# Population and Activity of On-road Vehicles in MOVES201X

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Assessment and Standards Division
Office of Transportation and Air Quality
Office of Air and Radiation
U.S. Environmental Protection Agency

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# 1. Introduction

The United States Environmental Protection Agency's Motor Vehicle Emission Simulator—commonly referred to as MOVES—is a set of modeling tools for estimating air pollution emissions produced by onroad (highway) and nonroad mobile sources. MOVES estimates the emissions of greenhouse gases (GHGs), criteria pollutants, and selected air toxics. The MOVES model is currently the official model for use for state implementation plan (SIP) submissions to EPA and for transportation conformity analyses outside of California. The model is also the primary modeling tool for estimating the impact of mobile source regulations on emission inventories.

MOVES calculates emission inventories by multiplying emission rates by the appropriate emission-related activity, applying correction and adjustment factors as needed to simulate specific situations, and then adding up the emissions from all sources and regions.

Vehicle population and activity data are critical inputs for calculating emission inventories from emissions processes such as running exhaust, start exhaust, and evaporative emissions. In MOVES, most running emissions are distinguished by operating modes, depending on road type and vehicle speed. Start emissions are determined based on the time a vehicle has been parked prior to the engine starting, known as a "soak." Evaporative emission modes are affected by vehicle operation and the time that vehicles are parked. Emission rates are further categorized by grouping vehicles with similar fuel type, regulatory classification, and other vehicle characteristics into "source bins."

This report describes the sources and derivation for onroad vehicle population and activity information and associated adjustments as stored in the MOVES201X default database. These data have been updated from previous versions of MOVES. In particular, this report describes the data used to fill the default database tables listed below in Table 1-1. Note that technical details on the default database values for emission rates, correction factors, and other inputs, including information on nonroad equipment, are described in other MOVES technical reports.[1]

Properly characterizing emissions from onroad vehicles requires a detailed understanding of the vehicles that comprise the national fleet and their patterns of operation. The MOVES default database has a domain that encompasses the entire United States, Puerto Rico, and the Virgin Islands. In MOVES201X, users may analyze emission inventories in 1990 and every year from 1999 to 2060. The national default activity information in MOVES provides a reasonable basis for estimating national emissions. As described in this report, the most important of these inputs, such as vehicle miles travelled (VMT) and population estimates, come from long-term systematic national measurements.

Due to the availability of these national measurements, the most recent year of measured data in the model, and the base year for projected emissions, is 2015.

It is important to note that uncertainties and variability in the default data contribute to the uncertainty in the resulting emission estimates. Therefore, MOVES has been specifically designed to accommodate the input of alternate, user-supplied activity data. In particular, when modellers estimate emissions for specific geographic locations, EPA guidance recommends replacing many of the MOVES fleet and activity defaults with local data. This is especially true for inputs where local data is more detailed or up-to-date than those provided in the MOVES defaults. EPA's Technical Guidance[2] provides more information on customizing MOVES with local inputs.

Population and activity data are ever changing as new historical data becomes available and new projections are generated. As part of the MOVES development process, the model undergoes major updates and review every few years. The development of fleet and activity inputs will continue to be an important area of focus and improvement for MOVES.

*Table 1-1 MOVES database elements covered in this report*

| Database Table Name | Content Summary | Report Sections |
|---|---|---|
| AvgSpeedDistribution | Distribution of time among average speed bins | Section 8 |
| DayVMTFraction | Distribution of VMT between weekdays and weekend days | Section 13 |
| DayTypeIdleAdjustment | Correction to off-network idle activity to account for variation by day type (weekend/weekday) | Section 10 |
| DriveSchedule | Average speed of each drive schedule | Section 9 |
| DriveScheduleAssoc | Mapping of which drive schedules are used for each combination of source type and road type | Section 9 |
| DriveScheduleSecond | Speed for each second of each drive schedule | Section 9 |
| FuelType | Broad fuel categories that indicate the fuel vehicles are capable of using | Section 2 |
| HotellingActivityDistribution | Distribution of hotelling activity to the various operating modes | Section 11 |
| HotellingCalendarYear | Rate of hotelling hours per total restricted access VMT | Section 11 |
| HourVMTFraction | Distribution of VMT among hours of the day | Section 13 |
| HPMSVtypeYear | Annual VMT by HPMS vehicle types | Section 3 |
| IdleFraction | Fraction of operating hours at idle | Section 10 |
| ModelYearGroup | A list of years and groups of years corresponding to vehicles with similar emissions performance | Section 2 |
| ModelYearGroupsForIdle | Groups of model years used to determine idle activity | Section 10 |
| MonthGroupHour | Coefficients to calculate air conditioning demand as a function of heat index | Section 16 |
| MonthIdleAdjustment | Correction to idle activity to account for variation by month | Section 10 |
| MonthVMTFraction | Distribution of annual VMT among months | Section 13 |
| OpModeDistribution | The distribution of engine start soak times for each source type, day type, hour of the day, and pollutant. | Section 12 |
| PollutantProcessModelYear | Assigns model years to appropriate groupings, which vary by pollutant and process | Section 2 |
| RegulatoryClass | Categorizes vehicles into weight-rating based groups used to assign emission rates. | Section 2 |
| RoadType | Distinguishes roadways as urban or rural and by type of access, particularly the use of ramps for entrance and exit | Section 2 |
| RoadTypeDistribution | Distribution of VMT among road types | Section 7 |
| SampleVehicleDay | Identifies vehicles in the SampleVehicleTrip table | Section 13 |
| SampleVehiclePopulation | Fuel type and regulatory class distributions by source type and model year. | Section 5 |
| SampleVehicleTrip | Trip start and end times used to determine parking times for evaporative emission calculations. | Section 13 |
| SCC | Source Classification Codes that identify the vehicle type, fuel type, road type and emission process in MOVES output | Section 2 |
| StartsHourFraction | The fraction of total starts that occur in each hour of the day.  This allocationFraction varies by county (zoneID) and day type. | Section12 |

*Table 1-1 MOVES database elements covered in this report*

| Database Table Name | Content Summary | Report Sections |
|---|---|---|
| StartsMonthAdjust | The monthAdjustFactor adjusts the starts per day to reflect monthly variation in the number of starts. | Section12 |
| StartsPerDay | StartsPerDay value is the number of starts per average vehicle (of all source types). This value varies by county (zoneID) and day type. | Section12 |
| StartsSourceTypeFraction | The allocation of total starts per day for all vehicles to each of the MOVES source types. | Section12 |
| SourceBinDistribution | Distribution of population among different vehicle sub-types (source bins) | Section 2 |
| SourceTypeAge | Rate of survival to subsequent age, relative mileage accumulation rates, and fraction of functional air conditioning equipment | Appendix C<br>Section 6<br>Section 16 |
| SourceTypeAgeDistribution | Distribution of vehicle population among ages | Section 6 |
| SourceTypeHour | The distribution of total daily hotelling among hours of the day | Section 13 |
| SourceTypeModelYear | Prevalence of air conditioning equipment | Section 16 |
| SourceTypePolProcess | Indicates which source bin discriminators are relevant for each source type and pollutant/process | Section 2 |
| SourceTypeYear | Source type vehicle counts by year | Section 4 |
| SourceUseType | Mapping from HPMS class to source type, including source type names | Section 2 |
| SourceUseTypePhysics | Road load coefficients and vehicle masses for each source type used to calculate vehicle specific power (VSP) and scaled tractive power (STP) | Section 15 |
| Zone | Allocation of activity to zone (county) | Section 14 |
| ZoneRoadType | Allocation of driving time to zone (county) and road type | Section 14 |

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# 2. MOVES Vehicle and Activity Classifications

Fundamentally, onroad mobile source emission inventories are estimated by applying vehicle populations and activity to appropriate emission rates. We wanted to enter vehicle population and activity data in a form as close as possible to how this data is collected by highway departments and vehicle registrars, but we had to map these to existing emission standards and in-use emission rates. Thus, EPA developed MOVES-specific terminology classifying vehicles according to how they are operated, such as "source types," and to emission-related characteristics, such as "regulatory classes" and "fuel types." At the most detailed level, vehicles are classified into "source bins" which have a direct mapping to emission rates by vehicle operating mode in the MOVES emission rate tables.

This section provides definitions of the various vehicle classifications used in MOVES. The MOVES terms introduced in this section will be used throughout the report. Later sections explain how default vehicle populations and activity are assigned and allocated to these classifications.

## 2.1. HPMS Class

In this report, MOVES HPMS class refers to one of five categories derived from the US Department of Transportation (DOT) Highway Performance Monitoring System (HPMS) based vehicle classes used by the Federal Highway Administration (FHWA) in the Table VM-1 of their annual Highway Statistics report.[3] The five HPMS classes used in MOVES are as follows: motorcycles (HPMSVTypeID 10), light-duty vehicles (25), buses (40), single-unit trucks (50), and combination trucks (60). Please note that the light-duty vehicles class (25) here represents the combination of the VM-1 categories for long wheelbase and short wheelbase light-duty vehicles. More details on how HPMS classes are used in MOVES may be found in Section 3.

## 2.2. Source Use Types

The primary vehicle classification in MOVES is source use type, or, more simply, source type. Source types are groups of vehicles with similar activity and usage patterns and are more specific than the HPMS vehicle classes described above.

Vehicles are classified into source types based on body type as well as other characteristics, such as whether they are registered to an individual, a commercial business, or a transit agency; whether they have specific travel routines such as a refuse truck; and whether they typically travel short- or long-haul routes (greater than 200 miles per day). The MOVES201X source types are listed in Table 2-1 along with the associated HPMS classes. More detailed source type definitions are provided in Section 5.1.

*Table 2-1 Onroad Source Types in MOVES201X*

| sourceTypeID | Source Type Name | HPMSVTypeID | HPMS Description |
|---|---|---|---|
| 11 | Motorcycles | 10 | Motorcycles |
| 21 | Passenger Cars | 25 | Light-Duty Vehicles |
| 31 | Passenger Trucks (primarily personal use) | 25 | Light-Duty Vehicles |
| 32 | Light Commercial Trucks (primarily non-personal use) | 25 | Light-Duty Vehicles |
| 41 | Other Buses (non-school, non-transit) | 40 | Buses |
| 42 | Transit Buses | 40 | Buses |
| 43 | School Buses | 40 | Buses |
| 51 | Refuse Trucks | 50 | Single-Unit Trucks |
| 52 | Single Unit Short-Haul Trucks | 50 | Single-Unit Trucks |
| 53 | Single Unit Long-Haul Trucks | 50 | Single-Unit Trucks |
| 54 | Motor Homes | 50 | Single-Unit Trucks |
| 61 | Combination Short-Haul Trucks | 60 | Combination Trucks |
| 62 | Combination Long-Haul Trucks | 60 | Combination Trucks |

In MOVES, the distinction between light-duty (LD) and heavy-duty (HD) source types is essential because light- and heavy-duty operating modes are assigned by source type and their calculation differs for light- and heavy-duty vehicles. Light-duty vehicles (sourceTypeIDs 11, 21, 31, and 32) use vehicle specific power (VSP) operating modes, which are dependent on the measured mass of the test vehicle. Heavy-duty vehicles (sourceTypeIDs 41, 42, 43, 51, 52, 53, 54, 61, and 62) use scaled tractive power (STP) operating modes which are scaled by a fixed mass factor since their emission rates correlates better with absolute vehicle power than vehicle specific power. For more discussion on VSP and STP definitions, please refer to Section 15 of this report and the MOVES technical reports on light-duty and heavy-duty vehicle emission rates.[4,5]

## 2.3. Regulatory Classes

In contrast to source types, regulatory classes are used to group vehicles subject to similar emission standards. The EPA regulates vehicle emissions based on groupings of technologies and classifications that do not necessarily correspond to DOT activity and usage patterns. To properly estimate emissions, it is critical for MOVES to account for these emission standards.

The regulatory classes used in MOVES are summarized in Table 2-2 below. The "doesn't matter" regulatory class is used internally in the model if the emission rates for a given pollutant and process are independent of regulatory class. The motorcycle (MC) and light-duty vehicle (LDV) regulatory classes have a one-to-one correspondence with source type. Other source types are allocated between regulatory classes based primarily on gross vehicle weight rating (GVWR) classification, which is a set of eight classes defined by FHWA based on the manufacturer-defined maximum combined weight of the vehicle and its load. Urban buses have their own regulatory definition, and therefore have an independent regulatory class.

*Table 2-2 Regulatory Classes in MOVES201X*

| regClassID | Regulatory Class Name | Description |
|---|---|---|
| 0 | Doesn't Matter | Doesn't Matter |
| 10 | MC | Motorcycles |
| 20 | LDV | Light-Duty Vehicles |
| 30 | LDT | Light-Duty Trucks |
| 40 | LHD<=10k | Class 2b Trucks with 2 Axles and 4 Tires (8,500 lbs. < GVWR <= 10,000 lbs.) |
| 41 | LHD<=14k | Class 2b Trucks with 2 Axles and at least 6 Tires or Class 3 Trucks (8,500 lbs. < GVWR <= 14,000 lbs.) |
| 42 | LHD45 | Class 4 and 5 Trucks (14,00 lbs. < GVWR <= 19,500 lbs.) |
| 46 | MHD | Class 6 and 7 Trucks (19,500 lbs. < GVWR < =33,000 lbs.) |
| 47 | HHD | Class 8a and 8b Trucks (GVWR > 33,000 lbs.) |
| 48 | Urban Bus | Urban Bus (see CFR Sec. 86.091_2) |

The EPA regulatory distinction between light-duty (LD) and heavy-duty (HD) trucks falls in the midst of FHWA GVWR Class 2. Trucks of 6,001-8,500 lbs. GVWR are Class 2a; in MOVES, they are considered light-duty trucks in regulatory class 30. Vehicles of 8,500-10,000 lbs. GVWR are Class 2b, and considered light heavy-duty vehicles (LHD) in regulatory classes 40 or 41.

Regulatory class 40 is for vehicles that are classified as light-duty by FHWA (because they have only two axles and four tires), and are thus mapped to source type 31 (passenger trucks) or 32 (light-commercial trucks) in MOVES, but have a GVWR that puts them in Class 2b, so are subject to heavy-duty emission standards. These regulatory class 40 vehicles use light-duty (VSP-based) operating modes because they are light-duty source types, but are mapped to emission rates that are more consistent with how these vehicles are regulated. Meanwhile, Class 2b trucks with two axles and at least six tires (colloquially known as "dualies") and Class 3 trucks are considered single-unit trucks by DOT; they fall into regulatory class 41 and are modeled as the heavy-duty source types using STP-based operating modes. In summary, the light-duty truck source types (31 and 32) map only to regulatory classes 30 and 40 in MOVES, while the heavy-duty vehicle source types (41 and above) map to regulatory classes 41 and above. Section 5.2 provides more information on the distribution of vehicles among regulatory classes.

## 2.4. Fuel Types

MOVES models vehicles powered by following fuel types: gasoline, diesel, E-85 (fuels containing 70 percent to 85 percent ethanol by volume), compressed natural gas (CNG), and electricity. Note that in some cases, a single vehicle can use more than one fuel. For example, flexible fuel vehicles (FFV) are capable of running on either gasoline or E-85. In MOVES, fuel type refers to the capability of the vehicle rather than the fuel in the tank. The fuel use actually modeled depends on a number of factors including the location, year, and month in which the fuel was purchased, as explained in the MOVES technical report on fuel supply.[6] Table 2-3 below summarizes the fuel types available in MOVES.

*Table 2-3 A List of Allowable Fuel Types to Power Vehicles in MOVES201X*

| fuelTypeID | defaultFormulationID | Description |
|---|---|---|
| 1 | 10 | Gasoline |
| 2 | 20 | Diesel Fuel |
| 3 | 30 | Compressed Natural Gas (CNG) |
| 5 | 50 | Ethanol (E-85) |
| 9 | 90 | Electricity |

It is important to note that not all fuel type/source type combinations can be modeled in MOVES. For example, MOVES will not model gasoline-fueled long-haul combination trucks or diesel motorcycles. Similarly, flexible fuel (E85-compatible) and electric vehicles are only modeled for passenger cars, passenger trucks, and light commercial trucks. In addition, MOVES does not explicitly model hybrid powertrains, but accounts for these vehicles in calculating fleet-average energy consumption and $CO_2$ rates.[a] For more information on how MOVES models the impact of fuels on emissions, please see the MOVES documentation on fuel effects.[7]

## 2.5. Road Types

MOVES calculates onroad emissions separately for each of four road types and for “off-network” activity when the vehicle is not moving. The road types used in MOVES are listed in Table 2-4. The four MOVES road types (2-5) are aggregations of FHWA functional facility types.

*Table 2-4 Road Types in MOVES201X*

| roadTypeID | Description | FHWA Functional Types |
|---|---|---|
| 1 | Off Network | Off Network |
| 2 | Rural Restricted Access | Rural Interstate |
| 3 | Rural Unrestricted Access | Rural Principal Arterial, Minor Arterial, Major Collector, Minor Collector & Local |
| 4 | Urban Restricted Access | Urban Interstate & Urban Freeway/Expressway |
| 5 | Urban Unrestricted Access | Urban Principal Arterial, Minor Arterial, Collector & Local |

The MOVES road types are based on two important distinctions in how FWHA classifies roads: 1) urban versus rural roadways are distinguished based on surrounding land use and human population density, and 2) unrestricted versus restricted are distinguished based on roadway access—restricted roads require the use of ramps. The urban/rural distinction is used primarily for national level calculations. It allows different default speed distributions in urban and rural settings. Of course, finer distinctions are possible. Users with more detailed information on

[a] While we have considered creating a separate category for hybrid vehicles, modeling their emissions separately is not required for regulatory purposes and presents a number of challenges, including obtaining representative detailed data on hybrid vehicle emissions and usage, and accounting for offsetting emissions allowed under the fleet-averaging provisions of the relevant emissions standards.

speeds and acceleration patterns may choose to create their own additional road types, or may run MOVES at project level where emissions can be calculated for individual links. In MOVES201X, we removed the ramp road type as discussed in Section 9.

### 2.6. Source Classification Codes (SCC)

Source Classification Codes (SCC) are used to group and identify emission sources in large-scale emission inventories. They are often used when post-processing MOVES output to further allocate emissions temporally and spatially when preparing inputs for air quality modeling. In MOVES, SCCs are numerical codes that identify the vehicle type, fuel type, road type, and emission process using MOVES identification (ID) values in the following form:

AAAFVVRRPP, where

- $AAA$ indicates mobile source (this has a value of 220 for both onroad and nonroad),
- $F$ indicates the MOVES fuelTypeID value,
- $VV$ indicates the MOVES sourceTypeID value,
- $RR$ indicates the MOVES roadTypeID value, and
- $PP$ indicates the MOVES emission processID value.

Building the SCC values in this way allows additional source types, fuel types, road types, and emission processes to be easily added to the list of SCCs as changes are made to future versions of MOVES. The explicit coding of fuel type, source type, road type, and emission process also allows the new SCCs to indicate aggregations. For example, a zero code (00) for any of the sourceTypeID, fuelTypeID, roadTypeID, and processID strings that make up the SCC indicates that the reported emissions are an aggregation of all categories of that type. Using the mapping described above, modelers can also easily identify the sourceTypeID, fuelTypeID, roadTypeID, and processID of emissions reported by SCC. Refer to earlier sections in this document for the descriptions of the sourceTypeID, fuelTypeID and roadTypeID values currently used by MOVES. Emission processes are discussed in other MOVES reports on emission rate development[4,5] and are not described here. All feasible SCC values are listed in the SCC table within the default database.

### 2.7. Model Year Groups

MOVES uses model year groups to avoid unnecessary duplication of emission rates for vehicles with similar technology and similar expected emission performance.  For example, there is a model year group for “1980 and earlier.”  In MOVES, model year refers to the year in which the vehicle was produced, built, and certified as compliant with emission standards.

The default ModelYearGroup table provides information on the model year group names, beginning and ending years, and a two-digit shorthand identifier (shortModelYrGroupID). However, the model year groups that are relevant for a given calculation can vary depending on pollutant and emission process as defined in the PollutantProcessModelYear table. For example, a 2011 vehicle belongs to the “2011” model year group for estimating hydrocarbon running exhaust emissions, but belongs to the “2011-2020” group for estimating nitrous oxide running emissions. Because these groupings are determined based on analysis of the actual or expected emissions performance, the rationale for each model year grouping is provided in the MOVES emission rate reports.[4,5]

## 2.8. Source Bins

The MOVES default database identifies emission rates by emission-related characteristics such as the type of fuel that a vehicle uses and the emission standards it is subject to. These classifications are called "source bins." They are named with a sourceBinID that is a unique 19-digit identifier in the following form:

$1FFEERRMM0000000000$, where

- 1 is a placeholder,
- $FF$ is a MOVES fuelTypeID,
- $EE$ is a MOVES engTechID,[b]
- $RR$ is a MOVES regClassID,
- $MM$ is a MOVES shortModYrGroupID, and
- 10 trailing zeros for future characteristics.

The model allocates vehicle activity and population to these source bins as described below. A mapping of model year to model year groups is stored in the PollutantProcessModelYear table. Distributions of fuel type and regulatory class by source type are stored by model year in the SampleVehiclePopulation table. The Source Bin Distribution Generator combines information from these two tables (see Table 2-5) to create a detailed SourceBinDistribution. In general, fuel type is relevant for all emission calculations, but the relevance of regulatory class and model year group depend on the pollutant and process being modeled. See Section 2.10 for more information on how MOVES uses generators to calculate detailed activity information.

[b] In MOVES201X, engTechID 1 is used for all fuel types except electric vehicles, where engTechID 30 is used instead. Thus, in the current version, engTechID is somewhat redundant with fuel type and adds no new information when determining source bin distributions or calculating emissions.

*Table 2-5 Data Tables Used to Allocate Source Type to Source Bin*

| Table Name | Key Fields* | Additional Fields | Notes |
|---|---|---|---|
| SourceTypePolProcess | sourceTypeID<br>polProcessID | isRegClassReqd<br>isMYGroupReqd | Indicates which pollutant-processes the source bin distributions may be applied to and indicates which discriminators are relevant for each sourceTypeID and polProcessID (pollutant/process combination) |
| PollutantProcessModelYear | polProcessID<br>modelYearID | modelYearGroupID | Assigns model years to appropriate model year groups for each polProcessID. |
| SampleVehiclePopulation | sourceTypeID<br>modelYearID<br>fuelTypeID<br>engTechID<br>regClassID | stmyFuelEngFraction<br>stmyFraction | Includes fuel type and regulatory class fractions for each source type and model year, even for some source type/fuel type combinations that do not currently have any appreciable market share (i.e. CNG motor homes). This table provides default fractions for the Alternative Vehicle Fuel & Technology (AFVT) importer. |

Note:
* In these tables, the sourceTypeID and modelYearID are combined into a single sourceTypeModelYearID.

While details of the SourceTypePolProcess and PollutantProcessModelYear tables are discussed in the reports on the development of the light- and heavy-duty emission rates,[4, 5] the SampleVehiclePopulation (SVP) table is a topic for this report and is discussed in Section 5.2

## 2.9. Allowable Vehicle Modeling Combinations

In theory, the MOVES source bins would allow users to model any combination of source type, model year, regulatory class, and fuel type. However, each combination must have accompanying emission rates; combinations that lack data from emissions testing or have negligible market share cannot be directly modeled in MOVES.

Table 2-6 summarizes the allowable source type-fuel type combinations. Most of the gasoline and diesel combinations exist with a few exceptions, but options for alternative fuels are limited, as discussed earlier in Section 2.4MOVES also stores regulatory class distributions by source type in the SampleVehiclePopulation table. Table 2-7 summarizes the allowable source type-regulatory class combinations in MOVES201X. Table 2-8 shows the full set of allowable source type, fuel type, and regulatory class combinations. Additional discussion about decisions to include and exclude certain types of vehicles can be found in Section 5

*Table 2-6 Matrix of the Allowable Source Type-fuel Type Combinations in MOVES201X (Allowable combinations are marked with an X)*

| | | **Source Use Types** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Motorcycles | Passenger Cars | Passenger Trucks | Light Commercial Trucks | Other Buses | Transit Buses | School Buses | Refuse Trucks | Short-Haul Single Unit Trucks | Long-Haul Single Unit Trucks | Motor Homes | Short-Haul Combination Trucks | Long-Haul Combination Trucks |
| **Fuel Types** | | 11 | 21 | 31 | 32 | 41 | 42 | 43 | 51 | 52 | 53 | 54 | 61 | 62 |
| Gasoline | 1 | X | X | X | X | X | X | X | X | X | X | X | X | |
| Diesel | 2 | | X | X | X | X | X | X | X | X | X | X | X | X |
| CNG | 3 | | | | | X | X | X | X | X | X | X | X | X |
| E85-Capable | 5 | | X | X | X | | | | | | | | | |
| Electricity | 9 | | X | X | X | | | | | | | | | |

*Table 2-7 Matrix of the allowable source type-regulatory class combinations in MOVES201X (Allowable combinations are marked with an X)*

| | | **Source Use Types** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Motorcycles | Passenger Cars | Passenger Trucks | Light Commercial Trucks | Other Buses | Transit Buses | School Buses | Refuse Trucks | Short-Haul Single Unit Trucks | Long-Haul Single Unit Trucks | Motor Homes | Short-Haul Combination Trucks | Long-Haul Combination Trucks |
| **Regulatory Classes** | | 11 | 21 | 31 | 32 | 41 | 42 | 43 | 51 | 52 | 53 | 54 | 61 | 62 |
| MC | 10 | X | | | | | | | | | | | | |
| LDV | 20 | | X | | | | | | | | | | | |
| LDT | 30 | | | X | X | | | | | | | | | |
| LHD<=10k | 40 | | | X | X | | | | | | | | | |
| LHD<=14k | 41 | | | | | | | X | X | X | X | X | | |
| LHD45 | 42 | | | | | X | X | X | X | X | X | X | | |
| MHD67 | 46 | | | | | X | X | X | X | X | X | X | X | X |
| HHD8 | 47 | | | | | X | X | X | X | X | X | X | X | X |
| Urban Bus | 48 | | | | | | X | | | | | | | |

*Table 2-8 A summary of source type, fuel type, and regulatory class combinations in MOVES201X*

| sourceTypeID | fuelTypeID | regClassID |
|---|---|---|
| 11 | 1 | 10 |
| 21 | 1, 2, 5, 9 | 20 |
| 31 | 1, 2 | 30, 40 |
| | 5, 9 | 30 |
| 32 | 1, 2 | 30, 40 |
| | 5, 9 | 30 |
| 41 | 1, 2, 3 | 42, 46, 47 |
| 42 | 1 | 42, 46, 47 |
| | 2, 3 | 42, 46, 48 |
| 43 | 1, 2, 3 | 41, 42, 46, 47 |
| 51 | 1, 2, 3 | 41, 42, 46, 47 |
| 52 | 1, 2, 3 | 41, 42, 46, 47 |
| 53 | 1, 2, 3 | 41, 42, 46, 47 |
| 54 | 1, 2, 3 | 41, 42, 46, 47 |
| 61 | 1, 2, 3 | 46, 47 |
| 62 | 2, 3 | 46, 47 |

## 2.10. Default Inputs and Fleet and Activity Generators

As explained in the introduction, vehicle population and activity data are critical inputs for calculating emission inventories, and MOVES calculators require information on vehicle population and activity at a very fine scale. In project-level modeling, this detailed information may be available and manageable. However, in other cases, the fleet and activity data used in the MOVES calculators must be generated from inputs in a condensed or more readily available format. MOVES uses "generators" to create fine-scale information from user inputs and MOVES defaults.

The MOVES Total Activity Generator (TAG) estimates hours of vehicle activity using vehicle miles traveled (VMT) and speed information to transform VMT into source hours operating (SHO). Other types of vehicle activity are generated by applying appropriate factors to vehicle populations. Vehicle starts, extended idle hours, and source hours (including hours operating and not-operating) are also generated. The default database for MOVES contains national estimates for VMT, vehicle population, and vehicle age distributions for every possible analysis year (1990 and 1999-2060). For national inventory runs, annual national activity is distributed temporally and spatially using allocation factors.

The Source Bin Distribution Generator (SBDG) uses information on fuel type fractions and regulatory class distributions to estimate activity fractions of each source bin as a function of source type, model year, pollutant, and process. The SBDG maps the activity data (by source types) to source bins which map directly to the MOVES emission rates.

There are a number of MOVES modules that generate operating mode distributions based on vehicle activity inputs. The Rates Operating Mode Distribution Generator and the Link Operating Mode Distribution Generator use information on speed distributions and driving patterns (driving schedules) to develop operating mode fractions for each source type, road type, and time of day. Similarly, the Evaporative Emissions Operating Mode Generator uses MOVES inputs to develop operating mode distributions for starts and vapor venting. The details of each these generators and other MOVES algorithms are described in the MOVES201X Module Reference.[8]

# 3. VMT by Calendar Year and Vehicle Type

At the national level, MOVES calculates source operating hours from national vehicle miles traveled (VMT) by vehicle type. The default database contains national VMT estimates for all analysis years, which include 1990 and 1999-2060. Years 1991-1998 are excluded because there is no regulatory requirement to analyze them and including them would increase model complexity. Calendar year 1990 is available to be modeled in MOVES because of the Clean Air Act Amendments of 1990.

The national VMT estimates are stored in the HPMSVTypeYear table,[c] which includes three data fields: HPMSBaseYearVMT (discussed below), baseYearOffNetVMT, and VMTGrowthFactor. Off network VMT refers to the portion of activity that is not included in travel demand model networks or any VMT that is not otherwise reflected in the other four road types. The field baseYearOffNetVMT is provided in case it is useful for modeling local areas. However, the reported HPMS VMT values, used to calculate the national averages discussed here, are intended to include all VMT. Thus, for MOVES national defaults, the baseYearOffNetVMT is zero for all vehicle types. Additionally, the VMTGrowthFactor field is not used in MOVES and is set to zero for all vehicle types.

## 3.1. Historic Vehicle Miles Traveled (1990 and 1999-2015)

In MOVES201X, VMT estimates for the historic years 1990 and 1999-2015 come from the VM-1 table of US DOT Federal Highway Administration's (FHWA) *Highway Statistics* series.[3] In reporting years 2007 and later, the VM-1 data are calculated with an updated methodology,[9] which implements state-reported data directly rather than a modeled approach and which has different vehicle categories. The current HPMS-based VM-1 categories are 1) light-duty short wheelbase, 2) light-duty long wheelbase, 3) motorcycles, 4) buses, 5) single-unit trucks, and 6) combination trucks. Because MOVES categorizes light-duty source types based on vehicle type and not wheelbase length, the short and long wheelbase categories are combined into a single category of light-duty vehicles (HPMSVTypeID 25). Internally, the MOVES Total Activity Generator[8] allocates this VMT to MOVES source types and ages using vehicle populations, age distributions, and relative mileage accumulation rates.

For years prior to 2007, the VM-1 data with historical vehicle type groupings are inconsistent with the current VM-1 vehicle categories used in MOVES and cannot be used as they are currently reported. However, in early 2011, FHWA released revised VMT data for years 2000-2006 to match the new category definitions. Shortly afterward, the agency replaced these revised

[c] In MOVES, users can enter VMT estimates using four different input methods: annual miles by HPMS class, annual miles by source type, annual average daily miles by HPMS class, and annual average daily miles by source type. As in previous versions of MOVES, the national defaults are stored as annual miles by HPMS class and any discussion in this report on annual VMT estimates will be in this context.

numbers with the previously published VMT data stating, "[FHWA] determined that it is more reliable to retain the original 2000-2006 estimates because the information available for those years does not fully meet the requirements of the new methodology."[d] However, needing continuity of the VM-1 vehicle categories, we used these FHWA-revised values by the new categories as the VMT for 2000-2006.

This left two years, 1990 and 1999, that needed to be adjusted to be consistent with the new HPMS vehicle categories. Since the methodology that FHWA used to revise the 2000-2006 data is undocumented, we adjusted 1990 and 1999 using the average ratio of the change for each vehicle category. This was found by dividing the FHWA-adjusted VMT for each vehicle category by the original VMT for each year 2000-2006 and then calculating the average ratio for each category. This ratio was then applied to the corresponding VMT values reported in VM-1 for 1990 and 1999. Since FHWA's adjustments conserved the original total VMT estimates, we normalized our adjusted values such that the original total VMT for the years were unchanged.

The resulting values for historic years by HPMS vehicle class are listed in Table 3-1. The VMT for 1990 and 1999 were EPA-adjusted from VM-1, 2000-2006 were FHWA-adjusted, and 2007-2015 were unadjusted, other than the simple combination of the short and long wheelbase classes into light-duty vehicles. In addition to these adjustments, for some years, the VMT values were revised by FHWA in subsequent publications. Table 3-2 summarizes the data source and revision date we used for each historical year.

*Table 3-1 Historic year VMT by HPMS vehicle class (millions of miles)*

| *Year* | **Motorcycles** | **Light-Duty Vehicles** | **Buses** | **Single Unit Trucks** | **Combination Trucks** |
|---|---|---|---|---|---|
| 1990 | 11,404 | 1,943,197 | 10,279 | 70,848 | 108,624 |
| … | | | | | |
| 1999 | 13,619 | 2,401,408 | 14,853 | 100,534 | 160,921 |
| 2000 | 12,175 | 2,458,221 | 14,805 | 100,486 | 161,238 |
| 2001 | 11,120 | 2,499,069 | 12,982 | 103,470 | 168,969 |
| 2002 | 11,171 | 2,555,467 | 13,336 | 107,317 | 168,217 |
| 2003 | 11,384 | 2,579,194 | 13,381 | 112,723 | 173,539 |
| 2004 | 14,975 | 2,652,092 | 13,523 | 111,238 | 172,960 |
| 2005 | 13,773 | 2,677,641 | 13,153 | 109,735 | 175,128 |
| 2006 | 19,157 | 2,680,535 | 14,038 | 123,318 | 177,321 |
| 2007 | 21,396 | 2,691,034 | 14,516 | 119,979 | 184,199 |
| 2008 | 20,811 | 2,630,213 | 14,823 | 126,855 | 183,826 |
| 2009 | 20,822 | 2,633,248 | 14,387 | 120,207 | 168,100 |
| 2010 | 18,513 | 2,648,456 | 13,770 | 110,738 | 175,789 |
| 2011 | 18,542 | 2,650,458 | 13,807 | 103,803 | 163,791 |
| 2012 | 21,385 | 2,664,060 | 14,781 | 105,605 | 163,602 |
| 2013 | 20,366 | 2,677,730 | 15,167 | 106,582 | 168,436 |
| 2014 | 19,970 | 2,710,556 | 15,999 | 109,301 | 169,830 |
| 2015 | 19,606 | 2,779,693 | 16,230 | 109,597 | 170,246 |

[d] This text appears in a footnote to FHWA's *Highway Statistics* Table VM-1 for publication years 2000-2009.

*Table 3-2 Highway Statistics publications used for historical years*

| Year | FHWA Publication Source (Publication/Revision Date) |
|---|---|
| 1990 | *Highway Statistics 1991* (October 1992) |
| 1999 | *Highway Statistics 1999* (October 2000) |
| 2000 | *Highway Statistics 2000* (April 2011) |
| 2001 | *Highway Statistics 2001* (April 2011) |
| 2002 | *Highway Statistics 2002* (April 2011) |
| 2003 | *Highway Statistics 2003* (April 2011) |
| 2004 | *Highway Statistics 2004* (April 2011) |
| 2005 | *Highway Statistics 2005* (April 2011) |
| 2006 | *Highway Statistics 2006* (April 2011) |
| 2007 | *Highway Statistics 2007* (April 2011) |
| 2008 | *Highway Statistics 2008* (April 2011) |
| 2009 | *Highway Statistics 2010* (December 2012) |
| 2010 | *Highway Statistics 2010* (December 2012) |
| 2011 | *Highway Statistics 2012* (January 2014) |
| 2012 | *Highway Statistics 2013* (January 2015) |
| 2013 | *Highway Statistics 2014* (December 2015) |
| 2014 | *Highway Statistics 2014* (December 2015) |
| 2015 | *Highway Statistics 2015* (January 2017) |

## 3.2. Projected Vehicle Miles Traveled (2016-2060)

The *Annual Energy Outlook* (AEO)[10] describes the future energy consumption forecasted by Department of Energy. Vehicle sales and miles traveled are included in the projections because they strongly influence fuel consumption. In MOVES201X, VMT for years beyond 2015 are based on the VMT projections from AEO2017. Because AEO vehicle categories are different from HPMS classes, the AEO projections were not used directly. Instead, year-to-year percent changes in the projected values were calculated and applied to the base year HPMS data. Since AEO2017 only projects out to 2050, VMT for years 2051-2060 were assumed to continue to grow at the same growth rate as between 2049 and 2050.

Table 3-3 shows the mappings between AEO VMT categories and HPMS categories. Where multiple AEO categories are listed, their VMT were summed before calculating the year-over-year growth rates. AEO's light-duty category was mapped to both the combined HPMS light-duty and the motorcycle categories. Motorcycles were included here because they were not explicitly accounted for elsewhere in AEO. Since buses span a large range of heavy-duty vehicles and activity, the combination of AEO's light-medium-, medium-, and heavy-heavy-duty categories was mapped to the HPMS bus category. AEO's light-medium- and medium-heavy-duty categories were combined for mapping to the HPMS single-unit truck category, and AEO's heavy-heavy-duty category was mapped to the HPMS combination truck category. We acknowledge that using VMT growth estimates from different vehicle types as surrogates for motorcycles and buses in particular will introduce additional uncertainty into these projections.

*Table 3-3 Mapping AEO categories to HPMS classes for projecting VMT*

| AEO VMT Category Groupings | HPMS Class |
|---|---|
| Total Light-Duty VMT[i] + Total Commercial Light Truck VMT[ii] | 10 – Motorcycles |
| | 25 – Light Duty Vehicles |
| Total Heavy-Duty VMT[c] | 40 – Buses |
| Light-Medium Subtotal VMT[iii] + Medium Subtotal VMT[iii] | 50 – Single Unit Trucks |
| Heavy Subtotal VMT[iii] | 60 – Combination Trucks |

Notes:
[i] From AEO2017 Table 42: Light-Duty VMT by Technology Type
[ii] From AEO2017 Table 47: Transportation Fleet Car and Truck VMT by Type and Technology
[iii] From AEO2017 Table 50: Freight Transportation Energy Use

The percent growth over time was calculated for each of the groups described above and applied by HPMS category to the 2015 base year VMT from *Highway Statistics* Table VM-1. The resulting values are presented in Table 3-4 below.

*Table 3-4 VMT projections for 2016-2060 by HPMS class (millions of miles)*

| *Year* | **Motorcycles** | **Light-Duty Vehicles** | **Buses** | **Single Unit Trucks** | **Combination Trucks** |
|---|---|---|---|---|---|
| 2016 | 20,215 | 2,866,029 | 16,125 | 109,127 | 168,927 |
| 2017 | 20,696 | 2,934,166 | 16,761 | 113,888 | 175,177 |
| 2018 | 21,081 | 2,988,761 | 17,076 | 116,595 | 177,933 |
| 2019 | 21,304 | 3,020,347 | 17,334 | 119,076 | 179,961 |
| 2020 | 21,492 | 3,047,076 | 17,654 | 122,541 | 182,128 |
| 2021 | 21,641 | 3,068,150 | 18,045 | 126,793 | 184,748 |
| 2022 | 21,752 | 3,083,900 | 18,406 | 131,029 | 186,869 |
| 2023 | 21,800 | 3,090,768 | 18,747 | 135,500 | 188,455 |
| 2024 | 21,829 | 3,094,780 | 19,046 | 139,552 | 189,720 |
| 2025 | 21,844 | 3,096,947 | 19,222 | 142,577 | 189,888 |
| 2026 | 21,910 | 3,106,276 | 19,307 | 144,888 | 189,172 |
| 2027 | 22,006 | 3,119,899 | 19,456 | 147,744 | 189,043 |
| 2028 | 22,139 | 3,138,780 | 19,634 | 150,763 | 189,240 |
| 2029 | 22,277 | 3,158,297 | 19,830 | 153,782 | 189,726 |
| 2030 | 22,404 | 3,176,375 | 20,030 | 156,474 | 190,604 |
| 2031 | 22,519 | 3,192,687 | 20,226 | 159,263 | 191,305 |
| 2032 | 22,638 | 3,209,536 | 20,410 | 161,669 | 192,174 |
| 2033 | 22,780 | 3,229,698 | 20,681 | 164,688 | 193,916 |
| 2034 | 22,930 | 3,250,954 | 21,001 | 167,897 | 196,315 |
| 2035 | 23,074 | 3,271,256 | 21,327 | 170,917 | 198,974 |
| 2036 | 23,236 | 3,294,223 | 21,631 | 173,795 | 201,397 |
| 2037 | 23,401 | 3,317,629 | 21,967 | 176,832 | 204,227 |
| 2038 | 23,577 | 3,342,592 | 22,352 | 180,322 | 207,437 |
| 2039 | 23,729 | 3,364,135 | 22,681 | 183,098 | 210,392 |
| 2040 | 23,872 | 3,384,458 | 23,010 | 186,389 | 212,856 |
| 2041 | 24,019 | 3,405,257 | 23,358 | 189,485 | 215,812 |
| 2042 | 24,182 | 3,428,359 | 23,727 | 192,911 | 218,833 |
| 2043 | 24,348 | 3,451,936 | 24,137 | 196,614 | 222,276 |
| 2044 | 24,514 | 3,475,528 | 24,540 | 200,164 | 225,739 |
| 2045 | 24,686 | 3,499,929 | 24,939 | 203,737 | 229,105 |
| 2046 | 24,869 | 3,525,747 | 25,356 | 207,610 | 232,513 |
| 2047 | 25,047 | 3,551,052 | 25,742 | 211,264 | 235,594 |
| 2048 | 25,238 | 3,578,097 | 26,140 | 215,158 | 238,669 |
| 2049 | 25,451 | 3,608,384 | 26,582 | 219,421 | 242,118 |
| 2050 | 25,664 | 3,638,556 | 27,037 | 223,742 | 245,753 |
| 2051 | 25,879 | 3,668,981 | 27,501 | 228,148 | 249,443 |
| 2052 | 26,095 | 3,699,660 | 27,972 | 232,641 | 253,188 |
| 2053 | 26,313 | 3,730,595 | 28,451 | 237,222 | 256,989 |
| 2054 | 26,533 | 3,761,789 | 28,939 | 241,894 | 260,847 |
| 2055 | 26,755 | 3,793,244 | 29,435 | 246,658 | 264,763 |
| 2056 | 26,979 | 3,824,962 | 29,940 | 251,515 | 268,738 |
| 2057 | 27,205 | 3,856,946 | 30,453 | 256,468 | 272,772 |
| 2058 | 27,432 | 3,889,196 | 30,975 | 261,519 | 276,867 |
| 2059 | 27,661 | 3,921,717 | 31,506 | 266,669 | 281,024 |
| 2060 | 27,893 | 3,954,509 | 32,046 | 271,920 | 285,243 |

# 4. Vehicle Populations by Calendar Year

MOVES uses vehicle populations to characterize emissions activity that is not directly dependent on VMT. These data are also used to allocate VMT from HPMS class to source type and age (for more details, see Section 6). The default database stores historic estimates and future projections of total US vehicle populations in 1990 and 1999-2060 by source type. The MOVES database stores this information in the SourceTypeYear table, which has three data fields: sourceTypePopulation, salesGrowthFactor, and migrationRate. However, the salesGrowthFactor and migrationRate fields are not used in MOVES.

## 4.1. Historic Source Type Populations (1990 and 1999-2015)

MOVES populations for calendar years 1990 and 1999-2015 are derived primarily from registration data in Table MV-1 of the Federal Highway Administration's annual *Highway Statistics* report.[11] In this table, vehicles are classified in four general categories: motorcycles, passenger cars, trucks, and buses.

Since MOVES vehicle populations are input by source type, a system had to be devised to map these population data to MOVES source types. While the motorcycle and passenger car have a one-to-one correspondence with those source types in MOVES, the general categories of truck and bus populations needed to be allocated to the remaining source types.

The numbers of single-unit and combination trucks were determined for each calendar year using registration data in the *Highway Statistics* Table VM-1. The remaining MV-1 truck registrations were allocated to the light-duty trucks. The populations were further allocated from the light-duty, single-unit, and combination truck categories to individual source types using the source type distribution fractions shown below in Table 4-1.

The source type distribution fractions were calculated from national vehicle registration data purchased from IHS[12,13] for calendar years 1999 and 2014. These fractions were calculated as the ratio of the individual source type registrations to their corresponding HPMS class totals (see Table 2-1 for this mapping). These fractions were then linearly interpolated to estimate the source type distribution fractions for all years between 1999 and 2014. However, there are a few caveats to this analysis:

- The distinction between passenger light-duty trucks (31) and commercial light-duty trucks (32) has been updated from previous versions of MOVES. In MOVES201X, a light-duty truck is considered a passenger truck if it is registered to an individual and a commercial light-duty truck if it is registered to an organization or business. Since this is inconsistent with the source type definitions used by the 1999 IHS data, the same ratio of passenger to commercial light-duty trucks was used for all calendar years.
- The 2014 IHS data was unable to distinguish between short-haul (52) and long-haul (53) single-unit trucks and consequentially grouped them together. These vehicles are differentiated in MOVES201X using an earlier IHS data set for 2011 which was able to differentiate between these vehicles. From the earlier data set, it was determined that of short-haul and long-haul single-unit trucks, 95.8 percent are short-haul. This percentage fraction was applied for all historic years to differentiate between these two source types.

- Source type distributions were needed to allocate the historic 2015 populations. Rather than projecting the linear interpolations, the distributions for 2014 were held constant for 2015.

*Table 4-1 Source type distributions used to allocate truck populations in MOVES201X**

| Year | 31/30 | 32/30 | 51/50 | 52/50 | 53/50 | 54/50 | 61/60 | 62/60 |
|---|---|---|---|---|---|---|---|---|
| 1990** | 0.895947 | 0.104053 | 0.013311 | 0.767722 | 0.033860 | 0.185107 | 0.625648 | 0.374352 |
| 1999*** | 0.895947 | 0.104053 | 0.015472 | 0.791929 | 0.034927 | 0.157671 | 0.574437 | 0.425563 |
| 2000 | 0.895947 | 0.104053 | 0.014852 | 0.797084 | 0.035155 | 0.152909 | 0.561208 | 0.438792 |
| 2001 | 0.895947 | 0.104053 | 0.014232 | 0.802239 | 0.035382 | 0.148146 | 0.547979 | 0.452021 |
| 2002 | 0.895947 | 0.104053 | 0.013612 | 0.807394 | 0.035610 | 0.143384 | 0.534750 | 0.465250 |
| 2003 | 0.895947 | 0.104053 | 0.012992 | 0.812549 | 0.035837 | 0.138622 | 0.521521 | 0.478479 |
| 2004 | 0.895947 | 0.104053 | 0.012372 | 0.817704 | 0.036064 | 0.133859 | 0.508292 | 0.491708 |
| 2005 | 0.895947 | 0.104053 | 0.011752 | 0.822859 | 0.036292 | 0.129097 | 0.495063 | 0.504937 |
| 2006 | 0.895947 | 0.104053 | 0.011133 | 0.828014 | 0.036519 | 0.124334 | 0.481835 | 0.518166 |
| 2007 | 0.895947 | 0.104053 | 0.010513 | 0.833169 | 0.036746 | 0.119572 | 0.468606 | 0.531394 |
| 2008 | 0.895947 | 0.104053 | 0.009893 | 0.838324 | 0.036974 | 0.114810 | 0.455377 | 0.544623 |
| 2009 | 0.895947 | 0.104053 | 0.009273 | 0.843479 | 0.037201 | 0.110047 | 0.442148 | 0.557852 |
| 2010 | 0.895947 | 0.104053 | 0.008653 | 0.848634 | 0.037428 | 0.105285 | 0.428919 | 0.571081 |
| 2011 | 0.895947 | 0.104053 | 0.008033 | 0.853789 | 0.037656 | 0.100523 | 0.415690 | 0.584310 |
| 2012 | 0.895947 | 0.104053 | 0.007413 | 0.858944 | 0.037883 | 0.095760 | 0.402461 | 0.597539 |
| 2013 | 0.895947 | 0.104053 | 0.006793 | 0.864099 | 0.038110 | 0.090998 | 0.389232 | 0.610768 |
| 2014*** | 0.895947 | 0.104053 | 0.006173 | 0.869254 | 0.038338 | 0.086235 | 0.376003 | 0.623997 |
| 2015 | 0.895947 | 0.104053 | 0.006173 | 0.869254 | 0.038338 | 0.086235 | 0.376003 | 0.623997 |

Note:
* Fractions may not sum to one due to rounding.
** Fractions from 1990 were retained from MOVES2014[14] with the exceptions noted in the text.
*** Fractions from 1999 and 2014 were calculated from IHS registration data with the exceptions noted in the text; fractions for other years were estimated from these values.

Buses were allocated using different data sources:

- School bus (43) populations for 2002-2015 come from the *School Bus Fleet Fact Book*[15] publication series' School Transportation Statistics tables. Since these values are presented as totals corresponding to academic years (e.g., 2014-2015) and MOVES requires national values to be entered for calendar years, the data were taken to correspond to the year in which the school year ends (2015, in the example). For 1990 and 1999-2001, school buses were assumed to be a constant proportion of the total bus population in each year based on the 2002 counts.
- Transit bus (42) populations were calculated from the Federal Transit Administration's National Transit Database (NTD)[16] data series on Revenue Vehicle Inventory and Rural Revenue Vehicle Inventory. See Section 5.1.4for more information on the definition of transit buses in MOVES. For 1990 and 1999-2001, transit buses were assumed to be a constant proportion of the total bus population in each year based on the 2002 counts.
- Other bus (41) populations were calculated as the remainder of the MV-1 bus registrations less the school bus and transit bus populations. Please note that the *Highway*

*Statistics* series on bus populations show a large drop in bus registrations for 2011 and 2012, but rebounds in 2013 and later years to levels consistent with historic populations. Given that the populations for 2011-2012 appear inconsistent with the rest of the data series, these values were dropped and estimated instead by linearly interpolating between the bus populations of 2010 and 2013 for MOVES201X.

For all source type populations, the national totals in MV-1 do not include Puerto Rico or the Virgin Islands. However, when MOVES is run at the national scale, it assumes Puerto Rico and the Virgin Islands are included in that national totals, and accordingly reduces the national populations by 0.64 percent so the national results correspond to the 50 states and Washington DC. Therefore, the national population values for each source type were increased by 0.64 percent, so that when MOVES is run at the national scale, the correct national values are used. The 0.64 percent value was derived based on the activity assigned to Puerto Rico and the Virgin Islands in the Zone table (see Section 14), in particular, they are the sum of these allocation factors from the SMOKE FF10 activity files for the 2011 NEI v2.

*Table 4-2 Historic source type populations for calendar years 1990 and 1999-2015 (in thousands)*

| Year | Motorcycle | Passenger Car | Passenger Truck | Light Commercial Truck | Other 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 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1990 | 4,287 | 144,474 | 34,774 | 4,039 | 173 | 48 | 320 | 58 | 3,322 | 147 | 801 | 1,017 | 608 |
| … | | | | | | | | | | | | | |
| 1999 | 4,179 | 133,285 | 66,947 | 7,775 | 228 | 64 | 421 | 103 | 5,264 | 232 | 1,048 | 1,329 | 985 |
| 2000 | 4,374 | 134,482 | 70,442 | 8,181 | 240 | 67 | 444 | 98 | 5,277 | 233 | 1,012 | 1,361 | 1,064 |
| 2001 | 4,935 | 138,520 | 74,484 | 8,650 | 241 | 67 | 446 | 100 | 5,630 | 248 | 1,040 | 1,363 | 1,124 |
| 2002 | 5,036 | 136,796 | 75,348 | 8,751 | 245 | 68 | 452 | 95 | 5,660 | 250 | 1,005 | 1,299 | 1,130 |
| 2003 | 5,405 | 136,544 | 77,091 | 8,953 | 239 | 69 | 473 | 92 | 5,771 | 255 | 984 | 1,256 | 1,153 |
| 2004 | 5,818 | 137,309 | 81,554 | 9,472 | 258 | 69 | 473 | 89 | 5,903 | 260 | 966 | 1,228 | 1,188 |
| 2005 | 6,267 | 137,448 | 84,702 | 9,837 | 266 | 70 | 476 | 88 | 6,146 | 271 | 964 | 1,227 | 1,252 |
| 2006 | 6,722 | 136,272 | 88,017 | 10,222 | 277 | 71 | 480 | 87 | 6,463 | 285 | 971 | 1,250 | 1,344 |
| 2007 | 7,184 | 136,809 | 89,942 | 10,446 | 268 | 83 | 489 | 86 | 6,806 | 300 | 977 | 1,243 | 1,409 |
| 2008 | 7,803 | 137,963 | 89,602 | 10,406 | 272 | 85 | 492 | 83 | 6,993 | 308 | 958 | 1,185 | 1,417 |
| 2009 | 7,981 | 135,748 | 89,800 | 10,429 | 295 | 87 | 465 | 78 | 7,094 | 313 | 925 | 1,165 | 1,469 |
| 2010 | 8,061 | 131,735 | 89,768 | 10,425 | 287 | 90 | 475 | 72 | 7,018 | 310 | 871 | 1,102 | 1,467 |
| 2011 | 8,492 | 126,466 | 97,552 | 11,329 | 293 | 89 | 476 | 63 | 6,719 | 296 | 791 | 1,026 | 1,442 |
| 2012 | 8,509 | 112,007 | 110,434 | 12,826 | 300 | 92 | 471 | 61 | 7,080 | 312 | 789 | 1,000 | 1,485 |
| 2013 | 8,459 | 114,409 | 110,311 | 12,811 | 299 | 95 | 476 | 56 | 7,067 | 312 | 744 | 968 | 1,519 |
| 2014 | 8,472 | 114,632 | 113,848 | 13,222 | 292 | 99 | 487 | 52 | 7,286 | 321 | 723 | 975 | 1,619 |
| 2015 | 8,656 | 113,591 | 117,271 | 13,620 | 302 | 104 | 488 | 53 | 7,398 | 326 | 734 | 1,039 | 1,725 |

Note that the decline in sales seen in the 2008 recession results in a flattening of total population growth rates, and eventually a decline in total population for passenger cars and long-haul combination trucks as shown in Table 4-2. This suggests that the decline in sales was accompanied by a delay in the scrappage of older vehicles. The dynamic vehicle survival rates in MOVES and their impact on age distributions are discussed in Section Appendix C

## 4.2. Projected Vehicle Populations (2016-2060)

Vehicle stock estimates from AEO2017 were used to project future populations, using a methodology similar to the VMT projections as described in Section 3.2. Because AEO vehicle categories differ from MOVES source types, the AEO projected vehicle stocks were not used directly. Instead, year-to-year percent changes in the projected values were calculated and applied to the base year populations. Since AEO2017 only projects out to 2050, populations for years 2051-2060 were assumed to continue to grow at the same growth rate as between 2049 and 2050.

