070	0.4377	0.0278	0.3077	0.1034	0.0000	0.1053	0.0408	0.0396	0.0000	0.0408

Hr	Passenger Car	Passenger Truck	Light Commercial Truck	Intercity Bus	Transit Bus	School Bus	Refuse Truck	Single Unit Short-haul Truck	Single Unit Long-haul Truck	Motor Home	Combination Short-haul Truck	Combination Long-haul Truck
19	0.3488	0.4420	0.4754	0.0417	0.0000	0.0000	0.0000	0.0000	0.0612	0.0424	0.0000	0.0612
20	0.2791	0.1348	0.1449	0.0278	0.0000	0.0000	0.0000	0.0000	0.0408	0.0258	0.0000	0.0408
21	0.1948	0.1375	0.1478	0.0556	0.0000	0.0000	0.0313	0.0000	0.0816	0.0184	0.0392	0.0816
22	0.1599	0.0916	0.0986	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0184	0.0000	0.0000
23	0.1308	0.0539	0.0580	0.0000	0.0000	0.0000	0.0469	0.0000	0.0000	0.0129	0.0588	0.0000
24	0.0930	0.0647	0.0696	0.0278	0.0000	0.0000	0.0156	0.0000	0.0408	0.0124	0.0196	0.0408

Weekdays

Hr	Passenger Car	Passenger Truck	Light Commercial Truck	Intercity Bus	Transit Bus	School Bus	Refuse Truck	Single Unit Short-haul Truck	Single Unit Long-haul Truck	Motor Home	Combination Short-haul Truck	Combination Long-haul Truck
1	0.0293	0.0496	0.0517	0.0847	0.0000	0.0000	0.0098	0.0000	0.1311	0.0031	0.0155	0.1311
2	0.0319	0.0136	0.0142	0.0688	0.0000	0.0000	0.0147	0.0000	0.1066	0.0037	0.0233	0.1066
3	0.0040	0.0062	0.0065	0.1005	0.0000	0.0000	0.0343	0.0000	0.1557	0.0006	0.0543	0.1557
4	0.0173	0.0074	0.0078	0.0952	0.0000	0.0000	0.0784	0.0000	0.1475	0.0011	0.1240	0.1475
5	0.0133	0.0236	0.0246	0.1164	0.0367	0.0296	0.0833	0.0360	0.1803	0.0017	0.1318	0.1803
6	0.0519	0.0385	0.0401	0.1270	0.2018	0.1778	0.1029	0.2162	0.1967	0.0061	0.1628	0.1967
7	0.1184	0.2655	0.2768	0.2222	0.1651	0.1704	0.2402	0.2072	0.3443	0.0131	0.3798	0.3443
8	0.3138	0.3598	0.3752	0.2169	0.1193	0.2444	0.3725	0.2973	0.3361	0.0370	0.5891	0.3361
9	0.3670	0.3660	0.3816	0.1429	0.7706	0.9481	0.3775	1.1532	0.2213	0.0368	0.5969	0.2213
10	0.2420	0.3536	0.3687	0.2222	0.3394	0.6222	0.3333	0.7568	0.3443	0.0214	0.5271	0.3443
11	0.2886	0.2903	0.3027	0.1958	0.3945	0.6074	0.3284	0.7387	0.3033	0.0282	0.5194	0.3033
12	0.3723	0.4206	0.4386	0.1270	0.5413	0.7259	0.2696	0.8829	0.1967	0.0344	0.4264	0.1967
13	0.4934	0.3896	0.4062	0.1270	0.4954	0.5778	0.2549	0.7027	0.1967	0.0449	0.4031	0.1967
14	0.3551	0.3747	0.3907	0.1429	0.3303	0.4074	0.2696	0.4955	0.2213	0.0324	0.4264	0.2213
15	0.4322	0.3065	0.3195	0.1587	0.3853	0.4296	0.2402	0.5225	0.2459	0.0422	0.3798	0.2459

Hr	Passenger Car	Passenger Truck	Light Commercial Truck	Intercity Bus	Transit Bus	School Bus	Refuse Truck	Single Unit Short-haul Truck	Single Unit Long-haul Truck	Motor Home	Combination Short-haul Truck	Combination Long-haul Truck
16	0.4388	0.4665	0.4864	0.1799	0.3945	0.4074	0.1765	0.4955	0.2787	0.0370	0.2791	0.2787
17	0.4894	0.4330	0.4515	0.0741	0.2569	0.2593	0.1912	0.3153	0.1148	0.0460	0.3023	0.1148
18	0.4934	0.4293	0.4476	0.0476	0.0367	0.0444	0.1324	0.0541	0.0738	0.0446	0.2093	0.0738
19	0.4096	0.3958	0.4127	0.0423	0.0826	0.0741	0.0539	0.0901	0.0656	0.0368	0.0853	0.0656
20	0.3271	0.2568	0.2678	0.0741	0.0275	0.0222	0.0588	0.0270	0.1148	0.0335	0.0930	0.1148
21	0.2021	0.2494	0.2600	0.0582	0.0000	0.0000	0.0392	0.0000	0.0902	0.0212	0.0620	0.0902
22	0.1689	0.1253	0.1307	0.0529	0.0000	0.0000	0.0441	0.0000	0.0820	0.0175	0.0698	0.0820
23	0.1237	0.1092	0.1138	0.0423	0.0000	0.0000	0.0343	0.0000	0.0656	0.0127	0.0543	0.0656
24	0.0878	0.0397	0.0414	0.0476	0.0000	0.0000	0.0098	0.0000	0.0738	0.0101	0.0155	0.0738

Appendix E

VEHICLE REGISTRATION POPULATION IN NEW CASTLE COUNTY, DE

PASSENGER CAR

Age / Model Year	2002	2004	2005	2007	2008	2009	2010	2011	2012
0	12075	10273	10480	11,788	10,284	7,439	7,722	8550	10140
1	19299	18333	16773	16,078	16,781	15,095	11,573	12777	12584
2	24260	20501	19262	17,819	16,908	17,338	15,676	12075	13367
3	20612	19965	20577	17,631	18,043	17,197	17,778	16195	12489
4	18944	22858	19464	19,548	17,565	17,973	17,081	18018	16359
5	18724	18516	21189	18,305	17,749	15,777	16,120	15280	16062
6	15749	17068	17345	16,408	17,116	16,148	14,214	14788	14069
7	18838	17037	16338	18,581	15,707	16,216	15,327	13718	14354
8	14884	14180	15866	15,530	17,580	14,529	15,185	14663	13222
9	13848	16379	13218	14,276	14,744	16,443	13,604	14430	13990
10	12131	12758	14642	13,139	13,089	13,458	15,143	12887	13565
11	11131	11584	11452	10,524	11,916	12,069	12,268	14103	12040
12	11147	9703	10095	11,175	9,311	10,448	10,583	11209	12922
13	9914	8454	8446	8,536	9,857	8,077	9,138	9549	10234
14	8063	8145	7050	7,086	7,256	8,000	6,774	7981	8417

Age / Model Year	2002	2004	2005	2007	2008	2009	2010	2011	2012
15	6778	6551	6697	5,730	5,999	5,981	6,762	5824	7097
16	5136	5038	5080	4,420	4,685	4,785	4,830	5722	4969
17	3470	4153	3854	3,986	3,651	3,734	3,864	4056	4825
18	2127	2979	3104	2,908	3,149	2,824	2,949	3106	3332
19	1124	2064	2219	2,089	2,296	2,462	2,208	2399	2543
20	662	1230	1532	1,760	1,640	1,710	1,871	1786	1953
21	540	684	945	1,277	1,382	1,304	1,334	1504	1451
22	472	394	518	892	1,037	1,075	1,002	1062	1193
23	472	394	518	892	1,037	1,075	1,002	1062	1193
24	5575	5428	5152	5017	5,189	5,528	5,936	6232	6522