Table 4-3 shows the mappings between AEO stock categories and MOVES source types. Where multiple AEO categories are listed, their stocks were summed before calculating the year-over-year growth rates. AEO's car category was mapped to both motorcycle and passenger car categories. Motorcycles were included here because they were not explicitly accounted for elsewhere in AEO. Since buses span a large range of heavy-duty vehicles and activity, the combination of AEO's light-medium-, medium-, and heavy-heavy-duty categories was mapped to each source type in the HPMS bus category. AEO's light-medium- and medium-heavy-duty categories were combined for mapping to each source type in the HPMS single-unit truck category, and AEO's heavy-heavy-duty category was mapped to each source type in the HPMS combination truck category. We acknowledge that using stock growth estimates from different vehicle types as surrogates for motorcycles and buses in particular will introduce additional uncertainty into these projections.

*Table 4-3 Mapping AEO categories to source types for projecting vehicle populations*

| AEO Stock Category Groupings | MOVES Source Type |
|---|---|
| Total Car Stock[i] | 11 – Motorcycle |
| | 21 – Passenger Car |
| Total Light Truck Stock[i] + Total Commercial Light Truck Stock[ii] | 31 – Passenger Truck |
| | 32 – Light Commercial Truck |
| Total Stock[iii] | 41 – Other Bus |
| | 42 – Transit Bus |
| | 43 – School Bus |
| Light-Medium Subtotal Stock[iii] + Medium Subtotal Stock[iii] | 51 – Refuse Truck |
| | 52 – Single Unit Short-haul Truck |
| | 53 – Single Unit Long-haul Truck |
| | 54 – Motor Home |
| Heavy Subtotal Stock[iii] | 61 – Combination Short-haul Truck |
| | 62 – Combination Long-haul Truck |

Notes:
[i] From AEO2017 Table 40: Light-Duty Vehicle Stock by Technology Type
[ii] From AEO2017 Table 46: Transportation Fleet Car and Truck Stock by Type and Technology
[iii] From AEO2017 Table 50: Freight Transportation Energy Use

The percent growth over time was calculated for each of the groups described above and applied to the 2015 base year source type populations. The resulting populations are presented in Table 4-4.

*Table 4-4 Projected source type populations for 2016-2060 (in thousands)*

| Year | Motorcycle | Passenger Car | Passenger Truck | Light Commercial Truck | Other 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 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2016 | 8,640 | 113,371 | 119,336 | 13,859 | 305 | 105 | 493 | 53 | 7,528 | 332 | 747 | 1,040 | 1,726 |
| 2017 | 8,631 | 113,254 | 121,902 | 14,157 | 309 | 107 | 500 | 55 | 7,693 | 339 | 763 | 1,043 | 1,731 |
| 2018 | 8,600 | 112,846 | 124,572 | 14,468 | 314 | 108 | 508 | 56 | 7,885 | 348 | 782 | 1,047 | 1,738 |
| 2019 | 8,555 | 112,255 | 126,764 | 14,722 | 319 | 110 | 516 | 57 | 8,074 | 356 | 801 | 1,052 | 1,747 |
| 2020 | 8,516 | 111,744 | 128,797 | 14,958 | 324 | 112 | 523 | 59 | 8,277 | 365 | 821 | 1,054 | 1,748 |
| 2021 | 8,491 | 111,422 | 130,817 | 15,193 | 329 | 114 | 532 | 60 | 8,497 | 375 | 843 | 1,056 | 1,752 |
| 2022 | 8,471 | 111,158 | 132,560 | 15,395 | 335 | 116 | 541 | 62 | 8,720 | 385 | 865 | 1,058 | 1,756 |
| 2023 | 8,451 | 110,903 | 134,124 | 15,577 | 339 | 117 | 547 | 63 | 8,918 | 393 | 885 | 1,055 | 1,750 |
| 2024 | 8,448 | 110,863 | 135,842 | 15,776 | 343 | 118 | 554 | 65 | 9,119 | 402 | 905 | 1,052 | 1,746 |
| 2025 | 8,452 | 110,912 | 137,415 | 15,959 | 347 | 120 | 561 | 66 | 9,320 | 411 | 925 | 1,051 | 1,744 |
| 2026 | 8,453 | 110,917 | 138,751 | 16,114 | 351 | 121 | 568 | 67 | 9,505 | 419 | 943 | 1,049 | 1,741 |
| 2027 | 8,463 | 111,057 | 139,983 | 16,257 | 355 | 123 | 574 | 69 | 9,685 | 427 | 961 | 1,047 | 1,738 |
| 2028 | 8,486 | 111,356 | 141,263 | 16,406 | 358 | 124 | 578 | 70 | 9,837 | 434 | 976 | 1,041 | 1,728 |
| 2029 | 8,514 | 111,721 | 142,474 | 16,547 | 362 | 125 | 586 | 71 | 10,042 | 443 | 996 | 1,040 | 1,726 |
| 2030 | 8,545 | 112,131 | 143,393 | 16,653 | 366 | 126 | 591 | 72 | 10,191 | 449 | 1,011 | 1,041 | 1,728 |
| 2031 | 8,583 | 112,624 | 144,364 | 16,766 | 372 | 128 | 601 | 74 | 10,444 | 461 | 1,036 | 1,043 | 1,731 |
| 2032 | 8,627 | 113,204 | 145,092 | 16,851 | 376 | 130 | 607 | 75 | 10,588 | 467 | 1,050 | 1,045 | 1,735 |
| 2033 | 8,676 | 113,850 | 145,734 | 16,925 | 379 | 131 | 612 | 76 | 10,751 | 474 | 1,067 | 1,042 | 1,730 |
| 2034 | 8,735 | 114,627 | 146,321 | 16,993 | 383 | 132 | 618 | 77 | 10,911 | 481 | 1,082 | 1,043 | 1,731 |
| 2035 | 8,797 | 115,437 | 146,882 | 17,058 | 388 | 134 | 627 | 79 | 11,100 | 490 | 1,101 | 1,050 | 1,743 |
| 2036 | 8,864 | 116,319 | 147,349 | 17,113 | 393 | 136 | 635 | 80 | 11,299 | 498 | 1,121 | 1,057 | 1,754 |
| 2037 | 8,935 | 117,243 | 147,772 | 17,162 | 399 | 138 | 645 | 82 | 11,509 | 508 | 1,142 | 1,067 | 1,771 |
| 2038 | 9,009 | 118,222 | 148,296 | 17,223 | 405 | 140 | 655 | 83 | 11,723 | 517 | 1,163 | 1,074 | 1,782 |
| 2039 | 9,078 | 119,124 | 148,584 | 17,256 | 409 | 141 | 662 | 84 | 11,858 | 523 | 1,176 | 1,084 | 1,799 |
| 2040 | 9,146 | 120,021 | 148,937 | 17,297 | 413 | 143 | 667 | 85 | 12,038 | 531 | 1,194 | 1,078 | 1,788 |
| 2041 | 9,219 | 120,968 | 149,300 | 17,339 | 416 | 144 | 672 | 86 | 12,135 | 535 | 1,204 | 1,084 | 1,799 |
| 2042 | 9,288 | 121,877 | 149,750 | 17,392 | 421 | 145 | 680 | 88 | 12,328 | 544 | 1,223 | 1,091 | 1,810 |
| 2043 | 9,354 | 122,751 | 150,263 | 17,451 | 429 | 148 | 693 | 90 | 12,604 | 556 | 1,250 | 1,102 | 1,829 |
| 2044 | 9,424 | 123,664 | 150,825 | 17,516 | 436 | 151 | 705 | 91 | 12,846 | 567 | 1,274 | 1,117 | 1,854 |
| 2045 | 9,496 | 124,607 | 151,452 | 17,589 | 442 | 153 | 714 | 93 | 13,031 | 575 | 1,293 | 1,129 | 1,873 |
| 2046 | 9,567 | 125,540 | 152,117 | 17,667 | 449 | 155 | 725 | 94 | 13,272 | 585 | 1,317 | 1,140 | 1,892 |

| Year | Motorcycle | Passenger Car | Passenger Truck | Light Commercial Truck | Other 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 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2047 | 9,630 | 126,372 | 152,777 | 17,743 | 456 | 157 | 736 | 96 | 13,505 | 596 | 1,340 | 1,152 | 1,912 |
| 2048 | 9,693 | 127,193 | 153,456 | 17,822 | 462 | 159 | 746 | 97 | 13,714 | 605 | 1,361 | 1,160 | 1,925 |
| 2049 | 9,758 | 128,051 | 154,219 | 17,911 | 468 | 162 | 756 | 99 | 13,932 | 614 | 1,382 | 1,171 | 1,943 |
| 2050 | 9,821 | 128,873 | 154,923 | 17,992 | 474 | 164 | 766 | 100 | 14,140 | 624 | 1,403 | 1,181 | 1,960 |
| 2051 | 9,884 | 129,701 | 155,630 | 18,075 | 480 | 166 | 776 | 102 | 14,351 | 633 | 1,424 | 1,192 | 1,977 |
| 2052 | 9,947 | 130,534 | 156,341 | 18,157 | 486 | 168 | 786 | 103 | 14,566 | 642 | 1,445 | 1,202 | 1,995 |
| 2053 | 10,011 | 131,372 | 157,054 | 18,240 | 493 | 170 | 796 | 105 | 14,783 | 652 | 1,467 | 1,213 | 2,013 |
| 2054 | 10,076 | 132,216 | 157,771 | 18,323 | 499 | 172 | 806 | 107 | 15,004 | 662 | 1,488 | 1,224 | 2,031 |
| 2055 | 10,140 | 133,066 | 158,491 | 18,407 | 506 | 175 | 817 | 108 | 15,228 | 672 | 1,511 | 1,234 | 2,049 |
| 2056 | 10,206 | 133,920 | 159,215 | 18,491 | 512 | 177 | 827 | 110 | 15,456 | 682 | 1,533 | 1,245 | 2,067 |
| 2057 | 10,271 | 134,781 | 159,941 | 18,575 | 519 | 179 | 838 | 111 | 15,686 | 692 | 1,556 | 1,256 | 2,085 |
| 2058 | 10,337 | 135,646 | 160,671 | 18,660 | 525 | 181 | 849 | 113 | 15,921 | 702 | 1,579 | 1,268 | 2,104 |
| 2059 | 10,403 | 136,518 | 161,405 | 18,745 | 532 | 184 | 860 | 115 | 16,159 | 713 | 1,603 | 1,279 | 2,122 |
| 2060 | 10,470 | 137,394 | 162,141 | 18,831 | 539 | 186 | 871 | 116 | 16,400 | 723 | 1,627 | 1,290 | 2,141 |

# 5. Fleet Characteristics

Despite the availability of vehicle registration databases, comprehensive surveys for characterizing travel pattern, and sophisticated sensors and cameras for measuring vehicle activity, it is still difficult to estimate vehicle populations in the categories needed for emissions inventory modeling. Differentiating, for example, between passenger car and trucks, or between light-duty and heavy-duty trucks presents substantial modeling challenges since the characteristics that are important for emissions are not always readily observable.[17,18] To develop MOVES defaults, we have merged registration and survey data with activity measurements in an effort to identify key vehicle parameters such as weight, axle and tire configuration, and typical trip range.

MOVES categorizes vehicles into thirteen source types as described in Section 2.1, which are defined using physical characteristics, such as number of axles and tires, and travel behavior characteristics, such as typical trip lengths. This section describes the defining characteristics of the source types in greater detail, explains how source type is related to fuel type and regulatory class through the SampleVehiclePopulation table, and how MOVES201X estimates and projects the number of vehicles in each category.

## 5.1. Source Type Definitions

MOVES source types are intended to further divide HPMS vehicle classifications into groups of vehicles with similar activity patterns. For example, passenger trucks and light commercial trucks are expected to have different daily trip patterns.

### 5.1.1. Motorcycles

According to the HPMS vehicle description, motorcycles (sourceTypeID 11) are, "all two- or three-wheeled motorized vehicles, typically with saddle seats and steered by handlebars rather than a wheel."[19] This category usually includes any registered motorcycles, motor scooters, mopeds, and motor-powered bicycles. Please note that off-road motorcycles are regulated as nonroad equipment and are not covered in this report.

### 5.1.2. Passenger Cars

Passenger cars are defined as any coupes, compacts, sedans, or station wagons with the primary purpose of carrying passengers.[19] All passenger cars (sourceTypeID 21) are categorized in the light-duty vehicle regulatory class (regClassID 20).

### 5.1.3. Light-Duty Trucks

Light-duty trucks include pickups, sport utility vehicles (SUVs), and vans.[19] FHWA's vehicle classification specifies that light-duty vehicles are those weighing less than 10,000 pounds, specifically vehicles with a GVWR in Class 1 and 2, except Class 2b trucks with two axles or more and at least six tires, as those are assigned to the single-unit truck category. In MOVES, a light-duty truck is considered a passenger truck if it is registered to an individual, or a commercial light-duty truck if it is registered to an organization or business.

### 5.1.4. Buses

MOVES has three bus source types: other (sourceTypeID 41), transit (sourceTypeID 42), and school buses (sourceTypeID 43).

Transit buses in MOVES are defined as any active vehicle with a bus body type ("bus", "articulated bus", "over-the-road bus", "double decked bus", and "cutaway") that must be reported to Federal Transit Administration's (FTA) National Transit Database (NTD). According to the FTA, these are buses owned by a public transit organization for the primary purpose of transporting passengers on fixed routes and schedules.[20]

School buses in MOVES are defined as according to FHWA: vehicles designed to carry more than ten passengers and are used to transport K-12 students between their home and school.[21]

Any other buses that do not fit into the transit or school bus categories are modeled in MOVES as "other" buses.[e] For example, these may include intercity buses not owned by transit agencies. Please note that these definitions allow similar vehicle types to be modeled in both the transit and other bus source types. For example, a shuttle bus operated by a transit agency would be modeled as a transit bus, but an airport shuttle bus operated by a private company would be modeled as an "other" bus. Due to the similarities between these source types, they have identical fuel type and regulatory class distributions. However, they do have different age distributions and driving schedules as described in subsequent sections.

#### 5.1.5. Single-Unit Trucks

The single-unit HPMS class in MOVES consists of refuse trucks (sourceTypeID 51), short-haul single-unit trucks (sourceTypeID 52), long-haul single-unit trucks (sourceTypeID 53), and motor homes (sourceTypeID 54). FHWA's vehicle classification specifies that single-unit trucks are single-frame trucks with a gross vehicle weight rating of greater than 10,000 pounds or with two axles and at least six tires—colloquially known as "dualies." The difference between short-haul and long-haul single-unit trucks is their primary trip length; short-haul trucks travel less than or equal to 200 miles a day, and long-haul trucks travel more than 200 miles a day.

#### 5.1.6. Combination Trucks

The combination truck HPMS class in MOVES consists of two source types: short-haul (sourceTypeID 61) and long-haul combination trucks (sourceTypeID 62). These are heavy-duty trucks that are not single-frame. Like single-unit trucks, short-haul and long-haul combination trucks are distinguished by their primary trip length; short-haul trucks travel less than or equal to 200 miles a day, and long-haul trucks travel more than 200 miles a day. Generally, short-haul combination trucks are older than long-haul combination trucks and these short-haul trucks often purchased in secondary markets, such as for drayage applications, after being used primarily for long-haul trips.[22]

### 5.2. Sample Vehicle Population

[e] Note, in previous versions of MOVES, "other" buses were called "intercity" buses and defined slightly differently.

To match source types to emission rates, MOVES must associate each source type with specific fuel types and regulatory classes. As vehicle markets shift, these distributions change with model year. This information is stored in the SampleVehiclePopulation table, which contains two fractions: stmyFraction and stmyFuelEngFraction.

The stmyFraction represents the default national fuel type and regulatory class allocation for each source type and model year. Written out mathematically in Equation 1, we define the stmyFraction as

$$f(stmy)_{i,j,k,l} = \frac{N_{i,j,k,l}}{\sum_{j\epsilon J,k\epsilon K} N_{i,j,k,l}}, \qquad \textbf{Equation 1}$$

where the number of vehicles $N$ in a given model year $i$, regulatory class $j$, fuel type $k$, and source type $l$ is divided by the sum of vehicles across the set of all regulatory classes $J$ and all fuel types $K$. That is, the denominator is the total for a given source type and model year, and so the stmyFraction must sum to one for each source type and model year. For example, model year 2010 passenger trucks have stmyFractions that indicate the distribution of these vehicles between gasoline, diesel, E85, and electricity and regulatory classes 30 and 40. A value of zero indicates that the MOVES default population of vehicles of that source type, model year, fuel type, and regulatory class is negligible or does not exist.

However, these default distributions in the stmyFraction may be modified by the user to model local conditions through the Alternative Fuel Vehicle and Technology (AVFT) table. To allow these user inputs, the stmyFuelEngFraction indicates the expected regulatory class distribution for each allowable combination of source type, model year and fuel type, whether or not these vehicles exist in the default. Similar to the stmyFraction above, we define stmyFuelEngFraction in Equation 2 as

$$f(stmyfueleng)_{i,j,k,l} = \frac{N_{i,j,k,l}}{\sum_{j\epsilon J} N_{i,j,k,l}}, \qquad \textit{Equation 2}$$

for number of vehicles $N$, model year $i$, regulatory class $j$, fuel type $k$, source type $l$, and the set of all regulatory classes $J$. In this case, the denominator is the total for a given source type, model year, and fuel type, and so the stmyFuelEngFraction must sum to one for each combination of source type, model year and fuel type. For example, for model year 2010 gasoline passenger trucks, the table will list a stmyFuelEngFraction for regulatory class 30 and another for regulatory class 40. In this example, while the stmyFraction indicates that the MOVES defaults assign zero fraction of model year 2010 passenger trucks to the electricity fuel type, the stmyFuelEngFraction indicates a default (hypothetical) regulatory class distribution if these vehicles existed. In this case, MOVES would model any electric passenger trucks as belonging to regulatory class 30. The stmyFraction is particularly important because users can edit fuel type distributions using the Alternative Vehicle Fuel and Technology (AVFT) importer. For instance, a user can create a future scenario in which there is a high penetration of electric passenger trucks. The stmyFuelEngFraction allows MOVES to assign vehicles to regulatory class without requiring this input from the user.

As noted in Section 2.4, these fuel type fractions indicate the fuel capability of the vehicle and not the fuel being used by the vehicle. MOVES allocates fuel to specific vehicles in a two-step process: 1) vehicles are classified by the type of fuel they can use in the fuel type fraction, and then 2) fuels are distributed according to how much of each fuel is used relative to the vehicles' total fuel consumption in the fuel usage fraction. For example, Figure 5-1 shows the national default fuel type fractions for all light-duty vehicles among the different MOVES fuel types. In this report's nomenclature, E85-capable and flexible fuel vehicles are synomous—meaning they can accept either gasoline or E-85 fuel. The amount of E-85 versus the amount of gasoline used out of all the fuel consumed by the vehicle is stored in the fuelUsageFraction table. Discussion on fuel usage can be found in the MOVES Fuel Supply Report.[6]

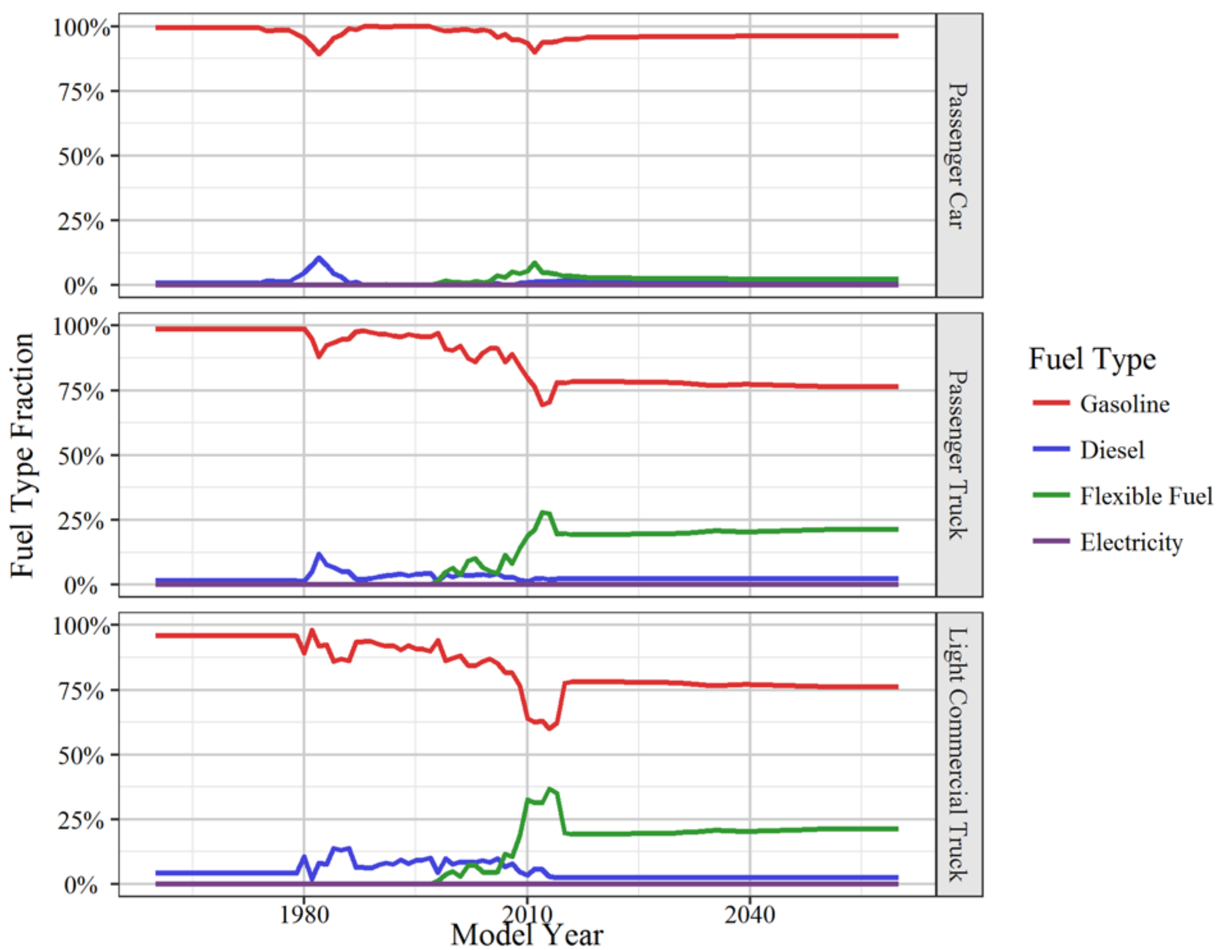


*Figure 5-1 Default fuel fractions for light-duty source types in MOVES201X*

Both the stmyFractions and the stmyFuelEngFractions were calculated primarily using the 2014 IHS data set. However, in MOVES201X, the fuel type and regulatory class distributions were unchanged from MOVES2014 for the following source type and model year combinations:

- Passenger cars, school buses, refuse trucks, short-haul and long-haul single-unit trucks, and short-haul and long-haul combination trucks prior to model year 2000
- Passenger trucks and light commercial trucks prior to model year 1981

The previous versions of MOVES relied on combining vehicle registration data sets from IHS with the Vehicle Inventory and Use Survey (VIUS). Because the last time the VIUS was performed was in 2002, we retained the previous analysis for model years before 2000, but used the 2014 IHS data set without combining it with the VIUS data for model years 2000 and later. However, passenger trucks and light commercial trucks used the 2014 IHS data for 1981 and later because we changed the definition of these vehicle types, as described in Section 5.1.2. Therefore, they are no longer consistent with the VIUS definition. Unfortunately, the data are too scarce in 2014 for pre-1981 model years, so we continued to rely on the previous analysis for those model years. The documentation of the previous analysis may be found in Appendix A The fuel type and regulatory class distributions for all other source type and model year combinations are described below.

Before the fuel type and regulatory class distributions could be calculated from the 2014 IHS data, the data set needed to be cleaned. For the source type field, there were many class 3 trucks that were classified as a light-duty source type; as MOVES requires class 3 trucks to be modeled in a heavy-duty source type, these were all re-classified as "other single-unit trucks" (see Section 5.2.5 for an explanation of this source categorization). For the fuel type field, electric hybrids with gasoline or diesel were grouped with fully gasoline or diesel vehicles, since MOVES does not model hybrids separately. Vehicles categorized as "ethanol" or "flexible" were considered to be in the MOVES E-85 fuel category. If the fuel type was unknown for light-duty source types or "other single-unit trucks," it was assumed to be gasoline. If it was unknown for buses, refuse trucks, or combination trucks, the fuel type was assumed to be diesel. All electric vehicles were dropped from the data set for reasons described in the light-duty sections below. Any remaining vehicles with unknown fuel, other alternative fuels (including hydrogen fuel cell, methanol, and "convertible"), or vehicles with source type/ fuel type combinations that MOVES cannot model (such as CNG light commercial trucks) were also dropped from the data set.

### 5.2.1. Motorcycles

All motorcycles fall into the motorcycle regulatory class (regClassID 10) and must be fueled by gasoline. Although some alternative fuel motorcycles may exist, they account for a negligible fraction of total US motorcycle sales and cannot be modeled in MOVES.

### 5.2.2. Passenger Cars

Any passenger car is considered to be in the light-duty vehicle regulatory class (regClassID 20). The 2014 IHS data set provided the split between gasoline, diesel, and E-85 capable cars in the SampleVehiclePopulation table. For model years 2015 and later, we used Department of Energy car sales projections from AEO2017's table "Light-Duty Vehicle Sales by Technology Type" to derive flexible fuel vehicle penetrations and applied them to the SVP fractions for regulatory class 20.[23]

In MOVES, all electric passenger cars are modeled in the national case to have zero penetration. This is because electric vehicle market penetration varies widely by geographic region, and MOVES does not have the capabilities to model this variance accurately at the national scale. However, MOVES may be run at the county or project scale with local information to accurately capture this detail. MOVES cannot model CNG passenger cars.

### 5.2.3. Light-Duty Trucks

Since passenger and light commercial trucks are defined as light-duty vehicles, they are constrained to regulatory class 30 and 40. Light-duty trucks in the 2014 IHS data set with a GVWR class of 1, 2, or 2a were classified as regulatory class 30, and Class 2b trucks were classified as regulatory class 40. The 2014 IHS data set also provided the split between gasoline, diesel, and E-85 capable trucks. Please note that all E-85 light-duty trucks are modeled as regulatory class 30.

For model years 2015 and later, we used Department of Energy light truck and light commercial truck sales projections from AEO2017's tables "Light-Duty Vehicle Sales by Technology Type" and "Transportation Fleet Car and Truck Sales by Type and Technology" to derive flexible fuel vehicle penetrations and applied them to the SVP fractions for regulatory class 30.[24,25]

In MOVES, all electric light-duty trucks are modeled in the national case to have zero penetration. This is because electric vehicle market penetration varies widely by geographic region, and MOVES does not have the capabilities to model this variance accurately at the national scale. However, MOVES may be run at the county or project scale with local information to accurately capture this detail. Please note that all electric light-duty trucks are modeled as regulatory class 30. MOVES cannot model CNG light-duty trucks.

### 5.2.4. Buses

Since school buses have a distinguishing characteristic in their VIN, they are well represented in the 2014 IHS data set, and we were able to calculate their fuel type and regulatory class distributions. However, the 2014 IHS data set was unable to distinguish between transit buses and other buses, and so these categories were grouped together. As the National Transit Database does not contain weight class information, that source could not be used to calculate regulatory class distributions for transit buses. Considering that the vehicle types in both the transit and "other" bus categories may overlap, we decided to keep these categories grouped together while determining fuel type and regulatory class distributions. The only difference between the transit and other bus distributions is in the categorization of class 8 buses, since urban transit buses are regulated separately from other heavy-duty vehicles, under 40 CFR 86.091-2.[26] For this reason, class 8 CNG and diesel transit buses were classified in regulatory class 48, whereas class 8 gasoline transit buses and all class 8 other buses were classified in regulatory class 47.

In MOVES201X, all CNG buses are modeled in the national case to have zero penetration. This is because CNG market penetration varies widely by geographic region, and MOVES does not have the capabilities to model this variance accurately at the national scale. However, MOVES may be run at the county or project scale with local information to accurately capture this detail. While the 2014 IHS data set did contain CNG buses, these vehicles were aggregated with the diesel buses in our analysis, as it was assumed that these vehicles were being used in lieu of diesel buses and we wanted to capture those vehicles when determining regulatory class splits. Finally, MOVES201X can only model CNG school buses and other buses in regulatory class 47, and it cannot model electric or E-85 buses.

### 5.2.5. Single-Unit Trucks

Single-unit vehicles are distributed among the heavy-duty regulatory classes (regClassIDs 41, 42, 46, and 47) and between diesel and gasoline fuels based on the 2014 IHS data set. The 2014 IHS data set categorized single-unit trucks into refuse trucks (based on ownership), motor homes, and "other single-unit trucks." Lacking a way to differentiate these trucks into short-haul and long-haul without resorting back to the VIUS, we used the fuel type and regulatory class distributions for "other single-unit trucks" identically for both short-haul and long-haul single-unit trucks.

While the 2014 IHS data set did contain CNG single-unit trucks, these vehicles were aggregated with the diesel trucks in our analysis, as it was assumed these vehicles were being used in lieu of diesel trucks, and we wanted to capture those vehicles when determining regulatory class splits. As with the other heavy-duty vehicles, MOVES201X can only model CNG single-unit trucks in regulatory class 47, and all CNG vehicles are modeled in the national case to have zero penetration. MOVES cannot model electric or E-85 single-unit trucks.

### 5.2.6. Combination Trucks

Combination trucks consist mostly of Class 8 trucks in the MOVES HHD regulatory class (regClassID 47) but also contain some Class 7 trucks in the MHD regulatory class (regClassID 46), predominantly in short-haul. Similarly, almost all combination trucks are diesel-fueled. MOVES does not model gasoline long-haul combination trucks. The regulatory class and fuel type distributions are based on the 2014 IHS data set, which differentiated between short-haul and long-haul combination trucks based on the absence or presence of sleeper cabs.

While the 2014 IHS data set did contain CNG combination trucks, these vehicles were aggregated with the diesel trucks in our analysis, as it was assumed these vehicles were being used in lieu of diesel trucks, and we wanted to capture those vehicles when determining regulatory class splits. As with the other heavy-duty vehicles, MOVES201X can only model CNG combination trucks in regulatory class 47, and all CNG vehicles are modeled in the national case to have zero penetration. MOVES cannot model electric or E-85 combination trucks.

# 6. Vehicle Age-Related Characteristics

Age is an important factor in calculating vehicle emission inventories. MOVES employs a number of different age dependent factors, including deterioration of engine and emission after-treatment technology due to tampering and mal-maintenance, vehicle scrappage and fleet turnover, and mileage accumulation over the lifetime of the vehicle. Deterioration effects are detailed in the MOVES reports on the development of light-duty and heavy-duty emission rates.[4,5] This section describes vehicle age distributions and relative mileage accumulation rates by source type.

## 6.1. Source Type Definitions

Vehicle age is defined in MOVES as the difference between a vehicle's model year and the year of analysis. Age distributions in MOVES vary by source type and range from 0 to 30+ years, so that all vehicles 30 years and older are modeled together. Therefore, an age distribution is comprised of 31 fractions, where each fraction represents the number of vehicles present at a certain age divided by the vehicle population for all ages. Since sales and scrappage rates are not constant, these distributions vary by calendar year. Ideally, all historic age distributions could be derived from registration data sources. However, acquiring such data is prohibitively costly, so MOVES201X only contains registration-based age distributions for two analysis years: 1990 and 2014. The age distributions for all other analysis years in MOVES201X were projected forwards or backwards from the 2014 base age distribution. All default age distributions are available in the SourceTypeAgeDistribution table.

Please note that the 1990 age distributions in MOVES201X have not been updated in this model release. Please refer to Appendix BAppendix C for more information.

### 6.1.1. Base Age Distributions

The 2014 base age distributions for cars and trucks were primarily derived from the 2014 IHS data set and the 2014 National Transit Database (NTD). The 2014 IHS data set had vehicle counts by age for motorcycles (11), passenger cars (21), passenger trucks (31), light commercial trucks (32), school buses (43), refuse trucks (51), motor homes (54), combination short-haul trucks (61), and combination long-haul trucks (62), as well as other single-unit trucks and non-school buses. The age distribution for the other single-unit trucks was applied to both short-haul (52) and long-haul (53) single-unit trucks, and the age distribution for non-school buses was applied to the other bus source type (41). Transit bus (42) age distributions were calculated from the NTD active fleet vehicles using the definition of a transit bus in Section 5.1.4.

Since the age distributions in MOVES represent the full calendar year, additional calculations were necessary for determining the fraction of age 0 vehicles in the fleet because the 2014 IHS data set and 2014 NTD did not capture all vehicles sold in 2014. Vehicle sales by source type in 2014 were calculated from a variety of sources as described in Section 0. The source type sales were divided by the 2014 source type populations (see Section 4.1) to determine the age 0 fractions. The other fractions for ages 1-30 were renormalized so that each source type's age distribution summed to 1. This was done instead of directly using the sales numbers to calculate the age distributions (i.e., using the sales values as age 0 counts) because the IHS data set is only used in MOVES to determine vehicle distributions, not for vehicle populations.

Figure 6-1 and Table 6-1 show the fraction of vehicles by age and source type for calendar year 2014, which formed the basis for forecasting and backcasting age distributions as described in the following sections. Please note that since all vehicles age 30 and older are modeled together, there is an uptick in this age bin for most source types.

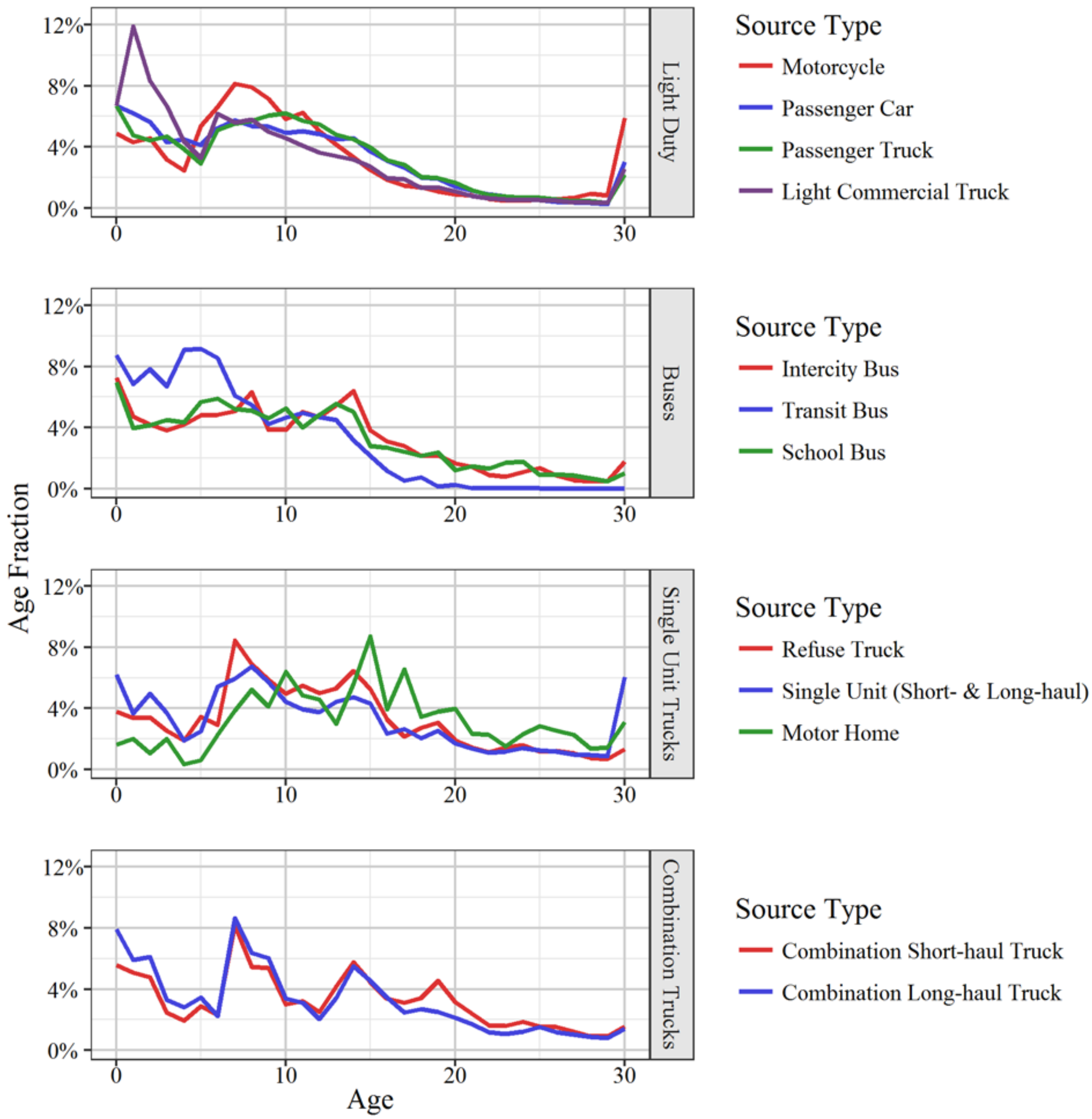


*Figure 6-1 2014 age distributions by source type in MOVES201X*

*Table 6-1 2014 age fractions by MOVES source type*

| Age | 11 | 21 | 31 | 32 | 41 | 42 | 43 | 51 | 52 | 53 | 54 | 61 | 62 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.048749 | 0.067075 | 0.066767 | 0.066767 | 0.072837 | 0.087654 | 0.069836 | 0.037865 | 0.062272 | 0.062272 | 0.016299 | 0.055691 | 0.079202 |
| 1 | 0.042924 | 0.061964 | 0.047716 | 0.119023 | 0.047215 | 0.068418 | 0.039713 | 0.033829 | 0.036611 | 0.036611 | 0.020135 | 0.050905 | 0.059113 |
| 2 | 0.045758 | 0.056152 | 0.044172 | 0.083282 | 0.042178 | 0.078347 | 0.041803 | 0.034106 | 0.049487 | 0.049487 | 0.010521 | 0.047936 | 0.060883 |
| 3 | 0.031549 | 0.043031 | 0.046773 | 0.066891 | 0.038117 | 0.066915 | 0.045112 | 0.025332 | 0.037268 | 0.037268 | 0.019962 | 0.024696 | 0.033144 |
| 4 | 0.024357 | 0.044877 | 0.038382 | 0.043327 | 0.041974 | 0.090937 | 0.043380 | 0.018752 | 0.018998 | 0.018998 | 0.003384 | 0.019356 | 0.028032 |
| 5 | 0.053659 | 0.041199 | 0.029116 | 0.032828 | 0.047949 | 0.091708 | 0.056681 | 0.034343 | 0.025040 | 0.025040 | 0.005989 | 0.029012 | 0.034727 |
| 6 | 0.066182 | 0.052143 | 0.051139 | 0.061667 | 0.048592 | 0.085745 | 0.058875 | 0.029047 | 0.053999 | 0.053999 | 0.022737 | 0.023073 | 0.022273 |
| 7 | 0.081538 | 0.057332 | 0.055358 | 0.055807 | 0.050785 | 0.060813 | 0.052376 | 0.084356 | 0.059404 | 0.059404 | 0.038799 | 0.081495 | 0.086511 |
| 8 | 0.079157 | 0.053820 | 0.056978 | 0.058020 | 0.063279 | 0.054740 | 0.051189 | 0.068844 | 0.067473 | 0.067473 | 0.052469 | 0.054521 | 0.063907 |
| 9 | 0.071324 | 0.053307 | 0.060561 | 0.049878 | 0.038752 | 0.042457 | 0.046074 | 0.058608 | 0.057204 | 0.057204 | 0.041156 | 0.053846 | 0.060395 |
| 10 | 0.058046 | 0.049173 | 0.062020 | 0.045780 | 0.038427 | 0.046542 | 0.052596 | 0.049756 | 0.044208 | 0.044208 | 0.063954 | 0.030149 | 0.033765 |
| 11 | 0.062351 | 0.050226 | 0.057092 | 0.040942 | 0.050263 | 0.049449 | 0.039994 | 0.054893 | 0.039326 | 0.039326 | 0.048349 | 0.032315 | 0.031191 |
| 12 | 0.050151 | 0.048462 | 0.055007 | 0.036421 | 0.047094 | 0.047076 | 0.048330 | 0.049993 | 0.037384 | 0.037384 | 0.045693 | 0.024980 | 0.020598 |
| 13 | 0.041655 | 0.045002 | 0.048183 | 0.034160 | 0.054325 | 0.044969 | 0.055483 | 0.053075 | 0.044271 | 0.044271 | 0.030069 | 0.041563 | 0.034303 |
| 14 | 0.033072 | 0.045704 | 0.044937 | 0.031612 | 0.063892 | 0.031786 | 0.050152 | 0.064437 | 0.047490 | 0.047490 | 0.056193 | 0.057629 | 0.054938 |
| 15 | 0.024850 | 0.036964 | 0.039505 | 0.027008 | 0.038284 | 0.021421 | 0.027986 | 0.052779 | 0.043121 | 0.043121 | 0.087104 | 0.044710 | 0.045365 |
| 16 | 0.018282 | 0.030852 | 0.031213 | 0.019471 | 0.031023 | 0.011808 | 0.026992 | 0.033098 | 0.023479 | 0.023479 | 0.039411 | 0.033750 | 0.034398 |
| 17 | 0.014802 | 0.026554 | 0.028363 | 0.018999 | 0.028111 | 0.005410 | 0.024274 | 0.021538 | 0.026495 | 0.026495 | 0.065630 | 0.031220 | 0.024509 |
| 18 | 0.013367 | 0.020137 | 0.020277 | 0.013165 | 0.021638 | 0.007407 | 0.021346 | 0.027190 | 0.020353 | 0.020353 | 0.034423 | 0.034261 | 0.026834 |
| 19 | 0.010992 | 0.019016 | 0.019572 | 0.013398 | 0.021781 | 0.001345 | 0.023788 | 0.030628 | 0.025485 | 0.025485 | 0.037894 | 0.045554 | 0.024970 |
| 20 | 0.009109 | 0.014037 | 0.016683 | 0.011014 | 0.016510 | 0.002512 | 0.012167 | 0.018851 | 0.017215 | 0.017215 | 0.039647 | 0.031652 | 0.021224 |
| 21 | 0.008085 | 0.011117 | 0.011640 | 0.007811 | 0.014453 | 0.000366 | 0.014562 | 0.014524 | 0.013776 | 0.013776 | 0.023489 | 0.023816 | 0.017113 |
| 22 | 0.005866 | 0.009004 | 0.008614 | 0.006198 | 0.008894 | 0.000544 | 0.013275 | 0.011540 | 0.011089 | 0.011089 | 0.022851 | 0.016466 | 0.011746 |
| 23 | 0.004800 | 0.007487 | 0.007305 | 0.005465 | 0.007729 | 0.000445 | 0.017004 | 0.014326 | 0.011776 | 0.011776 | 0.015131 | 0.015985 | 0.010478 |
| 24 | 0.004978 | 0.006083 | 0.006600 | 0.005063 | 0.010913 | 0.000544 | 0.017892 | 0.015966 | 0.013918 | 0.013918 | 0.022977 | 0.018710 | 0.012306 |
| 25 | 0.005475 | 0.005086 | 0.006762 | 0.005230 | 0.013515 | 0.000277 | 0.009126 | 0.011579 | 0.012477 | 0.012477 | 0.028532 | 0.015744 | 0.015104 |
| 26 | 0.005422 | 0.004188 | 0.005667 | 0.004675 | 0.008607 | 0.000109 | 0.009563 | 0.012034 | 0.011621 | 0.011621 | 0.025315 | 0.015033 | 0.011752 |
| 27 | 0.006760 | 0.003785 | 0.004271 | 0.003559 | 0.005702 | 0.000030 | 0.008774 | 0.010690 | 0.009758 | 0.009758 | 0.022812 | 0.011995 | 0.010406 |
| 28 | 0.009409 | 0.003289 | 0.004336 | 0.003829 | 0.004765 | 0.000010 | 0.006657 | 0.007608 | 0.009643 | 0.009643 | 0.013770 | 0.009313 | 0.008685 |
| 29 | 0.008320 | 0.002669 | 0.003155 | 0.003184 | 0.004757 | 0.000020 | 0.004937 | 0.006995 | 0.008551 | 0.008551 | 0.014229 | 0.009199 | 0.007987 |
| 30+ | 0.059011 | 0.030264 | 0.021833 | 0.025526 | 0.017637 | 0.000198 | 0.010062 | 0.013417 | 0.060808 | 0.060808 | 0.031076 | 0.015427 | 0.014141 |

### 6.1.2. Historic Age Distributions

The 1999-2013 age distributions were backcast from the 2014 base age distribution using historic population and sales estimates. Age distributions are calculated from population counts, if the populations are known by age:

$$f_{a,y} = \frac{p_a}{P_y} \qquad \textbf{Equation 3}$$

In **Equation 3**, $f_{a,y}$ is the age fraction, $p_a$ is the population of vehicles at age $a$, and $P_y$ is the total population in calendar year $y$. In this section, arrow notation will be used if the operations are to be performed for all ages. For example, $\overrightarrow{f_y}$ is used to represent all age fractions in calendar year $y$. Another example is $\overrightarrow{P_y}$; it represents an array of $p_a$ values at each permissible age in calendar year $y$. In contrast, $P_y$ represents the total population in year $y$.

Intuitively, backcasting an age distribution one year involves removing the new vehicles sold in the base year and adding the vehicles scrapped in the previous year, as shown in **Equation 4**:

$$\overrightarrow{P_{y-1}} = \overrightarrow{P_y} - \overrightarrow{N_y} + \overrightarrow{R_{y-1}} \qquad \textbf{Equation 4}$$

where $\overrightarrow{P_{y-1}}$ is the population (known at each age) of the previous year, $\overrightarrow{P_y}$ is the population in the base year, $\overrightarrow{N_y}$ is new vehicles sold in the base year, and $\overrightarrow{R_{y-1}}$ is the population of vehicles removed in the in the previous year. Please note that the sales term only includes new vehicles at age 0. This can be represented algorithmically as follows:

1. Calculate the base population distribution ($\overrightarrow{P_y}$) by multiplying the base age distribution ($\overrightarrow{f_y}$) and base population ($P_y$).
2. Remove the age 0 vehicles ($\overrightarrow{N_y}$).
3. Decrease the population age index by one (for example, 3-year-old vehicles are reclassified as 2-year-old vehicles).
4. Add the vehicles that were removed in the previous year ($\overrightarrow{R_{y-1}}$).
5. Convert the resulting population distribution into an age distribution using Equation 3.
6. Replace the new age 29 and 30+ fractions with the base year age 29 and 30+ fractions, and renormalize the new age distribution to sum to 1 while retaining the original age 29 and 30+ fractions.
7. This results in the previous year age distribution ($\overrightarrow{f_{y-1}}$). If this algorithm is to be repeated, $\overrightarrow{f_{y-1}}$ becomes $\overrightarrow{f_y}$ for the next iteration.

The fraction of age 30+ vehicles is kept constant because most source types have a sizeable fraction in this age bin in the base age distributions. If left unconstrained, the algorithm can either grow this age bin unreasonably large or shrink it unreasonably small, depending on the source type. This indicates that the base survival rates for the oldest age bins may be inappropriate. However, lacking better data, we decided to keep the age 30+ bin at a constant fraction for all historic age distributions.

Age 29 is additionally retained because when the number of scrapped vehicles are calculated, a large proportion of them come from the age 30 bin. In reality, these scrapped vehicles have a distribution well beyond age 30, but they are all grouped together in this analysis. When the scrapped vehicles are added to the index-shifted population distribution, this results in a large addition to the age 29 bin. To prevent this from happening, the base year age 29 fractions are also retained in each backcasted year.

Please see Appendix C, Detailed Derivation of Age Distributions, for more information on how this algorithm was applied to derive the historic national default age distributions in MOVES.

### 6.1.3. Projected Age Distributions

The method used to forecast the 2015-2060 age distributions from the 2014 distribution is similar to the backcasting method described above. To forecast an age distribution one year, **Equation 4** of the previous section can be rewritten as **Equation 5**:

$$\overrightarrow{P_{y+1}} = \overrightarrow{P_y} - \overrightarrow{R_y} + \overrightarrow{N_{y+1}} \qquad \textbf{Equation 5}$$

Essentially, this is done by taking the base year's population distribution, removing the vehicles scrapped in the base year and adding the new vehicles sold in the next year. This can be represented algorithmically as follows:

1. Calculate the base population distribution ($\overrightarrow{P_y}$) by multiplying the base age distribution ($\overrightarrow{f_y}$) and base population ($P_y$).
2. Remove the vehicles that did not survive ($\overrightarrow{R_y}$) at each age level.
3. Increase the population age index by one (for example, 3-year-old vehicles are reclassified as 4-year-old vehicles).
4. Add new vehicle sales ($\overrightarrow{N_{y+1}}$) as the age 0 cohort.
5. Convert the resulting population distribution into an age distribution using Equation 3.
6. Replace the new age 30+ fraction with the base year age 30+ fraction, and renormalize the new age distribution to sum to 1 while retaining the original age 0 and age 30+ fractions.
7. This results in the next year age distribution ($\overrightarrow{f_{y+1}}$). If this algorithm is to be repeated, $\overrightarrow{f_{y+1}}$ becomes $\overrightarrow{f_y}$ for the next iteration.

The fraction of age 30+ vehicles is kept constant in the projection algorithm for the same reasons given for the backcasting algorithm. However, there is no issue with an artificially growing population of age 29 vehicles when projecting forward. Therefore, the age 29 bin is calculated as the others are instead of being retained from the base age distribution.

Please see Appendix C,  Detailed Derivation of Age Distributions
,for more information on how this algorithm was applied to derive the projected national default age distributions in MOVES.

In addition to producing the default projected age distributions, this algorithm was implemented in the Age Distribution Projection Tool for MOVES201X.[27] This tool can be used to project future local age distributions from user-supplied baseline distributions, provided that the baseline year is 2011 or later. This requirement ensures that the 2008-2009 recession is fully accounted for in the baseline. The sales rates and scrappage assumptions are the same in the tool as they are in the national default. This is because local projections of sales and scrappage are generally unavailable, and the national trends are the best available data. Thus, projections made with the tool tend to converge with the national age distributions for far future years.

## 6.2. Relative Mileage Accumulation Rate

For emission calculations, MOVES needs to estimate the miles travelled by each age and source type. MOVES uses a relative mileage accumulation rate (RMAR) in combination with source type populations (see Section 4and age distributions described in Section 6.1to distribute the total annual miles driven by each HPMS vehicle type (see Section 3) to each source type and age group. Using this approach, the vehicle population and the total annual vehicle miles traveled (VMT) can vary from calendar year to calendar year, but the proportional travel by an individual vehicle of each age will not vary.

The RMAR is determined from the mileage accumulation rate (MAR) within each HPMS vehicle classification such that the annual mileage accumulation for a single vehicle of each age of a source type is relative to the mileage accumulation of all of the source types and ages within the HPMS vehicle classification. For example, passenger cars, passenger trucks and light commercial trucks are all within the same HPMS vehicle classification (HPMSVTypeID 25). By definition, new (age 0) passenger trucks and light commercial trucks have a RMAR of one (1.0).[f] New passenger cars have a RMAR of 0.885. This means that when the VMT assigned to the HPMS class 25 is allocated to passenger cars, passenger trucks and light commercial trucks, a passenger car of age 0 will be assigned only 88.5 percent of the annual VMT assigned to a passenger truck or light commercial truck of age 0.

The RMAR values for MOVES201X are unchanged from MOVES2014 for all sourcetypes described below.

### 6.2.1. Motorcycles

The RMAR values were calculated from mileage accumulations for motorcycles (sourceTypeID 11) based on the model years and odometer readings listed in motorcycle advertisements. A stratified sample of about 1,500 ads were examined. A modified Weibull curve was fit to the data to develop the relative mileage accumulation rates used in MOVES.[100]

### 6.2.2. Passenger Cars, Passenger Trucks and Light-Commercial Trucks

[f] Within each HPMS vehicle class, an RMAR value of one is assigned to the source type and age with the highest annual VMT accumulation. Because we use the same mileage accumulation data for passenger trucks and light commercial trucks, they both have a value of one.

The RMAR values for passenger cars, passenger trucks and light commercial trucks (sourceTypeID 21, 31 & 32) were taken from a NHTSA report on survivability and mileage schedules.[101] In the NHTSA analysis, annual mileage by age was determined for cars and for trucks using data from the 2001 National Household Travel Survey. In this NHTSA analysis, vehicles that were less than one-year old at the time of the survey were classified as "age 1", etc. NHTSA used a simple cubic regression to smooth the VMT by age estimates. We used NHTSA's regression coefficients to extrapolate mileage to ages 26 through 30 not covered by the report.

Passenger cars, passenger trucks and light commercial trucks are grouped together as light-duty vehicles (HPMSVTypeID 25). The NHTSA data for light-duty trucks were used for both the passenger truck and commercial truck source types. Since the trucks had a higher MAR than passenger cars, each source type's mileage by age was divided by truck mileage at age 1 to determine a relative MAR. For consistency with MOVES age categories, we then shifted the RMARs such that the NHTSA age 1 ratio was used for MOVES age 0, etc. Analysis of the data determined that new passenger cars (age 0) accumulate only 88.5 percent of the annual miles accumulated by new light trucks.

We conducted a preliminary analysis of the impact of updating the MARs based on results from the 2009 National Household Travel Survey. While the 2009 values may not fully represent current trends in vehicle usage due to the economic downturn in that year, the use of 2009 valuesresulted in changes to the MOVES allocation of VMT by one percent or less for each of the vehicle categories covered by the survey. Consequently, we feel that the MARs developed from the 2001 survey are still reasonable for use in MOVES201X.  However, this is an area where additional data collection and analysis would be useful.

*Table 6-2 NHTSA Vehicle Miles Traveled from 2001 National Household Travel Survey*

| | Annual Vehicle Miles Traveled | |
|---|---|---|
| **Vehicle Age** | **Passenger Cars** | **Light Trucks** |
| 1 | 14,417 | 15,806 |
| 2 | 13,803 | 15,683 |
| 3 | 13,692 | 15,859 |
| 4 | 13,415 | 15,302 |
| 5 | 13,183 | 14,762 |
| 6 | 12,301 | 13,836 |
| 7 | 12,253 | 13,542 |
| 8 | 11,709 | 13,615 |
| 9 | 11,893 | 12,875 |
| 10 | 11,855 | 12,203 |
| 11 | 10,620 | 11,501 |
| 12 | 9,986 | 10,815 |
| 13 | 10,248 | 11,391 |
| 14 | 9,515 | 10,843 |
| 15 | 9,168 | 10,378 |
| 16 | 8,636 | 9,259 |
| 17 | 8,941 | 8,358 |
| 18 | 7,267 | 9,371 |
| 19 | 8,890 | 7,352 |
| 20 | 8,759 | 8,363 |
| 21 | 6,878 | 6,999 |
| 22 | 7,242 | 7,327 |
| 23 | 6,350 | 6,969 |
| 24 | 5,745 | 6,220 |
| 25 | 4,130 | 6,312 |
| 26 | | 6,745 |
| 27 | | 9,515 |
| 28 | | 6,635 |
| 29 | | 12,108 |
| 30 | | 5,067 |
| 31 | | 4,577 |
| 32 | | 6,923 |

### 6.2.3. Buses

The "other" bus (sourceTypeID 41) annual mileage accumulation rate is taken from Motorcoach Census 2000.[28] The definition of buses for this source type has changed (see Section 5.1.4) from MOVES2014, but we have not changed the RMAR for this source type. The data did not distinguish vehicle age, so the same MAR (59,873 miles per year) was used for each age. The school bus (sourceTypeID 43) annual mileage accumulation rate (9,939 miles per year) is taken from the 1997 School Bus Fleet Fact Book. The MOVES model assumes the same annual mileage accumulation rate for each age. The Transit Bus (category 42) annual mileage accumulation rate are taken from the MOBILE6 values for diesel transit buses (HDDBT). This mileage data was obtained from the 1994 Federal Transportation Administration survey of transit agencies.[29] The MOBILE6 results were extended to calculate values for ages 26 through 30.

Although we do not expect that the relative average annual mileage accumulation rates for buses would vary significantly from year to year for buses, all of the MARs for buses could be updated with more current estimates for future versions of MOVES.

*Table 6-3 Annual mileage accumulation of transit buses from 1994 Federal Transit Administration data*

| Age | Miles | Age | Miles | Age | Miles |
|---|---|---|---|---|---|
| 1 | * | 11 | 32,540 | 21 | 19,588 |
| 2 | * | 12 | 32,605 | 22 | 22,939 |
| 3 | 46,791 | 13 | 27,722 | 23 | 26,413 |
| 4 | 41,262 | 14 | 28,429 | 24 | 23,366 |
| 5 | 42,206 | 15 | 32,140 | 25 | 11,259 |
| 6 | 39,160 | 16 | 28,100 | 26 | 23,228 |
| 7 | 38,266 | 17 | 24,626 | 27 | 21,515 |
| 8 | 36,358 | 18 | 23,428 | 28 | 25,939 |
| 9 | 34,935 | 19 | 22,575 | 29 | 20,117 |
| 10 | 33,021 | 20 | 23,220 | 30 | 17,515 |
| * Insufficient data | | | | | |

### 6.2.4. Other Heavy-Duty Vehicles

The RMAR values for source types 51 (refuse trucks), 52 (short-haul single-unit trucks), 53 (long-haul single-unit trucks), 61 (short-haul combination trucks) and 62 (long-haul combination trucks) use the data from the 2002 Vehicle Inventory and Use Survey (VIUS).[30] The total reported annual miles traveled by truck in each source type, as shown in Table 6-4, was divided by the vehicle population to determine the average annual miles traveled per truck by source type.

*Table 6-4 VIUS2002 annual mileage by vehicle age*

| Age | Model Year | Single-Unit Trucks | | | Combination Trucks | |
|---|---|---|---|---|---|---|
| | | **Refuse (51)** | **Short-Haul (52)** | **Long-Haul (53)** | **Short-Haul (61)** | **Long-Haul (62)** |
| 0 | 2002 | 26,703 | 21,926 | 40,538 | 119,867 | 109,418 |
| 1 | 2001 | 32,391 | 22,755 | 28,168 | 114,983 | 128,287 |
| 2 | 2000 | 31,210 | 24,446 | 30,139 | 110,099 | 117,945 |
| 3 | 1999 | 31,444 | 23,874 | 49,428 | 105,215 | 110,713 |
| 4 | 1998 | 31,815 | 21,074 | 33,266 | 100,331 | 99,925 |
| 5 | 1997 | 28,450 | 21,444 | 23,784 | 95,447 | 94,326 |
| 6 | 1996 | 25,462 | 16,901 | 21,238 | 90,563 | 85,225 |
| 7 | 1995 | 30,182 | 15,453 | 27,562 | 85,679 | 85,406 |
| 8 | 1994 | 20,722 | 13,930 | 21,052 | 80,795 | 71,834 |
| 9 | 1993 | 25,199 | 13,303 | 11,273 | 75,911 | 71,160 |
| 10 | 1992 | 23,366 | 11,749 | 18,599 | 71,026 | 67,760 |
| 11 | 1991 | 18,818 | 13,675 | 15,140 | 66,142 | 80,207 |
| 12 | 1990 | 12,533 | 11,332 | 13,311 | 61,258 | 48,562 |
| 13 | 1989 | 15,891 | 9,795 | 9,796 | 56,374 | 64,473 |
| 14 | 1988 | 19,618 | 9,309 | 12,067 | 51,490 | 48,242 |
| 15 | 1987 | 12,480 | 9,379 | 16,606 | 46,606 | 58,951 |
| 16 | 1986 | 12,577 | 4,830 | 8,941 | 41,722 | 35,897 |
| **0-3** | **1999-2002 Average** | **30,437** | **23,250** | **37,069** | **61,240** | **116,591** |

For each source type, in the first few years, the data showed only small differences in the annual miles per vehicle and no trend. After that, the average annual miles per vehicle declined in a fairly linear manner, at least until the vehicles are at age 16 (the limit of the data). MOVES, however, requires mileage accumulation rates for all ages to age 30. The relative mileage accumulation rate at age 30 were derived from the 1992 Truck Inventory and Use Survey (TIUS) as documented in the ARCADIS report.[31]

Mileage accumulation rates for these vehicles were determined for each age from 0 to 30 using the following method:

1) Ages 0 through 3 use the same average annual mileage accumulation rate for age 0-3 vehicles of that source type.
2) Ages 4 through 16 use mileage accumulation rates calculated using a linear regression of the VIUS data for the average of ages 0 to 3 as age 3 with ages 4 through 16 from the data summarized in Table 6-5,
3) Ages 17 through 29 use values from interpolation between the values in age 16 and age 30.
4) Age 30 uses the 1992 TIUS relative mileage accumulation rate for age 30. These rates were allocated to the MOVES source types from the MOBILE6 mileage accumulation rates.

*Table 6-5 Regression statistics for heavy-duty truck average annual mileage accumulation rates (ages 4-16)*

| Measurement | Refuse Truck (51) | Single-Unit Short-Haul (52) | Single-Unit Long-Haul (53) | Combination Short-Haul (61) | Combination Long-Haul (62) |
|---|---|---|---|---|---|
| Average 0-3[a] | 30,437 | 23,250 | 37,069 | 61,240 | 116,591 |
| | | | | | |
| Intercept[b] | 36,315 | 25,442 | 36,305 | 65,773 | 119,867 |
| Slope[b] | -1,510 | -1,209 | -1,794 | -3,447 | -4,884 |
| | | | | | |
| Age 30 RMAR | 0.0320 | 0.0518 | 0.1025 | 0.0320 | 0.0571 |

Notes:

[a] Average sample annual miles traveled for ages 0 through 3.

[b] Intercept and slope from ages 4 through 16.

The resulting relative mileage accumulation rates are shown in Table 6-6 below. Note that the first four values are identical and then decline linearly to age 16 and then linearly to age 30 with a different slope.

### 6.2.5. Motor Homes

For motor homes (sourceTypeID 54), the initial MARs were taken from an independent research study[32] conducted in October 2000 among members of the Good Sam Club. The members are active recreation vehicle (RV) enthusiasts who own motor homes, trailers and trucks. The average annual mileage was estimated to be 4,566 miles. The data did not distinguish vehicle age, so the same MAR was used for each age.

*Table 6-6 Relative mileage accumulation rates for heavy-duty trucks in MOVES201X*

| ageID | Refuse (51) | Short-Haul Single-Unit (52) | Long-Haul Single-Unit (53) | Motor Home (54) | Short-Haul Combination (61) | Long-Haul Combination (62) |
|---|---|---|---|---|---|---|
| 0 | 1.0000 | 0.6864 | 0.9729 | 0.0590 | 0.5269 | 1.0000 |
| 1 | 1.0000 | 0.6864 | 0.9729 | 0.0590 | 0.5269 | 1.0000 |
| 2 | 1.0000 | 0.6864 | 0.9729 | 0.0590 | 0.5269 | 1.0000 |
| 3 | 1.0000 | 0.6864 | 0.9729 | 0.0590 | 0.5269 | 1.0000 |
| 4 | 0.9525 | 0.6484 | 0.9165 | 0.0590 | 0.4941 | 0.9536 |
| 5 | 0.9050 | 0.6103 | 0.8601 | 0.0590 | 0.4613 | 0.9072 |
| 6 | 0.8575 | 0.5723 | 0.8036 | 0.0590 | 0.4286 | 0.8607 |
| 7 | 0.8099 | 0.5343 | 0.7472 | 0.0590 | 0.3958 | 0.8143 |
| 8 | 0.7624 | 0.4962 | 0.6908 | 0.0590 | 0.3631 | 0.7679 |
| 9 | 0.7149 | 0.4582 | 0.6343 | 0.0590 | 0.3303 | 0.7215 |
| 10 | 0.6674 | 0.4202 | 0.5779 | 0.0590 | 0.2975 | 0.6751 |
| 11 | 0.6199 | 0.3821 | 0.5215 | 0.0590 | 0.2648 | 0.6286 |
| 12 | 0.5724 | 0.3441 | 0.4650 | 0.0590 | 0.2320 | 0.5822 |
| 13 | 0.5249 | 0.3061 | 0.4086 | 0.0590 | 0.1993 | 0.5358 |
| 14 | 0.4773 | 0.2680 | 0.3522 | 0.0590 | 0.1665 | 0.4894 |
| 15 | 0.4298 | 0.2300 | 0.2957 | 0.0590 | 0.1338 | 0.4430 |
| 16 | 0.3823 | 0.1920 | 0.2393 | 0.0590 | 0.1010 | 0.3965 |
| 17 | 0.3573 | 0.1808 | 0.2293 | 0.0590 | 0.0950 | 0.3723 |
| 18 | 0.3323 | 0.1696 | 0.2194 | 0.0590 | 0.0890 | 0.3481 |
| 19 | 0.3073 | 0.1585 | 0.2094 | 0.0590 | 0.0830 | 0.3238 |
| 20 | 0.2822 | 0.1473 | 0.1994 | 0.0590 | 0.0770 | 0.2996 |
| 21 | 0.2572 | 0.1361 | 0.1894 | 0.0590 | 0.0710 | 0.2753 |
| 22 | 0.2322 | 0.1249 | 0.1795 | 0.0590 | 0.0649 | 0.2511 |
| 23 | 0.2072 | 0.1138 | 0.1695 | 0.0590 | 0.0589 | 0.2268 |
| 24 | 0.1821 | 0.1026 | 0.1595 | 0.0590 | 0.0529 | 0.2026 |
| 25 | 0.1571 | 0.0914 | 0.1496 | 0.0590 | 0.0469 | 0.1783 |
| 26 | 0.1321 | 0.0802 | 0.1396 | 0.0590 | 0.0409 | 0.1541 |
| 27 | 0.1071 | 0.0691 | 0.1296 | 0.0590 | 0.0349 | 0.1298 |
| 28 | 0.0820 | 0.0579 | 0.1197 | 0.0590 | 0.0289 | 0.1056 |
| 29 | 0.0570 | 0.0467 | 0.1097 | 0.0590 | 0.0229 | 0.0814 |
| 30 | 0.0320 | 0.0355 | 0.0997 | 0.0590 | 0.0169 | 0.0571 |

## 7. VMT Distribution of Source Type by Road Type

For each source type, the RoadTypeVMTFraction field in the RoadTypeDistribution table stores the fraction of total VMT for each source type that is traveled on each of the MOVES five road types nationally. Users may supply the VMT distribution by vehicle class for each road type for individual counties when using County Scale. For National Scale, the default distribution is allocated to individual counties using the SHOAllocFactor found in the ZoneRoadType table.

The national default distribution of VMT to source type for each road type in MOVES2014 were derived to reflect the VMT data included in the 2011 National Emission Inventory (NEI) Version 2.[33] This data is provided by states every three years as part of the NEI project and is supplemented by EPA estimates based on data provided by FHWA 2011 highway statistics[34] when state supplied estimates are not available. The FHWA road types mapped to the MOVES road type ID values (the eighth and ninth digits of the 10-digit onroad SCC) are shown below in Table 7-1.

*Table 7-1 Mapping of FHWA road types to MOVES road types*

| FHWA Road Type | MOVES Road Type ID | MOVES Road Type |
|---|---|---|
| Rural Interstate | 2 | Rural Restricted Access |
| Rural Other Principal Arterial | 3 | Rural Unrestricted Access |
| Rural Minor Arterial | 3 | Rural Unrestricted Access |
| Rural Major Collector | 3 | Rural Unrestricted Access |
| Rural Minor Collector | 3 | Rural Unrestricted Access |
| Rural Local | 3 | Rural Unrestricted Access |
| Urban Interstate | 4 | Urban Restricted Access |
| Urban Other Freeways & Expressways | 4 | Urban Restricted Access |
| Urban Other Principal Arterial | 5 | Urban Unrestricted Access |
| Urban Minor Arterial | 5 | Urban Unrestricted Access |
| Urban Collector | 5 | Urban Unrestricted Access |
| Urban Local | 5 | Urban Unrestricted Access |

The national distribution of road type VMT by source type is calculated from the NEI VMT estimates and is summarized in Table 7-2. The off-network road type (roadTypeID 1) is allocated no VMT.

The VMT distributions by source type and road type in MOVES 2014 will be updated to us the results from the 2014 NEI v2 analysis when those values become available. Since the 2014 NEI Version 2 has not yet been completed, the values in this table are placeholders. They have not yet been updated from the values used in MOVES2014.

*Table 7-2 MOVES201X road type distribution by source type*

| | | Road Type[a] | | | | |
|---|---|---|---|---|---|---|
| **Source Type** | **Description** | **Rural Restricted** | **Rural Unrestricted** | **Urban Restricted** | **Urban Unrestricted** | |
| | | **2** | **3** | **4** | **5** | **All** |
| 11 | Motorcycle | 0.0805 | 0.3019 | 0.1913 | 0.4263 | 1.000 |
| 21 | Passenger Car | 0.0847 | 0.2345 | 0.2374 | 0.4434 | 1.000 |
| 31 | Passenger Truck | 0.0859 | 0.2754 | 0.2178 | 0.4209 | 1.000 |
| 32 | Light Commercial Truck | 0.0867 | 0.2756 | 0.2180 | 0.4197 | 1.000 |
| 41 | Other Bus | 0.1409 | 0.2812 | 0.2196 | 0.3583 | 1.000 |
| 42 | Transit Bus | 0.1384 | 0.2813 | 0.2196 | 0.3607 | 1.000 |
| 43 | School Bus | 0.1384 | 0.2813 | 0.2196 | 0.3607 | 1.000 |
| 51 | Refuse Truck | 0.2396 | 0.2718 | 0.2525 | 0.2361 | 1.000 |
| 52 | Single-Unit Short-Haul Truck | 0.1635 | 0.2869 | 0.2346 | 0.3150 | 1.000 |
| 53 | Single-Unit Long-Haul Truck | 0.1638 | 0.2870 | 0.2346 | 0.3146 | 1.000 |
| 54 | Motor Home | 0.1234 | 0.2876 | 0.2255 | 0.3635 | 1.000 |
| 61 | Combination Short-Haul Truck | 0.2367 | 0.2744 | 0.2517 | 0.2372 | 1.000 |
| 62 | Combination Long-Haul Truck | 0.2476 | 0.2705 | 0.2543 | 0.2276 | 1.000 |

Note:
[a] RoadTypeID = 1 (Off Network) is assigned no VMT.

Note that because it is difficult to distinguish short-haul and long-haul trucks in roadway VMT measurements, the distributions for single-unit short-haul trucks are virtually the same as those for single-unit long-haul trucks, and likewise for long- and short-haul combination trucks.

# 8. Average Speed Distributions

Average speed is used in MOVES to convert VMT inputs into the source hours operating (SHO) units that MOVES uses for internal calculations. It is also used to select appropriate driving cycles, which are then used to calculate exhaust running operating mode distributions at the national, county, and sometimes project level. Instead of using a single average speed in these tasks, MOVES uses a distribution of average speeds by bin. The AvgSpeedDistribution table lists the default fraction of driving time for each source type, road type, day, and hour in each average speed bin. The fractions sum to one for each combination of source type, road type, day, and hour. The MOVES average speed bins are defined in Table 8-1.

*Table 8-1 MOVES speed bin categories*

| Bin | Average Speed (mph) | Average Speed Range (mph) |
|---|---|---|
| 1 | 2.5 | speed < 2.5 mph |
| 2 | 5 | 2.5 mph <= speed < 7.5 mph |
| 3 | 10 | 7.5 mph <= speed < 12.5 mph |
| 4 | 15 | 12.5 mph <= speed < 17.5 mph |
| 5 | 20 | 17.5 mph <= speed < 22.5 mph |
| 6 | 25 | 22.5 mph <= speed < 27.5 mph |
| 7 | 30 | 27.5 mph <= speed < 32.5 mph |
| 8 | 35 | 32.5 mph <= speed < 37.5 mph |
| 9 | 40 | 37.5 mph <= speed < 42.5 mph |
| 10 | 45 | 42.5 mph <= speed < 47.5 mph |
| 11 | 50 | 47.5 mph <= speed < 52.5 mph |
| 12 | 55 | 52.5 mph <= speed < 57.5 mph |
| 13 | 60 | 57.5 mph <= speed < 62.5 mph |
| 14 | 65 | 62.5 mph <= speed < 67.5 mph |
| 15 | 70 | 67.5 mph <= speed < 72.5 mph |
| 16 | 75 | 72.5 mph <= speed |

The Coordinating Research Council (CRC) Atmospheric Impacts panel has recently completed a study for the 2014 National Emission Inventory to provide updated average speed distributions for individual counties based on telematics data[35]. This data may be a good source to update the MOVES national default estimates for future versions of the model. In the meantime, average speed distributions in MOVES201X are unchanged from those in MOVES2014.

## 8.1. Light-Duty Average Speed Distributions

Light-duty average speed distributions are based on in-vehicle global position system (GPS) data. The data was obtained through a contract with Eastern Research Group (ERG), who subcontracted with TomTom to provide summarized vehicle GPS data.[g] TomTom makes in-vehicle GPS navigation devices and supports cell-phone navigation applications. ERG provided the US EPA with updated values for the AvgSpeedDistribution calculated from the TomTom delivered data.

Some of the characteristics of the TomTom GPS data are:

- Data is self-selected. Data is only recorded from users of TomTom GPS units and an iPhone application. Additionally, TomTom data is only collected when the units are on. This creates bias not only for users, but also for types of driving. Anecdotally, drivers who own GPS units are less likely to use them when they drive in familiar areas in comparison with unfamiliar areas. Compared to the default VMT by road type information in MOVES, TomTom over-represents behavior on rural restricted access roads, which suggests the higher usage of GPS on vacations and business trips.
- No information on vehicle type is available. TomTom suggests that "virtually all" the vehicles are light-duty cars, trucks, and vans. MOVES allows for separate average speed distributions for each source type. However, due to a lack of information on other source types, the average speed distribution derived from the TomTom light-duty GPS data is applied to all source types—although the combination long-haul trucks distribution was adjusted as described at the end of this section. Other heavy-duty source types such as single-unit long-haul trucks were not adjusted. We recognize this as a potential shortcoming, and look to incorporate source type specific average speed information in the future.
- The average speed distributions are based on the average speed in each roadway segment, not the average of all second-by-second speed measurements.
- Only data that is associated with the vehicle network is included in the average speed delivery. As part of the quality control methods, TomTom excludes data that does not "snap to the roadway grid" to remove points caused by loss of satellite signal and errors while the TomTom unit is trying to acquire the satellite signal. TomTom uses data quality control techniques to minimize data arising from non-vehicle use, such as from pedestrians, bicycles, and airplanes.

Some of the data characteristics present concerns regarding their representativeness of real-world driving. Despite these concerns, the TomTom data presented a great improvement to the speed distribution information used in previous versions of MOVES. There are new sources of vehicle speed information that are becoming available which can be used to further improve the national average default values used in future versions for MOVES.

Under direction of EPA's contractor, ERG, TomTom queried its database of historic traffic probes to produce a table of total distance and total time as a function of road type, weekday/weekend, hour of the day, and average speed bin for the calendar year 2011 for the 50 states and the District of Columbia. TomTom delivered a table identifying the total distance and

[g] Much of the following text and tables are excerpted from the ERG Work Plan (EPA-121019), submitted to US EPA on January 11, 2012.

total time of vehicles travelling at an average speed interval for all combinations of the following identifiers:

1. Average Speed Bin (20 levels): average speeds were binned in 5 mph increments, starting at 2.5mph: 0-2.5mph; 2.5mph-7.5mph; 7.5mph-12.5mph; 92.5mph-97.5mph.

2. Month of the Year (12 levels).

3. Day of the Week (2 levels): the period for weekday is Monday, 00:00:00 to Friday, 23:59:59, and the period for weekend is Saturday, 00:00:00 to Sunday, 23:59:59.

4. Time of Day (24 levels): times are binned in one hour increments, starting at midnight: 00:00:00 to 00:59:59; 01:00:00 to 01:59:59, …, 23:00:00 to 23:59:59.

5. Road Type (4 levels): TomTom used the information in Table 8-2 to classify between the TomTom Functional Classes and the MOVES road type description. TomTom also categorized the road types as rural or urban, according to the Census definitions used in MOVES[h].

*Table 8-2 Correspondence between TomTom functional class, census information, and MOVES road types*

| MOVES Road Type Description | Census Information for the TomTom Roadway Segment | TomTom Functional Road Class |
|---|---|---|
| Rural Restricted Access | Rural | 0 and 1 |
| Rural Unrestricted Access | Rural | 2 through 7 |
| Urban Restricted Access | Urban | 0 and 1 |
| Urban Unrestricted Access | Urban | 2 through 7 |

TomTom first “snapped” their data points onto road segments. Off-network driving data was not obtained from the TomTom data. Much of the TomTom data that does not “snap to the roadway grid” is caused by loss of satellite signal and errors while the TomTom unit is trying to acquire the satellite signal. An analysis to separate real off-network data from GPS error data would be resource intensive with high level of uncertainty. Consequently, only data that was associated with the roadway grid was used in the analysis.

Table 8-3 shows the method for using the internal TomTom data (Columns E through I) to produce the desired output, which ERG used to produce the MOVES tables. The example in the table uses 16 observations that might have been recorded on two urban unrestricted roadway segments (Column E) during TomTom personal navigation device use between 14:00:00 and 14:59:59 on a weekday in April 2011. Column F is an internal ID (1-5 occur on Segment A, and 11-21 occur on Segment B). Column G gives the length of the segment. Column H gives the time that the device spent on the segment. Column I gives the average speed of the device on the segment. The 16 observations are sorted by the average speed bin, which is given in Column J. The total distance traveled and the total time spent in each combination of road type, month,

[h] http://www.census.gov/geo/www/ua/2010urbanruralclass.html

weekday/weekend, hour of the day, and average speed bin are given in Columns K and L. TomTom provided Columns A, B, C, D, J, K, and L to ERG. The data in those columns was purchased by ERG from TomTom and is provided under license terms that permit free distribution to EPA and the public. The raw data in Columns E, F, G, H, and I were not provided to ERG and the US EPA.

*Table 8-3 Example of accumulating total distance and total time for the TomTom deliverable table*

| A | B | C | D | E | F | G | H | I | J | K | L |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Road Type (4 levels) | Month (12 levels) | Weekday/ Weekend (2 levels) | Hour of the Day (24 levels) | Segment | Data Point | Segment Length (feet) | Time in Segment (s) | Average Speed in Segment (mph) | Average Speed Bin (mph) (20 levels) | Total of Segment Lengths for this Speed Bin (feet) | Total of Segment Times for this Speed Bin (s) |
| Urban Unrestricted | April | Weekday | 14:00:00 to 14:59:59 | A | 5 | 300 | 15 | 13.64 | 15 | 550 | 27 |
| | | | | B | 16 | 250 | 12 | 14.20 | | | |
| | | | | A | 1 | 300 | 10 | 20.45 | 20 | 1800 | 60 |
| | | | | B | 11 | 250 | 8 | 21.31 | | | |
| | | | | B | 12 | 250 | 9 | 18.94 | | | |
| | | | | B | 15 | 250 | 8 | 21.31 | | | |
| | | | | B | 18 | 250 | 8 | 21.31 | | | |
| | | | | B | 20 | 250 | 9 | 18.94 | | | |
| | | | | B | 21 | 250 | 8 | 21.31 | | | |
| | | | | A | 2 | 300 | 9 | 22.73 | 25 | 1650 | 47 |
| | | | | A | 3 | 300 | 8 | 25.57 | | | |
| | | | | A | 4 | 300 | 9 | 22.73 | | | |
| | | | | B | 13 | 250 | 7 | 24.35 | | | |
| | | | | B | 14 | 250 | 7 | 24.35 | | | |
| | | | | B | 19 | 250 | 7 | 24.35 | | | |
| | | | | B | 17 | 250 | 6 | 28.41 | 30 | 250 | 6 |

Using the table delivered by TomTom, ERG calculated the time-based average speed distribution for each road type, day, and hour of the day using the average speed bin (Column J) and the total of segment times (Column L)[i]. ERG calculated the average speed distribution according to the 16 speed bins used in MOVES. Figure 8-1 plots the average speed distribution for one hour (5pm) stored in the averageSpeedDistribution table in MOVES, which contains average speed distributions for each hour of the day (24 hours). We are using the TomTom data to represent national default average speed distribution in MOVES.

[i] MOVES uses time-based speed because the emission rates are time-based (e.g. gram/hour).

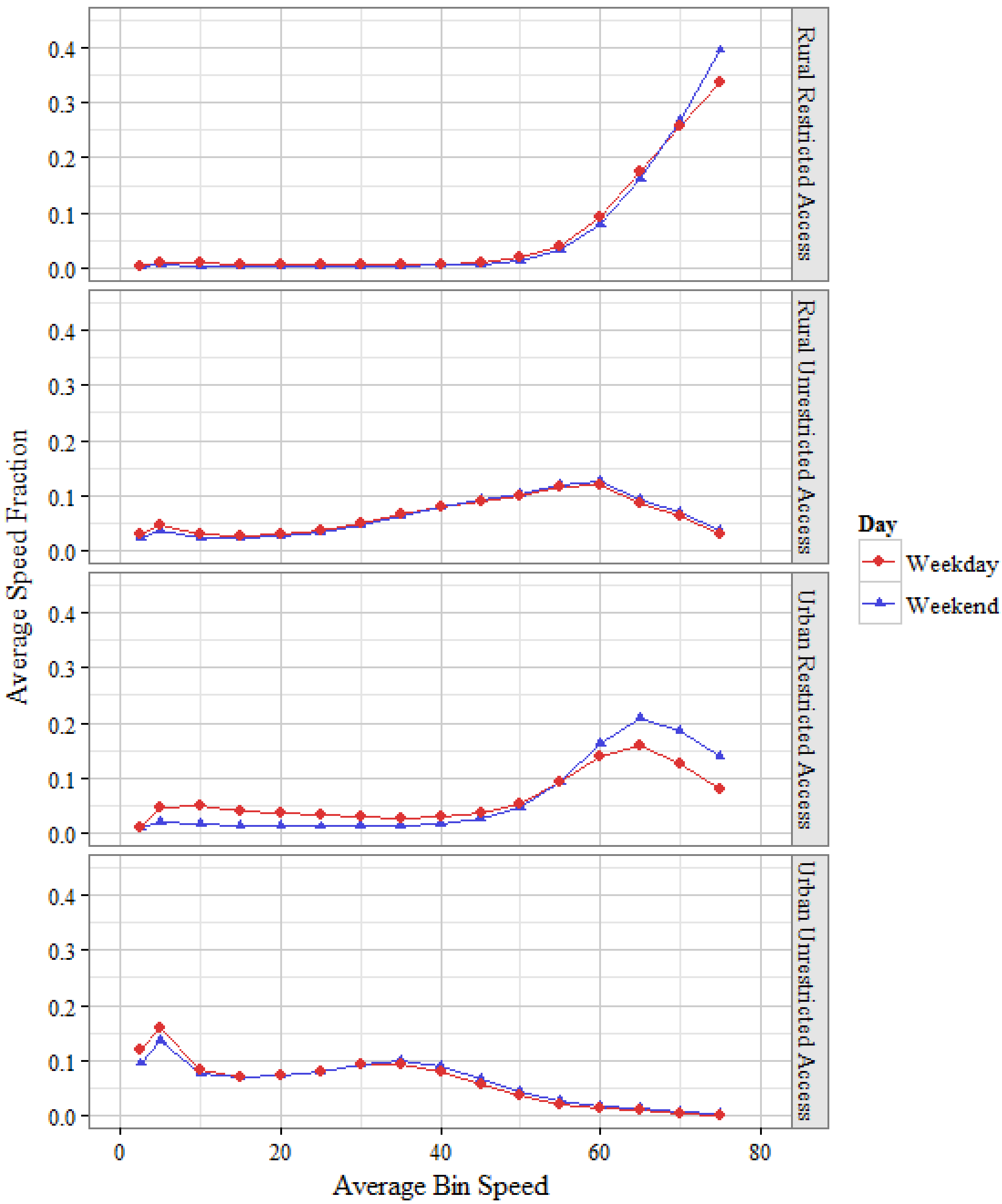


*Figure 8-1 Average speed distribution for 5pm (hourID 17) for source types 11 through 54 in MOVES201X*

## 8.2. Heavy-Duty Average Speed Distributions

We do not have average speeds data for heavy-duty vehicles across time of day, day type, and road types like for light-duty vehicles. Instead, we have based average speed for heavy-duty vehicles on data from light-duty vehicles, with some adjustments for combination trucks based on study that compared average speeds between combination trucks and the mean traffic speed traveling on urban freeways.[36]

It has been shown that combination trucks travel at approximately 92 percent of the speed of the mean traffic speed on restricted access roads.[36] Since the TomTom data captured only light-duty vehicles, the average speed distributions for both short-haul and long-haul combination trucks on rural and urban restricted road types were adjusted to have an 8 percent lower average speed than the respective TomTom average speed for light-duty vehicles. The equations and assumptions used to adjust the combination truck average speed distributions are located in Appendix D (Calculation of Combination Truck Average Speed Distributions
). Figure 8-2 illustrates the results of this analysis.

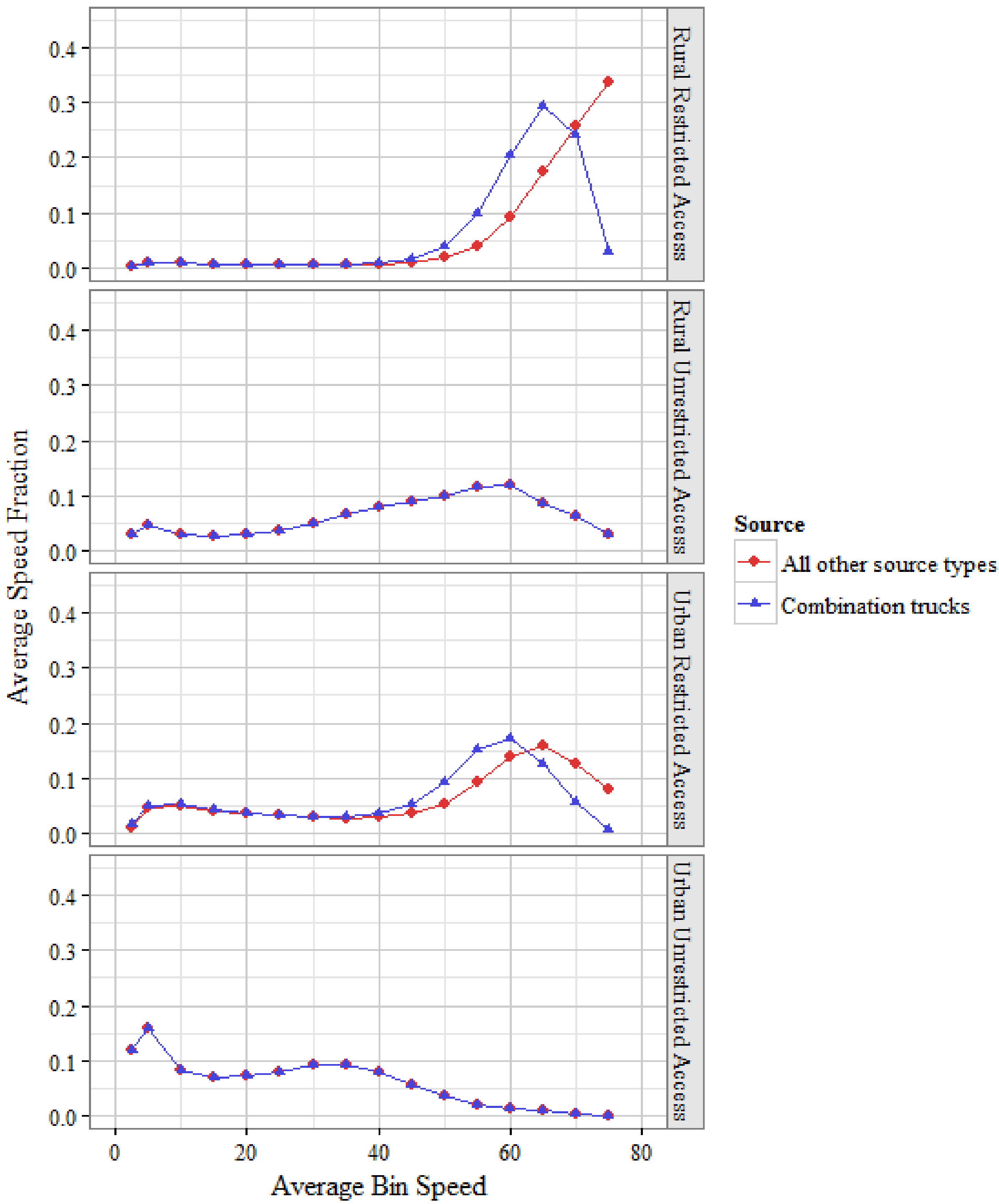


*Figure 8-2 Average weekday speed distribution for 5pm (hourID 17) by source type*

In the absence of additional data, all other heavy-duty vehicles (including single-unit heavy-duty vehicles) and all heavy-duty vehicles operating on unrestricted access roads, use the same average speed distributions as light-duty vehicles. We recognize that these assumptions are less than ideal, and we hope to update the heavy-duty average speed distributions using heavy-duty data in the future. Nonetheless, MOVES energy consumption and emission estimates from heavy-duty appear to be only moderately sensitive to changes in the average speed distribution. The 8 percent speed decrease in average speed distribution on restricted access roadways for combination trucks caused the total onroad predicted NOx emissions to decrease by only ~0.5 percent and the national onroad diesel fuel consumption to decrease by only ~1.3 percent. Other researchers[37] have found that other local inputs are significantly more important for emissions inventories than average speed distributions, including population, age distribution, and the combination truck fraction of heavy-duty VMT. Nonetheless, we strongly encourage MOVES users to use local average speed distributions when using MOVES at the regional and county-level.

# 9. Driving Schedules and Ramps

Drive schedule refers to a second-by-second vehicle speed trajectory. The drive schedules in MOVES are intended to includes all vehicle operation from the time the engine starts until the engine is keyed off, both driving (travel) and idling time.[j] Drive schedules are used in MOVES to determine the operating mode distribution for MOVES running processes for calculation of emissions and energy consumption. The drive schedules in MOVES201X are unchanged from those in MOVES2014, with the exception of drive schedules for transit and school buses, and the handling of ramps.

More specifically, each second of vehicle operation is assigned to an operating mode as a function of vehicle velocity in each second and the specific power (VSP) for light-duty vehicles, or scaled tractive power (STP) for heavy-duty vehicles. The distinction between VSP and STP is discussed in Section 15. Each operating mode is associated with an emission rate (in grams per hour of vehicle operation). The average speed distribution is used to weight the operating mode distributions determined from driving schedules with different average speeds into a composite operating mode distribution that represents overall travel by vehicles. The distribution of operating modes is used by MOVES to weight the emission rates to account for the vehicle operation.

## 9.1. Driving Schedules

A key feature of MOVES is the capability to accommodate a number of drive schedules to represent driving patterns across source type, road type, and average speed. For the national default case, MOVES employs 49 drive schedules with various average speeds, mapped to specific source types and road types.

MOVES stores all of the drive schedule information in three database tables. The DriveSchedule table provides the drive schedule name, identification number, and the average speed of the drive schedule. The DriveScheduleSecond table contains the second-by-second vehicle trajectories for each schedule. In some cases, the vehicle trajectories are not contiguous; as detailed below, they may be formed from several unconnected microtrips that overall represent driving behavior. The DriveScheduleAssoc table defines the set of schedules which are available for each combination of source use type and road type.

Table 9-1 through Table 9-6 below list the driving schedules used in MOVES. Some driving schedules are used for both restricted access (freeway) and unrestricted access (non-freeway) driving. In most cases, these represent atypical conditions, such as extreme congestion or unimpeded high speeds. In these conditions, we assume that the road type itself has little impact on the expected driving behavior (driving schedule). Normally, these conditions represent only a

[j] However, as described in Section 10, recent data suggests that drive schedules miss a substantial fraction of real-world idling and MOVES201X has been updated to better account for the idling that was not being captured in previous versions of the model.

small portion of overall driving. Similarly, some driving schedules are used for multiple source types where vehicle specific information was not available.

*Table 9-1 MOVES driving cycles for motorcycles, passenger cars, passenger trucks, and light commercial trucks (11, 21, 31, 32)*

| ID | Cycle Name | Average Speed | Unrestricted Access | | Restricted access | |
|---|---|---|---|---|---|---|
| | | | Rural | Urban | Rural | Urban |
| 101 | LD Low Speed 1 | 2.5 | X | X | X | X |
| 1033 | Final FC14LOSF | 8.7 | | | X | X |
| 1043 | Final FC19LOSAC | 15.7 | | | X | X |
| 1041 | Final FC17LOSD | 18.6 | X | X | | |
| 1021 | Final FC11LOSF | 20.6 | | | X | X |
| 1030 | Final FC14LOSC | 25.4 | X | X | | |
| 153 | LD LOS E Freeway | 30.5 | | | X | X |
| 1029 | Final FC14LOSB | 31.0 | X | X | | |
| 1026 | Final FC12LOSE | 43.3 | | X | | |
| 1020 | Final FC11LOSE | 46.1 | | | X | X |
| 1011 | Final FC02LOSDF | 49.1 | X | | | |
| 1025 | Final FC12LOSD | 52.8 | | X | | |
| 1019 | Final FC11LOSD | 58.8 | | | X | X |
| 1024 | Final FC12LOSC | 63.7 | X | X | | |
| 1018 | Final FC11LOSC | 64.4 | | | X | X |
| 1017 | Final FC11LOSB | 66.4 | | | X | X |
| 1009 | Final FC01LOSAF | 73.8 | X | X | X | X |
| 158 | LD High Speed Freeway 3 | 76.0 | X | X | X | X |

*Table 9-2 MOVES driving cycles for other buses (41)*

| ID | Cycle Name | Average Speed | Unrestricted access | | Restricted access | |
|---|---|---|---|---|---|---|
| | | | Rural | Urban | Rural | Urban |
| 398 | CRC E55 HHDDT Creep | 1.8 | X | X | X | X |
| 404 | New York City Bus | 3.7 | X | X | | |
| 201 | MD 5mph Non-Freeway | 4.6 | X | X | X | X |
| 405 | WMATA Transit Bus | 8.3 | X | X | | |
| 202 | MD 10mph Non-Freeway | 10.7 | X | X | X | X |
| 203 | MD 15mph Non-Freeway | 15.6 | X | X | X | X |
| 204 | MD 20mph Non-Freeway | 20.8 | X | X | X | X |
| 205 | MD 25mph Non-Freeway | 24.5 | X | X | X | X |
| 206 | MD 30mph Non-Freeway | 31.5 | X | X | X | X |
| 251 | MD 30mph Freeway | 34.4 | X | X | X | X |
| 252 | MD 40mph Freeway | 44.5 | X | X | X | X |
| 253 | MD 50mph Freeway | 55.4 | X | X | X | X |
| 254 | MD 60mph Freeway | 60.4 | X | X | X | X |
| 255 | MD High Speed Freeway | 72.8 | X | X | X | X |
| 397 | MD High Speed Freeway Plus 5mph | 77.8 | X | X | X | X |

*Table 9-3 MOVES driving cycles for transit and school buses (42, 43)*

| ID | Cycle Name | Average Speed | Unrestricted access | | Restricted access | |
|---|---|---|---|---|---|---|
| | | | Rural | Urban | Rural | Urban |
| 398 | CRC E55 HHDDT Creep | 1.8 | X | X | X | X |
| 401 | Bus Low Speed Urban | 3.1 | X | X | | |
| 404 | New York City Bus | 3.7 | X | X | | |
| 201 | MD 5mph Non-Freeway | 4.6 | | | X | X |
| 405 | WMATA Transit Bus | 8.3 | X | X | | |
| 202 | MD 10mph Non-Freeway | 10.7 | | | X | X |
| 402 | Bus 12mph Non-Freeway | 11.5 | X | X | | |
| 203 | MD 15mph Non-Freeway | 15.6 | | | X | X |
| 204 | MD 20mph Non-Freeway | 20.8 | | | X | X |
| 403 | Bus 30mph Non-Freeway * | 21.9 | X | X | | |
| 205 | MD 25mph Non-Freeway | 24.5 | | | X | X |
| 206 | MD 30mph Non-Freeway | 31.5 | | | X | X |
| 251 | MD 30mph Freeway | 34.4 | | | X | X |
| 252 | MD 40mph Freeway | 44.5 | | | X | X |
| 253 | MD 50mph Freeway | 55.4 | X | X | X | X |
| 254 | MD 60mph Freeway | 60.4 | X | X | X | X |
| 255 | MD High Speed Freeway | 72.8 | X | X | X | X |
| 397 | MD High Speed Freeway Plus 5mph | 77.8 | X | X | X | X |

*Table 9-4 MOVES driving cycles for refuse trucks (51)*

| ID | Cycle Name | Average Speed | Unrestricted access | | Restricted access | |
|---|---|---|---|---|---|---|
| | | | Rural | Urban | Rural | Urban |
| 398 | CRC E55 HHDDT Creep | 1.8 | | | X | X |
| 501 | Refuse Truck Urban | 2.2 | X | X | | |
| 301 | HD 5mph Non-Freeway | 5.8 | | | X | X |
| 302 | HD 10mph Non-Freeway | 11.2 | X | X | X | X |
| 303 | HD 15mph Non-Freeway | 15.6 | X | X | X | X |
| 304 | HD 20mph Non-Freeway | 19.4 | X | X | X | X |
| 305 | HD 25mph Non-Freeway | 25.6 | X | X | X | X |
| 306 | HD 30mph Non-Freeway | 32.5 | X | X | X | X |
| 351 | HD 30mph Freeway | 34.3 | X | X | X | X |
| 352 | HD 40mph Freeway | 47.1 | X | X | X | X |
| 353 | HD 50mph Freeway | 54.2 | X | X | X | X |
| 354 | HD 60mph Freeway | 59.4 | X | X | X | X |
| 355 | HD High Speed Freeway | 71.7 | X | X | X | X |
| 396 | HD High Speed Freeway Plus 5mph | 77.8 | X | X | X | X |

*Table 9-5 MOVES driving cycles for single-unit trucks and motor homes (52, 53, 54)*

| ID | Cycle Name | Average Speed | Unrestricted access | | Restricted access | |
|---|---|---|---|---|---|---|
| | | | Rural | Urban | Rural | Urban |
| 398 | CRC E55 HHDDT Creep | 1.8 | X | X | X | X |
| 201 | MD 5mph Non-Freeway | 4.6 | X | X | X | X |
| 202 | MD 10mph Non-Freeway | 10.7 | X | X | X | X |
| 203 | MD 15mph Non-Freeway | 15.6 | X | X | X | X |
| 204 | MD 20mph Non-Freeway | 20.8 | X | X | X | X |
| 205 | MD 25mph Non-Freeway | 24.5 | X | X | X | X |
| 206 | MD 30mph Non-Freeway | 31.5 | X | X | X | X |
| 251 | MD 30mph Freeway | 34.4 | X | X | X | X |
| 252 | MD 40mph Freeway | 44.5 | X | X | X | X |
| 253 | MD 50mph Freeway | 55.4 | X | X | X | X |
| 254 | MD 60mph Freeway | 60.4 | X | X | X | X |
| 255 | MD High Speed Freeway | 72.8 | X | X | X | X |
| 397 | MD High Speed Freeway Plus 5mph | 77.8 | X | X | X | X |

*Table 9-6 MOVES driving cycles for combination trucks (61, 62)*

| ID | Cycle Name | Average Speed | Unrestricted access | | Restricted access | |
|---|---|---|---|---|---|---|
| | | | Rural | Urban | Rural | Urban |
| 398 | CRC E55 HHDDT Creep | 1.8 | X | X | X | X |
| 301 | HD 5mph Non-Freeway | 5.8 | X | X | X | X |
| 302 | HD 10mph Non-Freeway | 11.2 | X | X | X | X |
| 303 | HD 15mph Non-Freeway | 15.6 | X | X | X | X |
| 304 | HD 20mph Non-Freeway | 19.4 | X | X | X | X |
| 305 | HD 25mph Non-Freeway | 25.6 | X | X | X | X |
| 306 | HD 30mph Non-Freeway | 32.5 | X | X | X | X |
| 351 | HD 30mph Freeway | 34.3 | X | X | X | X |
| 352 | HD 40mph Freeway | 47.1 | X | X | X | X |
| 353 | HD 50mph Freeway | 54.2 | X | X | X | X |
| 354 | HD 60mph Freeway | 59.4 | X | X | X | X |
| 355 | HD High Speed Freeway | 71.7 | X | X | X | X |
| 396 | HD High Speed Freeway Plus 5mph | 77.8 | X | X | X | X |

The default drive schedules for light-duty vehicles listed in the tables above were developed from several sources. “LD LOS E Freeway” and “HD High Speed Freeway” were retained from MOBILE6 and are documented in report M6.SPD.001.[38] “LD Low Speed 1” is a historic cycle used in the development of speed corrections for MOBILE5 and is meant to represent extreme stop-and-go “creep” driving. “LD High Speed Freeway 3” was developed for MOVES to represent very high speed restricted access driving. It is a 580-second segment of restricted access driving from an in-use vehicle instrumented as part of EPA’s On-Board Emission Measurement Shootout program,[39] with an average speed of 76 mph and a maximum speed of 90 mph. Fifteen additional light-duty “final” cycles were developed for MOVES based on urban and rural data collected in California in 2000 and 2004.[100] These cycles were selected to best cover the range of road types and average speeds modeled in MOVES.

Most of the driving schedules used for buses are borrowed directly from driving schedules used for single-unit trucks (described below). The "New York City Bus"[40] and "WMATA Transit Bus"[41] drive schedules are included for urban driving that includes transit-type bus driving behavior. The "CRC E55 HHDDT Creep" [42] cycle was included to cover extremely low speeds for heavy-duty trucks. The "Bus 12 mph Non-Freeway" (ID 402) and the "Bus 30 mph Non-Freeway" (ID 403) cycles used for transit and school buses were developed by EPA based on Ann Arbor Transit Authority buses instrumented in Ann Arbor, Michigan.[43] The bus "flow" cycles were developed using selected non-contiguous snippets of driving from one stop to the next stop, including bus-stop idling, to create cycles with the desired average driving speeds.[k] The "Bus Low Speed Urban" bus cycle (ID 401) is the last 450 seconds of the standard New York City Bus cycle.

The "Refuse Truck Urban" cycle represents refuse truck driving with many stops and a maximum speed of 20 mph but an average speed of 2.2 mph. This cycle was developed by West Virginia University for the State of New York. For restricted access driving of refuse trucks at extremely low speeds, the CRC E55 HHDDT Creep cycle is used instead. All of the other driving cycles used for refuse trucks are the same as the driving cycles developed for heavy-duty combination trucks, described below.

Single-unit and combination trucks use driving cycles developed specifically for MOVES, based on work performed for EPA by Eastern Research Group (ERG), Inc. and documented in the report "Roadway-Specific Driving Schedules for Heavy-Duty Vehicles."[44] ERG analyzed data from 150 medium- and heavy-duty vehicles instrumented to gather instantaneous speed and GPS measurements. ERG segregated the driving into restricted access and unrestricted access driving for medium- and heavy-duty vehicles, and then further stratified vehicles trips according the pre-defined ranges of average speed covering the range of vehicle operation. The medium-duty cycles are used with single-unit trucks and heavy-duty cycles are used with combination trucks.

The schedules developed by ERG are not contiguous schedules which could be run on a chassis dynamometer, but are made up of non-contiguous "snippets" of driving (microtrips) meant to represent target distributions. For use with MOVES, we modified the schedules' time field in order to signify when one microtrip ended and one began. The time field of the driving schedule table increments two seconds (instead of one) when each new microtrip begins. This two-second increment signifies that MOVES should not regard the microtrips as contiguous operation when calculating accelerations.

Both single-unit and combination trucks use the CRC E55 HHDDT Creep cycle for all driving at extremely low speeds. At the other end of the distribution, none of the existing driving cycles

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[k] In MOVES2014, the derived bus cycles 401, 402, and 403, were associated with the average speed of 15, 30, and 45 mph, respectively, even though the actual average speed of the cycles were 3.1, 11.5, and 21.9 mph, respectively. This was done assuming that the input average speed for buses on unrestricted access roadways was based on the traffic speed, while the actual speed was lower due to bus stops. In MOVES201X, we changed the driving cycle mapping in the DriveSchedule table to be the actual speed in MOVES201X for all bus drive cycles. Consistent with our changes, users should input the actual average speed distribution for transit buses, rather than the traffic speed.

for heavy-duty trucks included average speeds sufficiently high to cover the highest speed bin used by MOVES. To construct such cycles, EPA started with the highest speed driving cycle available from the ERG analysis and added 5 mph to each point, effectively increasing the average speed of the driving cycle without increasing the acceleration rate at any point. We have checked the feasibility of these new driving cycles (396 and 397) using simulations with the EPA's Greenhouse Gas Emissions Model (GEM)[45] for medium- and heavy-duty vehicle compliance. GEM is a forward-looking full vehicle simulation tool that calculates fuel economy and GHG emissions from an input drive trace and series of vehicle parameters. One of the aspects of forward-looking models is that the driver model is designed to demand torque until the vehicle drive trace is met. Our results indicate that the simulated vehicles were able to follow the speed demands of the proposed driving cycles without exceeding maximum torque or power.

### 9.2. Modeling of Ramps in MOVES

For MOVES201X, we simplified the modeling of emissions on restricted access roadways by removing the option to explicitly model emissions from ramp road types at the national and county-scale. Based on an analysis of instrumented real-world vehicles operating on highways with a variety of ramp configurations, we determined that the added complexity of modeling ramps separately from restricted access highways was not justified for county and national scale runs. Modeling ramps as part of highway driving using the current driving cycles overstates tailpipe exhaust emissions by less than 3 percent, and underestimates brake wear emissions by less than 9 percent. For more details on this analysis, see Appendix I, Freeway Ramp Contribution at the County-Scale

In addition to reducing run time and complexity, this approach eliminates the need for users to estimate the ramp fraction of highway driving, and removes the need for MOVES to extrapolate from limited data default operating mode distributions for ramps for each vehicle source type. For future versions of MOVES, we hope to investigate whether drive cycles can be further improved by incorporating a representative mix of ramp and highway driving.

However, at the project-scale, it is important to model ramps separately to identify localized areas where high acceleration and deceleration events cause increases in exhaust emissions[46] and brake emissions. Users can continue to estimate ramps as individual links in project-scale. Preferably, project-level users can characterize the operating mode or driving cycle of the ramps they are evaluating. In cases where users have limited data, we have developed a tool that estimates ramp operating mode distributions from an EPA light-duty activity study conducted in metropolitan Detroit, Michigan[46].

# 10. Off-Network Idle Activity

Recent data has shown that MOVES driving schedules substantially under-predict the amount of idle time (as indicated by non-zero engine rpm and vehicle speed less than one mph) that occurs during vehicle trips. To put this into perspective, the total idle fraction in MOVES2014 (national default) is around 14 percent for sourceTypeIDs 21 and 31, compared to 18–31 percent as derived from Verizon Telematics data described below. The difference is likely due to historical approaches to drive cycle development that exclude activity in drive-ways, parking lots, queues and during delivery operations. In addition, MOVES2014 may not have accounted for the increased amounts of congestion in recent years.

To better account for observed levels of idling, we have added a new emission calculation to MOVES201X. In MOVES2014, all vehicle engine operation (key on) was accounted for in four of the five road types; the vehicle idle occurred only during the driving schedules and varies by average speed by road type. For MOVES201X, we have added the capability to also model off-network idle emissions (i.e., on roadTypeID=1).

This section provides information on the idling data available for both light-duty and heavy-duty vehicles and then summarizes the calculation methodology employed by MOVES.

## 10.1. Light-Duty Off-Network Idle

### 10.1.1. Verizon Telematics Data

For MOVES201X, Verizon Telematics data for light-duty vehicles was purchased for the following five states – California, New Jersey, Illinois, Georgia and Colorado. The data was collected August 2015 through August 2016 using on-board diagnostic data loggers under contracts with State Farm insurance, Mercedes-Benz and Volkswagen. The Verizon Telematics data was used as a primary data source for the light-duty off-network idle defaults described in this chapter and also the soak and start defaults described in Section 12.1However, the data characteristics and pre-processing steps are all covered here.

The Verizon data contains the measurement of a variety of activity information gathered on vehicles over long periods of time from a sampling of vehicles in every part of the nation. In order to protect the identity of the vehicle owners, the information collected was summarized and processed into individual trips for analysis. The analysis summary database includes trip start time and date, trip end time and date, total trip time, total idle time, trip average speed, trip maximum speed and trip distance. Trips were defined as the time period from key on to key off. Engine idle was defined as any time during the trip where the recorded engine RPM was greater than zero and the vehicle speed was less than one mile per hour. Total idle time is defined as the ratio of the sum of the idle time periods in a trip and the total time of the trip from key on to key off. In addition to the trip data, each trip was associated with a vehicle ID. For each vehicle ID model year and vehicle registration postal ZIP code was provided. All vehicles were light duty, either passenger car or light duty truck. No information about where the trips occurred was provided in the samples.

Using the provided data, each vehicle was assigned to a county within the State based on the registration information. The counties were categorized as urban or rural based on the U.S. Census Metropolitan Statistical Area (MSA) classifications. Counties were also grouped as either including a State Inspection and Maintenance (I/M) program or not.

All vehicle owners in the samples allowed their vehicles to be measured for a variety of reasons, and were not statistically selected into the sample. None of the vehicle owners knew that their data was to be included in our study of vehicle activity. All of the activity by vehicles was assumed to occur within the county assigned to the vehicle by their registration location.