LIGHT TRUCKS

Age / Model Year	2002	2004	2005	2007	2008	2009	2010	2011	2012
0	10273	10888	10035	9551	7629	3996	5789	7525	6816
1	15253	16852	18653	15300	14279	12923	7286	9932	12542
2	15994	17256	17403	18123	15837	14783	13201	7583	10369
3	14164	15283	17008	19384	18175	16101	14871	13550	7737
4	11874	14261	14889	17319	19089	17908	15669	15003	13564
5	10582	11877	13149	14673	15505	16932	15807	13880	13365
6	8731	10490	11115	12199	13527	13956	15245	14484	12704
7	8871	9493	9989	11500	11608	12756	13202	14531	13924

Age / Model Year	2002	2004	2005	2007	2008	2009	2010	2011	2012
8	7846	7786	8855	9959	10873	10745	11955	12694	13979
9	5979	7754	7287	8804	9376	10082	9933	11305	12124
10	4668	6650	7008	7609	8157	8446	9281	9158	10737
11	4202	5027	6150	5896	6978	7303	7668	8656	8589
12	3970	3807	4376	5617	5253	6163	6463	6961	7950
13	4157	3328	3348	4732	5020	4671	5462	5824	6428
14	3728	3032	2882	3226	4130	4283	4047	4876	5134
15	2992	3055	2592	2379	2825	3524	3713	3570	4406
16	2403	2655	2497	1923	1946	2315	2976	3167	3138
17	1439	2060	2242	1680	1631	1622	1923	2609	2778
18	1066	1581	1699	1688	1436	1299	1326	1581	2191
19	662	923	1307	1477	1390	1176	1019	1143	1345
20	448	689	714	1072	1192	1141	960	863	946
21	292	437	549	773	851	969	909	813	726
22	224	290	340	416	621	680	799	771	678
23	224	290	340	416	621	680	799	771	678
24	1534	1277	1217	1183	1044	1263	1418	1854	2267

Appendix F

VEHICLE POPULATION REORGARNIZED BY MODEL YEAR AND AGE

Made Year/ Age	0	1	2	3	4	5	6	7	8	9	10	11	…
2012	10140												
2011	8550	12584											
2010	7722	12777	13367										
2009	7439	11573	12075	12489									
2008	10284	15095	15676	16195	16359								
2007	11788	16781	17338	17778	18018	16062							
2006		16078	16908	17197	17081	15280	14069						
2005	10480		17819	18043	17973	16120	14788	14354					
2004	10273	16773		17631	17565	15777	14214	13718	13222				
2003		18333	19262		19548	17749	16148	15327	14663	13990			
2002	12075		20501	20577		18305	17116	16216	15185	14430	13565		
2001		19299		19965	19464		16408	15707	14529	13604	12887	12040	
2000			24260			21189		18581	17580	16443	15143	14103	
1999				20612		18516	17345		15530	14744	13458	12268	
1998					18944		17068	16338		14276	13089	12069	
1997						18724		17037	15866		13139	11916	
1996							15749		14180	13218		10524	
1995								18838		16379	14642		Data Continued on next page
1994									14884		12758	11452	
1993										13848		11584	
1992											12131		
1991												11131	
...													

Made Year/ Age	…	12	13	14	15	16	17	18	19	20	21	22
…	Data Continued from previous page											
2000		12922										
1999		11209	10234									
1998		10583	9549	8417								
1997		10448	9138	7981	7097							
1996		9311	8077	6774	5824	4969						
1995		11175	9857	8000	6762	5722	4825					
1994			8536	7256	5981	4830	4056	3332				
1993		10095		7086	5999	4785	3864	3106	2543			
1992		9703	8446		5730	4685	3734	2949	2399	1953		
1991			8454	7050		4420	3651	2824	2208	1786	1451	
1990		11147		8145	6697		3986	3149	2462	1871	1504	1193
1989			9914		6551	5080		2908	2296	1710	1334	1062
1988				8063		5038	3854		2089	1640	1304	1002
1987					6778		4153	3104		1760	1382	1075
1986						5136		2979	2219		1277	1037
1985							3470		2064	1532		892
1984								2127		1230	945	
1983									1124		684	518
1982										662		394
1981											540	
1980												472