### 10.1.2. QA/QC of the Verizon Telematics Data

Table 10-1 shows a high-level summary of Verizon Telematics data. The original dataset provided by Verizon included around 41 million trip summary records from the five states. Such large datasets pose several challenges related to data quality and sampling. For example, for some trips, data were found to be missing or incomplete. Such trips were removed from the original dataset and the remainder were used to analyze the idle fraction as summarized in the "Total Trips (Idle)" column of Table 10-1.

*Table 10-1: Verizon Telematics data sample summary*

| State | Total Trips (Original) | Total Trips (Idle)* | Total Trips (Soak Time & Starts)** | %Trips*** |
|---|---|---|---|---|
| **California** | 1,958,858 | 1,886,947 | 1,761,184 | 90% |
| **Colorado** | 5,644,374 | 5,390,417 | 4,977,334 | 88% |
| **Georgia** | 15,457,392 | 14,654,336 | 13,465,865 | 87% |
| **Illinois** | 12,955,252 | 12,318,387 | 11,448,257 | 88% |
| **New Jersey** | 5,139,506 | 4,947,792 | 4,615,346 | 90% |

Notes:
* Only valid trips included in idle analysis.
** Only valid trips with previous recorded valid trips included in start and soak analysis.
*** Percent of total trips remaining after all screening (starts divided by original total).

In addition, not all vehicles in the sample had 12 complete months of data, due to termination of subscriptions, instrumentation failures, etc. during the sampling period. Thus we developed and algorithm to account for and sample only those vehicles and their associated monthly data for which there was at least one trip in the current month, the preceding and succeeding months. In addition, for a given vehicle, the first and last month of the data for each vehicle was kept in the sampling frame if there was there was at least one trip in the first week and the last week for the month, respectively. Figure 10-1 shows the Verizon Telematics sample vehicle population by state by month derived using this sampling. Overall, this inherent issue associated with the data led us to complete the activity analysis (starts, soaks and idle) on a month-to-month basis. Appropriate weighting was applied to the monthly results to generate annual default averages,

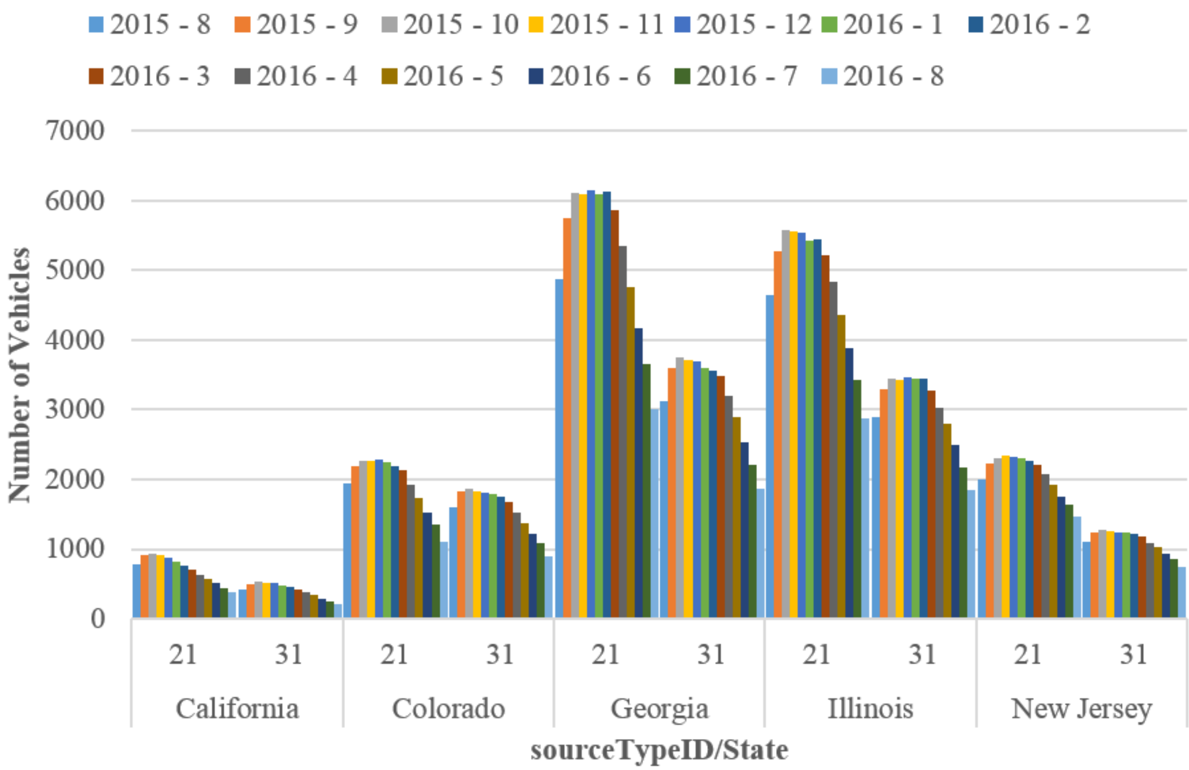


*Figure 10-1 Sample vehicle population in the Verizon Telematics data by month by state. Note: the legend indicates the "year-month" of the data collection.*

There were a few instances where the trip time was less than 1 second, or the soak time were less than two seconds, applicable in some scenarios such as when a vehicle crossed a different time zone or when the data logger recorded erroneous trip starts at midnight for trips that included midnight during the trip. Such trips represented less than 1 percent of the total trips for any given state, and were removed from the idle and starts/soak analysis. The remaining trips, with erroneous trip starts removed, were used to analyze engine starts and soaks; refer to "Total Trips (Soak Time & Starts)" column in Table 10-1 for the total trip counts. The erroneous trip starts removed from the start/soak analysis do not affect the results for the analysis of total idle time.

### 10.1.3. Estimating MOVES National Defaults from Verizon Telematics Data

While the Verizon Telematics data covered only five states, MOVES must model the entire U.S. Thus, we associated each state with nearby states to create vehicle-population weighted national averages for starts and soaks, and regional-specific values for idle time. Figure 10-2 shows how we mapped individual states to the Verizon data. Table 10-2 lists the vehicle populations used for computing national averages. The weighted average results for the light duty passenger trucks (indicated in the data as sourceTypeID 31) are used for light duty commercial trucks (sourceTypeID 32) as well.

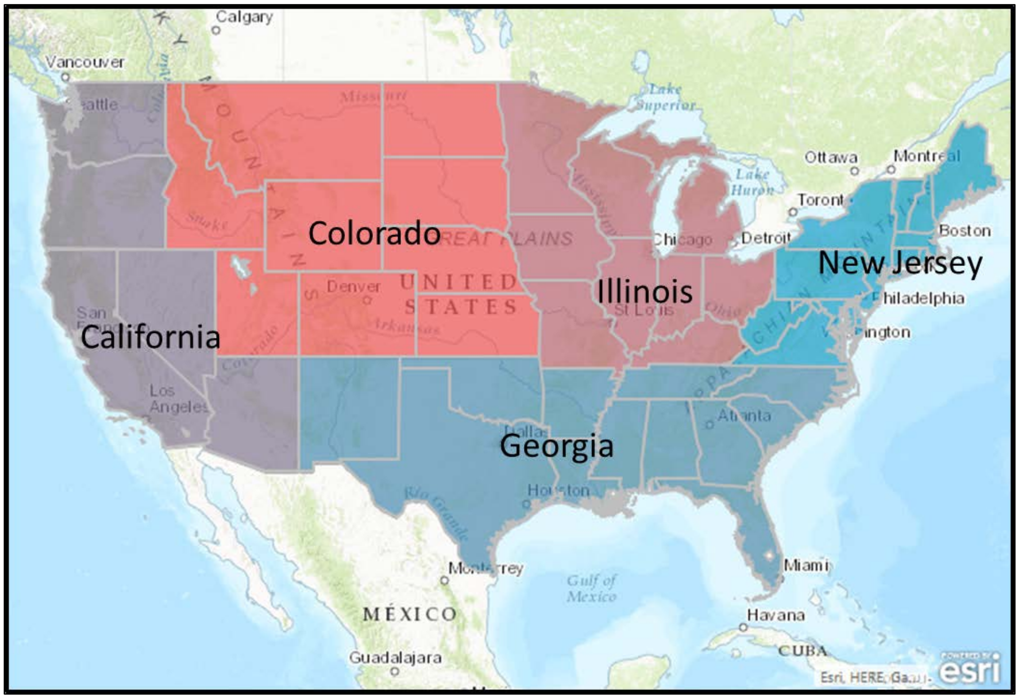


*Figure 10-2: Default Regions for Weighting Light Duty Activity*[1]

*Table 10-2: Vehicle populations of the idle regions*[71].

| Verizon data source state | sourceTypeID | Vehicle Population | idleRegionID |
|---|---|---|---|
| California | 21 | 23,114,006 | 105 |
| California | 31 | 19,917,792 | 105 |
| Colorado | 21 | 6,902,041 | 104 |
| Colorado | 31 | 8,823,105 | 104 |
| Georgia | 21 | 38,269,101 | 102 |
| Georgia | 31 | 39,358,137 | 102 |
| Illinois | 21 | 26,768,198 | 103 |
| Illinois | 31 | 25,510,186 | 103 |
| New Jersey | 21 | 27,625,575 | 101 |
| New Jersey | 31 | 23,077,050 | 101 |

Moreover, the Verizon Telematics data analysis suggested that the following factors are important when estimating total idling fraction:

- Month of the year

[1] Note, Alaska is associated with Colorado. Hawaii, Puerto Rico and the Virgin Islands are associated with California.

- State (or region), i.e., the State where the vehicle was registered
- County type, i.e., whether registered in an urban (MSA) or rural county
- Passenger car or light truck
- Day type, i.e., weekend vs. weekday variation

The analysis showed no significant variation with age or hour of the day. Henceforth, a simplified and unified linear regression model was built to capture the variability of the total idle fraction (TIF) across different variables (dayID, sourceTypeID, countyTypeID, idleRegionID and monthID). The equation below represents the form of the TIF model that gives MOVES default values for TIF.

$$TIF = dayID * i + sourceTypeID * j + countyTypeID * k + idleRegionID * monthID * l + m$$ **Equation 6**

where, i, j, k, l are coefficient values for the combinations of dayID (2=Weekend,5=Weekday), sourceTypeID, countyTypeID, idleRegionID and monthID and m is the intercept (a constant) for Equation 6 above. An example set of coefficients are available in Appendix F.

As one might expect, idling activity is more common in winter months in colder states and urban areas have more idling activity that rural areas. Idling activity is similar for passenger cars and light trucks, but separate idle fractions will be used for each of the source types. There is less idling activity on weekends versus weekdays.

The TIF values will apply to all calendar years. Note that idleRegionID and countyTypeID will vary depending on the county location. Each state will be assigned an idleRegionID in the MOVES State table as shown in Figure 10-2. Each county will be assigned an “urban” or “rural” countyTypeID in the MOVES County table based on the MSA designation.

Appendix G shows a sample calculation using MOVES201X default values for passenger cars in rural counties in idleRegionID=101 (New Jersey).

Figure 10-3 below illustrates the model fit of the multi-variable linear model Equation 6 discussed above against actual values. Note that there was no data available for New Jersey from Verizon Telematics for rural counties (i.e. countyTypeID=0). However, the regression model applies the rural/urban effect without regard to region. TIF model results are represented by solid lines versus average values from the Verizon Telematics data, shown as dashed lines. Both day types (weekend days dayID=2, weekdays dayID=5) are shown in each chart. Idle regions are shown in Table 10-2. As discussed earlier, the results for the light duty passenger trucks (indicated in the data as sourceTypeID 31) will be used for light duty commercial trucks (sourceTypeID 32) as well.

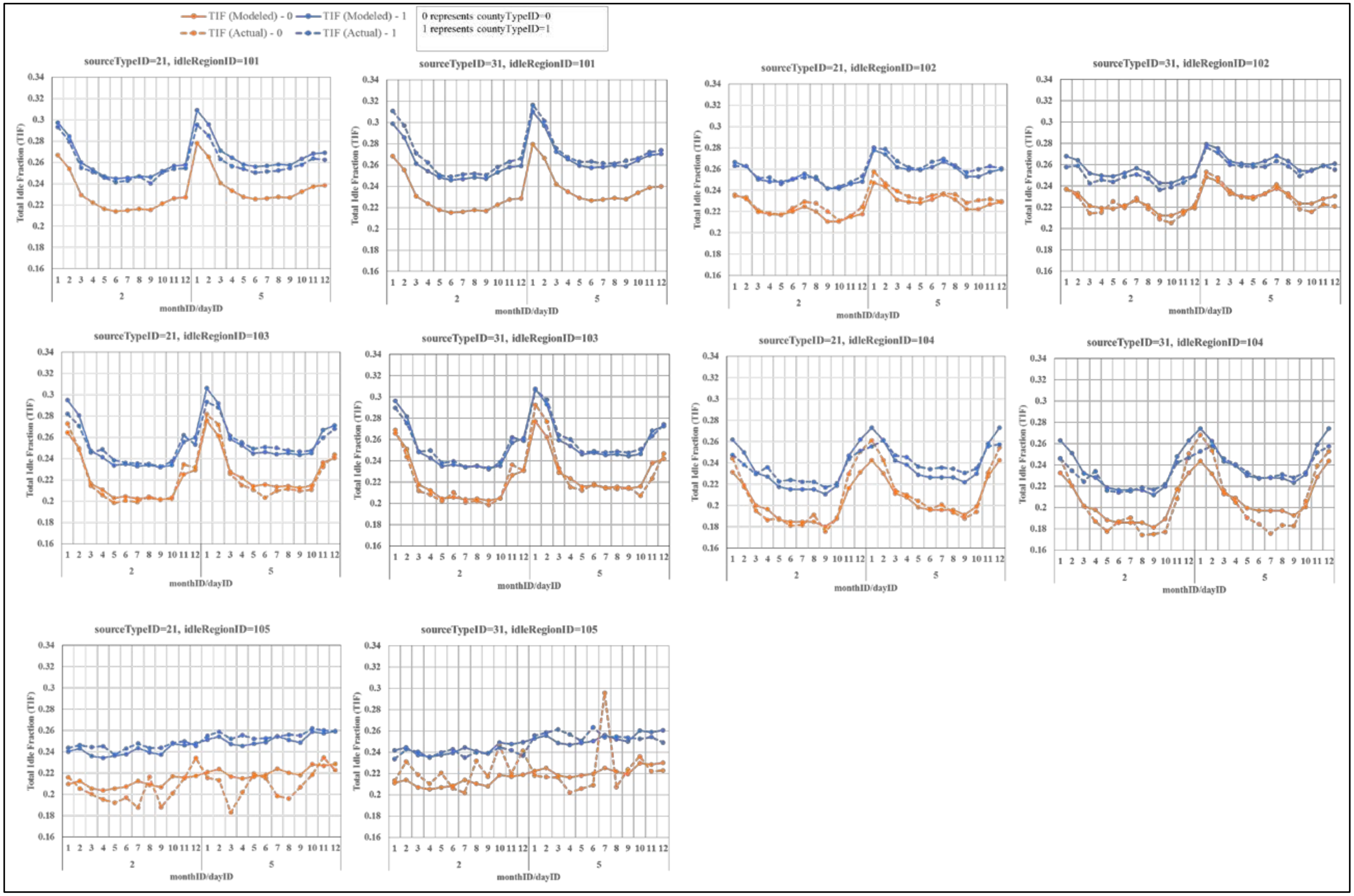


*Figure 10-3: TIF model results compared to the values from the Verizon Telematics data*

## 10.2. Heavy-Duty Off-Network Idle

Because the Verizon Telematics data did not cover heavy-duty vehicles, the University of California Riverside, Bourns College of Engineering Center for Environmental Research and Technology (CE-CERT) and the National Renewable Energy Laboratory (NREL) Fleet DNA clearinghouse of commercial fleet vehicle operating data described below were used as the source for the heavy-duty off-network idle defaults described in this section and also the soak and start defaults described in Section 12.2However, the data characteristics and shared pre-processing steps are all covered here.

Note that developing activity inputs for heavy-duty vehicles is complicated by the fact that heavy-duty vehicles are spread across a very wide range of vocations and activity patterns, yet there is less data available than for light-duty vehicles. This contributes to substantial uncertainty in these inputs.

### 10.2.1. NREL Fleet DNA Database

We partnered with NREL to make use of their expansive Fleet DNA database[47] of heavy-duty vehicles to develop idle activity estimates for heavy-duty vehicles. NREL's Fleet DNA database is developed from vehicles operating in the field with data recording devices to capture 1-Hz telematics and CAN (controller area network[48]) data.

While the Fleet DNA database includes a wide range of fuels, vehicle drivetrains and propulsion mechanisms, only diesel-powered conventional vehicles were included in the analysis to ensure the selected drive cycles are representative of traditional operation and not modified to accommodate the vehicle architecture. The sample sizes of conventional vehicles in the Fleet DNA database by MOVES Source Types are shown in  and the vocational classes within the MOVES short-haul source types are shown in Table 10-4.

**Table 10-3. Sample size of conventional vehicles in the Fleet DNA database by MOVES source type**

| sourceTypeID | Source Type Name | Number of Vehicles in Fleet DNA |
|---|---|---|
| 41 | Other Buses (non-school, non-transit) | |
| 42 | Transit Buses | 16 |
| 43 | School Buses | 7 |
| 51 | Refuse Trucks | 40 |
| 52 | Single-Unit Short-Haul Trucks | 119 |
| 53 | Single-Unit Long-Haul Trucks | |
| 54 | Motor Homes | |
| 61 | Combination Short-Haul Trucks | 160 |
| 62 | Combination Long-Haul Trucks | 85 |

*Table 10-4. Vocation types of the Combination Short-Haul and Single-Unit Short-Haul vehicles within the Fleet DNA database*

| Combination Short-Haul | Vehicles | Single-Unit Short Haul | Vehicles |
|---|---|---|---|
| Beverage Delivery | 10 | Warehouse Delivery | 10 |
| Food Delivery | 13 | Parcel Delivery | 39 |
| Local Delivery | 7 | Food Delivery | 30 |
| Parcel Delivery | 6 | Linen Delivery | 17 |
| Drayage | 29 | Snow Plow | 14 |
| Freight | 22 | Towing | 4 |
| Tanker | 25 | Shredder | 1 |
| Refrigerated Truck | 7 | Propane Tank | 1 |
| Dump Truck | 5 | Dump Truck | 3 |
| Concrete | 3 | | |
| Regional Haul | 1 | | |
| Transfer Truck | 29 | | |
| Dry Van | 3 | | |

The geographic distribution by state of the vehicle sample within the Fleet DNA database is provided in Table 10-5. The average total idle fractions are also calculated by state, which we suspect could be an influential factor in average idle emission rates, due to differences in congestion, topography, and local policies. For example, California has a regulation limited idling beyond five minutes.[49] However, it is not yet clear if the limited data will support separate regional default values for heavy-duty trucks.

*Table 10-5. Geographic distribution of activity by Source Type*

| Source Type | SourceTypeName | State | Vehicle sample |
|---|---|---|---|
| 42 | Transit Bus | CO | 4 |
| | | MN | 9 |
| | | TN | 3 |
| 51 | Refuse Truck | CO | 7 |
| | | FL | 13 |
| | | IN | 13 |
| | | OH | 4 |
| 52 | Single-Unit Short-Haul Truck | CA | 48 |
| | | CO | 11 |
| | | IN | 9 |
| | | MN | 11 |
| | | TN | 3 |
| | | TX | 6 |
| | | WA | 19 |
| 61 | Combination Short-Haul Truck | CA | 66 |
| | | CO | 11 |
| | | TN | 3 |
| | | TX | 5 |

After the initial filtering[m], idle is calculated using the vehicle's wheel speed in miles per hour and engine speed in rotations per minute (RPM). A vehicle is considered to be idling when its wheel speed is less than 1 mph and engine speed is greater than zero. Using these two logic statements, a binary output is created indicating if a vehicle is idling or not. Next, periods of contiguous idle are identified by length and the dayID corresponding to the start of the idle. The total operating time (engine RPM > 0) occurring within each dayID is then counted along with the idle activity. If an idle period starts during one dayID and ends on another, the idle time will only be counted for the dayID in which the trip started. Idle periods for long-haul combination trucks that last over an hour are considered as part of mandatory rest periods and are categorized separately as "extended idle" and are not included in the determination of work day idling used in the calculation of off-network idle fractions. Equation 7 shows the calculation of the total idle fraction for each day.

[m] For each vehicle dataset making up this idle analysis an initial filtering process is done to ensure a robust and representative result. This process involves eliminating the first and last days of data to avoid counting incomplete or unrepresentative operation when the data logger is being installed or removed. Next, zeros are filled in for periods between the first and last days when the logger was installed on the vehicle, and the vehicle was not operating. This helps ensure non-activity is captured. If the data-logger was installed but did not record any activity, the idle fraction is 0, however if the data-logger was not installed on a specific dayID, those values are denoted as "nan" and are removed from the results.

$$Idle\ Fraction = \frac{\sum Idle\ Time}{\sum Operating\ Time}$$ **Equation 7**

Combination trucks involved in long-haul operations have both work day idle and extended idle activity. To calculate both work-day and extended idle fractions, the idle segments were further classified into segments less than or equal to 1 hour as work-day idle and those greater than 1 hour as extended idle. The work-day and extended idle fractions were then calculated using Equation 8 and Equation 9, respectively, such that the sum of the work-day and extended idle is equal to the total idle as shown in  Equation 10.

$$Workday\ Idle\ Fraction = \frac{\sum Workday\ Idle\ Time}{\sum Operating\ Time}$$ **Equation 8**

$$Extended\ Idle\ Fraction = \frac{\sum Extended\ Idle\ Time}{\sum Operating\ Time}$$ **Equation 9**

$$Workday\ Idle\ Fraction + Extended\ Idle\ Fraction = Idle\ Fraction$$ **Equation 10**

The results of each vehicle are then averaged resulting in an even weighting for all vehicles in the sourceTypeID category. These results are presented and compared to the CE-CERT idle fractions in Section 10.2.3.

### 10.2.2. CE-CERT Study

The California Air Resources Board (CARB) contracted with CE-CERT and ERG to conducted a large scale study in which vehicle and engine activity data were collected from 90 heavy-duty vehicles that are mapped to 19 different groups defined by a combination of vocational use, gross vehicle weight rating, and geographic region within California. Almost all of the vehicles were of model year 2010-or newer and most were equipped with SCR technology. One drayage truck was model year 2008 (with no SCR) and all of the buses were CNG fueled. In addition, some of the vehicles in the study were hybrids; these vehicles were removed from the analysis.

Since a large amount of second-by-second data were collected from both GPS and electronic engine control units (ECU), CE-CERT and ERG completed several steps of data processing and quality assurance to filter and correct erroneous data, account for trips affected by start-stop technologies, and protect fleet confidentiality. In addition to the above QA checks, additional processing of the data was done to prepare the data for analysis. First, we identified trips in the database, where within the trip, that vehicles affected by the start-stop technology would stop and start again within the time period between the key on and key off. For purposes of this analysis, all vehicles were treated as if they did not utilize start-stop technology, so that only the “true starts” with engine start at the time of key on were used. Second, whenever the data logger was found to be recording erroneous data, a complete day of data was removed from the database. Lastly, all the hybrid vehicles (six out of 90 total vehicles) were removed for the activity analysis.

Table 10-6 below shows the vehicle population, number of trips and total seconds of data available by sourceTypeID from the CE-CERT study after the data has been processed using the QA/QC checks discussed above. The processed data were then used to analyze vehicle activity statistics related to engine start and engine soak discussed below.

*Table 10-6 Data summary from the CE-CERT study*

| sourceTypeID | Source type | Vehicle population | Total secs | Trips (All starts) * | Trips (True starts) ** |
|---|---|---|---|---|---|
| 42 | Transit Bus | 10 | 24,926,267 | 7,147 | 5,325 |
| 51 | Refuse Truck | 6 | 8,291,805 | 1,828 | 1,643 |
| 52 | Single Short Haul | 30 | 19,015,955 | 11,504 | 7,863 |
| 53 | Single Long Haul | 2 | 2,561,336 | 715 | 587 |
| 61 | Comb. Short Haul | 27 | 15,548,107 | 13,598 | 9,329 |
| 62 | Comb. Long Haul | 9 | 13,531,121 | 5,805 | 3,066 |
| **Total** | | **84** | **83,874,591** | **40,597** | **27,813** |

Notes:
* Total trips used for idle analysis. Including incidental starts.
** Total trips for starts and soak analysis. Not including incidental starts.

### 10.2.3. Heavy-duty Off-network Idle Results

Table 10-7 below shows the number of vehicles in the sample by source type for the two different data sources. There were some sourceTypeIDs (43 and 53) for which trip data exists only in one of the data sources. Note that the NREL's state-wide vehicle population total (243) did not match with the total population (418). The discrepancy is a result of not including the vehicles without location metadata in the state breakdown analysis. We hope to update this table and the analysis if NREL can reconcile the missing information by looking at vehicle GPS traces, and/or additional metadata available for the vehicles.

*Table 10-7: Sample vehicle population from the NREL and CE-CERT studies by source types.*

| source TypeID | Source type | *CE-CERT* | NREL-All | NREL state-wide vehicle population | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | CA | CO | FL | IN | MN | OH | TN | TX | WA | Total |
| **42** | Transit Bus | 10 | 16 | 0 | 4 | 0 | 0 | 9 | 0 | 3 | 0 | 0 | 16 |
| **43** | School Bus | 0 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **51** | Refuse Truck | 6 | 39 | 0 | 7 | 13 | 12 | 0 | 4 | 0 | 0 | 0 | 36 |
| **52** | Single Short Haul | 30 | 115 | 47 | 11 | 0 | 9 | 11 | 0 | 3 | 6 | 19 | 106 |
| **53** | Single Long Haul | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **61** | Comb. Short Haul | 27 | 156 | 66 | 11 | 0 | 0 | 0 | 0 | 3 | 5 | 0 | 85 |
| **62** | Comb. Long Haul | 9 | 85 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total** | | **84** | **418** | **113** | **33** | **13** | **21** | **20** | **4** | **9** | **11** | **19** | **243** |

Table 10-8 below shows the total idle fraction and extended idle fraction results for sourceTypeID 62 from the two studies; total idle fraction and extended idle fraction are defined in Section 10.2.1. There was no extended idle activity in the CE-CERT data sample (which was intended to represent only vehicles operated in California), whereas NREL has an extended idle fraction of 13 to 14 percent depending on a day type. The total idle fraction was higher on a weekend for vehicles in the CE-CERT database than for vehicles in the NREL database. It is also not clear from the NREL vehicle population classification (see Table 10-7) what percent of the data consisted of California vs. non-California operated vehicles.

*Table 10-8 Comparison of total idle fraction and extended idle fraction results for sourceTypeID 62 from the CE-CERT and NREL studies*

| | ***CE-CERT (All Starts)*** | ***CE-CERT (All Starts)*** | ***NREL-Avg*** | ***NREL-Avg*** |
|---|---|---|---|---|
| **sourceTypeID/dayID** | **Total Idle Fraction** | **Extended Idle Fraction** | **Total Idle Fraction** | **Extended Idle Fraction** |
| **62/2** | 0.34 | 0.00 | 0.25 | 0.13 |
| **62/5** | 0.24 | 0.00 | 0.25 | 0.14 |

Figure 10-4 shows the total idle fraction results for the different heavy-duty source types from the two studies. The CE-CERT results were found to be higher than the NREL's average results for most sourceTypeIDs across the two dayIDs. We also observed variability in the total idle fraction values across different states in the NREL database, as shown in Figure 10-5. However, the total idle fraction results from the CE-CERT study are reasonably consistent when compared with California vehicles' data from NREL (see results for sourceTypesIDs 52 and 61 in the Figure 10-4). Interestingly, the results from the NREL study for California, the total idle fractions for sourceTypeIDs 52 and 61 were found to be the minimum on weekends but maximum on weekdays when compared with other states (see Figure 10-5). Given the variability in the results across states, EPA is still working to understand whether the differences between idle fractions from different data sources, states and day types represent meaningful differences in activity or are simply an artifact of relatively small samples. For example, we have not yet decided whether heavy-duty off-network idling will vary by region.

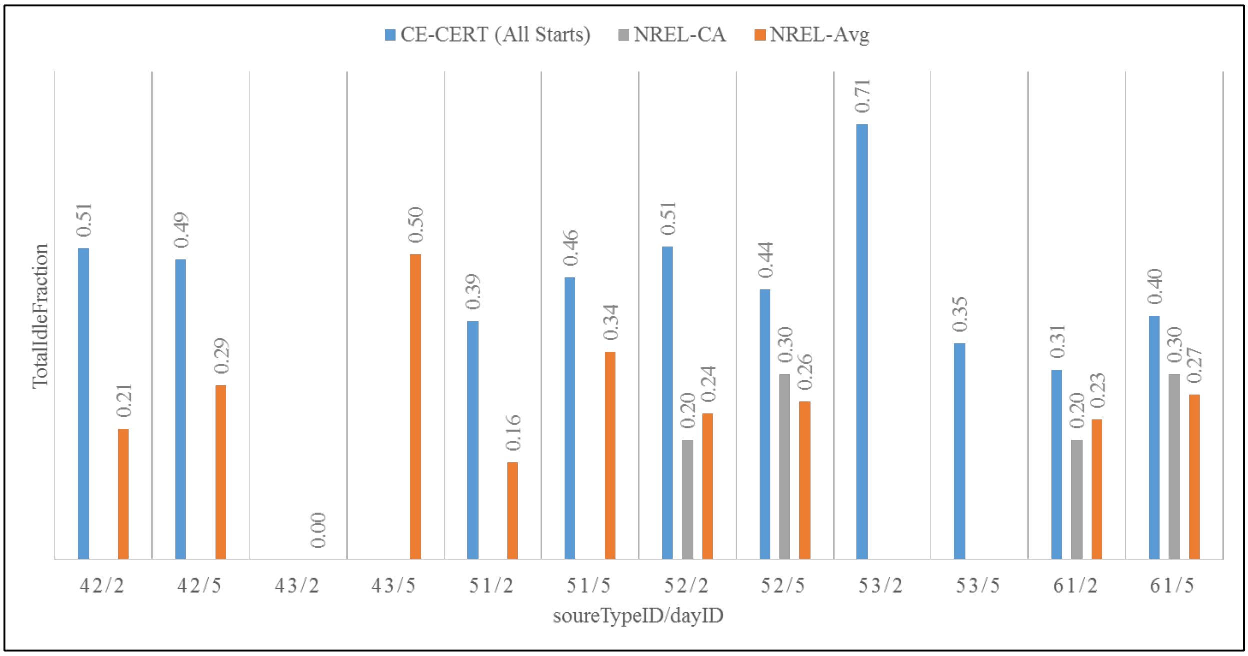


*Figure 10-4 Comparison of total idle fraction by sourceTypeID and dayID derived from the CE-CERT and NREL studies*

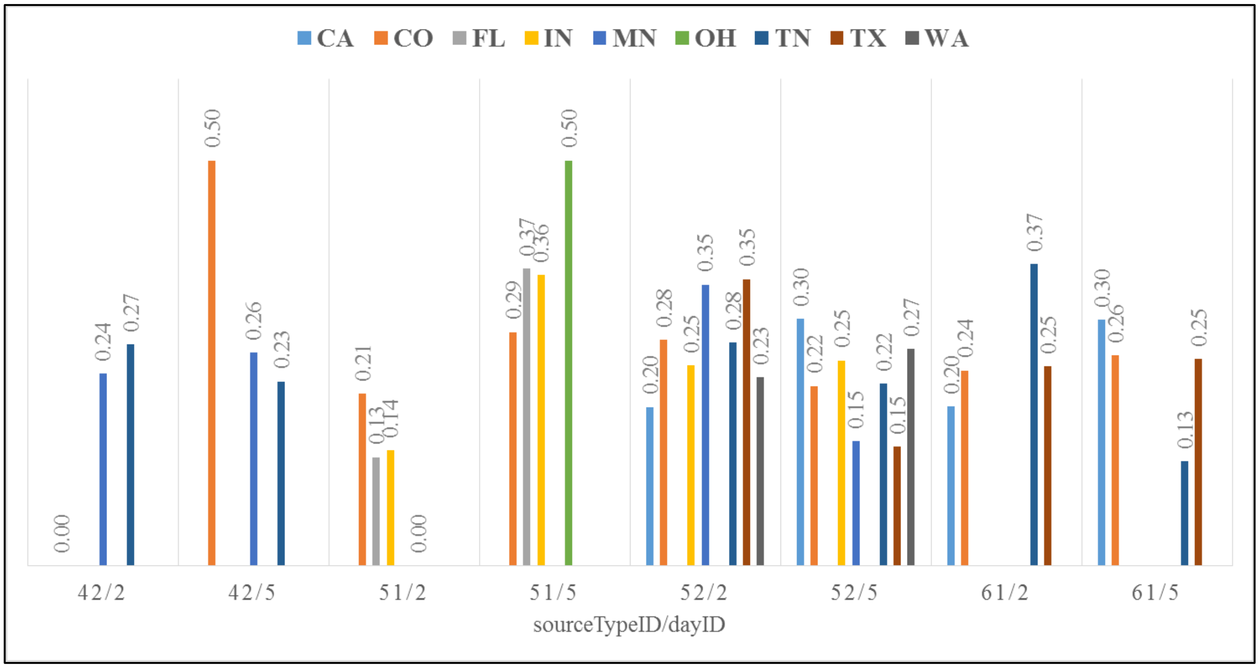


*Figure 10-5 Total idle fraction by state by sourceTypeID and dayID from the NREL study*

## 10.3. Work-day Idle Methodology and Definitions

As mentioned in the data analysis section above, for MOVES201X, we are defining the total idle fraction (TIF) as the ratio of the total source hours idling and total source hours operating. This value can be derived from instrumented vehicles as explained above. Apart from extended idling (see Section 11.2) MOVES defines "idle" as any seconds in the driving schedules where the speed is less than one mile per hour (opModeID=1) during engine operation. Using the fraction of vehicle operation hours that are opModeID=1, the hourly base source hours idle (BHI) for each of the four on-road road types (roadTypeIDs 2, 3, 4, & 5) can be determined from the driving schedules used for vehicle operation on roadways. We exclude any extended engine idle that occurs during the mandated rest period for combination long-haul truck (sourceTypeID 62), which we call hotelling.

Since the new estimates of TIF are greater than the idle time accounted for in the MOVES driving schedules (BHI), we also need to increase MOVES' estimate of total source hours operating (SHO). In particular, the off-network idle time (ONI) is defined as the additional idle hours that need to be added to the base source hours operating (BHO) in order to account for the additional idle time. The BHO is derived from the input VMT, speed distribution, and driving schedules. In MOVES, the additional ONI hours will be assigned to the running exhaust process (processID=1) for the off-network road type (roadTypeID=1).

SHO is calculated in MOVES2014 from vehicle miles traveled (VMT) and average speed using the driving cycles for all onroad roadTypeIDs 2, 3, 4 and 5. In MOVES201X, we are renaming this value as BHO to indicate that additional time needs to be added to account for off-network idle time. Any VMT provided for roadTypeID=1 will be ignored when calculating BHO. The SHO for all road types will now include the "extra" operating time (ONI) implied by the larger total idle fraction value:

$$SHO = \left(\sum_{i=2}^{4} BHOi\right) + ONI \text{ ,} where\ i = roadTypeID$$ **Equation 11**

Source hours idle (SHI) then is the total hours of idle, excluding diesel long-haul combination truck hotelling idle:

$$SHI = \left(\sum_{i=2}^{4} BHIi\right) + ONI$$ **Equation 12**

Where i = roadTypeID

All running exhaust activity for roadTypeID=1 is idle, so $BHO_1$=$BHI_1$ and represent ONI. Since the TIF values are the measured fraction of idle time during vehicle operation, the SHI is also the result of applying the TIF to the SHO:

$$SHI = TIF * (SHO)$$ **Equation 13**

Thus, from Equation 11, Equation 12 and Equation 13:

$$TIF = \frac{(\sum_{i=2}^{4} BHI_i) + ONI}{(\sum_{i=2}^{4} BHO_i) + ONI}$$ **Equation 14**

Using the TIF, total BHO and total BHI from the four network road types, MOVES will calculate the hours for off-network idle (ONI), by re-arranging Equation 14:

$$\mathrm{ONI} = \frac{(\sum_{i=2}^{4} \mathrm{BHOi}) \times \mathrm{TIF} - \sum_{i=2}^{4} \mathrm{BHIi}}{(1 - \mathrm{TIF})}$$ **Equation 15**

Where i = roadTypeID

In cases where the ONI is calculated to be less than zero, the ONI will be set to zero. As an example, the default values of TIF for light-duty vehicles in idleRegionID=101 (New Jersey) are presented in Appendix G.

Off-network idle emissions will be calculated for each hour by using the corresponding emissions rate (grams per hour) for opModeID=1 for that hour. All of the adjustments made to the emissions for opModeID=1 for other road types will apply to off-network idle emissions as well. MOVES201X will separately report the emissions calculated from the off-network idle hours in the movesOutput table as exhaust running process (processID=1) for road type “off-network” (roadTypeID=1). Since Project Level scale is link based, Project Level runs in MOVES201X will not generate off-network idle results. However, users can create a link with an average speed of zero in order to generate idle emissions.

# 11.Hotelling Activity

MOVES defines "hotelling" as any long period of time that drivers spend in their vehicles during mandated down times during long distance deliveries by tractor/trailer combination heavy-duty trucks. During the mandatory down time, drivers can stay in motels or other accommodations, but most of these trucks have sleeping spaces built into the cab of the truck and drivers stay with their vehicles. Hotelling hours are included in MOVES in order to account for use of the truck engine (referred to as “extended idling”) to power air conditioning, heat, and other accessories and account for the use of auxiliary power units (APU), which are small on-board power generators.

Many states have been looking into long-haul truck activity and can provide local estimates for this type of information. However, this type of local and regional information is difficult to use in developing national average default statistics for hotelling behavior. EPA is investigating obtaining long-haul operation data from nationwide sources, such as the American Transportation Research Institute (ATRI)[50] and the National Renewable Energy Laboratory (NREL) Fleet DNA[51] to provide better national estimates for hotelling activity.

In MOVES, only the long-haul combination truck source use type (sourceTypeID 62) is assumed to have any hotelling activity. All of the long-haul combination trucks are diesel-fueled. All source use types other than long-haul combination trucks have hotelling activity fractions set to zero.

## 11.1. National Default Hotelling Rate

In long-haul operations, drivers will stop periodically along their routes, but these idling stop periods are not necessarily hotelling. For MOVES, the total hours are estimated by using the MOVES’ national default estimate of VMT by long-haul combination trucks divided by an estimated average speed to calculate total hours of driving shown in Equation 16 below.

$$Total\ Hours = \frac{Total\ Vehicle\ Miles\ Traveled}{Average\ Speed} \qquad \text{Equation 16}$$

Where:

- Total Hours is the calculated time long-haul combination trucks spend driving.
- Total Vehicle Miles Traveled is the total miles traveled by diesel long-haul combination trucks in the nation in calendar year 2011 on all road types taken from MOVES defaults.
- Average Speed is an estimate of the average speed (distance divided by time) for diesel long-haul combination trucks on all road types while operating.

Federal law limits the time long-haul truck drivers can spend on the road. To estimate average annual hotelling hours, MOVES assumes drivers follow hours-of-service regulations from the Federal Motor Carrier Safety Administration (FMCSA).[52] Prior to 2004, the regulations limited drivers to no more than 10 hours driving followed by at least 8 hours of rest. The 2003 hours-of-service rule (effective January 2004) increased the allowable driving time to 11 hours and the required off-duty time to 10 hours, with flexibilities if drivers take appropriate 30 minute breaks or after 34 hours of time off.[53] The number of hours hotelling is calculated assuming drivers maximize the amount of driving and adhere to the required rest periods in a given shift as illustrated in Equation 17 and **Equation 18**. Note that previous versions of MOVES applied the same 10 hours driving/8 hours rest to all calendar years. MOVES201X aligns the driving and rest times with the hours-of-service regulations in place for a given calendar year, resulting in more hotelling hours in calendar years 2004 and later. Hotelling hours for calendar years before 2004 will still use the 10 hours driving/8 hours rest estimates.

$$Total\ Trips = \frac{Total\ Hours}{Allowed\ Driving\ Time} \qquad \text{Equation 17}$$

$$Hotelling\ Hours = Total\ Trips * Required\ Rest \qquad \textbf{Equation 18}$$

Where:

- Total Trips is the calculated number of trips by long-haul combination trucks.
- Allowed Driving Time is the maximum hours of driving allowed per shift (10 or 11 hours based on FMCSA hours-of-service regulations)
- Hotelling Hours is the calculated amount of rest time for long-haul combination trucks.
- Required Rest is the mandated rest period per shift (8 or 10 hours based on FMCSA hours-of-service regulations in effect that calendar year)

The driving time on all roads (total hours) contributes to the total hotelling hours calculation. However, long-haul trucks most frequently travel on restricted access roads (freeways) and most hotelling occurs at locations near those roadways (i.e., rest stops or truck stops). To allocate hotelling hours away from congested city centers to locations where long-haul drivers are likely to rest, MOVES uses a "hotelling rate." As described in Equation XX, the hotelling rate is the national total hours of hotelling divided by the national total miles driven by long-haul combination trucks on all restricted access roads (both urban and rural).

$$Hotelling\ Rate = \frac{Hotelling\ Hours}{Total\ Restricted\ Miles\ Traveled} \qquad \text{Equation XX}$$

Where:

- Total Restricted Miles Traveled is the total miles traveled by diesel long-haul combination trucks on rural and urban restricted access roads (freeways) in calendar year 2011 using MOVES defaults.
- Two separate hotelling hours estimates are used for the two sets of FMCSA hours-of-service regulations.

MOVES2014 used the VMT on *rural* restricted roads as the surrogate for allocating total hotelling hours, but MOVES201X expands the hotelling VMT to include urban restricted roads to capture the truck traffic around cities. MOVES2014 and earlier versions applied a constant default hotelling rate for all years, which was calculated using default national total VMT estimates for calendar year 2011. The hotelling rate for MOVES201X is based on hours-of-service regulations that were revised in 2004.[54] As a result, one of two hotelling rates is applied in MOVES201X depending on the calendar year modeled. Table 11-1 shows the values used in the hotelling rate calculations.

*Table 11-1 Calculation of hotelling rate from long-haul combination truck VMT for calendar year 2011*

| Description | Annual Value | Units |
|---|---|---|
| Rural Restricted VMT | 31,392,300,000 | miles |
| Rural Unrestricted VMT | 34,301,700,000 | Miles |
| Urban Restricted VMT | 32,243,100,000 | Miles |
| Urban Unrestricted VMT | 28,848,900,000 | Miles |
| Total VMT | 126,786,000,000 | Miles |
| Total VMT on Restricted Roads | 63,635,400,000 | Miles |
| Total Hours Driving (58.3 mph average) | 2,174,716,981 | Hours |
| *Years Prior to 2004* | | |
| Number of Trips (10 hours driving) | 217,471,698 | Trips |
| Hotelling Hours (8 hours rest) | 1,739,773,585 | Hours |
| Hotelling Rate (years 1960-2003) | 0.027340 | hours per mile |
| *Years 2004 and beyond* | | |
| Number of Trips (11 hours driving) | 197,701,544 | Trips |
| Hotelling Hours (10 hours rest) | 1,977,015,437 | Hours |
| Hotelling Rate (years 2004+) | 0.031068 | hours per mile |

The national rate of hotelling hours per mile of restricted access roadway VMT is stored in the HotellingCalendarYear table for each calendar year. As explained above, in order to prevent allocating large amounts of hotelling to congested urban areas, we use the VMT on restricted access roads as the surrogate for allocating total hotelling hours. When the hotelling rate is applied, it is multiplied by the rural and urban restricted access VMT by long-haul combination trucks to estimate the default hotelling hours for any location, month or day.

The County Data Manager includes the HotellingHours table which provides the opportunity for states and others to provide their own estimates of hotelling hours specific to their location and time. Whenever possible, states and local areas should obtain and use more accurate local estimates of hotelling hours when modeling local areas. The allocation of hotelling to specific hours of the day is described below in Section 13.5.

## 11.2. Hotelling Activity Distribution

In MOVES, hotelling hours are divided into operating modes which define the emissions associated with the type of hotelling activity. As explained above, long-haul trucks are often equipped with sleeping berths and other amenities to make the drive rest periods more comfortable. These amenities require power for operation, which can be obtained by running the main truck engine (extended idle) or by use of smaller on-board power generators (auxiliary power units, APU). Some truck stop locations include power hookups (truck stop electrification or shore power) to allow use of amenities without running either the truck engines or APUs. Some of rest time may occur without the use of amenities at all. Table 11-2 shows the hotelling operating modes available in MOVES.

*Table 11-2 Hotelling activity operating modes in MOVES*

| OpModeID | Description |
|---|---|
| 200 | Extended Idling of Main Engine |
| 201 | Hotelling Diesel Auxiliary Power Unit (APU) |
| 203 | Hotelling Battery or AC (plug in) |
| 204 | Hotelling All Engines and Accessories Off |

Previously, MOVES assumed drivers required power for the entire duration of hotelling, which was supplied by either idling or a combination of idling and APU use. In MOVES201X, we account for a fraction of their rest time spent without power using OpModeID 204.

In 2004, over 350 long-haul truck drivers completed a University of California Davis survey and the results showed that they idled 5.9 hours per day[55]. American Transportation Research Institute (ATRI) performed a survey in 2006 to understand fleet preferences[56]. The motor carriers that responded to ATRI's survey represent more than 55,000 trucks. The survey indicated that sleeper cab tractors idle 28 hours per week. Assuming a 5-day work-week, this equates to 5.6 hrs. idling per day. A study by Frey[57], et al. monitored engine ECU data and APU use, and found drivers had combined idling and APU use of 1,450 to 1,630 hours annually (i.e., 5.4-6.2 hours per day assuming a 5-day work week). Each of these studies suggest drivers do not require power for the entire duration of their 8 to 10 hours of mandated off-duty time. In FMCSA's 2001 update to their hours-of-service regulations, drivers in sleeper cab trucks are allowed to break their 10-hour rest period into 8 consecutive hours in the sleeper berth and 2 hours either in the sleeper berth or outside the truck.[58] For MOVES, we assume a constant 20 percent of the drivers' off-duty time does not require supplemental power.

The HotellingActivityDistribution, shown in Table 11-3, contains the MOVES default values for the distribution of hotelling activity to the operating modes. For model years before 2010, drivers are assumed to use extended idle for 80 percent of the hotelling time to power accessories. Starting with the 2010 model year, an increased number of trucks equipped with APUs and battery units are expected as a result of the Phase 1 Heavy Duty Greenhouse Gas Standards[59]. As a result, a fraction of the time that previously was in extended idle is now assigned to opModeIDs 201 and 203. The values shown in Table 11-3 represent a constant fraction of time with no supplemental power and the remaining fraction distributed among extended idle, APU use, and battery use based on EPA's assessment of technologies expected to be used by tractor manufacturers to comply with the Heavy-Duty Greenhouse Gas standards Phase1[83] and Phase 2[60].

*Table 11-3 Default hotelling activity distributions[a]*

| beginModelYearID | endModelYearID | opModeFraction for given opModeID | | | |
|---|---|---|---|---|---|
| | | **200** | **201** | **203** | **204** |
| | | Idle | APU | Electric | Off |
| 1960 | 2009 | 0.80 | 0.00 | 0.00 | 0.20 |
| 2010 | 2020 | 0.73 | 0.07 | 0.00 | 0.20 |
| 2021 | 2023 | 0.48 | 0.24 | 0.08 | 0.20 |
| 2024 | 2026 | 0.40 | 0.32 | 0.08 | 0.20 |
| 2027 | 2050 | 0.36 | 0.32 | 0.12 | 0.20 |

Note:
[a] Note that the fraction of time with no power in opModeID 204 is constant at 20 percent; the remaining 80 percent is distributed among extended idling, APU and battery use based values projected in the tractor program of the Heavy-duty Greenhouse Gas rulemaking.

# 12.Engine Start Activity

Immediately following the start of an internal combustion engine, the fuel is inefficiently burned due to the relatively cool temperature of the engine and the need to provide excess fuel promote combustion. During this time, the quantity and profile of the pollutants generated by the engine are significantly different than when the running engine is fully warm. Additionally, the after-treatment technology employed on modern vehicles often requires time to become fully functional as well. For these reasons, MOVES accounts for the effects of engine starts separately from the estimates for hot running emissions.

The temperature of the engine and after-treatment systems depend not only on ambient temperature, but the time since the last engine operation (soak time). MOVES accounts for the soak time using “soak time operating modes.” The distribution of the soak times for engine starts can have a significant effect on the emissions estimated for trips.

Although they could be overwritten with user data, in MOVES2014, the default number of engine starts and soak times and their temporal distributions were calculated from the same SampleVehicleTrip information as used for estimating evaporative emission activity (see Section 13.4) MOVES201X now uses the following set of tables in the default database to determine the default number of starts, soak times and their temporal distributions:

- StartsPerDay
- StartsMonthAdjust
- StartsSourceTypeFraction
- StartsHourFraction
- OpModeDistribution

The StartsPerDay table contains a factor (startsPerDay) which, when multiplied by the total number of all vehicles of all source types, calculates the number of starts in a day. The startsPerDay varies by county (zoneID) and by day type (weekday/weekend).

The StartsMonthAdjust table contains the monthAdjust factor which adjusts the starts per day to reflect monthly variation in the number engine starts.

The StartsSourceTypeFraction table allocates the total starts calculated using the starts per day to each of the MOVES source types.

The StartsHourFraction distributes the starts in a day to the hours of the day. The allocationFraction value varies by county (zoneID) and day type.

The OpModeDistribution table contains the distribution of engine start soak times for each source type, day type, hour of the day and pollutant.

The number of starts in any location will depend on the total number of vehicles and not the amount of driving (VMT). Since the data comes from different sources, the number of starts will conflict with the estimate for the number of trips found in the SampleVehicleTrip table used for estimating evaporative emission activity.  We plan to address this conflict in future versions of MOVES.

## 12.1. Light-Duty Start Activity

For MOVES201X, light-duty start activity are calculated from the same sample of vehicles from the Verizon Telematics data discussed in Section 10.1.1

### 12.1.1. Light-Duty Starts Per Day

MOVES2014 calculated the default start rate, defined as number of starts per day per vehicle, using trip information from a small set of older instrumented vehicles. The rate is distinguished by source type and day type and does not account for regional differences in vehicle activity.

Table 12-1 below compares the MOVES201X (derived from the Verizon Telematics data discussed in Section 10) and MOVES2014 starts per day per vehicle for passenger cars (sourceTypeID 21) and light-duty trucks (both sourceTypeIDs 31 and 32), and by weekend days (dayID 2) and weekdays (dayID 5). The values shown for light duty passenger trucks (sourceTypeID 31) will also be used for light-duty commercial trucks (sourceTypeID 32). Refer to Section 10.1.1 for the method used to calculate the national default values from the Verizon sample data, and Table 10-1 for the number of sample trips used. The starts per day per vehicle derived from the Verizon Telematics data were found to be lower than the MOVES2014 default values. As explained in Section 10.1.1, these national defaults were estimated by weighting the rates by the regional vehicle populations for the five states where data was collected.

*Table 12-1 Comparisons of Start Rate between MOVES2014 and MOVES201X based on the Verizon Telematics data*

| sourceTypeID | dayID | MOVES201X national average starts per vehicle per day | MOVES2014 starts per vehicle per day default |
|---|---|---|---|
| 21 | 2 | 3.36 | 5.5 |
| 21 | 5 | 3.96 | 5.5 |
| 31 | 2 | 3.49 | 5.5 |
| 31 | 5 | 4.09 | 5.5 |

### 12.1.2. Light-Duty Engine Start Temporal Distributions

National values for the distribution of starts per day by hour for passenger cars and light-duty trucks were calculated from the Verizon sample data described above in Section 10.1.1The resulting national defaults for start distribution in MOVES201X are illustrated in Figure 12-1. The start fraction values for hourIDs 1 through 24 sum to 1.0 for a given sourceTypeID and dayID combination. The proposed start distribution curve was found to be much smoother than the start distribution based on the MOVES2014 SampleVehicleTrip table data owing to large sample size of the Verizon data.

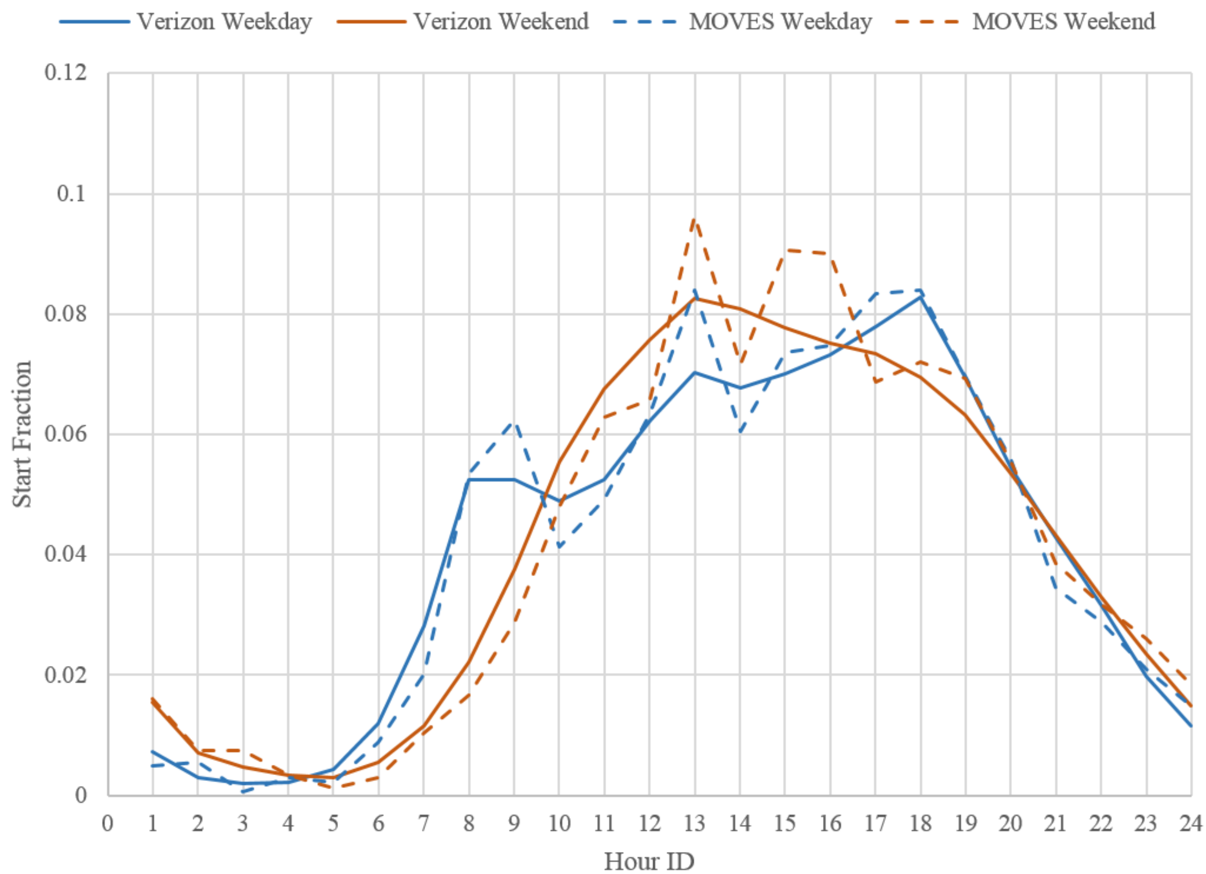


*Figure 12-1 Start distribution for source type 21: MOVES201X derived from Verizon data vs. MOVES2014*

### 12.1.3. Light-Duty Engine Soak Distributions

In MOVES, the soak times are binned into different operating modes, shown in Table 12-2. Moreover, engine soak times are represented in terms of hourly distribution of start fraction by soak operating modes, and are distinguished by source types and day types. MOVES2014 calculated the default engine soak time distribution using trip information from a set of instrumented vehicles.

Figure 12-2 shows theMOVES2014 defaults for engine soak time distribution for source type 21 and dayID=5. The MOVES201X engine soak time distributions for all source types are available in the OpModeDistribution table of the default database. Refer to Section 10.1 for the national default value calculation method from the Verizon sample data, and Table 10-1 for the number of sample trips used. Figure 12-3 illustrates the MOVES201X national default soak distribution for a weekday for passenger cars (sourceTypeID 21). The new soak distribution is similar to the data used in MOVES2014, but much smoother given the much larger dataset.

*Table 12-2 MOVES engine soak operating modes*

| opModeID | Description |
|---|---|
| 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 |

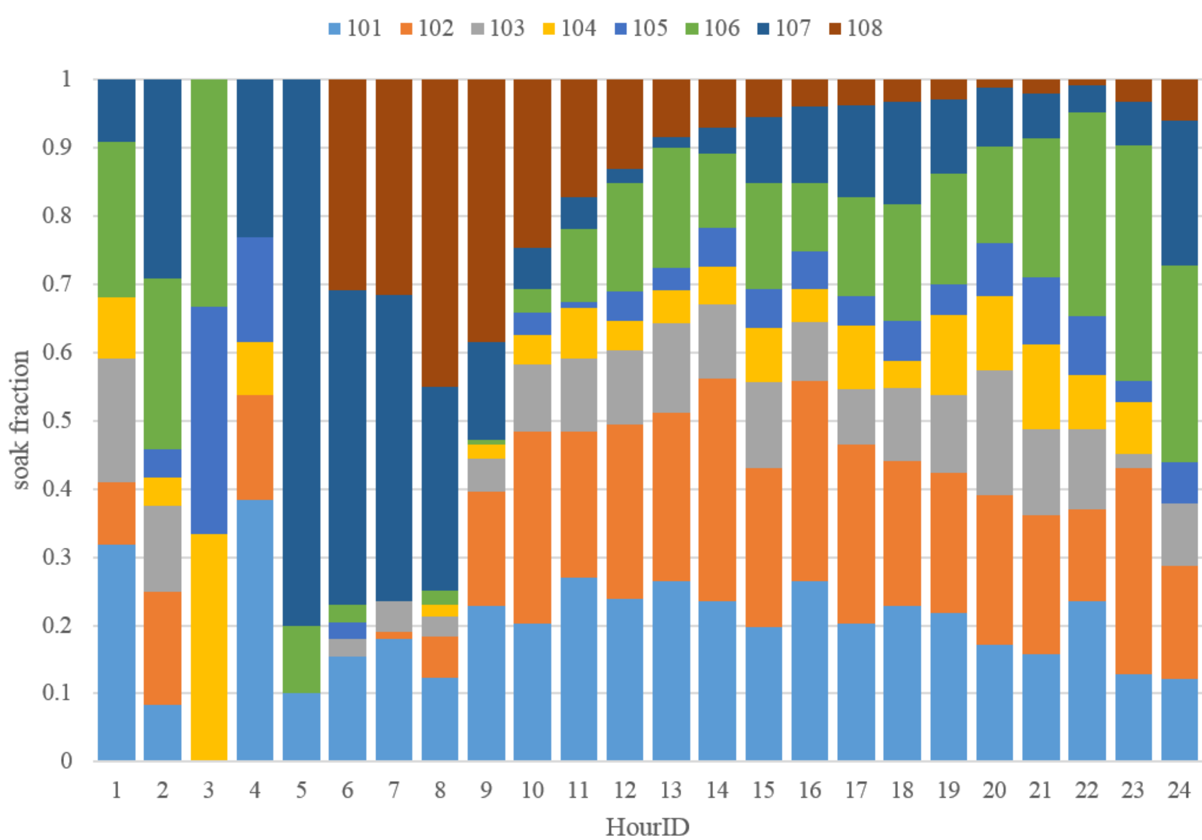


*Figure 12-2 MOVES2014 default engine soak time distribution for source type 21and weekday (dayID=5)*

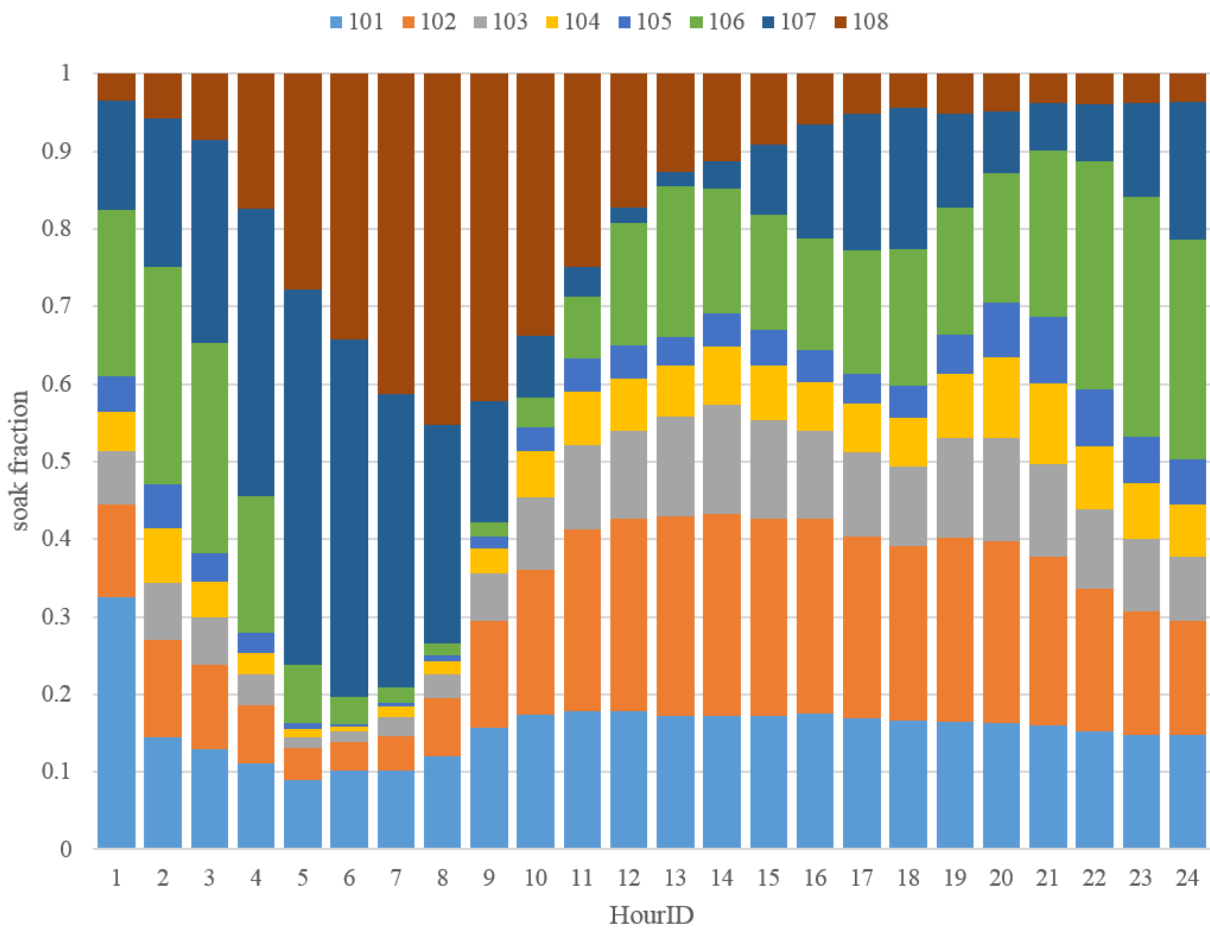


*Figure 12-3 MOVES201X national average engine soak distribution for source type 21 and weekday*

## 12.2. Heavy-Duty Start Activity

Starts from heavy-duty vehicles are also an important contributor to emission inventories, but there is less data on start activity and more subgroups of vehicles with potentially unique activity patterns. For example, delivery vehicles have different start and soak patterns than long-haul trucks. In MOVES2014, start activity for heavy-duty vehicles was derived from a small sample of instrumented heavy-duty trucks and extrapolated to different source types using assumptions about numbers of starts per day. For MOVES201X, there is more data available, but challenges remain in selecting and processing the appropriate data and mapping the available data to MOVES source types. There are two principal data sets available, each described below. This is followed by a description of comparisons between results from the two and the choices made for the MOVES201X defaults.

### 12.2.1. NREL Fleet DNA Database

Engine starts are calculated from the same sample of vehicles from the NREL Fleet DNA database introduced in Section 10. The data are filtered using the quality assurance criteria discussed earlier. Additional preprocessing steps were taken to account for gaps in the data and to address issues of identification of engine starts using the available activity data.

#### 12.2.1.1. Starts Per Day

Starts are identified in the data using the engine RPM data channel and locating all the instances when the engine RPM transitions from zero to greater than zero. This identifies all of the times when the vehicle started. For each unique day in the individual vehicle's dataset, the number of starts in each hour of the day are counted within each dayID (weekend day or weekday). The total starts per day per vehicle were averaged with other vehicles so that each vehicle contributes only one data point.

#### 12.2.1.2. Temporal Distribution of Starts

The starts per vehicle within each hour of the day for each day type were used (Equation 2.2.1) to calculate a start fraction for each hourID and dayID. The sum of the start fractions for each day type will add to one.

$$start\ fraction = \frac{\sum Starts\ in\ hourID}{\sum Starts\ in\ all\ hourIDs} \qquad \text{Equation 2.2.1}$$

The results for each vehicle were then averaged resulting in an even weighting for all vehicles in the sourceTypeID category regardless of how many days of data are available for that vehicle.

#### 12.2.1.3. Start Soak Distributions

In the NREL sample the first start identified for each vehicle must be removed since a soak time cannot be determined due to lack of previous data. The soak time was calculated using Equation 2.3.1 and binned according to the soak opModeIDs defined in Table 12-2 resulting in a table containing opModeIDs and time stamps.

$$soak\ time = \ stop\ time - start\ time \qquad \text{Equation 2.3.1}$$

Each entry was then binned according to dayID, hourID and sourceTypeID, and the number of occurrences for each opModeID were counted and normalized to 1.0 within the hourID bin using Equation 2.3.2.

$$opMode\ soak\ fraction = \frac{\sum Starts\ in\ opMode\ ID}{\sum Start\ in\ all\ opModeIDs} \qquad \text{Equation 2.3.2}$$

The sum of the eight opModeID soak fractions will equal 1.0 for each combination of dayID, hourID and sourceTypeID. If no starts occurred within a given dayID, hourID and sourceTypeID, the soak time distribution was taken from an adjacent hour containing a valid distribution.

### 12.2.2. CE-CERT Study Sample

An analysis parallel to that done with the NREL data was done for starts and soaks from the CE-CERT data described in Section 10.2.2It is important to note that the starts and soak activity were analyzed on the starts for a given source type in the CE-CERT database as described in Section 10 and Table 10-6. As explained above, for this analysis, all vehicles were treated as if they did not utilize start-stop technology, so that only "true starts" with engine starts at the time of key on were used.

### 12.2.3. MOVES201X Start Rates, Temporal Distributions and Soak Fractions

Preliminary evaluation of the CE-CERT and NREL start data suggests that more information and analysis is needed to develop default inputs for MOVES201X.

#### 12.2.3.1. Derivation of MOVES201X Heavy-Duty Start Activity

Figure 12-4 illustrates the comparison between the start rate results for the different heavy-duty source types by dayIDs from the two studies. As expected, the CE-CERT results for trips with "all starts" were found to be higher than for the "true start" trips used in the analysis due to the exclusion of starts due to start-stop technology in some vehicles as discussed in the Section 10.2.2

As evident in Figure 12-4, for a weekday for single-unit short-haul trucks (sourceTypeID 52), the start rate from the NREL study was found to be significantly higher than for other source types. This was due to data from a subsample of Texas and Minnesota vehicles which were primarily delivery trucks (see Figure 12-5). Since MOVES sourceTypeID 52 is not limited to just delivery trucks, we do not believe the NREL sample rates are representative for this source type. Moreover, there is variability in the start rate results across states, as shown in Figure 12-5. To investigate further we plan to disaggregate the results by state and by vocation type which will allow us to weight the results by state and vocation for MOVES201X.

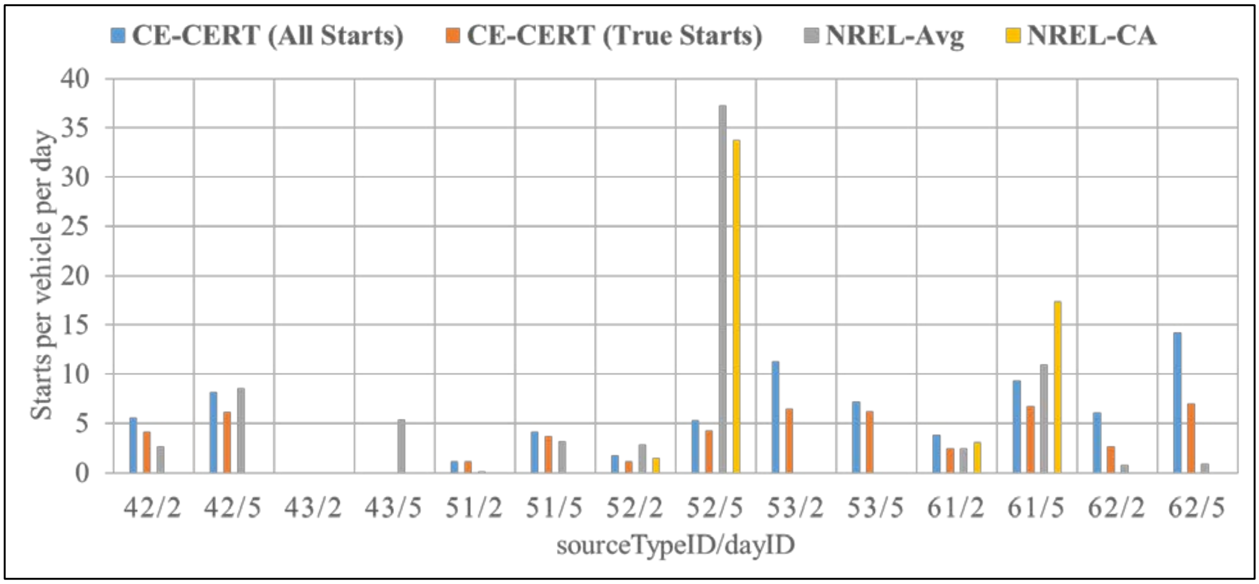


*Figure 12-4 Comparison of start rates by sourceTypeID and dayID from the NREL and CE-CERT studies*

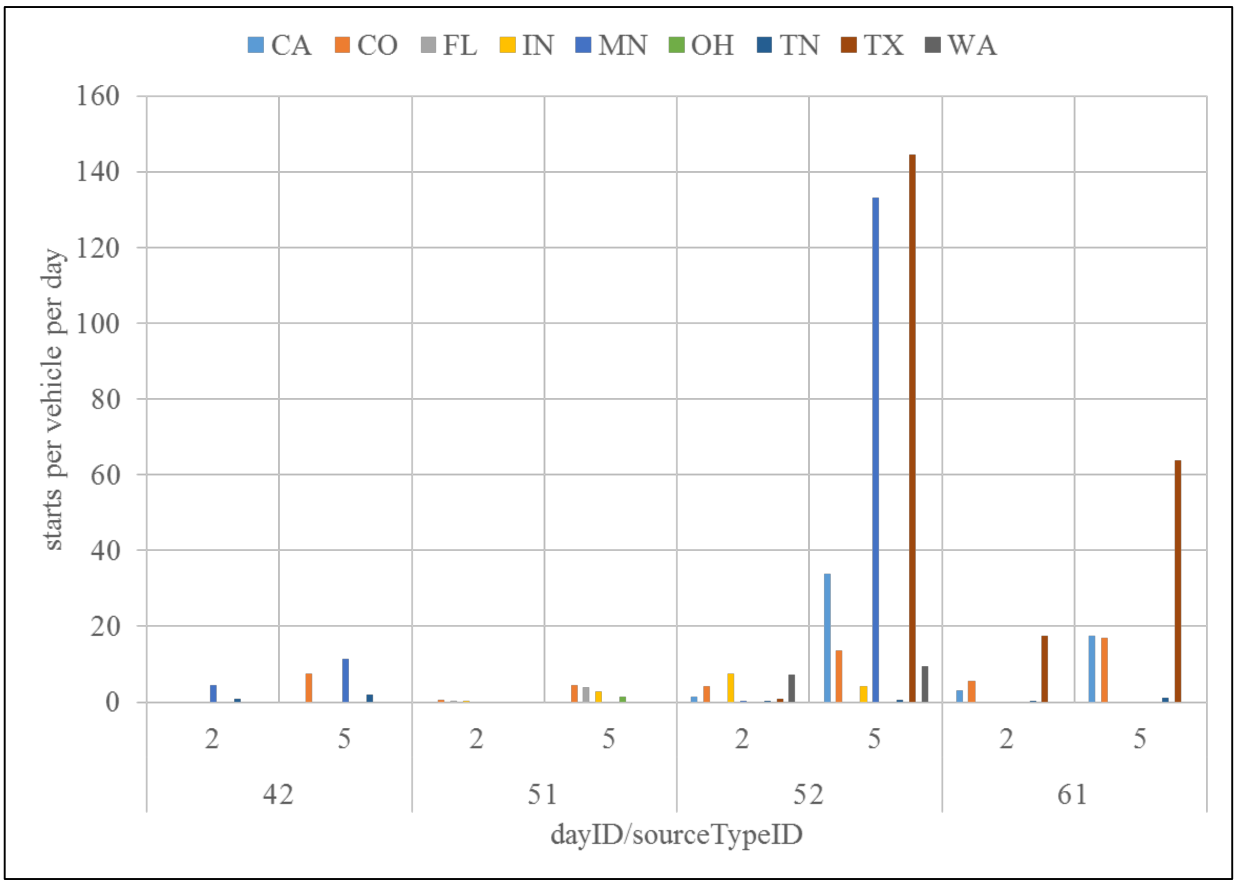


*Figure 12-5 Start rate results from the NREL study by dayID and sourceTypeID for different states*

Figure 12-6 shows the preliminary results for temporal distribution of starts for long-haul combination trucks (sourceTypeID 62) by day type (dayID) from the two studies. MOVES2014 derived the engine start distributions for long-haul trucks from VMT estimates. These studies provide the first look at the hourly temporal distribution of trip starts for these long-haul trucks. We have not yet resolved why the distributions appear so different, although the long-haul trucks in the CE-CERT study sampled in California were not involved in interstate travel.

Figure 12-7 illustrates the engine soak distributions by opModeIDs (as described in Table 12-2) for sourceTypeID 62 from the two data sources. The results were derived for both the “all starts” and “true starts” described in Section 10.2.2. Both the “all start” and the“true start” CE-CERT data suggests that most starts are associated with shorter soaks (opModeIDs 101 and 102) in a given day for both two day types. In contrast, NREL results showed that most starts were associated with higher soak periods (opModeIDs 107 and 108) across any hour of the day for sourceTypeID 62, irrespective of the day type

Given the discussion above and the variability in the results (as shown in the preliminary analysis from the two data sources), EPA will be developing methods to combine results from the two data sources and weigh the results appropriately, perhaps using vehicle population by state by source type or by vocation, in order derive the national defaults for the MOVES201X model for the heavy-duty source types. All of the final results for heavy-duty trucks await the final delivery of the summary data from the NREL study.

The resulting distribution of the daily starts for both light-duty and heavy-duty trucks will be recorded in the StartsHourFraction of the MOVES default database. The resulting distribution of soak times, derived from the distribution of engine starts, will be in the OpModeDistribution table. The number of starts per day per vehicles will be recorded in the StartsPerDay table.

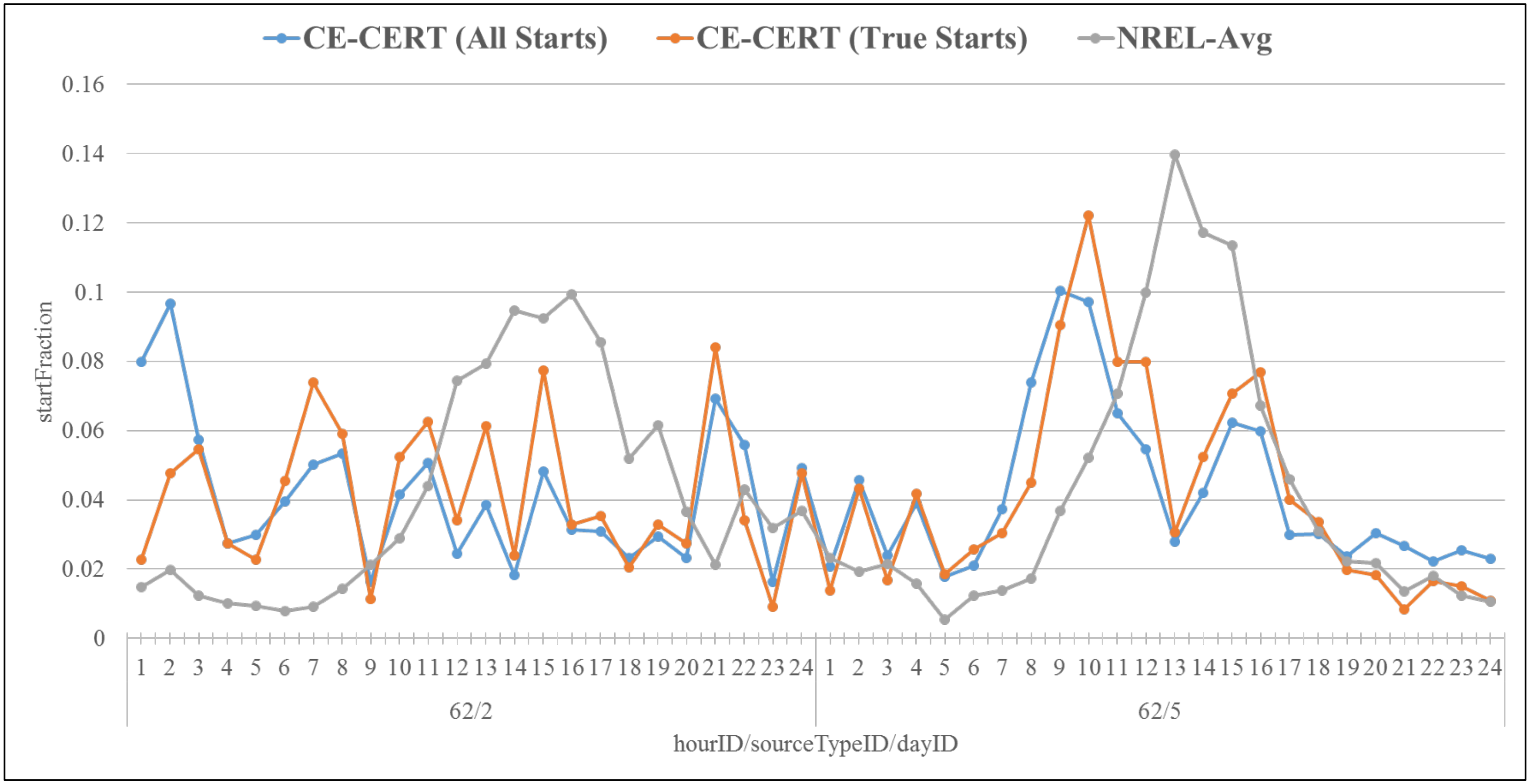


*Figure 12-6 Comparison of start distribution for sourceTypeID 62 by dayID derived from the NREL and CE-CERT studies*

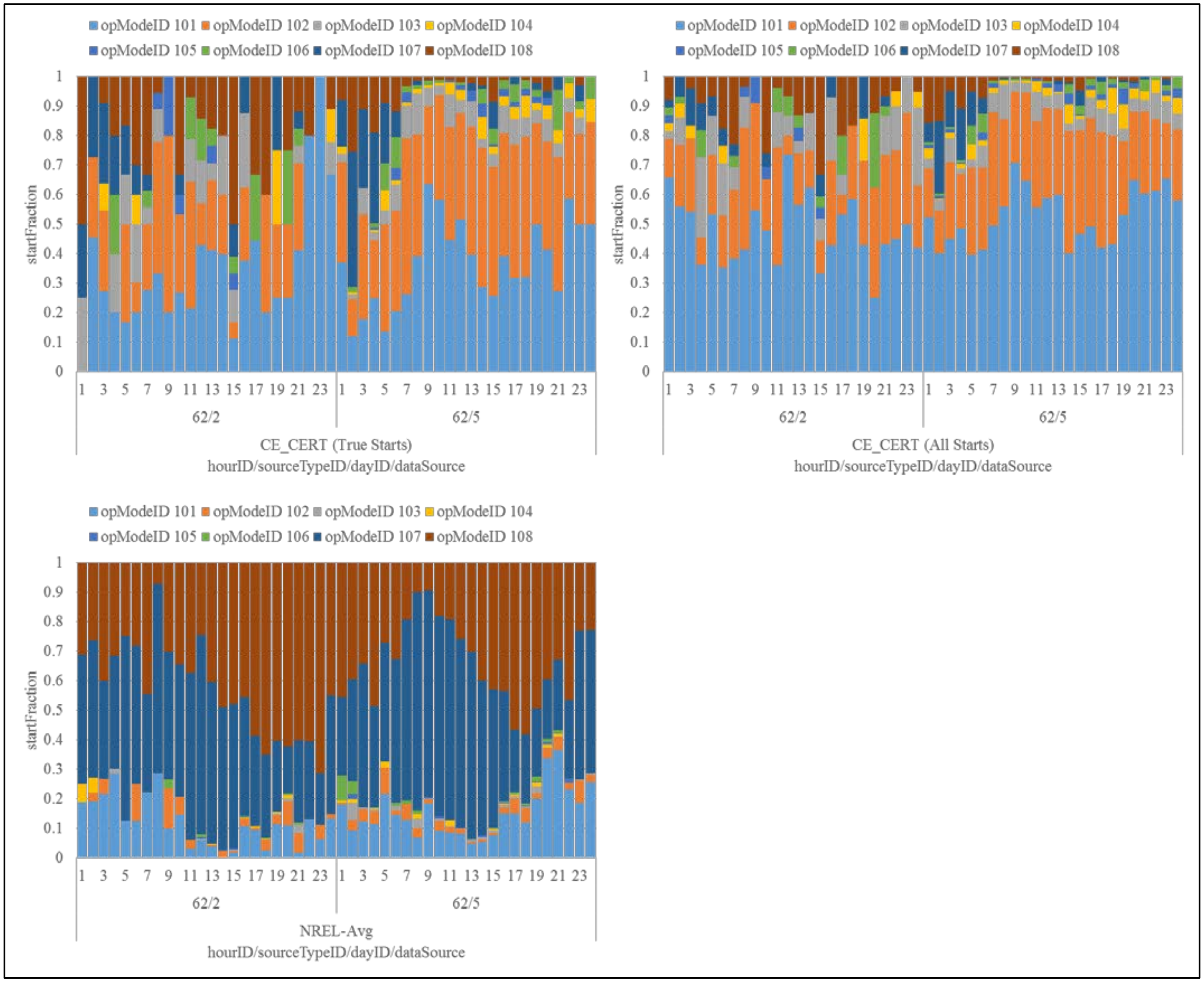


*Figure 12-7 Comparison of soak time distribution for sourceTypeID 62 by dayID derived from NREL and CE-CERT studies*

# 13. Temporal Distributions

MOVES is designed to estimate emissions for every hour of every day type in every month of the year. This section describes how VMT is allocated to months of the year, the two day types and to hours of the day. This section also addresses how sample vehicle trip data is used to determine and allocate evaporative soak periods to hours of the day. Finally, this section discusses the derivation of the allocation of hotelling activity for long-haul combination trucks. See also the discussion of temporal allocations for off-network idle in Section 10, and for engine starts in Section 12.

In MOVES, VMT are provided in terms of annual miles. These miles are allocated to months, days, and hours using allocation factors, either using default values or values provided by users. Default values for most temporal VMT allocations are derived from a 1996 report from the Office of Highway Information Management (OHIM).[61] The report describes analysis of a sample of 5,000 continuous traffic counters distributed throughout the United States. EPA obtained the data from the report and used it to generate the VMT temporal distribution inputs in the form needed for MOVES. This information has not been updated for MOVES201X.

The OHIM report does not specify VMT by vehicle type, so MOVES uses the same values for all source types, except motorcycles, as described below. In MOVES, daily truck hotelling hours are calculated as proportional to source hours operating (SHO) calculated by MOVES from the VMT and speed distributions for long-haul combination trucks. However, the hours of hotelling activity in each hour of the day are not proportional to VMT, as described in Section 13.5.

The temporal distributions for engine start are described in Section 12.1.2. These values are stored in the StartsMonthAdjust and StartsHourFraction Tables. However, for MOVES201X, we have not yet updated the data used to estimate vehicle parking time and associated evaporative emissions. As in MOVES2014, the engine soak (parked) distributions for evaporative emissions are calculated from vehicle activity data stored in the SampleVehicleDay and SampleVehicleTrip tables of the MOVES database. The inconsistency between the updated activity defaults now being used to calculate engine starts and soaks, and the older defaults that MOVES201X will continue using for evaporative emissions is not ideal. We plan to resolve this inconsistency in future versions of MOVES when the code used for the calculation of evaporative emissions is updated.

The allocation of vehicle activity will vary from location to location and EPA guidance encourages states and local areas to determine their own local vehicle activity parameters for use with MOVES.

EPA has plans for updating the default MOVES monthly allocation of VMT using more recent data sources as this data becomes available and resources allow. For example, the CRC has recently completed an analysis of vehicle telematics data[35] which includes detailed distributions of vehicle activity. EPA has also purchased vehicle telematics data[68] that can be used for this purpose as well.

### 13.1. VMT Distribution by Month of the Year

In MOVES, when VMT is entered as an annual value it is allocated to months of the year using the factors in the MonthVMTFraction table. For MOVES, we modified the data from the OHIM report (Figure 2.2.1 "Travel by Month, 1970-1995") to fit MOVES specifications. The table shows VMT/day taken from the OHIM report, normalized to one for January. For MOVES, we need the fraction of total annual VMT in each month. The report values of VMT per day were used to calculate the VMT in a month using the number of days in each month. The calculations in Table 13-1 assume a non-leap year (365 days). These monthly VMT allocations are used for all source types, except motorcycles, as described below.

*Table 13-1 MonthVMTFraction*

| Month | Normalized VMT/day | MOVES Distribution |
|---|---|---|
| January | 1.0000 | 0.0731 |
| February | 1.0560 | 0.0697 |
| March | 1.1183 | 0.0817 |
| April | 1.1636 | 0.0823 |
| May | 1.1973 | 0.0875 |
| June | 1.2480 | 0.0883 |
| July | 1.2632 | 0.0923 |
| August | 1.2784 | 0.0934 |
| September | 1.1973 | 0.0847 |
| October | 1.1838 | 0.0865 |
| November | 1.1343 | 0.0802 |
| December | 1.0975 | 0.0802 |
| **Sum** | | **1.0000** |

FHWA does not report monthly VMT information by vehicle classification. However, it is clear that in many regions of the United States, motorcycles are driven much less frequently in the winter months. For MOVES, an allocation for motorcycles was derived using monthly national counts of fatal motorcycle crashes from the National Highway Traffic Safety Administration Fatality Analysis System for 2010.[62] This allocation increases motorcycle activity (and emissions) in the summer months and decreases them in the winter compared to the other source types. These default values in Table 13-2 for motorcycles are only a national average and do not reflect the strong regional differences that would be expected due to climate.

*Table 13-2 MonthVMTFraction for motorcycles*

| Month | Month ID | Distribution |
|---|---|---|
| January | 1 | 0.0262 |
| February | 2 | 0.0237 |
| March | 3 | 0.0583 |
| April | 4 | 0.1007 |
| May | 5 | 0.1194 |
| June | 6 | 0.1269 |
| July | 7 | 0.1333 |
| August | 8 | 0.1349 |
| September | 9 | 0.1132 |
| October | 10 | 0.0950 |
| November | 11 | 0.0442 |
| December | 12 | 0.0242 |
| **Sum** | | **1.0000** |

The monthly allocation of VMT will vary from location to location and EPA guidance encourages states and local areas to determine their own monthly VMT allocation factors for use with MOVES.

EPA plans on updating the default MOVES monthly allocation of VMT using more recent data sources, including allocations derived from vehicle telematics, as this data becomes available and resources allow.

## 13.2. VMT Distribution by Type of Day

The distributions in the DayVMTFraction table divide the weekly VMT estimates into the two MOVES day types. The OHIM report provides VMT percentage values for each day and hour of a typical week for urban and rural roadway types for various regions of the United States. Since the day-of-the-week data obtained from the OHIM report is not disaggregated by month or source type, the same values were used for every month and for every source type. MOVES uses the 1995 data displayed in Figure 2.3.2 of the OHIM report.[61]

The DayVMTFraction needed for MOVES has only two categories; week days (Monday, Tuesday, Wednesday, Thursday and Friday) and weekend (Saturday and Sunday) days. The OHIM reported percentages for each day of the week were summed in their respective categories and converted to fractions, as shown in Table 13-3. The OHIM report explains that data for "3am" refers to data collected from 3am to 4am. Thus, the data labeled "midnight" was summed with the upcoming day.

*Table 13-3 DayVMTFractions*

| Fraction | Rural | Urban |
|---|---|---|
| Weekday | 0.72118 | 0762365 |
| Weekend | 0.27882 | 0.237635 |

| | | |
|---|---|---|
| **Sum** | **1.00000** | **1.000000** |

We assigned the “rural” fractions to the rural road types (roadTypeIDs 2 and 3) and the “urban” fractions to the urban road types (roadTypeIDs 4 and 5). The fraction of weekly VMT reported for a single weekday in MOVES will be one-fifth of the weekday fraction and the fraction of weekly VMT for a single weekend day will be one-half the weekend fraction.

The day type allocation of VMT will vary from location to location and EPA guidance encourages states and local areas to determine their own VMT allocation factors for use with MOVES.

EPA plans on updating the default MOVES day type allocation of VMT using more recent data sources, including allocations derived from vehicle telematics, as this data becomes available and resources allow.

### 13.3. VMT Distribution by Hour of the Day

HourVMTFraction uses the same data as for DayVMTFraction. We converted the OHIM report’s VMT data by hour of the day in each day type to percent of day by dividing by the total VMT for each day type, as described for the DayVMTFraction. There are separate sets of HourVMTFractions for "urban" and "rural" road types, but unrestricted and unrestricted roads use the same HourVMTFraction distributions. All source types use the same HourVMTFraction distributions, and Table 13-4 and Figure 13-1 summarize these default values.

*Table 13-4 MOVES distribution of VMT by hour of the day*

| hourID | Description | Urban | | Rural | |
|---|---|---|---|---|---|
| | | Weekday | Weekend | Weekday | Weekend |
| 1 | Hour beginning at 12:00 midnight | 0.00986 | 0.02147 | 0.01077 | 0.01642 |
| 2 | Hour beginning at 1:00 AM | 0.00627 | 0.01444 | 0.00764 | 0.01119 |
| 3 | Hour beginning at 2:00 AM | 0.00506 | 0.01097 | 0.00655 | 0.00854 |
| 4 | Hour beginning at 3:00 AM | 0.00467 | 0.00749 | 0.00663 | 0.00679 |
| 5 | Hour beginning at 4:00 AM | 0.00699 | 0.00684 | 0.00954 | 0.00722 |
| 6 | Hour beginning at 5:00 AM | 0.01849 | 0.01036 | 0.02006 | 0.01076 |
| 7 | Hour beginning at 6:00 AM | 0.04596 | 0.01843 | 0.04103 | 0.01768 |
| 8 | Hour beginning at 7:00 AM | 0.06964 | 0.02681 | 0.05797 | 0.02688 |
| 9 | Hour beginning at 8:00 AM | 0.06083 | 0.03639 | 0.05347 | 0.03866 |
| 10 | Hour beginning at 9:00 AM | 0.05029 | 0.04754 | 0.05255 | 0.05224 |
| 11 | Hour beginning at 10:00 AM | 0.04994 | 0.05747 | 0.05506 | 0.06317 |
| 12 | Hour beginning at 11:00 AM | 0.05437 | 0.06508 | 0.05767 | 0.06994 |
| 13 | Hour beginning at 12:00 Noon | 0.05765 | 0.07132 | 0.05914 | 0.07293 |
| 14 | Hour beginning at 1:00 PM | 0.05803 | 0.07149 | 0.06080 | 0.07312 |
| 15 | Hour beginning at 2:00 PM | 0.06226 | 0.07172 | 0.06530 | 0.07362 |
| 16 | Hour beginning at 3:00 PM | 0.07100 | 0.07201 | 0.07261 | 0.07446 |
| 17 | Hour beginning at 4:00 PM | 0.07697 | 0.07115 | 0.07738 | 0.07422 |
| 18 | Hour beginning at 5:00 PM | 0.07743 | 0.06789 | 0.07548 | 0.07001 |
| 19 | Hour beginning at 6:00 PM | 0.05978 | 0.06177 | 0.05871 | 0.06140 |
| 20 | Hour beginning at 7:00 PM | 0.04439 | 0.05169 | 0.04399 | 0.05050 |
| 21 | Hour beginning at 8:00 PM | 0.03545 | 0.04287 | 0.03573 | 0.04121 |
| 22 | Hour beginning at 9:00 PM | 0.03182 | 0.03803 | 0.03074 | 0.03364 |
| 23 | Hour beginning at 10:00 PM | 0.02494 | 0.03221 | 0.02385 | 0.02622 |
| 24 | Hour beginning at 11:00 PM | 0.01791 | 0.02457 | 0.01732 | 0.01917 |
| | **Sum of All Fractions** | 1.00000 | 1.00000 | 1.00000 | 1.00000 |

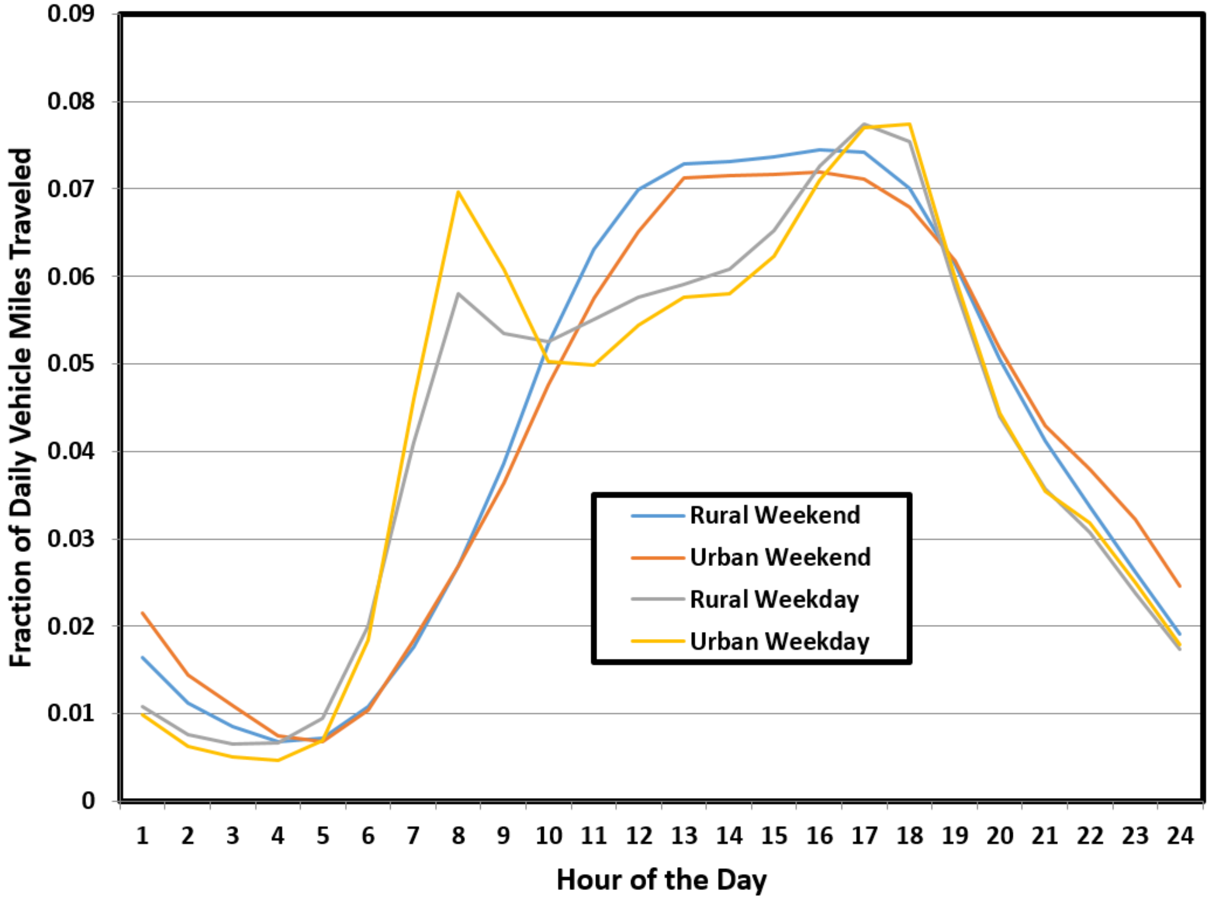


*Figure 13-1 Hourly VMT fractions by day type and road type*

The allocation of VMT to the hours of the day will vary from location to location and EPA guidance encourages states and local areas to determine their own VMT allocation factors for use with MOVES. Recent analysis by CRC has made county specific hourly VMT distributions available for calendar year 2014[35].

EPA plans on updating the default MOVES hourly allocation of VMT using more recent data sources, including allocations derived from vehicle telematics, as this data becomes available and resources allow.

### 13.4. Parking Activity

To properly estimate evaporative fuel vapor losses, it is important to estimate the number of starts by time of day, and the duration of time between vehicle trips. The time between trips with the engine off is referred to as "soak time". To determine typical patterns of trip starts and ends, MOVES uses information from instrumented vehicles. This data is stored in two tables in the MOVES default database, as discussed below. Unlike the information used to determine exhaust start emissions (see Section 12.1.2), these tables are unchanged from MOVES2014. Note that the activity described below is applied only to gasoline vehicles since diesel evaporative emissions (other than refueling spillage) are expected to be negligible and are not calculated by MOVES.

The first table, SampleVehicleDay, lists a sample population of vehicles, each with an identifier (vehID), an indication of vehicle type (sourceTypeID), and an indication (dayID) of whether the vehicle is part of the weekend or weekday vehicle population. Some vehicles were added to this table to increase the number of vehicles in each day which do not take any trips to better match a more representative study of vehicle activity in Georgia.[63] This change is described in greater detail in the report describing evaporative emissions in MOVES201X.[64]

The second table, SampleVehicleTrip, lists the trips in a day made by each of the vehicles in the SampleVehicleDay table. It records the vehID, dayID, a trip number (tripID), the hour of the trip (hourID), the trip number of the prior trip (priorTripID), and the times at which the engine was turned on and off for the trip. The keyOnTime and keyOffTime are recorded in minutes since midnight of the day of the trip. 439 trips (about 1.1 percent) were added to this table to assure that at least one trip is done by a vehicle from each source type in each hour of the day to assure that emission rates will be calculated in each hour. Table 13-5 shows the resulting number of vehicles in the SampleVehicleDay table with trip information.

*Table 13-5 SampleVehicleDay table*

| Source Type | | Number of Records | |
|---|---|---|---|
| **sourceTypeID** | **Description** | **Weekday (dayID 5)** | **Weekend (dayID 2)** |
| 11 | Motorcycle | 2214 | 983 |
| 21 | Passenger Car | 821 | 347 |
| 31 | Passenger Truck | 834 | 371 |
| 32 | Light Commercial Truck | 773 | 345 |
| 41 | Other Bus | 190 | 73 |
| 42 | Transit Bus | 110 | 14 |
| 43 | School Bus | 136 | 59 |
| 51 | Refuse Truck | 205 | 65 |
| 52 | Single-Unit Short-Haul Truck | 112 | 58 |
| 53 | Single-Unit Long-Haul Truck | 123 | 50 |
| 54 | Motor Home | 5431 | 2170 |
| 61 | Combination Short-Haul Truck | 130 | 52 |
| 62 | Combination Long-Haul Truck | 122 | 49 |

To account for overnight soaks, many first trips reference a prior trip with a null value for keyOnTime and a negative value for keyOffTime. The SampleVehicleDay table also includes some vehicles that have no trips in the SampleVehicleTrip table to account for vehicles that sit for one or more days without any driving.

The data and processing algorithms used to populate these tables are detailed in two contractor reports.[65,66] The data comes from a variety of instrumented vehicle studies, summarized in Table 13-6. This data was cleaned, adjusted, sampled and weighted to develop a distribution intended to represent average urban vehicle activity.

*Table 13-6 Source data for sample vehicle trip information*

| Study | Study Area | Study Years | Vehicle Types | Vehicle Count |
|---|---|---|---|---|
| 3-City FTP Study | 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 | Diesel dump trucks | 4 |

For vehicle classes that were not represented in the available data, the contractor synthesized trips using trip-per-operating hour information from the EPA MOBILE6[67] model and soak time and time-of-day information from source types that did have data. The application of synthetic trips is summarized in Table 13-7.

*Table 13-7 Synthesis of sample vehicles for source types lacking data*

| Source Type | Based on Direct Data? | Synthesized From |
|---|---|---|
| Motorcycles | No | Passenger Cars |
| Passenger Cars | Yes | n/a |
| Passenger Trucks | Yes | n/a |
| Light Commercial Trucks | No | Passenger Trucks |
| Other 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 | n/a |
| Single-Unit Long-Haul Trucks | No | Combination Long-Haul Trucks |
| Motor Homes | No | Passenger Cars |
| Combination Short-Haul trucks | Yes | n/a |
| Combination Long-Haul trucks | Yes | n/a |

The resulting trip-per-day estimates are summarized in Table 13-8. The same estimate for trips per day is used for all ages of vehicles in any calendar year.

*Table 13-8 Starts per day by source type*

| Source Type | Weekday | Weekend |
|---|---|---|
| Motorcycles | 0.78 | 0.79 |
| Passenger Cars | 5.89 | 5.30 |
| Passenger Trucks | 5.80 | 5.06 |
| Light Commercial Trucks | 6.05 | 5.47 |
| Other Buses | 2.77 | 0.88 |
| Transit Buses | 4.58 | 3.46 |
| School Buses | 5.75 | 1.26 |
| Refuse Trucks | 3.75 | 0.92 |
| Single-Unit Short-Haul Trucks | 6.99 | 1.28 |
| Single-Unit Long-Haul Trucks | 4.29 | 1.29 |
| Motor Homes | 0.57 | 0.57 |
| Combination Short-Haul trucks | 5.93 | 1.16 |
| Combination Long-Haul trucks | 4.29 | 1.29 |

Knowing the sequence of starts for each vehicle in the sampleVehicleTrip table allows MOVES to calculate the length and time of day when each soak occurs. Using this information, the distribution of soak times in each hour of the day can be calculated for use in the determination of evaporative emissions from parked vehicles.

The evaporative vapor losses from gasoline vehicle fuel tanks are affected by many factors, including the number of hours a vehicle is parked without an engine start, referred to as engine soak time. Most modern gasoline vehicles are equipped with emission control systems designed to capture most evaporative vapor losses and store them. These stored vapors are then burned in the engine once the vehicle is operated. However, the vehicle storage capacity for evaporative vapors is limited and multiple days of parking (diurnals) will overload the storage capacity of these systems, resulting in larger losses of evaporative vapors in subsequent days.

The detailed description of the calculation for the number of vehicles that have been soaking for more than a day and the amount of time that the vehicles have been soaking can be found in the MOVES technical report on evaporative emissions.[66]

Note, the MOVES County Data Manager allows users to specify the number of engine starts in each month, day type and hour of the day, as well as by source type and vehicle age. These user inputs override the default start activity values provided by MOVES described in Section 12. However, these user inputs will not update the soak times used in the calculations for evaporative emissions, which rely solely on the sample trip data.

## 13.5. Hourly Hotelling Activity

While total hotelling activity has been updated for MOVES201X (see Section 11) the distribution of this activity to hour of the day has not been updated and, thus, the two analyses use different assumptions about required driver rest hours. We believe this will have little impact on the hourly distribution of emissions, but for future versions of MOVES we hope to update both the total activity and the hourly distributions using information from a representative sample of instrumented long-haul combination trucks.

The hotelling hours in each day should not directly correlate with the miles traveled in each hour, since hotelling occurs only when drivers are not driving. Instead, the fraction of hours spent hotelling by time of day can be derived from other sources. In particular, the report, *Roadway-Specific Driving Schedules for Heavy-Duty Vehicles*[44] combines data from several instrumented truck studies and contains detailed information about truck driver behavior. While none of the trucks in that study were involved in long-haul interstate activity, for lack of better data, we have assumed that long-haul truck trips have the same hourly truck trip distribution as the heavy heavy-duty trucks that were studied.

For each hour of the day, we estimated the number of trips that would end in that hour, based on the number of trips that started 10 hours earlier. The hours of hotelling in that hour is the number that begin in that hour, plus the number that began in the previous hour, plus the number that began in the hour before that, and so on, up to the required eight hours of rest time. Table 13-9 shows the number of trip starts and inferred trip ends over the hours of the day in the sample of trucks assuming all trips are 10 hours long. For example, the number of trip ends in hour 1 is the same as the number of trip starts 10 hours earlier in hour 15 of the previous day.

*Table 13-9 Hourly distribution of truck trips used to calculate hotelling hours*

| hourID | Hour of the Day | Trip Starts | Trip Ends |
|---|---|---|---|
| 1 | Hour beginning at 12:00 midnight | 78 | 171 |
| 2 | Hour beginning at 1:00 AM | 76 | 167 |
| 3 | Hour beginning at 2:00 AM | 65 | 144 |
| 4 | Hour beginning at 3:00 AM | 94 | 98 |
| 5 | Hour beginning at 4:00 AM | 107 | 71 |
| 6 | Hour beginning at 5:00 AM | 131 | 73 |
| 7 | Hour beginning at 6:00 AM | 194 | 71 |
| 8 | Hour beginning at 7:00 AM | 230 | 52 |
| 9 | Hour beginning at 8:00 AM | 279 | 85 |
| 10 | Hour beginning at 9:00 AM | 267 | 48 |
| 11 | Hour beginning at 10:00 AM | 275 | 78 |
| 12 | Hour beginning at 11:00 AM | 240 | 76 |
| 13 | Hour beginning at 12:00 Noon | 201 | 65 |
| 14 | Hour beginning at 1:00 PM | 211 | 94 |
| 15 | Hour beginning at 2:00 PM | 171 | 107 |
| 16 | Hour beginning at 3:00 PM | 167 | 131 |
| 17 | Hour beginning at 4:00 PM | 144 | 194 |
| 18 | Hour beginning at 5:00 PM | 98 | 230 |
| 19 | Hour beginning at 6:00 PM | 71 | 279 |
| 20 | Hour beginning at 7:00 PM | 73 | 267 |
| 21 | Hour beginning at 8:00 PM | 71 | 275 |
| 22 | Hour beginning at 9:00 PM | 52 | 240 |
| 23 | Hour beginning at 10:00 PM | 85 | 201 |
| 24 | Hour beginning at 11:00 PM | 48 | 211 |

An estimate of the distribution of truck hotelling duration times is derived from a 2004 CRC paper[68] based on a survey of 365 truck drivers at six different locations. Table 13-10 lists the fraction of trucks in each duration bin. Some trucks are hotelling for more than the required eight hours, but some are hotelling for less than eight hours.

*Table 13-10 Distribution of truck hotelling activity duration*

| Hotelling Duration (hours) | Fraction of Trucks |
|---|---|
| 2 | 0.227 |
| 4 | 0.135 |
| 6 | 0.199 |
| 8 | 0.191 |
| 10 | 0.156 |
| 12 | 0.057 |
| 14 | 0.014 |
| 16 | 0.021 |
| **Total** | **1.000** |

We assume that all hotelling activity begins at the trip ends shown in Table 13-9. However, not all trip ends have the same number of hotelling hours. The distribution of hotelling durations from Table 13-10 is applied to the hotelling that occurs at each of these trip ends.
Table 13-11 illustrates the hotel activity calculations based on the number of trip starts and trip ends. The hours of hotelling in any hour of the day is the number of trip ends in the current hour plus the trip ends from the previous hours that are still hotelling. However, since not all trips begin and end precisely on the hour, we have discounted the oldest hour included in the calculation by 60 percent to account for those unsynchronized trips.

For example, there are 171 trip ends in hourID 1. If all trip ends idle for two hours, the number of hours is 171 (for hourID 1) and 40 percent of 211 (for hourID 24), and thus 171 + (0.4*211) = 255.4 hours of hotelling. Similarly, the number of hours can be calculated for other hotelling time periods. For four hour hotelling periods, the hotelling hours would be 171 + 211 + 201 + (0.4*240) = 679. Only the oldest hour of the day is discounted.

This calculation accounts for the time in the current hour of the day which is a result of hotelling from trips that ended in the current hour and trips that ended in previous hours. This approach assumes that all hotelling begins at the trip end. For example, in the hour of the day 1 for the four hours hotelling bin, the trip ends in hourID 22 contribute to the hours of hotelling in hourID 1, since these trip ends are still hotelling (four hours) after the trip end. The trip ends in hourID 21 do not contribute to the four hours hotelling bin, since it has been more than four hours since the trip ends occurred.

The initial calculated hours assume that all trucks idle the same amount of time, indicated by the hotelling hours bin. The distribution (weight) from Table 13-10 is applied to the hour estimate in each hotelling hours bin to calculate the weighted total idle hours for each hour of the day.

*Table 13-11 Calculation of hourly distributions of hotelling activity*

| hourID | Trip Starts | Trip Ends* | 2 hours | 4 hours | 6 hours | 8 hours | 10 hours | 12 hours | 14 hours | 16 hours | Weighted Total Idle Hours | Distribution |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 78 | 171 | 255.4 | 679 | 1204.8 | 1736 | 2120.4 | 2343.6 | 2495.4 | 2638.2 | 1276 | 0.0628 |
| 2 | 76 | 167 | 235.4 | 629.4 | 1100 | 1643.6 | 2118.6 | 2408.8 | 2593 | 2739.2 | 1234 | 0.0611 |
| 3 | 65 | 144 | 210.8 | 566.4 | 990 | 1515.8 | 2047 | 2431.4 | 2654.6 | 2806.4 | 1166 | 0.0577 |
| 4 | 94 | 98 | 155.6 | 477.4 | 871.4 | 1342 | 1885.6 | 2360.6 | 2650.8 | 2835 | 1056 | 0.0526 |
| 5 | 107 | 71 | 110.2 | 379.8 | 735.4 | 1159 | 1684.8 | 2216 | 2600.4 | 2823.6 | 930 | 0.0458 |
| 6 | 131 | 73 | 101.4 | 299.6 | 621.4 | 1015.4 | 1486 | 2029.6 | 2504.6 | 2794.8 | 823 | 0.0407 |
| 7 | 194 | 71 | 100.2 | 254.2 | 523.8 | 879.4 | 1303 | 1828.8 | 2360 | 2744.4 | 728 | 0.0357 |
| 8 | 230 | 52 | 80.4 | 224.4 | 422.6 | 744.4 | 1138.4 | 1609 | 2152.6 | 2627.6 | 630 | 0.0306 |
| 9 | 279 | 85 | 105.8 | 237.2 | 391.2 | 660.8 | 1016.4 | 1440 | 1965.8 | 2497 | 581 | 0.0289 |
| 10 | 267 | 48 | 82 | 213.4 | 357.4 | 555.6 | 877.4 | 1271.4 | 1742 | 2285.6 | 507 | 0.0255 |
| 11 | 275 | 78 | 97.2 | 231.8 | 363.2 | 517.2 | 786.8 | 1142.4 | 1566 | 2091.8 | 479 | 0.0238 |
| 12 | 240 | 76 | 107.2 | 236 | 367.4 | 511.4 | 709.6 | 1031.4 | 1425.4 | 1896 | 457 | 0.0221 |
| 13 | 201 | 65 | 95.4 | 238.2 | 372.8 | 504.2 | 658.2 | 927.8 | 1283.4 | 1707 | 434 | 0.0221 |
| 14 | 211 | 94 | 120 | 266.2 | 395 | 526.4 | 670.4 | 868.6 | 1190.4 | 1584.4 | 447 | 0.0221 |
| 15 | 171 | 107 | 144.6 | 296.4 | 439.2 | 573.8 | 705.2 | 859.2 | 1128.8 | 1484.4 | 476 | 0.0238 |
| 16 | 167 | 131 | 173.8 | 358 | 504.2 | 633 | 764.4 | 908.4 | 1106.6 | 1428.4 | 526 | 0.0255 |
| 17 | 144 | 194 | 246.4 | 469.6 | 621.4 | 764.2 | 898.8 | 1030.2 | 1184.2 | 1453.8 | 635 | 0.0323 |
| 18 | 98 | 230 | 307.6 | 597.8 | 782 | 928.2 | 1057 | 1188.4 | 1332.4 | 1530.6 | 767 | 0.0374 |
| 19 | 71 | 279 | 371 | 755.4 | 978.6 | 1130.4 | 1273.2 | 1407.8 | 1539.2 | 1693.2 | 933 | 0.0458 |
| 20 | 73 | 267 | 378.6 | 853.6 | 1143.8 | 1328 | 1474.2 | 1603 | 1734.4 | 1878.4 | 1068 | 0.0526 |
| 21 | 71 | 275 | 381.8 | 913 | 1297.4 | 1520.6 | 1672.4 | 1815.2 | 1949.8 | 2081.2 | 1194 | 0.0594 |
| 22 | 52 | 240 | 350 | 893.6 | 1368.6 | 1658.8 | 1843 | 1989.2 | 2118 | 2249.4 | 1268 | 0.0628 |
| 23 | 85 | 201 | 297 | 822.8 | 1354 | 1738.4 | 1961.6 | 2113.4 | 2256.2 | 2390.8 | 1289 | 0.0645 |
| 24 | 48 | 211 | 291.4 | 762 | 1305.6 | 1780.6 | 2070.8 | 2255 | 2401.2 | 2530 | 1308 | 0.0645 |
| **Totals** | **3428** | **3428** | **4799** | **11655** | **18511** | **25367** | **32223** | **39079** | **45935** | **52791** | **20213** | **1.0000** |
| Weight | | | 0.227 | 0.135 | 0.199 | 0.191 | 0.156 | 0.057 | 0.014 | 0.021 | | |

Note:
*Assumes every trip ends 10 hours after it starts, such that all trips are 10 hours long. For the first hour of hotelling in each hour bin, the column sum is reduced by 60 percent to account for trip ends in a column that are not a full hour.

The distribution calculated using this method is similar to the behavior observed in a dissertation[69] at the University of Tennessee, Knoxville. This study observed the trucks parking at the Petro truck travel center located at the I40/I75 and Watt Road interchange between mid-December 2003 and August 2004. Rather than use results from a single study at a specific location, MOVES uses the more generic simulated values to determine the diurnal distribution of hotelling behavior. The distribution of total hotelling hours to hours of the day is calculated from the total hotelling hours and stored in the SourceTypeHour table in MOVES.

MOVES uses this same default hourly distribution from Table 13-11 for all days and locations, as shown below in Figure 13-2. Note this distribution of hotelling by hour of the day is similar to the inverse of the VMT distribution used for these trucks by hour of the day.

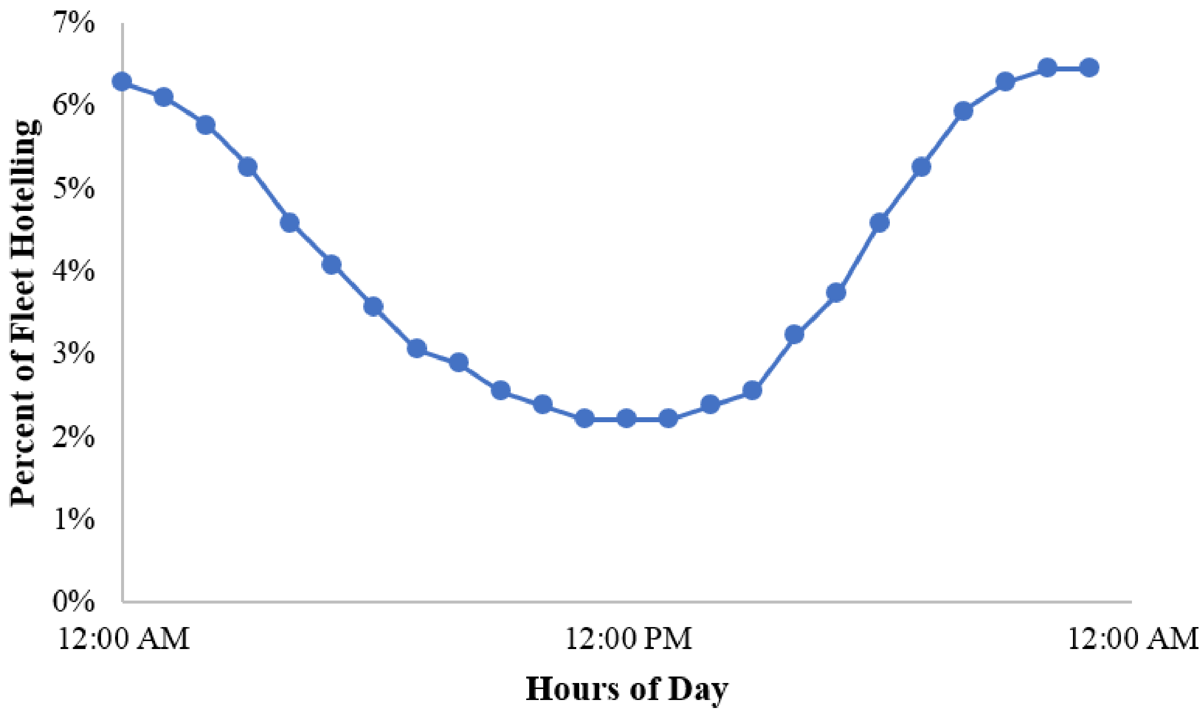


*Figure 13-2 Truck hotelling distribution by hour of the day in MOVES*

## 14. Geographical Allocation of Activity

MOVES is designed to model activity at a "domain" level and then to allocate that activity to "zones." The MOVES default database is populated for a domain of the entire United States (including Puerto Rico and the Virgin Islands), and the default zones correspond to individual counties. The MOVES design only allows for one set of geographic allocations to be stored in the default database. While geographic allocations clearly change over time, the MOVES defaults are used for all calendar years. Thus, it is often more accurate to use information other than the default values. National-level emissions can be generated with calendar year specific geographical information by running each year separately, with different user-input allocations for each run. County- and Project-level calculations do not use the default geographical allocation factors at all. Instead, County and Project scales require that the user input local total activity for each individual year being modeled.[70] The MOVES geographic allocation factors are stored in two tables, Zone and ZoneRoadType.

The current geographic allocations are the same as those found in the MOVES2014 and based on the 2011 NEI v2[71]. EPA intends to update these allocation factors using the same methodology using the 2014 NEI v2 inputs when they become available.

In MOVES201X, hotelling hours (including extended idling and auxiliary power unit usage) are calculated from combination long-haul combination truck VMT in each location and have their own allocation factors. (See Section 11.)

## 14.1. Source Hours Operating Allocation to Zones

Most of the emission rate calculations in MOVES are based on emission rates by time units (hour). Using time units for emissions is the most flexible approach, since the activity for some onroad processes (like leaks and idling) are more naturally in units of time. As a result, MOVES converts activity data to hours in many cases in order to produce the hours needed for emissions calculations.

The national total source hours of operation (SHO) are calculated from the estimates of VMT and speed as described in sections above. This total VMT for each road type is allocated to county using the SHOAllocFactor field in the ZoneRoadType table.

The MOVES default estimates for the VMT by county come from Version 2 of the 2011National Emission Inventory (NEI) analysis.[33] These estimates are based on the Highway Performance Monitoring System (HPMS) state level data collected by the Federal Highway Administration[72] annually for use in transportation planning. The HPMS state level VMT is distributed to the individual counties in each state as part of the NEI analysis. This data is reviewed and updated by the states as necessary prior to use in the NEI. The default inputs for SHOAllocFactor in MOVES were calculated using the VMT estimates obtained from Version 2 of the 2011 NEI[73] for each county by road type.

Vehicle miles traveled can be converted to hours of travel using average speeds. The average speed estimates were taken directly from the AvgSpeedDistribution table of the MOVES2014 default database (See Section 8). The default average speed distributions do not vary by county or source type, but do vary by road type, day type (weekday and weekend day) and hour of the day. The 2011 NEI VMT was aggregated into the annual sum for the four MOVES road types in each county. The VMT by road type in each county was then allocated to day type and hour of the day using the day type and hour distributions from the MOVES default database tables, DayMVTFraction and HourVMTFraction.

Using the nominal speeds for each average speed bin in the AvgSpeedDistribution table for each hour of each day type and the corresponding VMT, the hours of vehicle operation (SHO) can be calculated for each hour of the day on each road type for each day type in each county. The average speed distribution is in units of time, so the distribution must be converted to units of distance to be applied to the VMT values. For this step, we multiplied each value of each distribution (in terms of time) by the corresponding nominal average speed value for that average speed bin to calculate distance (hours * miles/hour). Then, we divided each distance value in the distribution by the sum of all distance values in that distribution to calculate the average speed distribution in terms of distance.

Finally, we multiplied the total VMT corresponding to each average speed distance distribution (by road type, by day type, by hour of the day) by each of the values in the distribution to calculate the VMT corresponding to each average speed bin. We then calculated operating hours by dividing the VMT in each average speed bin by the corresponding nominal average speed value, shown in.

$$SHO = VMT\ (miles)\ /\ Speed\ (miles\ per\ hour) \qquad \textbf{Equation 19}$$

Once the hours of operation were calculated, the hours in each county were summed by road type. The allocation factor for each county in Equation 20 was calculated by dividing the county hours for each road type by the national total hours of operation for each road type.

$$SHOAllocFactor = County\ SHO\ /\ National\ SHO \qquad \textbf{Equation 20}$$

The county allocation values for each roadway type sum to one (1.0) for the nation. The same SHOAllocFactor set is the default for all calendar years at the National scale. County- and Project-level calculations do not use the default SHOAllocFactor allocations at all. Instead, County and Project scales require that the user input all local activity.

## 14.2. Engine Start Allocations to Zones

The allocation of the domain-wide count of engine starts to zones is stored in the StartAllocFactor in the Zone table. In the default database for MOVES, the domain is the nation and the zones are counties. There is no national source for data on the number of trip starts by county, so for MOVES, we have used VMT to determine this allocation. VMT for each county was taken from the most recent National Emission Inventory analysis for calendar year 2011.[73]

VMT estimates for each county in each state and the allocation is calculated using Equation 21, where $i$ represents each individual county and $I$ is the set of all US counties.

$$CountyAllocation_i = \mathrm{CountyVMT}_i \Big/ \sum_{i \epsilon I} \mathrm{CountyVMT}_i \qquad \textbf{Equation 21}$$

The county allocation values sum to one (1.0) for the nation. The same StartAllocFactor set is the default for all calendar years at the National scale. County- and Project-level calculations do not use the default StartAllocFactor allocations at all. Instead, County and Project scales require that the user input all local activity.

### 14.3. Parking Hours Allocation to Zones

The allocation of the domain-wide hours of parking (time when vehicles are not operating but continue to have evaporative emissions) to zones is stored in the SHPAllocFactor in the Zone table. In the default database for MOVES, the domain is the nation and the zones are the counties. There is no national source for hours of parking by county, so we have used the same VMT-based allocation as used for the allocation of starts in the StartAllocFactor (see above).

The county allocation values for parking hours sum to one (1.0) for the nation. The same SHPAllocFactor set is the default for all calendar years at the National scale. County- and Project-level calculations do not use the default SHPAllocFactor allocations at all. Instead, County and Project scales require that the user input all local activity.

## 15. Vehicle Mass and Road Load Coefficients

The MOVES model calculates emissions using a weighted average of emisson rates by operating mode. For running exhaust emissions, the operating modes are defined by either vehicle specific power (VSP) or scaled tractive power (STP). Both VSP and STP estimate the tractive power exerted by a vehicle, and are calculated based on a vehicle's speed and acceleration, but differ in how they are scaled (or normalized). VSP is used for light-duty vehicles (source types 11 through 32) and STP is used for heavy-duty vehicles (source types 41 through 62).

The SourceUseTypePhysics table describes the vehicle characteristics needed for the VSP and STP calculations, including average vehicle mass, a fixed mass factor, and three road load coefficients for each combinations of source type and regulatory class averaged over all ages. In MOVES2014, the SourceUseTypePhysics table was only by source types. However, regulatory class was added in MOVES201X as one of the key fields to model the Heavy-Duty Greenhouse Gas Phase 2 rulemaking[74] which anticipates improvements to vehicle and trailer design. MOVES uses these values to calculate VSP and STP for each source type/regulatory class combinations according to Equation 22 and Equation 23:

$$VSP = \left(\frac{A}{M}\right) \cdot v + \left(\frac{B}{M}\right) \cdot v^2 + \left(\frac{C}{M}\right) \cdot v^3 + (a + g \cdot \sin\theta) \cdot v \qquad \textbf{Equation 22}$$

$$STP = \frac{Av + Bv^2 + Cv^3 + M \cdot (a + g \cdot sin\theta) \cdot v}{f_{scale}} \qquad \textbf{Equation 23}$$

where $A$, $B$, and $C$ are the road load coefficients in units of kW-s/m, kW-s$^2$/m$^2$, and kW-s$^3$/m$^3$ respectively. $A$ is associated with tire rolling resistence, $B$ with mechanical rotating friction as well as higher order rolling resistance losses, and $C$ with aerodynamic drag. $M$ is the source mass for the source type in metric tons, $g$ is the acceleration due to gravity $(9.8\ \mathrm{m/s^2})$, $v$ is the instantaneous vehicle speed in m/s, $a$ is the instantaneous vehicle acceleration in m/s$^2$, $\sin\theta$ is the (fractional) road grade, and $f_{scale}$ is a scaling factor.

When mapping actual emissions data to VSP bins with Equation 22, the vehicle's measured weight is used as the source mass factor. In contrast, when calculating average VSP distributions for an entire source type with MOVES, the average source type mass is used instead. STP is calculated with Equation 23, which is very similar to the VSP equation except the denominators are different. In the case of VSP, the power is normalized by the mass of the vehicle ($f_{scale} = M$). For heavy-duty vehicles using STP, $f_{scale}$ depends on their regulatory class and is used to bring the numerical range of tractive power into the same numerical range as the VSP values when assigning operating modes. Class 40 trucks (Class 2b trucks with 2 axles and 4 tires with 8,500 lbs. < GVWR ≤ 10,000 lbs.) use $f_{scale} = 2.06$, which is equal to the mass of source type 32 (light commercial truck) in metric tons. This is because operating modes for passenger trucks and light-commercial trucks are assigned operating modes using VSP, and using a fixed mass factor of 2.06 essentially calculates VSP-based emission rates. Running operating modes for all the heavy-duty source types (buses, single-unit, and combination trucks) are assigned using STP with $f_{scale}$ =17.1, which is roughly equivalent to the average running weight in metric tons of all heavy-duty vehicles. Additional discussion regarding VSP and STP are provided in the MOVES light-duty[4] and heavy-duty[5] emission rate reports, respectively.

In both cases, operating mode distributions are derived by combining second-by-second speed and acceleration data from a specific drive schedule with the proper coefficients for a specific source type. More information about drive schedules can be found in Section 9.1 The following sections detail the derivation of values used in Equation 22 and Equation 23.

### 15.1. Source Mass and Fixed Mass Factor

The two mass factors stored in the SourceUseTypePhysics table are the source mass and fixed mass factor. The source mass represents the average weight of a given source type, which includes the weight of the vehicle, occupants, fuel, and payload ($M$ in Equation 22 and Equation 23), and the fixed mass factor represents the STP scaling factor ($f_{scale}$ in Equation 23).

In MOVES201X, the source masses were unchanged from MOVES2014 for the following source type and model year combinations:

- Motorcycles, passenger cars, passenger trucks, light commercial trucks, transit buses, school buses, other buses, refuse trucks, and motor homes for all model years
- Short-haul and long-haul single-unit trucks prior to model year 2021
- Short-haul and long-haul combination trucks prior to model year 2018

The documentation of this previous analysis may be found in Appendix H. The updates to the source masses to account for the Heavy-Duty Greenhouse Gas Phase 2 rule are described here.

In the Phase 2 rule, the changes in sources masses are expected – for single-unit trucks, the technologies that could be used to meet the standards are expected to result in weight reductions; for combination trucks, increases in source masses are expected as a byproduct of vehicle and engine improvements made to those trucks. The changes in source masses from MOVES2014 reflecting the Phase 2 rule are shown in Table 15-1. The details of the analyses used to estimate the changes in source masses can be found in the docket for the Phase 2 rule.[75,76] The final sourceMass and fixedMassFactor in MOVES201X are listed in Table 15-17.

*Table 15-1 Changes in Source Masses for Heavy-Duty Trucks in MOVES201X*

| **Source Type**[1] | **Model Years** | **Change in Source Mass from MOVES2014 (lbs.)** |
|---|---|---|
| Single-Unit Short-haul Truck | 2021-2023 | -4.4 |
| | 2024-2026 | -10.4 |
| | 2027+ | -16.5 |
| Single-Unit Long-haul Truck | 2021-2023 | -7.9 |
| | 2024-2026 | -23.6 |
| | 2027+ | -39.4 |
| Combination Short-haul Truck | 2018-2020 | 23 |
| | 2021-2023 | 43 |
| | 2024-2026 | 43 |
| | 2027+ | 43 |
| Combination Long-haul Truck | 2018-2020 | 140 |
| | 2021-2023 | 199 |
| | 2024-2026 | 294 |
| | 2027+ | 360 |

Note:
[1] No change in source masses is expected for other source types.

## 15.2. Road Load Coefficients

As indicated above, in MOVES, road load coefficients are used in the calculation of both VSP and STP. $A$, $B$, and $C$ are the road load coefficients in units of kW-s/m, kW-$s^2/m^2$, and kW-$s^3/m^3$, respectively. $A$ is associated with rolling resistance, $B$ with mechanical rotating friction as well as higher order rolling resistance losses, and $C$ with aerodynamic drag. The information available on road load coefficients varied by regulatory class.

### 15.2.1. Light-Duty and Motorcycles

Motorcycle road load coefficients, given in Equation 24 through Equation 26, were empiricially derived in accordance with standard practice:[77,78]

$$A = 0.088 \cdot M$$ **Equation 24**

$$B = 0$$ **Equation 25**

$$C = 0.00026 + 0.000194 \cdot M$$ **Equation 26**

For light-duty vehicles, the road load coefficients were calculated according to Equation 27 through Equation 29:[79]

$$A = \frac{0.7457}{50 \cdot 0.447} \cdot 0.35 \cdot TRLHP_{@50\text{mph}}$$ **Equation 27**

$$B = \frac{0.7457}{(50 \cdot 0.447)^2} \cdot 0.10 \cdot TRLHP_{@50\text{mph}}$$ **Equation 28**

$$C = \frac{0.7457}{(50 \cdot 0.447)^3} \cdot 0.55 \cdot TRLHP_{@50\text{mph}}$$ **Equation 29**

In each of the above equations, the first factor is the appropriate unit conversion to allow $A$, $B$, and $C$ to be used in Equation 22 and Equation 23, the second factor is the power distribution into each of the three load categories, and the third is the tractive road load horsepower rating (TRLHP). Average values for $A$, $B$, and $C$ for source types 21, 31, and 32 were derived from applying TRLHP values recorded in the Mobile Source Observation Database (MSOD)[80] to Equation 27 through Equation 29. While we expect light-duty road load coefficients to improve over time due to the 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions Rule, the impact of these changes have been directly incorporated into the emission and energy rates.[81] Therefore, these coefficients remain constant over time in the MOVES (if not in the real-world) to avoid double counting the impacts of actual road load improvements in the fleet.

#### 15.2.2. Heavy-Duty Vehicles

For heavy-duty source types, no road load parameters were available in the MSOD. Therefore, for the heavy-duty source types other than combination trucks, relationships of historical road load coefficent to vehicle mass came from a study done by V.A. Petrushov,[82] as shown in Table 15-2. These relationships are grouped by regulatory class; source type values were determined by weighting the combination of weight categories that comprise the individual source types. As noted in the table below, the $B$ term is set to zero to reflect that the frictional forces that are linearly related to vehicle speed in heavy-duty vehicles are very low when compared to the rolling resistance and aerodynamic forces. In MOVES201X, the road load parameters for combination trucks have been revised for model years 1960-2060 using the methods described in Section 15. The revised road load coefficients for heavy-duty source types other than combination trucks for model years 2014-2060 are described in Section 15.2.2.3

*Table 15-2 Road Load Coefficients for Buses, Motor Homes, and Heavy-duty Trucks other than Combination Trucks for MY 1960-2013 Vehicles*

| Coefficient | 8500 to 14000 lbs. (3.855 to 6.350 metric ton) | 14000 to 33000 lbs. (6.350 to 14.968 metric ton) | >33000 lbs. (>14.968 metric ton) | Buses and Motor Homes |
|---|---|---|---|---|
| $A\left(\frac{kW\text{-}s}{m}\right)$ | $0.0996 \cdot M$ | $0.0875 \cdot M$ | $0.0661 \cdot M$ | $0.0643 \cdot M$ |
| $B\left(\frac{kW\text{-}s^2}{m^2}\right)$ | 0 | 0 | 0 | 0 |
| $C\left(\frac{kW\text{-}s^3}{m^3}\right)$ | $0.00289 + 5.22 \times 10^{-5} \cdot M$ | $0.00193 + 5.90 \times 10^{-5} \cdot M$ | $0.00289 + 4.21 \times 10^{-5} \cdot M$ | $0.0032 + 5.06 \times 10^{-5} \cdot M$ |

#### 15.2.2.1. Heavy-Duty Vehicle Update for MOVES201X

EPA set GHG emission standards for heavy-duty vehicles in two separate rulemakings. The Phase 1 rulemaking became effective in 2014 model year. The Phase 2 rulemaking becomes effective in 2018 model year for trailers and 2021 model year for other heavy-duty truck types, and is fully phased-in in 2027 model year. The road load coefficients in MOVES201X have been updated to reflect the projected improvements to the vehicles in different model year groups. The first age group includes model years 1960-2013 to reflect the time period prior to the first heavy-duty truck GHG emission standards. Due to improvements in trailers, the first model year group is split into pre-2008 and 2008-2013 for combination tractor-trailers. The Phase 1 standards are applied to model years 2014-2017 (or through 2020 depending on category). The Phase 2 combination tractor-trailer standards are phased-in through steps that include model year groups 2018-2020, 2021-2023, 2024-2026, and 2027 and later. The Phase 2 standards for the source types other than combination trucks are grouped in to 2021-2023, 2024-2026, and 2027 and later groups. To account for the improvements from the rules, a separation of road load forces into individual road load coefficients is necessary because significant improvements are expected in aerodynamic drag and rolling resistance, particularly for tractor-trailers. The aerodynamic and rolling resistance components of the overall road load are determined separately and updated in MOVES201X as a result of greenhouse gas emissions standards.

The aerodynamic drag force, $F_{aero}$ as a function of speed is represented as:

$$F_{aero} = \frac{1}{2}\rho C_d A_f v_{air}^2$$ **Equation 30**

where $\rho$ is the density of air, $C_d$ is the aerodynamic drag coefficient, $A_f$ is the frontal area of the vehicle, and $v_{air}$ is the air speed relative to the vehicle as it is traveling. In zero wind conditions, the relative air speed is equal to vehicle speed. Consequently, the aerodynamic drag component of STP can be represented as:

$$STP_{aero} = \left(\frac{1}{f_{scale}}\right) \cdot \frac{1}{2} \rho C_d A_f v^3 \qquad \text{Equation 31}$$

Thus, the *C* road load coefficient can be represented as:

$$C = \frac{1}{2} \rho C_d A_f \qquad \text{Equation 32}$$

The quantity $C_dA_f$, shortened to $C_dA$, is called the drag area and is used to characterize the overall aerodynamic drag forces for a vehicle.

The tire rolling resistance force is represented using the *A* coefficient in the SourceUseTypePhysics table. It is related to the coefficient of rolling resistance, $C_{RR}$, and source mass M, using the following equation:

$$A = C_{RR} M_g \qquad \text{Equation 33}$$

where g is the gravitational acceleration.

Section 15.2.2.2 describes the analysis to update road load coefficients for combination long-haul (sourceTypeID 62) and short-haul (sourceTypeID 61) trucks in MOVES201X. Section 15.2.2.3describes the updates applied to heavy-duty source types other than combination trucks to account for HD GHG Phase 1 and Phase 2 rulemakings. The details on the discussion of incorporating Phase 1 and Phase 2 energy reductions from engine technology improvements into MOVES201X can be found in the MOVES201X Heavy-Duty Emission Rate Report.[5]

While we expect road load coefficients for Heavy-Duty Pickups and Vans (regulatoryclassID 40 and 41) to improve over time due to the Phase 1 and Phase 2 Heavy-Duty Vehicle Greenhouse Gas Emissions Rules, the impact of these changes have been directly incorporated into the emission and energy rates.[74,83] Since nearly all HD pickup trucks and vans are certified on a chassis dynamometer, the improvements in road loads expected from the greenhouse gas standards are modeled as total vehicle improvements without separating out the engine and road load components. Therefore, these coefficients remain constant over time in MOVES (if not in the real-world) to avoid double counting the impacts of actual road load improvements in the fleet.

#### 15.2.2.2. Combination Trucks for Model Years 1960-2060

This section describes the updates to both the aerodynamic and rolling resistance components of the overall road load reflecting the greenhouse gas emissions standards for combination trucks in MOVES201X.

A new aerodynamic assessment of all model years of combination trucks was conducted to utilize a consistent method in MOVES201X. In the Greenhouse Gas Emission and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles promulgated by EPA and NHTSA, certification test procedures were developed to evaluate the aerodynamic performance of tractors and trailers. The test procedures varied between Phase 1 and Phase 2 of the standards. Trailers were not included in the Phase 1 program and tractor aerodynamic performance was measured at no wind conditions. In Phase 2, trailers were added to the program and new test procedures were developed that approximate a wind-averaged drag performance. Wind-averaged drag reflects a vehicle's average performance for a range of yaw angles (the angle of attack of the air during travel) at a given vehicle speed and wind speed and is more representative of real-world performance. The wind-averaged drag result in the Phase 2 rule is determined by an average of drag values two yaw positions which represents a vehicle speed of 65 mph and a wind speed of 7 mph. In the tractor programs, the drag value is represented by the aerodynamic drag area, $C_dA$. In the trailer program, the drag value is represented as a reduction in drag area, $\Delta C_dA$, relative to a commonly available baseline trailer that is not equipped with aerodynamic devices.

The Phase 2 rule also creates bins for aerodynamic certification, so that a precise drag value is not needed to certify every tractor or trailer. A representative aerodynamic value from each bin is used, along with other aspects of the powertrain and vehicle, as an input into the Greenhouse Gas Emissions Model (GEM) to determine a vehicle configuration's $CO_2$ emissions result. Tractors are categorized in the rule by their roof height and cab type – sleeper cabs and day cabs – and different aerodynamic bins exist for each category and a mid-point from each bin is used as the GEM input. The trailer program used the bottom boundaries of the bins for GEM input values, which represent a conservative estimate of aerodynamic improvements. For this analysis, midpoints of the bins were used to reflect average performance within the trailer bins. Bin I represents no improvement, so a $\Delta C_dA$ value of 0 $m^2$ was used in this analysis. Non-box trailers, including flatbed and tank trailers, have standards based on tire technologies in the HD Phase 2 GHG program, and aerodynamic improvements for those trailer types are neither expected nor included in this analysis. The $C_dA$ bin structures for tractors and trailers are shown below.[84,85] The trailer bin structure is common to all box van trailer types.

*Table 15-3 Phase 2 GHG Aerodynamic Drag Area Bin Structure for Tractors [$m^2$]*

| | **High-roof Sleeper Cab** | | **High-roof Day Cab** | | **Low-roof Sleeper & Day Cabs** | | **Mid-roof Sleeper & Day Cabs** | |
|---|---|---|---|---|---|---|---|---|
| **Tractor $C_dA$ Bin** | $C_dA$ range | $C_dA$ input | $C_dA$ range | CdA input | $C_dA$ range | $C_dA$ input | $C_dA$ range | $C_dA$ input |
| **I** | ≥6.9 | 7.15 | ≥7.2 | 7.45 | ≥5.4 | 6.00 | ≥5.9 | 7.00 |
| **II** | 6.3-6.8 | 6.55 | 6.6.7.1 | 6.85 | 4.9-5.3 | 5.60 | 5.5-5.8 | 6.65 |
| **III** | 5.7-6.2 | 5.95 | 6.0-6.5 | 6.25 | 4.5-4.8 | 5.15 | 5.1-5.4 | 6.25 |
| **IV** | 5.2-5.6 | 5.40 | 5.5-5.9 | 5.70 | 4.1-4.4 | 4.75 | 4.7-5.0 | 5.85 |
| **V** | 4.7-5.1 | 4.90 | 5.0-5.4 | 5.20 | 3.8-4.0 | 4.40 | 4.4-4.6 | 5.50 |
| **VI** | 4.2-4.6 | 4.40 | 4.5-4.9 | 4.70 | 3.5-3.7 | 4.10 | 4.1-4.3 | 5.20 |
| **VII** | ≤4.1 | 3.90 | ≤4.4 | 4.20 | ≤3.4 | 3.80 | ≤4.0 | 4.90 |

*Table 15-4 Phase 2 GHG Aerodynamic Drag Area Bin Structure for Box Van Trailers [$m^2$]*

| Trailer $\Delta C_dA$ Bin | $\Delta C_dA$ range | $\Delta C_dA$ input for GEM | Midpoint of $\Delta C_dA$ range |
|---|---|---|---|
| **I** | ≤0.09 | 0.0 | 0 |
| **II** | 0.10-0.39 | 0.1 | 0.25 |
| **III** | 0.40-0.69 | 0.4 | 0.55 |
| **IV** | 0.70-0.99 | 0.7 | 0.85 |
| **V** | 1.00-1.39 | 1.0 | 1.2 |
| **VI** | 1.40-1.79 | 1.4 | 1.6 |
| **VII** | ≥1.80 | 1.8 | 1.9 |

The tractor and trailer bin structures were used to estimate adoption rates of improved aerodynamic technologies. For tractors, EPA conducted such analyses for Phase 1 GHG and Phase 2 GHG rulemakings, for both their respective baselines and the rulemaking scenarios. For tractor certification in the GHG rules, different tractor types are assumed to be matched with specific trailer types. High-roof tractors are matched with 53-foot box van trailers. In Phase 2, that trailer is equipped with a trailer skirt. Mid-roof tractors are matched with tank trailers, and low-roof tractors are matched with flatbed trailers.

In MOVES201X, the aerodynamic values were updated for all model years to reflect the aerodynamic technology analysis and projections in the Phase 1 and Phase 2 rulemakings.[86,87] The Phase 1 GHG baseline analysis was used for model years prior to implementation of the Phase 1 GHG rule (pre-2014 model years). The Phase 2 GHG baseline analysis was used for model years 2014 through 2020, which are predominantly the Phase 1 GHG implementation years. The Phase 2 GHG technology penetration analysis was the basis for the adoption rates for model years 2021 and later, with different rates for different types of cabs and each of the major steps established in the rulemaking – model years 2021-2023, 2024-2026, and 2027 and beyond. The bin-weighted average $C_dA$ (i.e., the "$C_dA$ input" from Table 15-3) was then calculated by model year group. For the high-roof sleeper cab and high-roof day cab subcategories, the effect of the trailer skirt was removed to calculate the $C_dA$ of a tractor-trailer combination with a baseline trailer. Through extensive testing in the Phase 2 GHG rulemaking development, the trailer skirt was estimated to have Trailer Bin III performance of 0.55 $m^2$, as seen in Table 15-4.

*Table 15-5 Tractor aerodynamic technology adoption rates by model year groups*

| | Tractor Bin | Tractor Bin CdA input [$m^2$] | 1960-2013 | Phase 1 GHG 2014-2020 | Phase 2 GHG 2021-2023 | Phase 2 GHG 2024-2026 | Phase 2 GHG 2027+ |
|---|---|---|---|---|---|---|---|
| **High-roof sleeper cabs** | I | 7.15 | 25% | 0% | 0% | 0% | 0% |
| | II | 6.55 | 70% | 10% | 0% | 0% | 0% |
| | III | 5.95 | 5% | 70% | 60% | 40% | 20% |
| | IV | 5.40 | 0% | 20% | 30% | 40% | 30% |
| | V | 4.90 | 0% | 0% | 10% | 20% | 50% |
| | VI | 4.40 | 0% | 0% | 0% | 0% | 0% |
| | VII | 3.90 | 0% | 0% | 0% | 0% | 0% |
| | Mean CdA (w/ skirt) [$m^2$] | | 6.67 | 5.9 | 5.68 | 5.52 | 5.26 |
| | *Skirt effect [$m^2$]* | | *0.55* | *0.55* | *0.55* | *0.55* | *0.55* |
| | **Mean CdA (w/o skirt)** [$m^2$] | | **7.22** | **6.45** | **6.23** | **6.07** | **5.81** |
| **Hi gh-** | I | 7.45 | 25% | 0% | 0% | 0% | 0% |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | II | 6.85 | 70% | 30% | 0% | 0% | 0% |
| | III | 6.25 | 5% | 60% | 60% | 40% | 30% |
| | IV | 5.70 | 0% | 10% | 35% | 40% | 30% |
| | V | 5.20 | 0% | 0% | 5% | 20% | 40% |
| | VI | 4.70 | 0% | 0% | 0% | 0% | 0% |
| | VII | 4.20 | 0% | 0% | 0% | 0% | 0% |
| | Mean CdA (w/ skirt) [$m^2$] | | 6.97 | 6.375 | 6.005 | 5.82 | 5.665 |
| | *Skirt effect [$m^2$]* | | *0.55* | *0.55* | *0.55* | *0.55* | *0.55* |
| | **Mean CdA (w/o skirt)** [$m^2$] | | **7.52** | **6.925** | **6.555** | **6.37** | **6.215** |
| **Mid-roof Sleeper cabs** | I | 7.00 | 100% | 15% | 10% | 0% | 0% |
| | II | 6.65 | 0% | 15% | 10% | 20% | 20% |
| | III | 6.25 | 0% | 70% | 70% | 60% | 50% |
| | IV | 5.85 | 0% | 0% | 10% | 20% | 30% |
| | V | 5.50 | 0% | 0% | 0% | 0% | 0% |
| | VI | 5.20 | 0% | 0% | 0% | 0% | 0% |
| | VII | 4.90 | 0% | 0% | 0% | 0% | 0% |
| | **Mean CdA [$m^2$]** | | **7.00** | **6.4225** | **6.325** | **6.25** | **6.21** |
| **Mid-roof day cabs** | I | 7.00 | 100% | 20% | 10% | 0% | 0% |
| | II | 6.65 | 0% | 20% | 10% | 20% | 20% |
| | III | 6.25 | 0% | 60% | 70% | 60% | 50% |
| | IV | 5.85 | 0% | 0% | 10% | 20% | 30% |
| | V | 5.50 | 0% | 0% | 0% | 0% | 0% |
| | VI | 5.20 | 0% | 0% | 0% | 0% | 0% |
| | VII | 4.90 | 0% | 0% | 0% | 0% | 0% |
| | **Mean CdA [$m^2$]** | | **7.00** | **6.48** | **6.325** | **6.25** | **6.21** |
| **Low-roof sleeper cabs** | I | 6.00 | 100% | 15% | 10% | 0% | 0% |
| | II | 5.60 | 0% | 15% | 10% | 20% | 20% |
| | III | 5.15 | 0% | 70% | 70% | 60% | 50% |
| | IV | 4.75 | 0% | 0% | 10% | 20% | 30% |
| | V | 4.40 | 0% | 0% | 0% | 0% | 0% |
| | VI | 4.10 | 0% | 0% | 0% | 0% | 0% |
| | VII | 3.80 | 0% | 0% | 0% | 0% | 0% |
| | **Mean CdA [$m^2$]** | | **6.00** | **5.345** | **5.24** | **5.16** | **5.12** |
| **Low-roof day cabs** | I | 6.00 | 100% | 20% | 10% | 0% | 0% |
| | II | 5.60 | 0% | 20% | 10% | 20% | 20% |
| | III | 5.15 | 0% | 60% | 70% | 60% | 50% |
| | IV | 4.75 | 0% | 0% | 10% | 20% | 30% |
| | V | 4.40 | 0% | 0% | 0% | 0% | 0% |
| | VI | 4.10 | 0% | 0% | 0% | 0% | 0% |
| | VII | 3.80 | 0% | 0% | 0% | 0% | 0% |
| | **Mean CdA [$m^2$]** | | **6.00** | **5.41** | **5.24** | **5.16** | **5.12** |

However, since trailers were not regulated in the Phase 1 GHG rulemaking, a survey conducted by the North American Council for Freight Efficiency (NACFE) was used to estimate that trailer aerodynamic technologies were not in significant use prior to 2008.[88] Therefore for trailers, we split the model year groups prior to 2018, the year that the Phase 2 GHG rule takes effect for trailers. The model years between 1960-2007 reflect the time period prior to the use of trailer aerodynamic improvements. The model year groups of 2008-2014 and 2014-2018 reflect voluntary improvements to trailer aerodynamics. As a result, the following trailer technology adoption rates were used to determine the average $\Delta C_d A$ by model year group for 53-ft box van trailers. Separate rates were developed for several trailer categories, as shown in Table 15-6. Short box vans are 50 feet and shorter, and the shortest ones are often pulled in tandem. However, for simplicity and consistency with the compliance framework of the HD GHG Phase 2 rule, a single-trailer configuration is the basis for this analysis for both long and short trailers.

*Table 15-6 Trailer aerodynamic technology adoption rates by model year groups*

| | Trailer Bin | 1960-2007 | 2008-2013 | 2014-2017 | 2018-2020 | Phase 2 GHG 2021-2023 | Phase 2 GHG 2024-2026 | Phase 2 GHG 2027+ |
|---|---|---|---|---|---|---|---|---|
| **Long box vans** | I | 100% | 65% | 55% | 0% | 0% | 0% | 0% |
| | II | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | III | 0% | 35% | 40% | 100% | 0% | 0% | 0% |
| | IV | 0% | 0% | 5% | 0% | 100% | 0% | 0% |
| | V | 0% | 0% | 0% | 0% | 0% | 100% | 30% |
| | VI | 0% | 0% | 0% | 0% | 0% | 0% | 70% |
| | VII | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | **Average $\Delta C_dA$ [m²]** | **0** | **0.1925** | **0.2625** | **0.55** | **0.85** | **1.2** | **1.48** |
| **Short box vans** | I | 100% | 100% | 100% | 100% | 0% | 0% | 0% |
| | II | 0% | 0% | 0% | 0% | 100% | 0% | 0% |
| | III | 0% | 0% | 0% | 0% | 0% | 100% | 40% |
| | IV | 0% | 0% | 0% | 0% | 0% | 0% | 60% |
| | V | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | VI | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | VII | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | **Average $\Delta C_dA$ [m²]** | **0** | **0** | **0** | **0** | **0.25** | **0.55** | **0.73** |
| **Partial-aero long box vans** | I | 100% | 100% | 100% | 0% | 0% | 0% | 0% |
| | II | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | III | 0% | 0% | 0% | 100% | 100% | 100% | 100% |
| | IV | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | V | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | VI | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | VII | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | **Average $\Delta C_dA$ [m²]** | **0** | **0** | **0** | **0.55** | **0.55** | **0.55** | **0.55** |
| **Partial-aero short box vans** | I | 100% | 100% | 100% | 100% | 0% | 0% | 0% |
| | II | 0% | 0% | 0% | 0% | 100% | 100% | 100% |
| | III | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | IV | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | V | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | VI | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | VII | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | **Average $\Delta C_dA$ [m²]** | **0** | **0** | **0** | **0** | **0.25** | **0.25** | **0.25** |

The average $\Delta C_dA$ values by model year group for tractor-trailer combinations were determined by estimating the distribution of each trailer category within each tractor subcategory. Following the analysis performed for the HD GHG Phase 2 rulemaking, the distribution in Table 15-7 was used. Trailers in the non-aero category are incompatible with aerodynamic improvements and standards are based on tire technologies in the Phase 2 regulations. These trailers are assumed to be matched entirely within the low-roof and mid-roof tractor types and no aerodynamic improvements are applied to these trailers. Trailers with work-performing equipment that impedes the use of some aerodynamic devices are considered partial-aero trailers. These trailers are assumed to be used in short haul operations, and assigned to high roof day cab tractors. The remaining trailers are full-aero box vans capable of adopting a range of aerodynamic devices and we assume these trailer types are used in long haul with sleeper cab tractors. Using a combination of data from the 2002 VIUS database and trailer production results from ACT Research, over 70 percent of the full-aero capable trailers are assumed to be long box vans (longer than 50-feet). Partial-aero box vans used in short-haul applications, however, are more than 60 percent short trailer (50 feet and shorter).

*Table 15-7 Trailer category distribution by tractor category*

| Trailer Category | Sleeper Cabs | | | Day Cabs | |
|---|---|---|---|---|---|
| | Low-roof | Mid-roof | High-roof | Low-roof | High-roof |
| Full-aero long | 0% | 0% | 73% | 0% | 0% |
| Full-aero short | 0% | 0% | 27% | 0% | 0% |
| Partial-aero long | 0% | 0% | 0% | 0% | 36% |
| Partial-aero short | 0% | 0% | 0% | 0% | 64% |
| Non-aero | 100% | 100% | 0% | 100% | 0% |

We assume no aerodynamic improvements for trailers pulled by low- and mid-roof tractors, so all aerodynamic improvements for these vehicles come from the tractors only. Aerodynamic improvements for the high-roof tractors pulling box trailers are calculated by combining the aerodynamic drag estimates from the tractor and trailer. The average trailer $\Delta C_dA$ values by model year group and tractor category are listed in Table 15-8. Trailer aerodynamic improvements are calculated using the trailer distribution shown in Table 15-7 and the adoption rates of Table 15-6. The average $C_dA$ for a tractor-trailer combination by model year can be calculated by subtracting the average trailer $\Delta C_dA$ values from the average tractor $C_dA$ values in Table 15-5. For the mid-roof and low-roof tractor subcategories, no adjustment for the trailer was needed because the trailer types associated with those tractor subcategories have tire-based standards under the Phase 2 GHG program are not expected to implement any aerodynamic improvement technologies.

*Table 15-8 Average trailer $\Delta C_dA$ values by tractor category and model year group [$m^2$]*

| Model years / Category | Pre-2008 | 2008-2013 | 2014-2017 | 2018-2020 | 2021-2023 | 2024-2026 | 2027+ |
|---|---|---|---|---|---|---|---|
| High-roof sleeper cab | 0 | 0.140 | 0.191 | 0.400 | 0.687 | 1.023 | 1.276 |
| High-roof day cab | 0 | 0 | 0 | 0.199 | 0.358 | 0.358 | 0.358 |

The resulting drag values that include aerodynamic improvements from tractors and trailers are shown below.

*Table 15-9 Drag area, $C_dA$ [$m^2$], by tractor-trailer subcategory and model year group*

| Model years / Category | Pre-2008 | 2008-2013 | 2014-2017 | 2018-2020 | 2021-2023 | 2024-2026 | 2027+ |
|---|---|---|---|---|---|---|---|
| High-roof sleeper cab | 7.2200 | 7.0798 | 6.2589 | 6.0495 | 5.5431 | 5.0467 | 4.5339 |
| High-roof day cab | 7.5200 | 7.4505 | 6.9250 | 6.7263 | 6.1966 | 6.0116 | 5.8566 |
| Mid-roof | 7.0000 | 7.0000 | 6.4225 | 6.4225 | 6.3250 | 6.2500 | 6.2100 |
| Low-roof | 6.0000 | 6.0000 | 5.3450 | 5.3450 | 5.2400 | 5.1600 | 5.1200 |
| Vocational tractor | 6.0000 | 6.0000 | 6.0000 | 6.0000 | 6.0000 | 6.0000 | 6.0000 |

In MOVES, the values for sleeper cab tractors (with trailers) used for long-haul combination trucks (sourceTypeID 62), and the values for day cab tractors (with trailers) are used for short-haul combination trucks (sourceTypeID 61). Both the sleeper cab and day cab categories contain a mix of high-roof, mid-roof, and low-roof types. Day cab tractors also contain a vocational tractor subcategory, for which the aerodynamic requirements of the Phase 2 rule do not apply. They are of a low-roof height configuration and assumed to have the aerodynamic characteristics of pre-2008 MY low-roof tractors for all model years. The combined average $C_dA$ for the MOVES combination trucks shown in Table 15-11 was calculated using the distribution from Table 15-10 and the drag areas from Table 15-9.

*Table 15-10 Roof height distribution within cab types*

| Roof height | Sleeper Cab | Day Cab |
|---|---|---|
| Low-roof | 5% | 47% |
| Mid-roof | 15% | 0% |
| High-roof | 80% | 45% |
| Vocational | 0% | 8% |

*Table 15-11 Average $C_dA$ for each source type by model year group weighted by roof height*

| | Pre-2008 | 2008-2013 | 2014-2017 | 2018-2020 | 2021-2023 | 2024-2026 | 2027+ |
|---|---|---|---|---|---|---|---|
| Sleeper cab (sourceType 62) | 7.1260 | 7.0139 | 6.2377 | 6.0702 | 5.6452 | 5.2328 | 4.8146 |
| Day cab (sourceType 61) | 6.6840 | 6.6840 | 6.1390 | 6.0496 | 5.7313 | 5.6104 | 5.5219 |

To convert from $C_dA$ to the C coefficient, Equation 32 was used with an estimate for air density. A national annual MOVES run produced an average temperature of 61°F. At standard atmospheric air pressure, the air density is 1.22 kg/$m^3$. The resulting C coefficient values are listed below.

*Table 15-12 C coefficients [kW-$s^3$/$m^3$] of source types 61 and 62 by model year group*

| | Pre-2008 | 2008-2013 | 2014-2017 | 2018-2020 | 2021-2023 | 2024-2026 | 2027+ |
|---|---|---|---|---|---|---|---|
| Sleeper cab (sourceType 62) | 0.00435 | 0.00428 | 0.00381 | 0.00370 | 0.00344 | 0.00319 | 0.00294 |
| Day cab (sourceType 61) | 0.00408 | 0.00408 | 0.00374 | 0.00369 | 0.00350 | 0.00342 | 0.00337 |

The Phase 1 and Phase 2 GHG emission standards also project improvements to the tire rolling resistance. MOVES201X reflects these improvements through revisions to the *A* coefficient in the SourceUseTypePhysics table. It is related to the coefficient of rolling resistance, $C_{RR}$, and source mass M, using the following equation:

$$A = C_{RR} M g \qquad \text{Equation 34}$$

where g is the gravitational acceleration.

For combination tractor-trailers, the tires typically differ by axle position (steer, drive, and trailer). The HD GHG Phase 1 and Phase 2 rulemakings developed adoption rates of lower rolling resistance tires for the steer, drive, and trailer axles for all model years.[89,90] The overall rolling resistance of the vehicle is a weighted average of rolling resistance over axle based on axle loading.

$$C_{RR} = C_{RR,steer}\frac{M_{steer}}{M} + C_{RR,drive}\frac{M_{drive}}{M} + C_{RR,trailer}\frac{M_{trailer}}{M} \qquad \textit{Equation 35}$$

Tire rolling resistance for tractor-trailers was updated using the same trailer type distributions described in Table 15-7. Rolling resistance distributions, based on tire rolling resistance levels from the GHG rules are shown in Table 15-13.

*Table 15-13 $C_{RR}$ by axle and tractor type*

| | | **Tire $C_{rr}$ level** | **Tire $C_{rr}$ value [kg/metric ton]** | **Pre-2014** | **Phase 1 GHG 2014-2017** | **Phase 1 2018-2020** | **Phase 2 GHG 2021-2023** | **Phase 2 GHG 2024-2026** | **Phase 2 GHG 2027+** |
|---|---|---|---|---|---|---|---|---|---|
| **High-roof sleeper cabs** | Steer tire | Base | 7.8 | 100% | 10% | 10% | 5% | 5% | 5% |
| | | 1 | 6.6 | 0% | 70% | 70% | 35% | 15% | 10% |
| | | 2 | 5.7 | 0% | 20% | 20% | 50% | 60% | 50% |
| | | 3 | 4.9 | 0% | 0% | 0% | 10% | 20% | 35% |
| | | **Avg Crr [kg/metric ton]** | | **7.8** | **6.54** | **6.54** | **6.04** | **5.78** | **5.615** |
| | Drive tire | Base | 8.1 | 100% | 10% | 10% | 5% | 5% | 5% |
| | | 1 | 6.9 | 0% | 70% | 70% | 35% | 15% | 10% |
| | | 2 | 6.0 | 0% | 20% | 20% | 50% | 60% | 50% |
| | | 3 | 5.0 | 0% | 0% | 0% | 10% | 20% | 35% |
| | | **Avg Crr [kg/metric ton]** | | **8.1** | **6.84** | **6.84** | **6.32** | **6.04** | **5.845** |
| | Trailer tire | 1 | 6.5 | 0% | 0% | 0% | 0% | 0% | 0% |
| | | 2 | 6.0 | 100% | 100% | 0% | 0% | 0% | 5% |
| | | 3 | 5.1 | 0% | 0% | 100% | 0% | 0% | 0% |
| | | 4 | 4.7 | 0% | 0% | 0% | 100% | 100% | 95% |
| | | **Avg Crr [kg/metric ton]** | | **6.0** | **6.0** | **5.1** | **4.7** | **4.7** | **4.765** |
| **Low- and mid-roof sleeper cabs** | Steer tire | Base | 7.8 | 100% | 30% | 30% | 5% | 5% | 5% |
| | | 1 | 6.6 | 0% | 60% | 60% | 35% | 25% | 20% |
| | | 2 | 5.7 | 0% | 10% | 10% | 50% | 55% | 50% |
| | | 3 | 4.9 | 0% | 0% | 0% | 10% | 15% | 25% |
| | | **Avg Crr [kg/metric ton]** | | **7.8** | **6.87** | **6.87** | **6.04** | **5.91** | **5.785** |
| | Drive tire | Base | 8.1 | 100% | 30% | 30% | 15% | 10% | 5% |
| | | 1 | 6.9 | 0% | 60% | 60% | 35% | 25% | 10% |
| | | 2 | 6.0 | 0% | 10% | 10% | 50% | 65% | 85% |
| | | 3 | 5.0 | 0% | 0% | 0% | 0% | 0% | 0% |
| | | **Avg Crr [kg/metric ton]** | | **8.1** | **7.17** | **7.17** | **6.63** | **6.435** | **6.195** |
| | Trailer tire | 1 | 6.5 | 100% | 100% | 100% | 0% | 0% | 0% |
| | | 2 | 6.0 | 0% | 0% | 0% | 0% | 0% | 0% |
| | | 3 | 5.1 | 0% | 0% | 0% | 100% | 100% | 0% |
| | | 4 | 4.7 | 0% | 0% | 0% | 0% | 0% | 100% |
| | | **Avg Crr [kg/metric ton]** | | **6.5** | **6.5** | **6.5** | **5.1** | **4.7** | **4.7** |
| **Hi** | St | Base | 7.8 | 100% | 30% | 30% | 5% | 5% | 5% |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 6.6 | 0% | 60% | 60% | 35% | 15% | 10% |
| | | 2 | 5.7 | 0% | 10% | 10% | 50% | 60% | 50% |
| | | 3 | 4.9 | 0% | 0% | 0% | 10% | 20% | 35% |
| | | **Avg Crr [kg/metric ton]** | | **7.8** | **6.87** | **6.87** | **6.04** | **5.78** | **5.615** |
| | Drive tire | Base | 8.1 | 100% | 30% | 30% | 5% | 5% | 5% |
| | | 1 | 6.9 | 0% | 60% | 60% | 35% | 15% | 10% |
| | | 2 | 6.0 | 0% | 10% | 10% | 50% | 60% | 50% |
| | | 3 | 5.0 | 0% | 0% | 0% | 10% | 20% | 35% |
| | | **Avg Crr [kg/metric ton]** | | **8.1** | **7.17** | **7.17** | **6.32** | **6.04** | **5.845** |
| | Trailer tire | 1 | 6.5 | 0% | 0% | 100% | 0% | 0% | 0% |
| | | 2 | 6.0 | 100% | 100% | 0% | 0% | 0% | 0% |
| | | 3 | 5.1 | 0% | 0% | 0% | 0% | 0% | 0% |
| | | 4 | 4.7 | 0% | 0% | 0% | 100% | 100% | 100% |
| | | **Avg Crr [kg/metric ton]** | | **6.0** | **6.0** | **5.1** | **4.7** | **4.7** | **4.7** |
| **Low-roof day cabs** | Steer tire | Base | 7.8 | 100% | 40% | 40% | 5% | 5% | 5% |
| | | 1 | 6.6 | 0% | 50% | 50% | 35% | 25% | 20% |
| | | 2 | 5.7 | 0% | 10% | 10% | 50% | 55% | 50% |
| | | 3 | 4.9 | 0% | 0% | 0% | 10% | 15% | 25% |
| | | **Avg Crr [kg/metric ton]** | | **7.8** | **6.99** | **6.99** | **6.04** | **5.91** | **5.785** |
| | Drive tire | Base | 8.1 | 100% | 40% | 40% | 15% | 10% | 5% |
| | | 1 | 6.9 | 0% | 50% | 50% | 35% | 25% | 10% |
| | | 2 | 6.0 | 0% | 10% | 10% | 50% | 65% | 85% |
| | | 3 | 5.0 | 0% | 0% | 0% | 0% | 0% | 0% |
| | | **Avg Crr [kg/metric ton]** | | **8.1** | **7.29** | **7.29** | **6.63** | **6.435** | **6.195** |
| | Trailer tire | 1 | 6.5 | 100% | 100% | 100% | 0% | 0% | 0% |
| | | 2 | 6.0 | 0% | 0% | 0% | 0% | 0% | 0% |
| | | 3 | 5.1 | 0% | 0% | 0% | 100% | 100% | 0% |
| | | 4 | 4.7 | 0% | 0% | 0% | 0% | 0% | 100% |
| | | **Avg Crr [kg/metric ton]** | | **6.5** | **6.5** | **6.5** | **5.1** | **4.7** | **4.7** |
| **Vocational tractors** | Steer tire | Base | 7.8 | 100% | 10% | 10% | 5% | 5% | 5% |
| | | 1 | 6.6 | 0% | 70% | 70% | 35% | 15% | 10% |
| | | 2 | 5.7 | 0% | 20% | 20% | 50% | 60% | 50% |
| | | 3 | 4.9 | 0% | 0% | 0% | 10% | 20% | 35% |
| | | **Avg Crr [kg/metric ton]** | | **7.8** | **6.54** | **6.54** | **6.04** | **5.78** | **5.615** |
| | Drive tire | Base | 8.1 | 100% | 10% | 10% | 5% | 5% | 5% |
| | | 1 | 6.9 | 0% | 70% | 70% | 35% | 15% | 10% |
| | | 2 | 6.0 | 0% | 20% | 20% | 50% | 60% | 50% |
| | | 3 | 5.0 | 0% | 0% | 0% | 10% | 20% | 35% |
| | | **Avg Crr [kg/metric ton]** | | **8.1** | **6.84** | **6.84** | **6.32** | **6.04** | **5.845** |
| | Trailer tire | 1 | 6.5 | 6.5 | 100% | 100% | 100% | 0% | 0% |
| | | 2 | 6.0 | 6.0 | 0% | 0% | 0% | 0% | 0% |
| | | 3 | 5.1 | 5.1 | 0% | 0% | 0% | 100% | 100% |
| | | 4 | 4.7 | 4.7 | 0% | 0% | 0% | 0% | 0% |
| | | **Avg Crr [kg/metric ton]** | | **6.5** | **6.5** | **6.5** | **5.1** | **4.7** | **4.7** |

The average Crr values of each tire type were weighted based on a typical loading of a heavy-duty vehicle – 42.5 percent over the trailer axle, 42.5 percent over the drive axle, and 15 percent over the steer axle.[n] The result is shown below:

*Table 15-14 $C_{rr}$ [kg/metric ton] by tractor category*

| | **Pre-2014** | **2014-2017** | **2018-2020** | **2021-2023** | **2024-2026** | **2027+** |
|---|---|---|---|---|---|---|
| High-roof sleeper cab | 7.163 | 6.438 | 6.056 | 5.590 | 5.432 | 5.352 |
| High-roof day cab | 7.163 | 6.628 | 6.245 | 5.590 | 5.432 | 5.324 |
| Low and Mid-roof sleeper cab | 7.375 | 6.840 | 6.245 | 5.891 | 5.619 | 5.498 |
| Low-roof day cab | 7.375 | 6.909 | 6.314 | 5.891 | 5.619 | 5.498 |
| Vocational tractor | 7.375 | 6.909 | 6.314 | 5.935 | 5.679 | 5.515 |

Using the roof height distributions in Table 15-10, the resulting Crr values are:

*Table 15-15 $C_{rr}$ [kg/metric ton] values by model year group*

| | **Pre-2014** | **2014-2018** | **2018-2020** | **2021-2023** | **2024-2026** | **2027+** |
|---|---|---|---|---|---|---|
| Sleeper cab (sourceType 62) | 7.2050 | 7.2050 | 6.5185 | 6.0935 | 5.6499 | 5.4690 |
| Day cab (sourceType 61) | 7.2794 | 7.2794 | 6.7826 | 6.2832 | 5.7589 | 5.5393 |

To calculate the A coefficient, Equation 34 was used in combination with the source mass values and Crr values from Table 15-15.

*Table 15-16 A coefficient values [kW-s/m] by model year group*

| | **Pre-2014** | **2014-2018** | **2018-2020** | **2021-2023** | **2024-2026** | **2027+** |
|---|---|---|---|---|---|---|
| Sleeper cab (sourceType 62) | 1.739 | 1.562 | 1.464 | 1.358 | 1.317 | 1.298 |
| Day cab (sourceType 61) | 1.641 | 1.519 | 1.408 | 1.291 | 1.242 | 1.215 |

The average road load coefficients are updated by source type and regulatory class through the beginModelYearID and endModelYearID fields in the SourceUseTypePhysics table.

##### 15.2.2.3. Heavy-Duty Source Types other than Combination Trucks for Model Years 2014-2060

For buses, refuse trucks, motor homes and long-haul and short-haul single-unit trucks (sourceTypeIDs 41 through 54), the *A* coefficient values determined through tire rolling resistance reductions projected in the HD GHG Phase 1[83] and Phase 2[74] rulemakings were used directly. The aerodynamic drag coefficient (*C* coefficient) was not updated for these heavy-duty vehicles because no significant improvements in *C* coefficients is expected from the Phase 2 standards.[91]

The final road load coefficients for all regulatory classes and sourcetypes in MOVES201X are shown in Table 15-17.

[n] This distribution is equivalent to the federal over-axle weight limits for an 80,000 GVWR 5-axle tractor-trailer: 12,000 pounds over the steer axle, 34,000 pounds over the tandem drive axles (17,000 pounds per axle) and 34,000 pounds over the tandem trailer axles (17,000 pounds per axle).

*Table 15-17 MOVES201X SourceUseTypePhysics table*

| regClassID | sourceTypeID | Begin Model Year | End Model Year | Rolling Term A (kW-s/m) | Rotating Term B ($kW\text{-}s^2/m^2$) | Drag Term C ($kW\text{-}s^3/m^3$) | Source Mass (metric tons) | Fixed Mass Factor (metric tons) |
|---|---|---|---|---|---|---|---|---|
| 10 | 11 | 1960 | 2060 | 0.0251 | 0 | 0.0003 | 0.2850 | 0.2850 |
| 20 | 21 | 1960 | 2060 | 0.1565 | 0.0020 | 0.0005 | 1.4788 | 1.4788 |
| 30, 40 | 31 | 1960 | 2060 | 0.2211 | 0.0028 | 0.0007 | 1.8669 | 1.8669 |
| | 32 | 1960 | 2060 | 0.2350 | 0.0030 | 0.0007 | 2.0598 | 2.0598 |
| 42, 46, 47 | 41 | 1960 | 2013 | 1.2952 | 0 | 0.0037 | 19.5937 | 17.1 |
| | | 2014 | 2020 | 1.2304 | 0 | 0.0037 | 19.5937 | 17.1 |
| | | 2021 | 2023 | 1.0065 | 0 | 0.0037 | 19.5937 | 17.1 |
| | | 2024 | 2026 | 0.9745 | 0 | 0.0037 | 19.5937 | 17.1 |
| | | 2027 | 2060 | 0.9265 | 0 | 0.0037 | 19.5937 | 17.1 |
| 42, 46, 47, 48 | 42 | 1960 | 2013 | 1.0944 | 0 | 0.0036 | 16.5560 | 17.1 |
| | | 2014 | 2020 | 1.0397 | 0 | 0.0036 | 16.5560 | 17.1 |
| | | 2021 | 2023 | 1.0397 | 0 | 0.0036 | 16.5560 | 17.1 |
| | | 2024 | 2026 | 1.0397 | 0 | 0.0036 | 16.5560 | 17.1 |
| | | 2027 | 2060 | 0.9139 | 0 | 0.0036 | 16.5560 | 17.1 |
| 41 | 43 | 1960 | 2013 | 0.7467 | 0 | 0.0022 | 9.0699 | 17.1 |
| | 43 | 2014 | 2060 | 0.7094 | 0 | 0.0022 | 9.0699 | 17.1 |
| 42, 46, 47 | 43 | 1960 | 2013 | 0.7467 | 0 | 0.0022 | 9.0699 | 17.1 |
| | | 2014 | 2020 | 0.7094 | 0 | 0.0022 | 9.0699 | 17.1 |
| | | 2021 | 2023 | 0.6377 | 0 | 0.0022 | 9.0699 | 17.1 |
| | | 2024 | 2026 | 0.6037 | 0 | 0.0022 | 9.0699 | 17.1 |
| | | 2027 | 2060 | 0.5696 | 0 | 0.0022 | 9.0699 | 17.1 |
| 41 | 51 | 1960 | 2013 | 1.5835 | 0 | 0.0036 | 23.1135 | 17.1 |
| | 51 | 2014 | 2060 | 1.5043 | 0 | 0.0036 | 23.1135 | 17.1 |
| 42, 46, 47 | 51 | 1960 | 2013 | 1.5835 | 0 | 0.0036 | 23.1135 | 17.1 |
| | | 2014 | 2020 | 1.5043 | 0 | 0.0036 | 23.1135 | 17.1 |
| | | 2021 | 2023 | 1.5043 | 0 | 0.0036 | 23.1135 | 17.1 |
| | | 2024 | 2026 | 1.5043 | 0 | 0.0036 | 23.1135 | 17.1 |
| | | 2027 | 2060 | 1.3223 | 0 | 0.0036 | 23.1135 | 17.1 |
| 41 | 52 | 1960 | 2013 | 0.6279 | 0 | 0.0016 | 8.5390 | 17.1 |
| | 52 | 2014 | 2060 | 0.5965 | 0 | 0.0016 | 8.5390 | 17.1 |
| 42, 46, 47 | 52 | 1960 | 2013 | 0.6279 | 0 | 0.0016 | 8.5390 | 17.1 |
| | | 2014 | 2020 | 0.5965 | 0 | 0.0016 | 8.5390 | 17.1 |
| | | 2021 | 2023 | 0.5583 | 0 | 0.0016 | 8.5370 | 17.1 |
| | | 2024 | 2026 | 0.5583 | 0 | 0.0016 | 8.5342 | 17.1 |
| | | 2027 | 2060 | 0.5357 | 0 | 0.0016 | 8.5315 | 17.1 |
| | 53 | 1960 | 2013 | 0.5573 | 0 | 0.0015 | 6.9845 | 17.1 |
| | 53 | 2014 | 2060 | 0.5294 | 0 | 0.0015 | 6.9845 | 17.1 |
| 42, 46, 47 | 53 | 1960 | 2013 | 0.5573 | 0 | 0.0015 | 6.9845 | 17.1 |
| | | 2014 | 2020 | 0.5294 | 0 | 0.0015 | 6.9845 | 17.1 |
| | | 2021 | 2023 | 0.4849 | 0 | 0.0015 | 6.9809 | 17.1 |
| | | 2024 | 2026 | 0.4590 | 0 | 0.0015 | 6.9738 | 17.1 |
| | | 2027 | 2060 | 0.4590 | 0 | 0.0015 | 6.9666 | 17.1 |

| regClassID | sourceTypeID | Begin Model Year | End Model Year | Rolling Term A (kW-s/m) | Rotating Term B ($kW\text{-}s^2/m^2$) | Drag Term C ($kW\text{-}s^3/m^3$) | Source Mass (metric tons) | Fixed Mass Factor (metric tons) |
|---|---|---|---|---|---|---|---|---|
| 42, 46, 47 | 54 | 1960 | 2013 | 0.6899 | 0 | 0.0021 | 7.5257 | 17.1 |
| | | 2014 | 2020 | 0.6554 | 0 | 0.0021 | 7.5257 | 17.1 |
| | | 2021 | 2023 | 0.5191 | 0 | 0.0021 | 7.5257 | 17.1 |
| | | 2024 | 2026 | 0.5191 | 0 | 0.0021 | 7.5257 | 17.1 |
| | | 2027 | 2060 | 0.4935 | 0 | 0.0021 | 7.5257 | 17.1 |
| 46, 47 | 61 | 1960 | 2007 | 1.6406 | 0 | 0.00408 | 22.9745 | 17.1 |
| | 61 | 2008 | 2013 | 1.6406 | 0 | 0.00408 | 22.9745 | 17.1 |
| | 61 | 2014 | 2017 | 1.5190 | 0 | 0.00374 | 22.8289 | 17.1 |
| | 61 | 2018 | 2020 | 1.4078 | 0 | 0.00369 | 22.8393 | 17.1 |
| | 61 | 2021 | 2023 | 1.2908 | 0 | 0.00350 | 22.8484 | 17.1 |
| | 61 | 2024 | 2026 | 1.2416 | 0 | 0.00342 | 22.8484 | 17.1 |
| | 61 | 2027 | 2060 | 1.2151 | 0 | 0.00337 | 22.8484 | 17.1 |
| | 62 | 1960 | 2007 | 1.7388 | 0 | 0.00435 | 24.6010 | 17.1 |
| | 62 | 2008 | 2013 | 1.7388 | 0 | 0.00428 | 24.6010 | 17.1 |
| | 62 | 2014 | 2017 | 1.5615 | 0 | 0.00381 | 24.4196 | 17.1 |
| | 62 | 2018 | 2020 | 1.4635 | 0 | 0.00370 | 24.4831 | 17.1 |
| | 62 | 2021 | 2023 | 1.3585 | 0 | 0.00344 | 24.5099 | 17.1 |
| | 62 | 2024 | 2026 | 1.3173 | 0 | 0.00319 | 24.5530 | 17.1 |
| | 62 | 2027 | 2060 | 1.2976 | 0 | 0.00294 | 24.5829 | 17.1 |

# 16. Air Conditioning Activity Inputs

This report describes three inputs used in determining the impact of air conditioning on emissions. The ACPenetrationFraction is the fraction of vehicles equipped with air conditioning. FunctioningACFraction describes the fraction of these vehicles in which the air conditioning system is working correctly. The ACActivityTerms relate air conditioning use to local heat and humidity. These factors have not been updated for MOVES201X. More information on air conditioning effects is provided in the MOVES technical report on adjustment factors.[92]

## 16.1. ACPenetrationFraction

The ACPenetrationFraction is a field in the SourceTypeModelYear table that describes the fraction of vehicles equipped with air conditioning. Default values, by source type and model year were taken from MOBILE6.[93] Market penetration data by model year were gathered from Ward's Automotive Handbook for light-duty vehicles and light-duty trucks for model years 1972 through the 1995 for cars, and 1975-1995 for light trucks. Rates in the first few years of available data are quite variable, so values for early model years were estimated by applying the 1972 and 1975 rates for cars and trucks, respectively. Projections beyond 1995 were developed by calculating the average yearly rate of increase in the last five years of data and applying this rate until a predetermined cap was reached. A cap of 98 percent was placed on cars and 95 percent on trucks under the assumption that there will always be vehicles sold without air conditioning, more likely trucks than cars. No data was available on heavy-duty trucks. While VIUS asks if trucks are equipped with A/C, "no response" was coded the same as "no," making the data unusable for this purpose. For MOVES, the light-duty vehicle rates were applied to passenger cars, and the light-duty truck rates were applied to all other source types (except motorcycles, for which A/C penetration is assumed to be zero), as summarized in Table 16-1.

*Table 16-1 AC penetration fractions in MOVES*

| | Motorcycles | Passenger Cars | All Trucks and Buses |
|---|---|---|---|
| 1972-and-earlier | 0 | 0.592 | 0.287 |
| 1973 | 0 | 0.726 | 0.287 |
| 1974 | 0 | 0.616 | 0.287 |
| 1975 | 0 | 0.631 | 0.287 |
| 1976 | 0 | 0.671 | 0.311 |
| 1977 | 0 | 0.720 | 0.351 |
| 1978 | 0 | 0.719 | 0.385 |
| 1979 | 0 | 0.694 | 0.366 |
| 1980 | 0 | 0.624 | 0.348 |
| 1981 | 0 | 0.667 | 0.390 |
| 1982 | 0 | 0.699 | 0.449 |
| 1983 | 0 | 0.737 | 0.464 |
| 1984 | 0 | 0.776 | 0.521 |
| 1985 | 0 | 0.796 | 0.532 |
| 1986 | 0 | 0.800 | 0.544 |
| 1987 | 0 | 0.755 | 0.588 |
| 1988 | 0 | 0.793 | 0.640 |
| 1989 | 0 | 0.762 | 0.719 |
| 1990 | 0 | 0.862 | 0.764 |
| 1991 | 0 | 0.869 | 0.771 |
| 1992 | 0 | 0.882 | 0.811 |
| 1993 | 0 | 0.897 | 0.837 |
| 1994 | 0 | 0.922 | 0.848 |
| 1995 | 0 | 0.934 | 0.882 |
| 1996 | 0 | 0.948 | 0.906 |
| 1997 | 0 | 0.963 | 0.929 |
| 1998 | 0 | 0.977 | 0.950 |
| 1999+ | 0 | 0.980 | 0.950 |

## 16.2. FunctioningACFraction

The FunctioningACFraction field in the SourceTypeAge table (see Table 16-2) indicates the fraction of the air-conditioning-equipped fleet with fully functional A/C systems, by source type and vehicle age. A value of one means all systems are functional. This is used in the calculation of total energy to account for vehicles without functioning A/C systems. Default estimates were developed for all source types using the "unrepaired malfunction" rates used for 1992-and-later model years in MOBILE6. The MOBILE6 rates were based on the average rate of A/C system failure by age reported in the 1997 Consumer Reports Magazine Automobile Purchase Issue and assumptions about repair frequency during and after the warranty period. The MOBILE6 rates were applied to all source types except motorcycles, which were assigned a value of zero for all years.

*Table 16-2 FunctioningACFraction by age (for all source types except motorcycles)*

| ageID | functioningACFraction |
|---|---|
| 0 | 1 |
| 1 | 1 |
| 2 | 1 |
| 3 | 1 |
| 4 | 0.99 |
| 5 | 0.99 |
| 6 | 0.99 |
| 7 | 0.99 |
| 8 | 0.98 |
| 9 | 0.98 |
| 10 | 0.98 |
| 11 | 0.98 |
| 12 | 0.98 |
| 13 | 0.96 |
| 14 | 0.96 |
| 15 | 0.96 |
| 16 | 0.96 |
| 17 | 0.96 |
| 18 | 0.95 |
| 19 | 0.95 |
| 20 | 0.95 |
| 21 | 0.95 |
| 22 | 0.95 |
| 23 | 0.95 |
| 24 | 0.95 |
| 25 | 0.95 |
| 26 | 0.95 |
| 27 | 0.95 |
| 28 | 0.95 |
| 29 | 0.95 |
| 30 | 0.95 |

## 16.3. ACActivityTerms

In the MonthGroupHour table, ACActivityTerms A, B, and C are coefficients for a quadratic equation that calculates air conditioning activity demand as a function of the heat index. These terms are applied in the calculation of the A/C adjustment in the energy consumption calculator. The methodology and the terms themselves were originally derived for MOBILE6 and are documented in the report, *Air Conditioning Activity Effects in MOBILE6*.[93] They are based on analysis of air conditioning usage data collected in Phoenix, Arizona, in 1994.

In MOVES, ACActivityTerms are allowed to vary by monthGroup and Hour, in order to provide the possibility of different A/C activity demand functions at a given heat index by season and time of day (this accounts for differences in solar loading observed in the original data). However, the default data uses one set of coefficients for all MonthGroups and Hours. These default coefficients represent an average A/C activity demand function over the course of a full day. The coefficients are listed in Table 16-3.

*Table 16-3 Air conditioning activity coefficients*

| A | B | C |
|---|---|---|
| -3.63154 | 0.072465 | -0.000276 |

The A/C activity demand function that results from these coefficients is shown in Figure 16-1. A value of 1 means the A/C compressor is engaged 100 percent of the time; a value of 0 means no A/C compressor engagement.

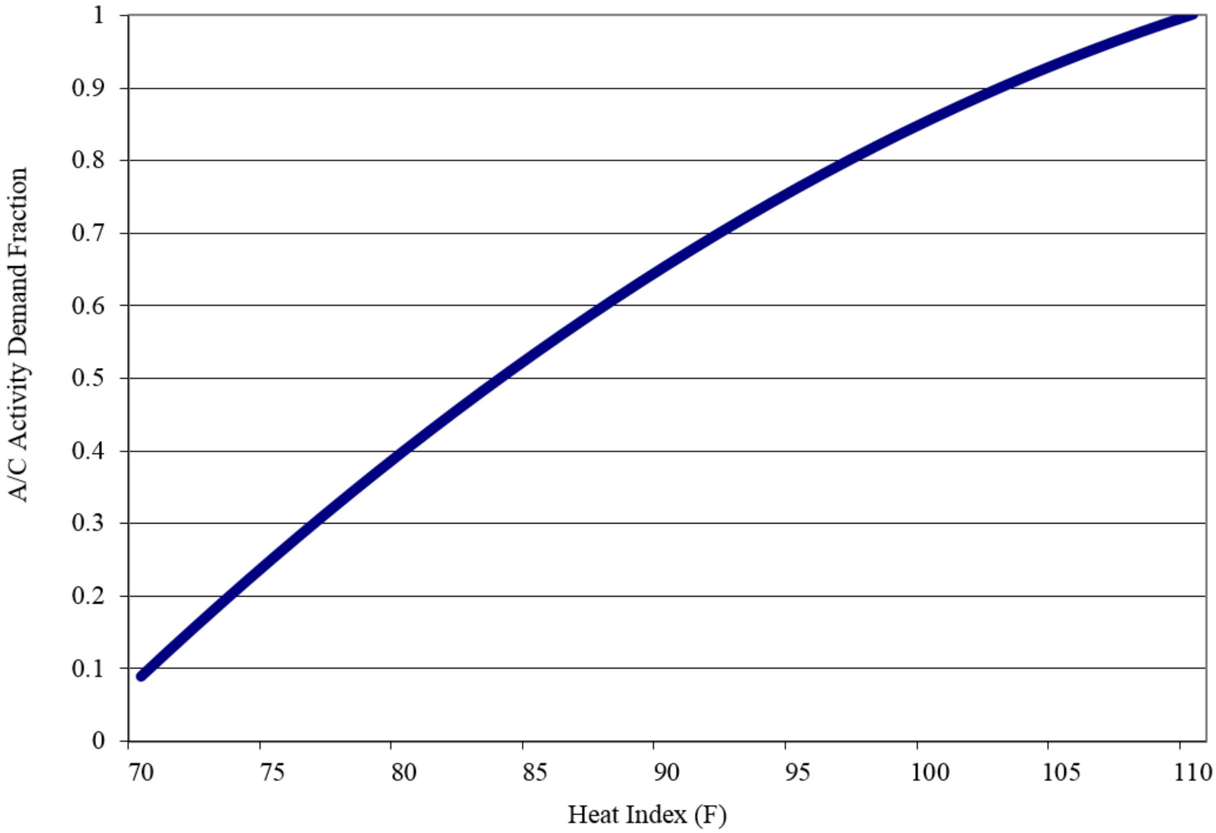


*Figure 16-1 Air conditioning activity demand as a function of heat index*

# 17.Conclusion and Areas for Future Research

Properly characterizing emissions from vehicles requires a detailed understanding of the cars and trucks that make up the vehicle fleet and their patterns of operation. The national default information in MOVES201X provide a reliable basis for estimating national emissions. The most important of these inputs are well-established: base year VMT and population estimates come from long-term, systematic national measurements by US Department of Transportation. The relevant characteristics for prevalent vehicle classes are well-known; base year age distributions are well-measured, and driving activity has been the subject of much study in recent years. We also work to evaluate MOVES performance, including the population and activity defaults.

Still, the fleet and activity inputs do have significant limitations. In particular, local variations from the national defaults can contribute to discrepancies in resulting emission estimates. Thus, it is often appropriate to replace many of the MOVES fleet and activity defaults with local data as explained in EPA's Technical Guidance.[2]

The fleet and activity defaults also are limited by the necessity of forecasting future emissions. EPA utilizes annual US Department of Energy forecasts of vehicle sales and activity. The inputs for MOVE201X were developed for a 2015 base year and much of the source data is from 2015 and earlier. This information needs to be updated periodically to assure that the model defaults reflect the latest available data and projections on the US fleet.

Moreover, for data that is specific to MOVES, we are also limited by available staff and funding. Collecting data on vehicle fleet and activity is expensive, especially when the data is intended to accurately represent the entire United States. Even when EPA does not generate data directly (for example, compilations of state vehicle registration data), obtaining the information needed for MOVES can be costly and, thus, dependent on budget choices.

With this in mind, future updates to vehicle population and activity defaults will need to continue to focus on the vehicles that contribute the most air pollution nationally, namely gasoline light-duty cars and trucks, and common diesel heavy-duty trucks. Information collection on motorcycles, refuse trucks, motor homes, diesel light-duty vehicles, and gasoline heavy-duty vehicles will be a lower priority. Similarly, in addition to updating the model defaults, we will need to consider whether the current MOVES design continues to meet our modeling needs. Simplifications to the model to remove categories, such as source types or road types, might simplify data collection and make noticeable improvements in run time without affecting the validity of fleet-wide emission estimates.

In addition to these general limitations, there are also specific MOVES data elements that could be improved with additional research, including:

- Updates to the trip information used to generate evaporative activity to be consistent with the new engine start and soak distributions based on the telematics data; this will likely require modification to the MOVES code as well as updates to the default database.
- Incorporation of existing data from a recent CRC study (XX CRC A-100 add citation) that provided local data for hourly speeds and VMT distributions by MOVES source

use types--this data could be summarized nationally to update the MOVES default distributions;

- Updated real-world highway driving cycles and operating mode distributions, including incorporating ramp activity into the default highway driving cycles;
- Additional instrumented vehicle data from a wider sample of heavy duty vehicles to better characterize off-network behavior including vehicle starts and soaks;
- Improved information on truck hotelling durations, locations and temporal distributions, particularly extended engine idling and APU use;
- VSP/STP adjustments for road grade and vehicle load;
- Better data on activity changes with age, such as mileage accumulation rates, start activity, and soak distributions. Telematics will provide important insights here, but gathering representative data for the oldest vehicles in the fleet will continue to be a challenge;
- Updated estimates of vehicle scrappage rates used to project vehicle age distributions;
- Updated air conditioning system usage, penetration, and failure rates;
- Finer vehicle type distinctions in temporal activity and road type distributions;

At the same time, the fundamental MOVES assumption that vehicle activity varies by source type and not by fuel type or other source bin characteristic may be challenged by the growing market share of alternative vehicles such as autonomous, shared and electric vehicles which may have distinct activity patterns. As we progress with MOVES, the development of vehicle population and activity inputs will continue to be an essential area of research.

# Appendix A Fuel Type and Regulatory Class Fractions from Previous Versions of MOVES

Fuel type and regulatory class distributions for most source types are described in Section 5.2. In MOVES201X, the fuel type and regulatory class distributions were unchanged from previous versions of the model for the following source type and model year combinations:

- Passenger cars, school buses, refuse trucks, short-haul and long-haul single-unit trucks, and all combination trucks prior to model year 2000
- Passenger trucks and light commercial trucks prior to model year 1981

This appendix describes the derivation of these fuel type and regulatory class distributions.

## Appendix A.1 Distributions for Model Years 1960-1981

The fuel type distributions between 1960 and 1981 for each source type have been summarized in Table 17-1 and Table 17-2. Truck diesel fractions in Table 17-1 were derived using the 1999 IHS vehicle registrations and the 1997 VIUS,[94] except for refuse trucks and motor homes. We assumed 96 percent of refuse trucks were manufactured to run on diesel fuel in 1980 and earlier according to the average diesel fraction from VIUS across all model years.

*Table 17-1 Diesel fractions for truck source types**

| | **Source Type** | | | | | |
|---|---|---|---|---|---|---|
| **Model Year** | **Passenger Trucks (31)** | **Light Commercial Trucks (32)** | **Refuse Trucks (51)** | **Single-Unit Trucks (52 & 53)** | **Short-Haul Combination Trucks (61)** | **Long-Haul Combination Trucks (62)** |
| 1960-1979 | 0.0139 | 0.0419 | 0.96 | 0.2655 | 0.9146 | 1.0000 |
| 1980 | 0.0124 | 0.1069 | 0.96 | 0.2950 | 0.9146 | 1.0000 |
| 1981 | 0.0178 | 0.0706 | 0.96 | 0.3245 | 0.9146 | 1.0000 |

Note:
*All other trucks are assumed to be gasoline-powered. Motor homes do not appear in this table because MOVES201X did not use the previous analysis for that source type.

For the non-truck source types, school bus fuel type fractions were reused from MOBILE6, originally based on 1996 and 1997 IHS data,[95] and passenger cars were split between gasoline and diesel for 1960-1981 using the 1999 IHS vehicle registrations data set. As in previous versions of MOVES, motorcycles were assumed to be all gasoline.

*Table 17-2 Diesel fractions for non-truck source types**

| | Source Type | | |
|---|---|---|---|
| **Model Year** | **Motorcycles(11)** | **Passenger Cars (21)** | **School Buses (43)** |
| 1960-1974 | 0 | 0.0069 | 0.0087 |
| 1975 | 0 | 0.0180 | 0.0087 |
| 1976 | 0 | 0.0165 | 0.0086 |
| 1977 | 0 | 0.0129 | 0.0240 |
| 1978 | 0 | 0.0151 | 0.0291 |
| 1979 | 0 | 0.0312 | 0.0460 |
| 1980 | 0 | 0.0467 | 0.0594 |
| 1981 | 0 | 0.0764 | 0.2639 |

Note:
*All other vehicles are assumed to be gasoline-powered. Transit buses and other buses do not appear in this table because MOVES201X did not use the previous analysis for that source type.

The 1960-1981 regulatory class distributions were derived from the 1999 IHS data set and VIUS. Motorcycles (sourceTypeID 11 and regClassID 10) and passenger cars (sourceTypeID 21 and regClassID 20) have one-to-one relationships between source types and regulatory classes for all model years. Passenger trucks (sourceTypeID 31) and light commercial trucks (sourceTypeID 32) are split between fuel type and regulatory class (regClassID 30 and 40) as shown in Table 17-3.

*Table 17-3 Percentage by regulatory class and fuel type for passenger trucks (sourceTypeID 31) and light commercial truck (sourceTypeID 32)*

| | **Passenger Trucks (31)** | | | | **Light Commercial Trucks (32)** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Gasoline** | | **Diesel** | | **Gasoline** | | **Diesel** | |
| **Model Year** | **LDT (30)** | **LHD (40)** | **LDT (30)** | **LHD (40)** | **LDT (30)** | **LHD (40)** | **LDT (30)** | **LHD (40)** |
| 1960-1966 | 81% | 19% | 38% | 62% | 24% | 76% | 7% | 93% |
| 1967 | 90% | 10% | 38% | 62% | 72% | 28% | 7% | 93% |
| 1968 | 88% | 12% | 38% | 62% | 67% | 33% | 7% | 93% |
| 1969 | 100% | 0% | 38% | 62% | 91% | 9% | 7% | 93% |
| 1970 | 99% | 1% | 38% | 62% | 80% | 20% | 7% | 93% |
| 1971 | 96% | 3% | 38% | 62% | 94% | 6% | 7% | 93% |
| 1972 | 96% | 4% | 38% | 62% | 75% | 25% | 7% | 93% |
| 1973 | 95% | 5% | 38% | 62% | 59% | 41% | 7% | 93% |
| 1974 | 95% | 5% | 38% | 62% | 65% | 35% | 7% | 93% |
| 1975 | 97% | 3% | 38% | 62% | 72% | 28% | 7% | 93% |
| 1976 | 95% | 5% | 38% | 62% | 88% | 12% | 7% | 93% |
| 1977 | 89% | 11% | 38% | 62% | 79% | 21% | 7% | 93% |
| 1978 | 85% | 15% | 38% | 62% | 81% | 19% | 7% | 93% |
| 1979 | 87% | 13% | 38% | 62% | 78% | 22% | 7% | 93% |
| 1980 | 90% | 10% | 38% | 62% | 74% | 26% | 40% | 60% |
| 1981 | 96% | 4% | 38% | 62% | 89% | 11% | 12% | 88% |

The school bus regulatory class fractions were reused from MOBILE6, originally based on 1996 and 1997 IHS data. The 1960-1981 regulatory class distributions for diesel-fueled single-unit and combination trucks have been summarized in Table 17-4 below. All 1960-1981 gasoline-fueled single-unit and combination trucks fall into the medium heavy-duty (MHD) regulatory class (regClassID 46).

*Table 17-4 Percentange of MHD trucks (regClass 46) among diesel-fueled single-unit and combination trucks**

| **Model Year** | **Refuse Trucks (51)** | **Single-Unit Trucks (52 & 53)** | **Short-haul Combination Trucks (61)** | **Long-haul Combination Trucks (62)** |
|---|---|---|---|---|
| 1960-1972 | 100% | 0% | 0% | 0% |
| 1973 | 100% | 3% | 8% | 0% |
| 1974 | 0% | 6% | 30% | 0% |
| 1975 | 0% | 14% | 3% | 0% |
| 1976 | 0% | 44% | 13% | 0% |
| 1977 | 0% | 43% | 31% | 0% |
| 1978 | 0% | 36% | 18% | 0% |
| 1979 | 0% | 34% | 16% | 0% |
| 1980 | 0% | 58% | 29% | 5% |
| 1981 | 0% | 47% | 31% | 6% |

Note:
* For these source types, all remaining trucks are in the HHD regulatory class (regClassID 47)

## Appendix A.2 Distributions for Model Years 1982-1999

VIUS was our main source of information for determining fuel and regulatory class fractions for these model years. Table 17-5 summarizes how the VIUS2002 parameters were used to classify the VIUS data to calculate fuel and regulatory class fractions for the light-duty, single-unit, and combination truck source types.

Axle arrangement (AXLE_CONFIG) was used to define four categories: straight trucks with two axles and four tires (codes 1, 6, 7, 8), straight trucks with two axles and six tires (codes 2, 9, 10, 11), all straight trucks (codes 1-21), and all tractor-trailer combinations (codes 21+). Primary distance of operation (PRIMARY_TRIP) was used to define short-haul (codes 1-4) for vehicles with primary operation distances less than 200 miles and long-haul (codes 5-6) for 200 miles and greater. The VIN-decoded gross vehicle weight (ADM_GVW) and survey weight (VIUS_GVW) were used to distinguish vehicles less than 10,000 lbs. as light-duty and vehicles greater than or equal to 10,000 lbs. as heavy-duty. Any vehicle with two axles and at least six tires was considered a single-unit truck regardless of weight. We also note that refuse trucks have their own VIUS vocational category (BODYTYPE 21) and that MOVES distinguishes between personal (OPCLASS 5) and non-personal use.

*Table 17-5 VIUS2002 parameters used to distinguish trucks in previous versions of MOVES*

| Source Type | Axle Arrangement | Primary Distance of Operation | Weight | Body Type | Operator Class |
|---|---|---|---|---|---|
| Passenger Trucks | AXLE_CONFIG in (1,6,7,8)* | Any | ADM_GVW in (1,2) & VIUS_GVW in (1,2,3) | Any | OPCLASS =5 |
| Light Commercial Trucks | AXLE_CONFIG in (1,6,7,8)* | Any | ADM_GVW in (1,2) & VIUS_GVW in (1,2,3) | Any | OPCLASS ≠5 |
| Refuse Trucks** | AXLE_CONFIG in (2,9,10,11) | TRIP_PRIMARY in (1,2,3,4) | Any | BODYTYPE =21 | Any |
| | AXLE_CONFIG <=21 | TRIP_PRIMARY in (1,2,3,4) | ADM_GVW > 2 & VIUS_GVW > 3 | BODYTYPE =21 | Any |
| Single-Unit Short-Haul Trucks** | AXLE_CONFIG in (2,9,10,11) | TRIP_PRIMARY in (1,2,3,4) | Any | BODYTYPE ≠21 | Any |
| | AXLE_CONFIG <=21 | TRIP_PRIMARY in (1,2,3,4) | ADM_GVW > 2 & VIUS_GVW > 3 | BODYTYPE ≠21 | Any |
| Single-Unit Long-Haul Trucks** | AXLE_CONFIG in (2,9,10,11) | TRIP_PRIMARY in (5,6) | Any | Any | Any |
| | AXLE_CONFIG <=21 | TRIP_PRIMARY in (5,6) | ADM_GVW > 2 & VIUS_GVW > 3 | Any | Any |
| Combination Short-Haul Trucks | AXLE_CONFIG >=21 | TRIP_PRIMARY in (1,2,3,4) | Any | Any | Any |
| Combination Long-Haul Trucks | AXLE_CONFIG >=21 | TRIP_PRIMARY in (5,6) | Any | Any | Any |

Notes:

* In the MOVES2014 analysis, we did not constrain axle configuration of light-duty trucks, so there are some, albeit very few, light-duty trucks that have three axles or more and/or six tires or more. These vehicles are classified as light-duty trucks based primarily on their weight. Only 0.27 percent of light-duty trucks have such tire and/or axle parameters and they have a negligible impact on vehicle populations and emissions.

** For a source type with multiple rows, the source type is applied to any vehicle with either set of parameters.

## Appendix A.2.1 Source Type Definitions

Motorcycles and passenger cars in MOVES borrow vehicle definitions from the FHWA Highway Performance Monitoring System (HPMS) classifications from the *Highway Statistics* Table MV-1. Source type definitions for school buses are taken from various US Department of Transportation sources. While refuse trucks were identified and separated from other single-unit trucks in VIUS, motor homes were not.

### Appendix A.2.2.1 Light-Duty Trucks

Light-duty trucks include pickups, sport utility vehicles (SUVs), and vans.[19] Depending on use and GVWR, we categorize them into two different MOVES source types: 1) passenger trucks (sourceTypeID 31), and 2) light commercial trucks (sourceTypeID 32). FHWA's vehicle classification specifies that light-duty vehicles are those weighing less than 10,000 pounds, specifically vehicles with a GVWR in Class 1 and 2, except Class 2b trucks with two axles or more and at least six tires are assigned to the single-unit truck category.

VIUS contains many survey questions on weight; we chose to use both a VIN-decoded gross vehicle weight rating (ADM_GVW) and a respondent self-reported GVWR (VIUS_GVW) to differentiate between light-duty and single-unit trucks. For the passenger trucks, there is a final VIUS constraint that the most frequent operator classification (OPCLASS) must be personal transportation. Inversely, light commercial trucks (sourceTypeID 32) have a VIUS constraint that their most frequent operator classification must not be personal transportation.

#### Appendix A.2.2.2 Buses

Previous versions of MOVES had three bus source types: intercity (sourceTypeID 41), transit (sourceTypeID 42), and school buses (sourceTypeID 43). Since the definition of sourceTypeIDs 41 and 42 changed in MOVES201X, only school bus distributions for model years prior to 2000 were retained in MOVES201X. According to FHWA, school buses are defined as vehicles designed to carry more than ten passengers, used to transport K-12 students between their home and school.

#### Appendix A.2.2.3 Single-Unit Trucks

The single-unit HPMS class in MOVES consists of refuse trucks (sourceTypeID 51), short-haul single-unit trucks (sourceTypeID 52), long-haul single-unit trucks (sourceTypeID 53), and motor homes (sourceTypeID 54). FHWA's vehicle classification specifies that a single-unit truck as a single-frame truck with a gross vehicle weight rating of greater than 10,000 pounds or with two axles and at least six tires—colloquially known as a "dualie." As with light-duty truck source types, single-unit trucks are sorted using VIUS parameters, in this case that includes axle configuration (AXLE_CONFIG) for straight trucks (codes 1-21), vehicle weight (both ADM_GVW and VIUS_GVW), most common trip distance (TRIP_PRIMARY), and body type (BODYTYPE). All short-haul single-unit trucks must have a primary trip distance of 200 miles or less and must not be refuse trucks and all long-haul trucks must have a primary trip distance of greater than 200 miles. Refuse trucks are short-haul single-unit trucks with a body type (code 21) for trash, garbage, or recyclable material hauling. Motor home distributions from previous versions of MOVES were not retained in MOVES201X.

#### Appendix A.2.2.4 Combination Trucks

A combination truck is any truck-tractor towing at least one trailer according to VIUS. MOVES divides these tractor-trailers into two MOVES source types: short-haul (sourceTypeID 61) and long-haul combination trucks (sourceTypeID 62). Like single-unit trucks, short-haul and long-haul combination trucks are distinguished by their primary trip length (TRIP_PRIMARY) in VIUS. If the tractor-trailer's primary trip length is equal to or less than 200 miles, then it is considered short-haul. If the tractor-trailer's primary trip length is greater than 200 miles, then it is considered long-haul. Short-haul combination trucks are older than long-haul combination trucks and these short-haul trucks often purchased in secondary markets, such as for drayage applications, after being used primarily for long-haul trips.[96]

### Appendix A.2.2 Fuel Type and Regulatory Class Distributions

The SampleVehiclePopulation table fractions were developed by EPA using the sample vehicle counts data set, which primarily joins calendar year 2011 registration data from IHS and the 2002 Vehicle Inventory and Use Survey (VIUS) results. The sample vehicle counts data set were generated by multiplying the 2011 IHS vehicle populations by the source type allocations from VIUS.

While VIUS provide source type classifications, we relied primarily on the 2011 IHS vehicle registration data set to form the basis of the fuel type and regulatory class distributions in the SampleVehiclePopulation table. The IHS data were provided with the following fields: vehicle type (cars or trucks), fuel type, gross vehicle weight rating (GVWR) for trucks, household vehicle counts, and work vehicle counts. We combined the household and work vehicle counts. The MOVES distinction between personal and commercial travel for light-duty trucks comes from VIUS.

The IHS records by FHWA truck weight class were grouped into MOVES GVWR-based regulatory classes, as shown in Table 17-6 below. As stated above, all passenger cars were assigned to regClassID 20. The mapping of weight class to regulatory class is straightforward with one notable exception: delineating trucks weighing more or less than 8,500 lbs.

*Table 17-6 Initial mapping from FHWA truck classes to MOVES regulatory classes*

| Vehicle Category | FHWA Truck Weight Class | Weight Range (lbs.) | regClassID |
|---|---|---|---|
| Trucks | 1 | < 6,000 | 30 |
| Trucks | 2a | 6,001 – 8,500 | 30* |
| Trucks | 2b | 8,501 – 10,000 | 41* |
| Trucks | 3 | 10,001 – 14,000 | 41 |
| Trucks | 4 | 14,001 – 16,000 | 42 |
| Trucks | 5 | 16,001 – 19,500 | 42* |
| Trucks | 6 | 19,501 – 26,000 | 46 |
| Trucks | 7 | 26,001 – 33,000 | 46 |
| Trucks | 8a | 33,001 – 60,000 | 47 |
| Trucks | 8b | > 60,001 | 47 |
| Cars | | | 20 |

Note:
*After the IHS data had been sorted into source types (described later in this section), some regulatory classes were merged or divided. Any regulatory class 41 vehicles in light-duty truck source types were reclassified into the new regulatory class 40 (see explanation in Section 2.3), any regulatory class 30 vehicles in single-unit truck source types were reclassified into regulatory class 41, and any regulatory class 42 vehicles in combination truck source types were reclassified into regulatory class 46.

Since the IHS dataset did not distinguish between Class 2a (6,001-8,500 lbs.) and Class 2b (8,501-10,000 lbs.) trucks, but MOVES regulatory classes 30, 40, and 41 all fall within Class 2, we needed a secondary data source to allocate the IHS gasoline and diesel trucks between Class 2a and 2b. We derived information from an Oak Ridge National Laboratory (ORNL) paper,[97] summarized in Table 17-7, to allocate the IHS Class 2 gasoline and diesel trucks into the regulatory classes. Class 2a trucks fall in regulatory class 30 and Class 2b trucks fall in either regulatory class 40 or 41.

*Table 17-7 Fractions used to distribute Class 2a and 2b trucks*[o]

| Truck Class | Fuel Type | |
|---|---|---|
| | **Gasoline** | **Diesel** |
| 2a | 0.808 | 0.255 |
| 2b | 0.192 | 0.745 |

Additionally, the IHS dataset includes a variety of fuels, some that are included in MOVES and others that are not. Only the IHS diesel, gasoline, or gasoline and another fuel were included in our analysis; all other alternative fuel vehicles were omitted. While MOVES2014 did model light-duty E-85 and electric vehicles, and compressed natural gas (CNG) transit buses, these relative penetrations of alternative fuel vehicles have been developed from secondary data sources rather than IHS because IHS excludes some government fleets and retrofit vehicles that could potentially be large contributors to these alternative fuel vehicle populations. Instead, we used flexible fuel vehicle sales data reported for EPA certification, and dedicated CNG bus populations from the National Transit Database. The Table 17-8 illustrates how IHS fuels were mapped to MOVES fuel types, and which IHS fuels were not used in MOVES.

The “N/A” mapping shown in Table 17-8 led us to discard 0.22 percent, roughly 530,000 vehicles (mostly dedicated or aftermarket alternative fuel vehicles), of IHS’s 2011 national fleet in developing the default fuel type fractions. However, because the MOVES national population is derived top-down from FHWA registration data, as outlined in Section 4.1, the total population is not affected. We considered the IHS vehicle estimates to be a sufficient sample for the fuel type and regulatory class distributions in the SampleVehiclePopulation table.

[o] Note, the values from the ORNL report were applied incorrectly in MOVES2014, leading to an overestimate in the fraction of gasoline and Class 2a trucks and an underestimate in the fraction of diesel and Class 2b trucks.

*Table 17-8 List of fuels from the IHS dataset used to develop MOVES fuel type distributions*

| IHS Fuel Type | MOVES fuelTypeID | MOVES Fuel Type |
|---|---|---|
| Unknown | N/A | |
| Undefined | N/A | |
| Both Gas and Electric | 1 | Gasoline |
| Gas | 1 | Gasoline |
| Gas/Elec | 1 | Gasoline |
| Gasoline | 1 | Gasoline |
| Diesel | 2 | Diesel |
| Natural Gas | N/A | |
| Compressed Natural Gas | N/A | |
| Natr.Gas | N/A | |
| Propane | N/A | |
| Flexible (Gasoline/Ethanol) | 1 | Gasoline |
| Flexible | 1 | Gasoline |
| Electric | N/A | |
| Cnvrtble | N/A | |
| Conversion | N/A | |
| Methanol | N/A | |
| Ethanol | 1 | Gasoline |
| Convertible | N/A | |

Next, we transformed the VIUS dataset into MOVES format. The VIUS vehicle data was first assigned to MOVES source types using the constraints in Table 17-5 and then to MOVES regulatory classes using the mapping described in Table 17-6, including the allocation between Class 2a and 2b trucks from the ORNL study in Table 17-7. Similar to our fuel type mapping of the IHS dataset, we chose to omit alternative fuel vehicles, as summarized below in Table 17-9.

*Table 17-9 Mapping of VIUS2002 fuel types to MOVES fuel types*

| VIUS Fuel Type | VIUS Fuel Code | MOVES fuelTypeID | MOVES Fuel Type |
|---|---|---|---|
| Gasoline | 1 | 1 | Gasoline |
| Diesel | 2 | 2 | Diesel |
| Natural gas | 3 | N/A | |
| Propane | 4 | N/A | |
| Alcohol fuels | 5 | N/A | |
| Electricity | 6 | N/A | |
| Gasoline and natural gas | 7 | 1 | Gasoline |
| Gasoline and propane | 8 | 1 | Gasoline |
| Gasoline and alcohol fuels | 9 | 1 | Gasoline |
| Gasoline and electricity | 10 | 1 | Gasoline |
| Diesel and natural gas | 11 | 2 | Diesel |
| Diesel and propane | 12 | 2 | Diesel |
| Diesel and alchol fuels | 13 | 2 | Diesel |
| Diesel and electricity | 14 | 2 | Diesel |
| Not reported | 15 | N/A | |
| Not applicable | 16 | N/A | |

This process yielded VIUS data by MOVES source type, model year, regulatory class, and fuel type. The VIUS source type distributions were calculated in a similar fashion to the SampleVehiclePopulation fractions discussed above for each regulatory class-fuel type-model year combination. Stated formally, for any given model year $i$, regulatory class $j$, and fuel type $k$, the source type population fraction $f$ for a specified source type $l$ will be the number of VIUS trucks $N$ in that source type divided by the sum of VIUS trucks across the set of all source types $L$. The source type population fraction is summarized in Equation 36:

$$f(VIUS)_{i,j,k,l} = \frac{N_{i,j,k,l}}{\sum_{l \epsilon L} N_{i,j,k,l}} \qquad \textbf{Equation 36}$$

The VIUS data in our analysis spanned model year 1986 to 2002. The 1986 distribution was used for all prior to MY 1986.

From there the source type distributions from VIUS were multiplied by the IHS vehicle populations to generate the sample vehicle counts by source type, as shown schematically in . Expressed in Equation 37, the sample vehicle counts are:

$$N(SVP)_{i,j,k,l} = P(Polk)_{i,j,k,l} \cdot f(VIUS)_{i,j,k,l}, \qquad \textit{Equation 37}$$

where $N$ is the number of vehicles used to generated the SampleVehiclePopulation table, $P$ is the 2011 IHS vehicle populations, and $f$ is the source type distributions from VIUS.

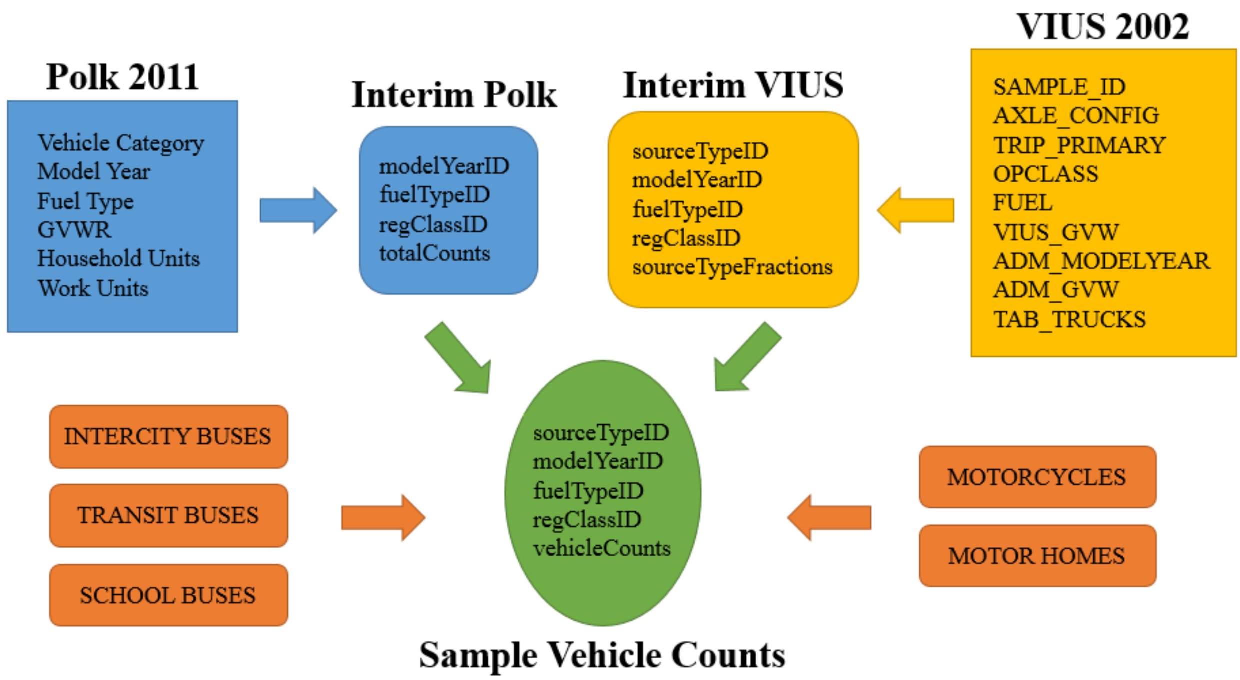


*Figure 17-1 Flowchart of data sources of fuel and regulatory class distributions for model years 1982-1999*

These sample vehicle counts by source type were then utilized to calculate the SVP fractions, stmyFraction and stmyFuelEngFraction, as defined above. All Class 2b and 3 trucks were initially assigned to regulatory class 41 until vehicles were sorted into source types. Once the sample vehicle counts were available by source type, any light-duty trucks (sourceTypeID 31 or 32) in the original LHD regulatory class less than 14,000 lbs. (regClassID 41) were reclassified in the new LHD regulatory class less than 10,000 lbs. (regClassID 40), whereas any heavy-duty vehicles (sourceTypeID 41 and above) remained in regClassID 41. Similarly, any single-unit trucks (sourceTypeID 52 and 53) in the LDT regulatory class (regClassID 30) were reclassified in regClassID 41 as heavy-duty vehicles. We also moved any regClassID 42 vehicles in combination truck source types to regClassID 46 because tractor-trailers must be either Class 7 or 8 trucks. This ensures a clean break between light- and heavy-duty emission results and that the emission calculations use the appropriate fixedMassFactor when calculating vehicle-specific power (VSP) for light-duty vehicles and scaled tractive power (STP) for heavy-duty vehicles.

As noted above, the initial sample vehicle counts dataset did not contain buses, so information on these source types was appended. In the subsections below, we have provided more detailed descriptions by source type.

### Appendix A.2.2.1 Motorcycles

The representation of motorcycles in the SampleVehiclePopulation table is straightforward. All motorcycles fall into the motorcycle regulatory class (regClassID 10) and must be fueled by gasoline.

### Appendix A.2.2.2 Passenger Cars

Any passenger car is considered to be in the light-duty vehicle regulatory class (regClassID 20). Cars were included in the IHS dataset purchased in 2012, and EPA's subsequent sample vehicle counts dataset, which provided the split between gasoline and diesel cars in the SampleVehiclePopulation table. Flexible fuel (E85-capable) cars were also included in the SVP fuel type distributions but added after the sample vehicle counts analysis. We assume that a flexible fuel vehicle would directly displace its gasoline counterpart. For model years 2011 and earlier, we used manufacturer reported sales to EPA in order to calculate the fraction of sales of flexible fuel cars among sales of all gasoline and flexible fuel cars and added those penetrations as the fraction of E85 (fuelTypeID 5) vehicles and deducted them from the gasoline cars in the IHS dataset.

### Appendix A.2.2.3 Light-Duty Trucks

Since passenger and light commercial trucks are defined as light-duty vehicles, they are constrained to regulatory class 30 and 40. Within the sample vehicle counts, GVWR Class 1 and 2a trucks were classified as regulatory class 30 and Class 2b trucks with two axles and four tires were classified as regulatory class 40. Both light-duty truck source types are divided between gasoline and diesel using the underlying splits in the sample vehicle counts data. Passenger trucks and light commercial trucks have similar but distinct distributions. Similar to cars, a penetration of flexible fuel (E-85-capable) light-duty trucks was calculated using EPA certification sales for MY 2011 and earlier.

### Appendix A.2.2.4 Buses

Only school bus distributions from MOVES2014 for model years prior to 2000 were retained in MOVES201X. The MOVES2014 school bus fuel type distributions were based on MOBILE6 estimates, originally calculated from 1996 and 1997 IHS bus registration data, for model years 1982-1996, and are summarized in Table 17-10. The Union of Concerned Scientists estimates that roughly one percent of school buses run on non-diesel fuels, so we have assumed that one percent of school buses were gasoline fueled for MY 1997 and later.[98] The school bus regulatory class distributions were also derived from 2011 FHWA data[99] as listed in Table 17-11, which were applied to model years prior to 2000 for both gasoline and diesel.

*Table 17-10 Fuel type market shares by model year for school buses*

| Model Year | MOVES Fuel Type | |
|---|---|---|
| | Gasoline | Diesel |
| 1982 | 67.40% | 32.60% |
| 1983 | 67.62% | 32.38% |
| 1984 | 61.55% | 38.45% |
| 1985 | 48.45% | 51.55% |
| 1986 | 32.67% | 67.33% |
| 1987 | 26.55% | 73.45% |
| 1988 | 24.98% | 75.02% |
| 1989 | 22.90% | 77.10% |
| 1990 | 12.40% | 87.60% |
| 1991 | 8.95% | 91.05% |
| 1992 | 1.00% | 99.00% |
| 1993 | 12.05% | 87.95% |
| 1994 | 14.75% | 85.25% |
| 1995 | 11.43% | 88.57% |
| 1996 | 4.15% | 95.85% |
| 1997-1999 | 1.00% | 99.00% |

*Table 17-11 Regulatory class fractions of school buses using 2011 FHWA data*

| Vehicle Type | MOVES regClassID | | | | |
|---|---|---|---|---|---|
| | 41 | 42 | 46 | 47 | Total |
| School Buses | 0.0106 | 0.0070 | 0.9371 | 0.0453 | 1 |

## Appendix A.2.2.5 Single-Unit and Combination Trucks

The fuel type and regulatory class distributions for the single-unit and combination trucks were calculated directly from the EPA's sample vehicle counts datasets. The single-unit and short-haul combination truck source types were split between gasoline and diesel only, and long-haul combination trucks only contained diesel vehicles. Single-unit vehicles were distributed among all the heavy-duty regulatory classes (regClassIDs 41, 42, 46, and 47) and combination trucks were distributed among the MHD and HHD regulatory classes (46 and 47) based on the underlying sample vehicle data.

# Appendix B 1990 Age Distributions

In MOVES201X, the 1990 age distributions were unchanged from previous versions of the model. This appendix describes their derivation; details on the derivations of the other age distributions in MOVES201X may be found in Appendix C.

## Appendix B.1 Motorcycles

The motorcycle age distributions are based on Motorcycle Industry Council estimates of the number of motorcycles in use, by model year, in 1990. However, data for individual model years starting from 1978 and earlier were not available. A logarithmic regression curve ($R^2$ value = 0.82) was fitted to available data, which was then used to extrapolate age fractions for earlier years beginning in 1978.

## Appendix B.2 Passenger Cars

To determine the 1990 age fractions for passenger cars, we began with IHS NVPP® 1990 data on car registration by model year. However, this data presents a snapshot of registrations on July 1, 1990, and we needed age fractions as of December 31, 1990. To adjust the values, we used monthly data from the IHS new car database to estimate the number of new cars registered in the months July through December 1990. Model Year 1989 cars were added to the previous estimate of "age 1" cars and Model Year 1990 and 1991 cars were added to the "age 0" cars. Also the 1990 data did not detail model year for ages 15+. Hence, regression estimates were used to extrapolate the age fractions for individual ages 15+ based on an exponential curve ($R^2$ value =0.67) fitted to available data.

## Appendix B.3 Trucks

For the 1990 age fractions for passenger trucks, light commercial trucks, refuse trucks, short-haul and long-haul single-unit trucks and short-haul and long-haul combination trucks, we used data from the TIUS92 (1992 Truck Inventory and Use Survey) database. Vehicles in the TIUS92 database were assigned to MOVES source types as summarized in Table 17-12. TIUS92 does not include a model year field and records ages as 0 through 10 and 11-and-greater. Because we needed greater detail on the older vehicles, we determined the model year for some of the older vehicles by using the responses to the questions "How was the vehicle obtained?" (TIUS field "OBTAIN") and "When did you obtain this vehicle?" (TIUS field "ACQYR") and we adjusted the age-11-and-older vehicle counts by dividing the original count by model year by the fraction of the older vehicles that were coded as "obtained new."

*Table 17-12 VIUS1997 codes used for distinguishing truck source types*

| Source Type | Axle Arrangement | Primary Area of Operation | Body Type | Major Use |
|---|---|---|---|---|
| Passenger Trucks | 2 axle/4 tire (AXLRE= 1,5,6,7) | Any | Any | personal transportation (MAJUSE=20) |
| Light Commercial Trucks | 2 axle/4 tire (AXLRE= 1,5,6,7) | Any | Any | any but personal transportation |
| Refuse Trucks | Single-Unit (AXLRE=2-4, 8-16) | Off-road, local or short-range (AREAOP <=4) | Garbage hauler (BODTYPE=30) | Any |
| Single-Unit Short-Haul Trucks | Single-Unit (AXLRE=2-4, 8-16) | Off-road, local or short-range (AREAOP<=4) | Any except garbage hauler | Any |
| Single-Unit Long-Haul Trucks | Single-Unit (AXLRE=2-4, 8-16) | Long-range (AREAOP>=5) | Any | Any |
| Combination Short-Haul Trucks | Combination (AXLRE>=17) | Off-road, local or medium (AREAOP<=4) | Any | Any |
| Combination Long-Haul Trucks | Combination (AXLRE>=17) | Long-range (AREAOP>=5) | Any | Any |

## Appendix B.4 Other Buses

For 1990, we were not able to identify a data source for estimating age distributions of other buses. Because the purchase and retirement of these buses is likely to be driven by general economic forces rather than trends in government spending, we will use the 1990 age distributions that were derived for short-haul combination trucks, as described above.

## Appendix B.5 School Buses and Motor Homes

To determine the age fractions of school buses and motor homes, we used information from the IHS TIP® 1999 database. School bus and motor home counts were available by model year. Unlike the IHS data for passenger cars, these counts reflect registration at the end of the calendar year and, thus, did not require adjustment. We converted model year to age and calculated age fractions. Because we did not have access to 1990 data, these fractions were used for 1990.

## Appendix B.6 Transit Buses

For 1990 Transit Bus age distributions, we used the MOBILE6 age fractions since 1990 data on transit buses was not available from the Federal Transit Administration database. MOBILE6 age fractions were based on fitting curves through a snapshot of vehicle registration data as of July 1, 1996, which was purchased from IHS (then known as R.L. Polk Company). To develop a general curve, the 1996 model year vehicle populations were removed from the sample because it did not represent a full year, and a best-fit analysis was performed on the remaining population data. The best-fit analyses resulted in age distribution estimates for vehicles ages 1 through 25+. However, since the vehicle sales year begins in October, the estimated age 1 population was multiplied by 0.75 to account for the fact that approximately 75 percent of the year's sales will have occurred by July 1$^{st}$ of a given calendar year.

Both Weibull curve fitting and exponential curve fitting were used to create the age distributions. The nature of the Weibull curve fitting formula is to produce an "S" shaped curve, which is relatively flat for the first third of the data, decreases rapidly for the next third, and flattens again for the final third. While using this formula resulted in a better overall fit for transit buses, the flatness of the final third for each curve resulted in unrealistically low vehicle populations for the older vehicle ages. For this reason, the original Weibull curve was used where it fit best, and exponential curves were fit through the data at the age where the Weibull curves began to flatten. Table 17-13 presents the equations used to create the age distribution and the years in which the equations were used.

*Table 17-13 Curve fit equations for registration distribution data by age*

| Vehicle Age | Equation |
| --- | --- |
| 1-17 | $y = 3462 * \mathrm{e}^{-\left(\left(\frac{\mathrm{age}}{17.16909475}\right)^{12.53214119}\right)}$ |
| 18-25+ | $24987.0776 * \mathrm{e}^{-0.2000 * \mathrm{age}}$ |

# Appendix C Detailed Derivation of Age Distributions

Since purchasing registration data for all calendar years is prohibitively costly for historic years, the base age distribution described in Section e is forecast and backcast for all other calendar years in the model. While sales data for historic years are well known and projections for future years are common in economic modeling, national trends in vehicle survival for every MOVES source type at all ages are not well studied. For MOVES201X, a generic survival rate was scaled up or down for each calendar year based on our assumptions of sales and changes in total populations. The following sections summarize the derivation of the generic survival rate, the estimation of vehicle sales by source type, and the algorithms used to forecast and backcast age distributions for each year.

## Appendix C.1 Generic Survival Rates

The survival rate describes the fraction of vehicles of a given source type and age that remain on the road from one year to the next. Although this rate changes from year to year, a single generic rate was calculated from available data.

Survival rates for motorcycles were calculated based on a smoothed curve of retail sales and 2008 national registration data as described in a study conducted for the EPA.[100] Survival rates for passenger cars, passenger trucks and light commercial trucks came from NHTSA's survivability Table 3 and Table 4.[101] These survival rates are based on a detailed analysis of IHS vehicle registration data from 1977 to 2002. We modified these rates to be consistent with the MOVES format using the following guidelines:

- NHTSA rates for light trucks were used for both the MOVES passenger truck and light commercial truck source types.
- MOVES calculates emissions for vehicles up to age 30 (with all older vehicles lumped into the age 30 category), but NHSTA car survival rates were available only to age 25. Therefore, we extrapolated car rates to age 30 using the estimated survival rate equation in Section 3.1 of the NHTSA report. When converted to MOVES format, this caused a striking discontinuity at age 26 which we removed by interpolating between ages 25 and 27.
- According to the NHTSA methodology, NHTSA age 1 corresponds to MOVES ageID 2, so the survival fractions were shifted accordingly.
- Because MOVES requires survival rates for ageIDs < 2, these values were linearly interpolated with the assumption that the survival rate prior to ageID 0 is 1.
- NHTSA defines survival rate as the ratio of the number of vehicles remaining in the fleet at a given year as compared to a base year. However, MOVES defines the survival rate as the ratio of vehicles remaining from one year to the next, so we transformed the NHTSA rates accordingly.

Quantitatively, the following piecewise formulas were used to derive the MOVES survival rates. In them, $s_a$ represents the MOVES survival rate at age $a$, and $\sigma_a$ represents the NHTSA survival rate at age $a$. When this generic survival rate is discussed below, the shorthand notation $\overrightarrow{S_0}$ will represent a one-dimensional array of $s_a$ values at each permissible age $a$ as described in Equation 38 through **Equation 40** below:

Age 0: $$s_0 = 1 - \frac{1 - \sigma_2}{3}$$ **Equation 38**

Age 1: $$s_1 = 1 - \frac{2(1 - \sigma_2)}{3}$$ **Equation 39**

Ages 2-30: $$s_a = s_{2\ldots30} = \frac{\sigma_{a-1}}{\sigma_{a-2}}$$ **Equation 40**

With limited data available on heavy-duty vehicle scrappage, survivability for all other source types came from the *Transportation Energy Data Book*.[102] We used the heavy-duty vehicle survival rates for model year 1980 (TEDB35, Table 3.14). The 1990 model year rates were not used because they were significantly higher than rates for the other model years in the analysis (i.e. 45 percent survival rate for 30 year-old trucks), and seemed unrealistically high. While limited data exists to confirm this judgment, a snapshot of 5-year survival rates can be derived from VIUS 1992 and 1997 results for comparison. According to VIUS, the average survival rate for model years 1988-1991 between the 1992 and 1997 surveys was 88 percent. The comparable survival rate for 1990 model year heavy-duty vehicles from TEDB was 96 percent, while the rate for 1980 model year trucks was 91 percent. This comparison lends credence to the decision that the 1980 model year survival rates are more in line with available data. TEDB does not have separate survival rates for medium-duty vehicles; the heavy-duty rates were applied uniformly across the bus, single-unit truck, and combination truck categories. The TEDB survival rates were transformed into MOVES format in the same way as the NHTSA rates.

The resulting survival rates are listed in the default database's SourceTypeAge table, shown below in Table 17-14. Please note that since MOVES201X does not calculate age distributions during a run, these survival rates are not actively used by MOVES. However, they were used in the development of the national age distributions stored in the SourceTypeAgeDistribution table, and remain in the default database for reference. In addition, the survival rates in the SourceTypeAge table are listed by source type, but the values are identical for the grouping of vehicles listed in e.

*Table 17-14 Vehicle survival rate by age*

| Age | Motorcycles | Passenger Cars | Light-duty Trucks (Passenger and Light Commercial) | Heavy-duty Vehicles (Buses, Single-Unit Trucks, and Combination Trucks) |
|---|---|---|---|---|
| 0 | 1.000 | 0.997 | 0.991 | 1.000 |
| 1 | 0.979 | 0.997 | 0.991 | 1.000 |
| 2 | 0.940 | 0.997 | 0.991 | 1.000 |
| 3 | 0.940 | 0.993 | 0.986 | 1.000 |
| 4 | 0.940 | 0.990 | 0.981 | 0.990 |
| 5 | 0.940 | 0.986 | 0.976 | 0.980 |
| 6 | 0.940 | 0.981 | 0.970 | 0.980 |
| 7 | 0.940 | 0.976 | 0.964 | 0.970 |
| 8 | 0.940 | 0.971 | 0.958 | 0.970 |
| 9 | 0.940 | 0.965 | 0.952 | 0.970 |
| 10 | 0.940 | 0.959 | 0.946 | 0.960 |
| 11 | 0.940 | 0.953 | 0.940 | 0.960 |
| 12 | 0.940 | 0.912 | 0.935 | 0.950 |
| 13 | 0.940 | 0.854 | 0.929 | 0.950 |
| 14 | 0.940 | 0.832 | 0.913 | 0.950 |
| 15 | 0.940 | 0.813 | 0.908 | 0.940 |
| 16 | 0.940 | 0.799 | 0.903 | 0.940 |
| 17 | 0.940 | 0.787 | 0.898 | 0.930 |
| 18 | 0.940 | 0.779 | 0.894 | 0.930 |
| 19 | 0.940 | 0.772 | 0.891 | 0.920 |
| 20 | 0.940 | 0.767 | 0.888 | 0.920 |
| 21 | 0.940 | 0.763 | 0.885 | 0.920 |
| 22 | 0.940 | 0.760 | 0.883 | 0.910 |
| 23 | 0.940 | 0.757 | 0.880 | 0.910 |
| 24 | 0.940 | 0.757 | 0.879 | 0.910 |
| 25 | 0.940 | 0.754 | 0.877 | 0.900 |
| 26 | 0.940 | 0.754 | 0.875 | 0.900 |
| 27 | 0.940 | 0.567 | 0.875 | 0.900 |
| 28 | 0.940 | 0.752 | 0.873 | 0.890 |
| 29 | 0.940 | 0.752 | 0.872 | 0.890 |
| 30 | 0.940 | 0.752 | 0.871 | 0.890 |

## Appendix C.2 Vehicle Sales by Source Type

Knowing vehicle sales by source type for every calendar year is essential for estimating age distributions in both historic and projected years. Since MOVES201X doesn't calculate age distributions at run time, this information isn't stored in the default database.[p] However, sales data are used in the age distribution backcasting and projection algorithms, which are described in subsequent sections. They are also used in calculating the age 0 fractions of vehicles in the base age distribution, which is described in Section 6.1.1.

[p] Previous versions of MOVES used to calculate age distributions during runtime and therefore required sales data to be stored in the default database. Consequently, the SourceTypeYear table has a salesGrowthFactor column. Since MOVES no longer needs this information, this column contains 0s in the MOVES201X default database.

Historic motorcycles sales came from the Motorcycle Industry Council's 2015 *Motorcycle Statistical Annual*,[103] which contains estimates of annual on-highway motorcycle sales going back to 1989.

Historic passenger car sales came from the TEDB35 Table 4.6 estimate for total new retail car sales.

Historic light truck sales came from the TEDB35 Table 4.7 estimate for total light truck sales. These were then split into passenger truck and light commercial truck sales using the source type distribution fractions described in Section 4.1.

Historic school bus sales came from the 2001, 2010, and 2017 publications of *School Bus Fleet Fact Book*.[15] Each publication contains estimates for 10 years of historic annual national sales.

Historic transit bus sales were calculated from the Federal Transit Administration's National Transit Database (NTD)[16] data series on Revenue Vehicle Inventory and Rural Revenue Vehicle Inventory. Since the annual publication does not necessarily contain all model year vehicles sold in the year of publication, transit bus sales are instead estimated from 1-year-old buses. This assumes 0 scrappage of new transit buses, which is consistent with the heavy-duty survival rate presented in Table 17-14. The 1-year-old transit bus populations were estimated from the NTD active fleet vehicles using the definition of a transit bus as given in Section 5.1.4. Since the Revenue Vehicle Inventory tables are not available for years before 2002, constant transit bus sales are assumed for years 1999-2000 using the 1-year-old bus populations in the 2002 NTD.

Lacking a direct source of historic other bus sales, these were derived from the average sales rate for school buses and transit buses. The ratio of total school and transit bus sales to school and transit bus populations was applied to the other bus population, as shown in Equation 41 below. The historic populations for each of the bus source types were determined as described in Section 4.1.

$$Sales_{other} = \frac{Sales_{school} + Sales_{transit}}{Pop_{school} + Pop_{transit}} \cdot Pop_{other} \qquad \textit{Equation 41}$$

Historic sales for heavy-duty trucks were derived from the TEDB35 Table 5.3 estimate for truck sales by gross vehicle weight. These were translated to source type sales by calculating the source type distribution for each weight class 3-8 from the 2014 IHS data set. Since the 2014 IHS data set grouped short-haul (52) and long-haul (53) single-unit trucks, sales were further allocated to the individual source types 52 and 53 using the source type distribution fractions described in Section 4.1.

Projected sales for all source types were derived from AEO2017. Because AEO vehicle categories differ from MOVES source types, the AEO projected vehicle sales were not used directly. Instead, ratios of vehicle sales to stock were calculated and applied to the projected populations (see Section 4.2 for the derivation of projected populations). Since AEO2017 only projects out to 2050, sales for years 2051-2060 were assumed to continue to grow at the same growth rate as between 2049 and 2050.

Table 17-15 shows the mappings between AEO sales categories and MOVES source types. Where multiple AEO categories are listed, their values were summed before calculating the sales to stock ratios. These are the same groupings as presented for the stock categories in Table 4-3, and more details on the selection of the groupings may be found in Section 4.2. We acknowledge that using sales projections from different vehicle types as surrogates for motorcycles and buses in particular will introduce additional uncertainty into these projections.

The sales to stock ratios for each year and group were calculated and applied to the projected source type populations using the mappings given in Table 17-15 to derive projected sales for each source type.

*Table 17-15 Mapping AEO categories to source types for projecting vehicle populations*

| AEO Sales Category Groupings | MOVES Source Type |
|---|---|
| Total Car Sales[i] | 11 – Motorcycle |
| | 21 – Passenger Car |
| Total Light Truck Sales[i] + Total Commercial Light Truck Sales[ii] | 31 – Passenger Truck |
| | 32 – Light Commercial Truck |
| Total Sales[iii] | 41 – Other Bus |
| | 42 – Transit Bus |
| | 43 – School Bus |
| Light Medium Subtotal Sales[iii] + Medium Subtotal Sales[iii] | 51 – Refuse Truck |
| | 52 – Single-Unit Short-haul Truck |
| | 53 – Single-Unit Long-haul Truck |
| | 54 – Motor Home |
| Heavy Subtotal Sales[iii] | 61 – Combination Short-haul Truck |
| | 62 – Combination Long-haul Truck |

[i] From AEO2017 Table 39: Light-Duty Vehicle Sales by Technology Type
[ii] From AEO2017 Table 45: Transportation Fleet Car and Truck Sales by Type and Technology
[iii] From AEO2017 Table 50: Freight Transportation Energy Use

## Appendix C.3 Historic Age Distributions

The base algorithm for backcasting age distributions is as follows:

1. Calculate the base population distribution ($\overrightarrow{P_y}$) by multiplying the base age distribution ($\overrightarrow{f_y}$) and base population ($P_y$).
2. Remove the age 0 vehicles ($\overrightarrow{N_y}$).
3. Decrease the population age index by one (for example, 3-year-old vehicles are reclassified as 2-year-old vehicles).
4. Add the vehicles that were removed in the previous year ($\overrightarrow{R_{y-1}}$).
5. Convert the resulting population distribution into an age distribution using **Equation 3**.

6. Replace the new age 20 and 30+ fractions with the base year age 29 and 30+ fractions, and renormalize the new age distribution to sum to 1 while retaining the original age 29 and 30+ fractions.
7. This results in the previous year age distribution ($\overrightarrow{f_{y-1}}$). If this algorithm is to be repeated, $\overrightarrow{f_{y-1}}$ becomes $\overrightarrow{f_y}$ for the next iteration.

This is mathematically described with the following equation (reprinted from Section 6.1.2 for reference):

$$\overrightarrow{P_{y-1}} = \overrightarrow{P_y} - \overrightarrow{N_y} + \overrightarrow{R_{y-1}} \qquad \textit{Equation 4}$$

Unfortunately, as described in Section 0, the only survival information we have is a single snapshot. Because vehicle populations and new sales change differentially (for example, the historic populations shown in Section 4.1 leveled off during the recent recession; at the same time, sales of most vehicle types plummeted), it is important to adjust the survival curve in response to changes in population and sales. We did so by defining a scalar adjustment factor $k_y$ that can be algebraically calculated from population and sales estimates. Its use in calculating the scrapped vehicles with generic survival rate $\overrightarrow{S_0}$ is given by Equation 42 Note that the open circle operator (∘) represents entrywise product; that is, each element in an array is multiplied by the corresponding element in the other one, and it results in an array with the same number of elements. In this case, the scalar adjustment factor is applied to the scrappage rate (1 minus the survival rate) at each age, which is then applied to the population of vehicles at each corresponding age; this results in the number of removed vehicles by age.

$$\overrightarrow{R_{y-1}} = k_{y-1} \cdot \left(1 - \overrightarrow{S_0}\right) \circ \overrightarrow{P_{y-1}} \qquad \textbf{Equation 42}$$

Substituting **Equation 42** into **Equation 4** yields **Equation 43**:

$$\overrightarrow{P_{y-1}} = \overrightarrow{P_y} - \overrightarrow{N_y} + k_{y-1} \cdot \left(1 - \overrightarrow{S_0}\right) \circ \overrightarrow{P_{y-1}} \qquad \textbf{Equation 43}$$

To solve for $k_{y-1}$, Equation 43 can be transformed into Equation 44 using known total populations and sales:

$$P_{y-1} = P_y - N_y + k_{y-1} \cdot \sum_a \left(\left(1 - \overrightarrow{S_0}\right) \circ \overrightarrow{P_{y-1}}\right) \qquad \textbf{Equation 44}$$

However, this still leaves a $\overrightarrow{P_{y-1}}$ term, which is unavoidable because the total number of vehicles removed is dependent on the age distribution of those vehicles. To solve Equation 44, an iterative approach was used. The first time the algorithm described above is run, $\overrightarrow{P_{y-1}}$ is approximated by applying the base age distribution $\overrightarrow{f_y}$ to the population of the previous year $P_{y-1}$. The scaling factor $k_{y-1}$ is calculated using this approximation in Equation 44, and then a guess for $\overrightarrow{P_{y-1}}$ is calculated from Equation 43. The guess for the resulting age distribution $\overrightarrow{f_{y-1}}$ is then calculated using the known $P_{y-1}$. The algorithm is repeated for the same year using the updated guess for the resulting age distribution. This is repeated until the resulting age distribution matches the guessed age distribution at each age fraction within $1\times10^{-6}$, which occurred within 10 iterations for most source types and calendar years.

This algorithm was then repeated for each historic year from 2013 to 1999 and for each source type using the following data sources:

- Total populations $P_y$ and $P_{y-1}$ as described in Section 4.
- Generic survival rates $\overrightarrow{S_0}$ as described in Section 0.
- Vehicle sales $N_y$ as described in Section 0.
- Base age distributions $\overrightarrow{f_{2014}}$ as described in Section 6.1.1. All other $\overrightarrow{f_y}$ come from the $\overrightarrow{f_{y-1}}$ of the previous iteration.

With all of this information, the age distributions were algorithmically determined for years 1999-2013 and are stored in the SourceTypeAgeDistribution table of the default database.

## Appendix C.4 Projected Age Distributions

The base algorithm for forecasting age distributions is as follows:

1. Calculate the base population distribution ($\overrightarrow{P_y}$) by multiplying the base age distribution ($\overrightarrow{f_y}$) and base population ($P_y$).
2. Remove the vehicles that did not survive ($\overrightarrow{R_y}$) at each age level.
3. Increase the population age index by one (for example, 3-year-old vehicles are reclassified as 4-year-old vehicles).
4. Add new vehicle sales ($\overrightarrow{N_{y+1}}$) as the age 0 cohort.
5. Convert the resulting population distribution into an age distribution using **Equation 3**.
6. Replace the new age 30+ fraction with the base year age 30+ fraction, and renormalize the new age distribution to sum to 1 while retaining the original age 0 and age 30+ fractions.
7. This results in the next year age distribution ($\overrightarrow{f_{y+1}}$). If this algorithm is to be repeated, $\overrightarrow{f_{y+1}}$ becomes $\overrightarrow{f_y}$ for the next iteration.

This is mathematically described with the following equation (reprinted from Section 6.1.3 for reference):

$$\overrightarrow{P_{y+1}} = \overrightarrow{P_y} - \overrightarrow{R_y} + \overrightarrow{N_{y+1}} \qquad \textbf{Equation 5}$$

As with the backcasting algorithm, the scrapped vehicles need to be estimated by scaling the generic survival rate. The equation governing vehicle removal discussed the previous section is also applicable here. Taking careful note of the subscripts, **Equation 5** and **Equation 42** can be combined into **Equation 45**:

$$\overrightarrow{P_{y+1}} = \overrightarrow{P_y} - k_y \cdot (1 - \overrightarrow{S_0}) \circ \overrightarrow{P_y} + \overrightarrow{N_{y+1}} \qquad \textbf{Equation 45}$$

To solve for $k_y$, Equation 45 can be transformed into Equation 46 using the population and sales totals:

$$P_{y+1} = P_y - k_y \sum_a \left( \left(1 - \overrightarrow{S_0}\right) \circ \overrightarrow{P_y} \right) + N_{y+1} \qquad \textbf{Equation 46}$$

This can be algebraically solved for $k_y$ and evaluated for each source type as all of the other values are known. Please note that the iterative approach to solving this equation as described in the backcasting section is not necessary here, as the number of scrapped vehicles depends on the base age distribution, which is known. After $k_y$ is calculated, Equation 45 is used to determine $\overrightarrow{P_{y+1}}$. The resulting age distribution $\overrightarrow{f_{y+1}}$ is then calculated using the known $P_{y+1}$.

This algorithm was then repeated for each projected year from 2015 to 2060 and for each source type using the following data sources:

- Total populations $P_y$ and $P_{y+1}$ as described in Section 4.
- Generic survival rates $\overrightarrow{S_0}$ as described in Section 0.
- Vehicle sales $N_{y+1}$ as described in Section 0.
- Base age distributions $\overrightarrow{f_{2014}}$ as described in Section 6.1.1. All other $\overrightarrow{f_y}$ come from the $\overrightarrow{f_{y+1}}$ of the previous iteration.

With all of this information, the age distributions were algorithmically determined for years 2015-2060 and are stored in the SourceTypeAgeDistribution table of the default database. An illustration of passenger car age distributions is presented in Figure 17-2. For clarity, only four years are shown: 2014, 2020, 2030, and 2040.

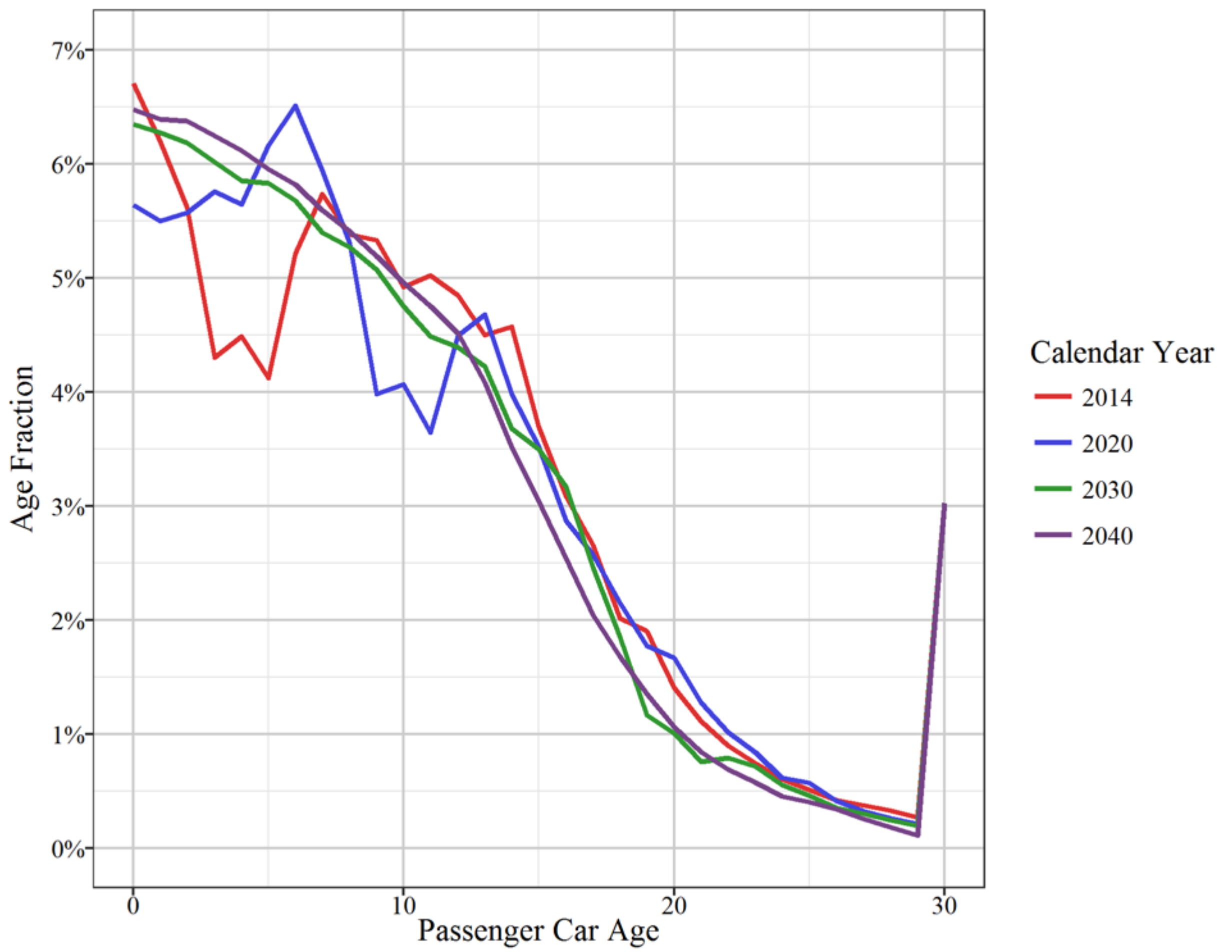


*Figure **17-2** Selected age distributions for passenger cars in MOVES201X*

# Appendix D Calculation of Combination Truck Average Speed Distributions

As discussed in Section 8.2, the default average speed distribution for heavy-duty vehicles are based on light-duty vehicles, because we did not have a comprehensive data set of average speed by day type, hour of the day, and road type for heavy-duty vehicles. For combination trucks we adjusted the average speed distribution for combination trucks based on the observation that combination trucks travel 8 percent lower than the mean traffic speed based on a study conducted on California freeway.[36]

The average speed for each roadway type, day type, and hour can be calculated by multiplying the average speed of each bin by the corresponding distribution of time as shown in Equation 47. Here, $\bar{v}$ is the average speed of the distribution, $v_i$ is the average speed of bin $i$, and $\rho_i$ is the proportion of time spent in bin $i$.

$$\bar{v} = \sum v_i \cdot \rho_i$$
$$= 2.5 \cdot \rho_1 + 5 \cdot \rho_2 + \cdots + 70 \cdot \rho_{15} + 75 \cdot \rho_{16}$$

**Equation 47**

To adjust the average speed for heavy-duty combination trucks, we redistributed the proportion of time spent in each speed bin such that its contribution to the average speed was 92 percent of the light-duty speed, as shown in Equation 18. This redistributed proportion of time in each speed bin is given by $\rho_i'$.

$$\bar{v}_{combination} = (0.92)\, \bar{v}_{\text{light-duty}}$$
$$= \sum v_i \cdot \rho_i'$$

**Equation 48**

To perform this redistribution, we defined two new variables, $\alpha$ and $\beta$, where $\alpha_i$ is the fraction of $\rho_i$ that is shifted down one speed bin, and $\beta_i$ is the fraction of $\rho_i$ shifted down two speed bins. The new distribution at speed bin $i$ (given by $\rho_i'$) starts with the original distribution ($\rho_i$), gains the proportions moved down from the higher speed bins ($\alpha_{i+1} \cdot \rho_{i+1}$ and $\beta_{i+2} \cdot \rho_{i+2}$), and loses the proportion that is moved to a lower speed bin ($\alpha_i \cdot \rho_i$ and $\beta_i \cdot \rho_i$). This is shown in Equation 49:

$$\rho_i' = \rho_i + (\alpha_{i+1} \cdot \rho_{i+1}) + (\beta_{i+2} \cdot \rho_{i+2}) - (\alpha_i \cdot \rho_i) - (\beta_i \cdot \rho_i)$$

**Equation 49**

For speed bins with an average speed of less than or equal to 60 mph, we only needed to shift distributions using a fraction of one speed bin (or 5 mph). Thus we only calculated $\alpha_i$ and set $\beta_i = 0$. Mathematically, reducing a bin's average speed by a certain fraction ($\eta$) can be expressed with Equation 50:

$$(1 - \eta) \cdot v_i = \alpha_i \cdot (v_i - 5) + (1 - \alpha_i) \cdot v_i$$

**Equation 50**

Essentially, the fraction that is moved to the next slower bin ($\alpha_i$) is multiplied by the slower speed (note that each of the speed bins are 5 mph apart, so this is $v_i - 5$), and the fraction that remains ($1 - \alpha_i$) is multiplied by the original speed $v_i$. Since the average speed of the combination trucks is 92 percent of cars, $(1 - \eta) = 92\%$ and $\eta = 0.08$.

By rearranging terms from Equation 20, and solving for $\alpha_i$ we obtain Equation 51:

$$\alpha_i = \frac{v_i \cdot \eta}{5}$$ **Equation 51**

However, for speed bins ≥ 65 mph, Equation 51 yields $\alpha_i$ greater than 1. Since that logically can't happen, some of the distribution needed to be moved to the second next slower speed bin to fully account for the 8 percent speed reduction. This is mathematically shown in Equation 52, which is the logical extension of Equation 50:

$$(1 - \eta) \cdot v_i = \beta_i \cdot (v_i - 10) + \alpha_i \cdot (v_i - 5) + (1 - \alpha_i - \beta_i) \cdot v_i$$ **Equation 52**

The difference between Equation 50 and Equation 52 is that an additional fraction ($\beta_i$) is removed from the original speed bin and is given the speed of two speed bins slower (or 10 mph slower). With this additional factor, there is an infinite combination of solutions that could satisfy Equation 52. We solved this problem with a linear equation solver by setting Equation 52 to a constraint (see Equation 53), adding the constraint that $\alpha_i + \beta_i$ are less than or equal to 1 (see Equation 54), and choosing the solution that minimized $\beta_i$.

$$\alpha_i \cdot (v_i - 5) + \beta_i \cdot (v_i - 10) + v_i \cdot (\eta - \alpha_i - \beta_i) = 0$$ **Equation 53**

$$\alpha_i + \beta_i \leq 1$$ **Equation 54**

This linear program was used to solve for $\alpha_i$ and $\beta_i$ for each speed bin between 65 and 75 mph. With $\alpha_i$ and $\beta_i$ known for each bin, the new distributions $\rho_i'$ were calculated.

An additional adjustment was made for the highest speed bins because we assumed that the maximum speed bin had a triangular distribution with an average speed of 75 mph, see Figure 17-3. In the figure, the original speed distribution is shown in light gray. The darker gray is the proportion of speed bin 55 that is moved out to the slower speed bin 50 mph, and the black areas are the distributions from speed bin 60 and 65 that are moved in to speed bin 55 mph.

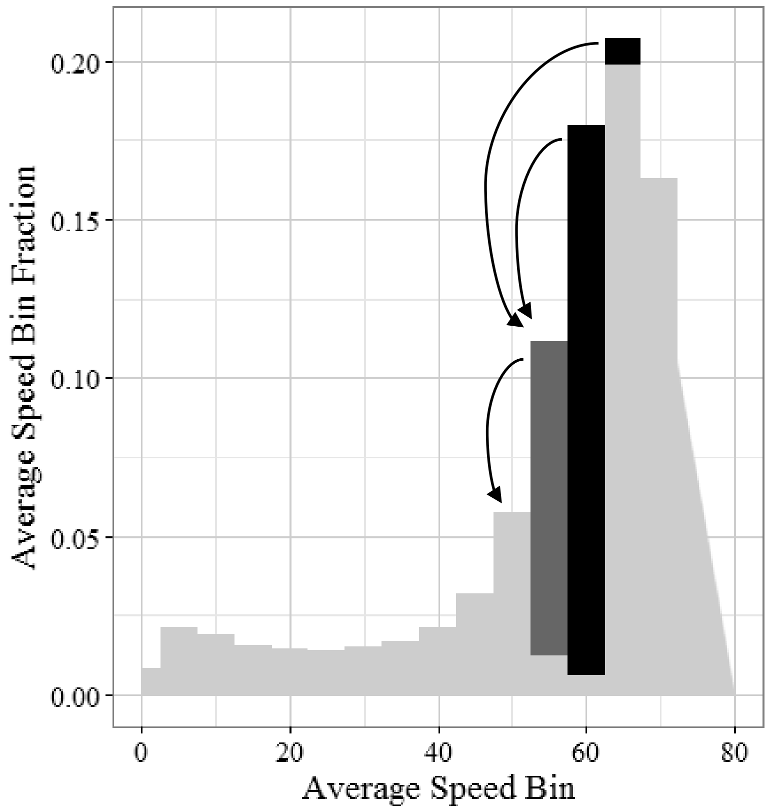


*Figure 17-3 An illustration of adjustments made to the average speed bin 55 mph for heavy-duty vehicles*

In the new distribution, all of the maximum speed bin fraction was redistributed to the 65 and 70 mph bins. Therefore, the new maximum speed bin (70 mph) was also assumed to have a triangular distribution. Geometrically, 1/9$^{th}$ of a triangular distribution averaging 70 mph is faster than 72.5 mph. Since the 75 mph speed bin is defined as any speed ≥72.5 mph, 1/9$^{th}$ of the new 70 mph fraction ($\rho'_{15}$) was reclassified as the new fraction for the 75 mph bin.

This process was repeated for both short- and long-haul combination trucks on restricted access road types for every hour and day type combination.

## Appendix E Driving Schedules

A key feature of MOVES is the capability to accommodate a number of drive schedules to represent driving patterns across source type, roadway type and average speed. For the national default case, MOVES201X employs 49 drive schedules with various average speeds, mapped to specific source types and roadway types. These are unchanged from MOVES2014.

Table 17-16 below lists the driving schedules used in MOVES201X. Some driving schedules are used for both restricted access (freeway) and unrestricted access (non-freeway) driving. Some driving schedules are used for multiple source types or multiple road types where vehicle specific information was not available.

*Table 17-16 MOVES201X default driving schedule statistics*

| drive schedule id | drive schedule name | avg speed | max speed | idle time (sec) | percent of time idling | miles | time (sec) | minutes | hours |
|---|---|---|---|---|---|---|---|---|---|
| 101 | LD Low Speed 1 | 2.5 | 10.00 | 280 | 46.5% | 0.419 | 602.00 | 10.03 | 0.167 |
| 153 | LD LOS E Freeway | 30.5 | 63.00 | 5 | 1.1% | 3.863 | 456.00 | 7.60 | 0.127 |
| 158 | LD High Speed Freeway 3 | 76.0 | 90.00 | 0 | 0.0% | 12.264 | 581.00 | 9.68 | 0.161 |
| 201 | MD 5mph Non-Freeway | 4.6 | 24.10 | 85 | 29.0% | 0.373 | 293.00 | 4.88 | 0.081 |
| 202 | MD 10mph Non-Freeway | 10.7 | 34.10 | 61 | 19.6% | 0.928 | 311.00 | 5.18 | 0.086 |
| 203 | MD 15mph Non-Freeway | 15.6 | 36.60 | 57 | 12.6% | 1.973 | 454.00 | 7.57 | 0.126 |
| 204 | MD 20mph Non-Freeway | 20.8 | 44.50 | 95 | 9.1% | 6.054 | 1046.00 | 17.43 | 0.291 |
| 205 | MD 25mph Non-Freeway | 24.5 | 47.50 | 63 | 11.1% | 3.846 | 566.00 | 9.43 | 0.157 |
| 206 | MD 30mph Non-Freeway | 31.5 | 55.90 | 54 | 5.5% | 8.644 | 988.00 | 16.47 | 0.274 |
| 251 | MD 30mph Freeway | 34.4 | 62.60 | 0 | 0.0% | 15.633 | 1637.00 | 27.28 | 0.455 |
| 252 | MD 40mph Freeway | 44.5 | 70.40 | 0 | 0.0% | 43.329 | 3504.00 | 58.40 | 0.973 |
| 253 | MD 50mph Freeway | 55.4 | 72.20 | 0 | 0.0% | 41.848 | 2718.00 | 45.30 | 0.755 |
| 254 | MD 60mph Freeway | 60.1 | 68.40 | 0 | 0.0% | 81.299 | 4866.00 | 81.10 | 1.352 |
| 255 | MD High Speed Freeway | 72.8 | 80.40 | 0 | 0.0% | 96.721 | 4782.00 | 79.70 | 1.328 |
| 301 | HD 5mph Non-Freeway | 5.8 | 19.90 | 37 | 14.2% | 0.419 | 260.00 | 4.33 | 0.072 |
| 302 | HD 10mph Non-Freeway | 11.2 | 29.20 | 70 | 11.5% | 1.892 | 608.00 | 10.13 | 0.169 |
| 303 | HD 15mph Non-Freeway | 15.6 | 38.30 | 73 | 12.9% | 2.463 | 567.00 | 9.45 | 0.158 |
| 304 | HD 20mph Non-Freeway | 19.4 | 44.20 | 84 | 15.1% | 3.012 | 558.00 | 9.30 | 0.155 |
| 305 | HD 25mph Non-Freeway | 25.6 | 50.70 | 57 | 5.8% | 6.996 | 983.00 | 16.38 | 0.273 |
| 306 | HD 30mph Non-Freeway | 32.5 | 58.00 | 43 | 5.3% | 7.296 | 809.00 | 13.48 | 0.225 |
| 351 | HD 30mph Freeway | 34.3 | 62.70 | 0 | 0.0% | 21.659 | 2276.00 | 37.93 | 0.632 |
| 352 | HD 40mph Freeway | 47.1 | 65.00 | 0 | 0.0% | 41.845 | 3197.00 | 53.28 | 0.888 |
| 353 | HD 50mph Freeway | 54.2 | 68.00 | 0 | 0.0% | 80.268 | 5333.00 | 88.88 | 1.481 |
| 354 | HD 60mph Freeway | 59.7 | 69.00 | 0 | 0.0% | 29.708 | 1792.00 | 29.87 | 0.498 |
| 355 | HD High Speed Freeway | 71.7 | 81.00 | 0 | 0.0% | 35.681 | 1792.00 | 29.87 | 0.498 |
| 396 | HD High Speed Freeway Plus 5mph | 76.7 | 86.00 | 0 | 0.0% | 38.170 | 1792.00 | 29.87 | 0.498 |

*Table 17-16 MOVES201X default driving schedule statistics*

| drive schedule id | drive schedule name | avg speed | max speed | idle time (sec) | percent of time idling | miles | time (sec) | minutes | hours |
|---|---|---|---|---|---|---|---|---|---|
| 397 | MD High Speed Freeway Plus 5mph | 77.8 | 85.40 | 0 | 0.0% | 103.363 | 4782.00 | 79.70 | 1.328 |
| 398 | CRC E55 HHDDT Creep | 1.8 | 8.24 | 107 | 42.3% | 0.124 | 253.00 | 4.22 | 0.070 |
| 401 | Bus Low Speed Urban | 3.1 | 19.80 | 288 | 63.9% | 0.393 | 451.00 | 7.52 | 0.125 |
| 402 | Bus 12mph Non-Freeway | 11.5 | 33.80 | 109 | 37.5% | 0.932 | 291.00 | 4.85 | 0.081 |
| 403 | Bus 30mph Non-Freeway | 21.9 | 47.00 | 116 | 28.3% | 2.492 | 410.00 | 6.83 | 0.114 |
| 404 | New York City Bus | 3.7 | 30.80 | 403 | 67.2% | 0.615 | 600.00 | 10.00 | 0.167 |
| 405 | WMATA Transit Bus | 8.3 | 47.50 | 706 | 38.4% | 4.261 | 1840.00 | 30.67 | 0.511 |
| 501 | Refuse Truck Urban | 2.2 | 20.00 | 416 | 66.9% | 0.374 | 622.00 | 10.37 | 0.173 |
| 1009 | Final FC01LOSAF Cycle (C10R04-00854) | 73.8 | 84.43 | 0 | 0.0% | 11.664 | 569.00 | 9.48 | 0.158 |
| 1011 | Final FC02LOSDF Cycle (C10R05-00513) | 49.1 | 73.06 | 34 | 5.0% | 9.283 | 681.00 | 11.35 | 0.189 |
| 1017 | Final FC11LOSB Cycle (C10R02-00546) | 66.4 | 81.84 | 0 | 0.0% | 9.567 | 519.00 | 8.65 | 0.144 |
| 1018 | Final FC11LOSC Cycle (C15R09-00849) | 64.4 | 78.19 | 0 | 0.0% | 16.189 | 905.00 | 15.08 | 0.251 |
| 1019 | Final FC11LOSD Cycle (C15R10-00068) | 58.8 | 76.78 | 0 | 0.0% | 11.922 | 730.00 | 12.17 | 0.203 |
| 1020 | Final FC11LOSE Cycle (C15R11-00851) | 46.1 | 71.50 | 1 | 0.1% | 12.468 | 973.00 | 16.22 | 0.270 |
| 1021 | Final FC11LOSF Cycle (C15R01-00876) | 20.6 | 55.48 | 23 | 2.5% | 5.179 | 905.00 | 15.08 | 0.251 |
| 1024 | Final FC12LOSC Cycle (C15R04-00582) | 63.7 | 79.39 | 0 | 0.0% | 15.685 | 887.00 | 14.78 | 0.246 |
| 1025 | Final FC12LOSD Cycle (C15R09-00037) | 52.8 | 73.15 | 12 | 1.5% | 11.754 | 801.00 | 13.35 | 0.223 |
| 1026 | Final FC12LOSE Cycle (C15R10-00782) | 43.3 | 70.87 | 0 | 0.0% | 10.973 | 913.00 | 15.22 | 0.254 |
| 1029 | Final FC14LOSB Cycle (C15R07-00177) | 31.0 | 63.81 | 27 | 3.6% | 6.498 | 754.00 | 12.57 | 0.209 |
| 1030 | Final FC14LOSC Cycle (C10R04-00104) | 25.4 | 53.09 | 41 | 8.0% | 3.617 | 513.00 | 8.55 | 0.143 |
| 1033 | Final FC14LOSF Cycle (C15R05-00424) | 8.7 | 44.16 | 326 | 38.2% | 2.066 | 853.00 | 14.22 | 0.237 |
| 1041 | Final FC17LOSD Cycle (C15R05-00480) | 18.6 | 50.33 | 114 | 16.1% | 3.659 | 709.00 | 11.82 | 0.197 |
| 1043 | Final FC19LOSAC Cycle (C15R08-00267) | 15.7 | 37.95 | 67 | 7.7% | 3.802 | 870.00 | 14.50 | 0.242 |

# Appendix F Example Total Idle Fraction Regression Coefficients

*Table 17-17* Example result for total idle fraction regression coefficients for light-duty trucks in urban counties for weekdays

| *Variable* | *Coefficients* | *Comments* |
|---|---|---|
| *(Intercept)* | *0.209770278* | |
| *dayID5* | *0.01126165* | *Applicable when dayID=5* |
| *sourceTypeID31* | *0.001328731* | *Applicable when sourceTypeID=31* |
| *countyTypeID1* | *0.030580086* | *Applicable when equation is used for an urban county (countyTypeID=1)* |
| *idleRegionID104* | *0.021341588* | *Applicable when idleRegionID=104* |
| *idleRegionID102* | *0.026097089* | *Applicable when idleRegionID=102* |
| *idleRegionID103* | *0.054609956* | *Applicable when idleRegionID=103* |
| *idleRegionID101* | *0.057215976* | *Applicable when idleRegionID=101* |
| *monthID2* | *0.002789102* | *Applicable when monthID=2* |
| *monthID3* | *-0.004290649* | *Applicable when monthID=3* |
| *monthID4* | *-0.006087151* | *Applicable when monthID=4* |
| *monthID5* | *-0.004123423* | *Applicable when monthID=5* |
| *monthID6* | *-0.002637001* | *Applicable when monthID=6* |
| *monthID7* | *0.002913621* | *Applicable when monthID=7* |
| *monthID8* | *-0.000662777* | *Applicable when monthID=8* |
| *monthID9* | *-0.002960034* | *Applicable when monthID=9* |
| *monthID10* | *0.007288183* | *Applicable when monthID=10* |
| *monthID11* | *0.005849819* | *Applicable when monthID=11* |

| *Variable* | *Coefficients* | *Comments* |
|---|---|---|
| *monthID12* | *0.007585819* | *Applicable when monthID=12* |
| *idleRegionID104:monthID2* | *-0.014777342* | *Applicable when monthID=2 and idleRegionID=104* |
| *idleRegionID102:monthID2* | *-0.006638333* | *Applicable when monthID=2 and idleRegionID=102* |
| *idleRegionID103:monthID2* | *-0.017303092* | *Applicable when monthID=2 and idleRegionID=103* |
| *idleRegionID101:monthID2* | *-0.015947997* | *Applicable when monthID=2 and idleRegionID=101* |
| *idleRegionID104:monthID3* | *-0.026662158* | *Applicable when monthID=3 and idleRegionID=104* |
| *idleRegionID102:monthID3* | *-0.01167098* | *Applicable when monthID=3 and idleRegionID=102* |
| *idleRegionID103:monthID3* | *-0.043578722* | *Applicable when monthID=3 and idleRegionID=103* |
| *idleRegionID101:monthID3* | *-0.033397602* | *Applicable when monthID=3 and idleRegionID=101* |

| *Variable* | *Coefficients* | *Comments* |
|---|---|---|
| *idleRegionID104:monthID4* | *-0.028548744* | *Applicable when monthID=4 and idleRegionID=104* |
| *idleRegionID102:monthID4* | *-0.011944882* | *Applicable when monthID=4 and idleRegionID=102* |
| *idleRegionID103:monthID4* | *-0.047593842* | *Applicable when monthID=4 and idleRegionID=103* |
| *idleRegionID101:monthID4* | *-0.038414264* | *Applicable when monthID=4 and idleRegionID=101* |
| *idleRegionID104:monthID5* | *-0.040105796* | *Applicable when monthID=5 and idleRegionID=104* |
| *idleRegionID102:monthID5* | *-0.014531686* | *Applicable when monthID=5 and idleRegionID=102* |
| *idleRegionID103:monthID5* | *-0.057127644* | *Applicable when monthID=5 and idleRegionID=103* |
| *idleRegionID101:monthID5* | *-0.046499987* | *Applicable when monthID=5 and idleRegionID=101* |
| *idleRegionID104:monthID6* | *-0.04388419* | *Applicable when monthID=6 and idleRegionID=104* |
| *idleRegionID102:monthID6* | *-0.012980897* | *Applicable when monthID=6 and idleRegionID=102* |
| *idleRegionID103:monthID6* | *-0.057285679* | *Applicable when monthID=6 and idleRegionID=103* |
| *idleRegionID101:monthID6* | *-0.050253407* | *Applicable when monthID=6 and idleRegionID=101* |
| *idleRegionID104:monthID7* | *-0.049352207* | *Applicable when monthID=7 and idleRegionID=104* |
| *idleRegionID102:monthID7* | *-0.013796675* | *Applicable when monthID=7 and idleRegionID=102* |
| *idleRegionID103:monthID7* | *-0.064939617* | *Applicable when monthID=7 and idleRegionID=103* |
| *idleRegionID101:monthID7* | *-0.055021202* | *Applicable when monthID=7 and idleRegionID=101* |
| *idleRegionID104:monthID8* | *-0.045892406* | *Applicable when monthID=8 and idleRegionID=104* |
| *idleRegionID102:monthID8* | *-0.01495486* | *Applicable when monthID=8 and idleRegionID=102* |
| *idleRegionID103:monthID8* | *-0.060514513* | *Applicable when monthID=8 and idleRegionID=103* |
| *idleRegionID101:monthID8* | *-0.050001647* | *Applicable when monthID=8 and idleRegionID=101* |
| *idleRegionID104:monthID9* | *-0.04806906* | *Applicable when monthID=9 and idleRegionID=104* |

| *Variable* | *Coefficients* | *Comments* |
|---|---|---|
| *idleRegionID102:monthID9* | *-0.021947448* | *Applicable when monthID=9 and idleRegionID=102* |
| *idleRegionID103:monthID9* | *-0.060010652* | *Applicable when monthID=9 and idleRegionID=103* |
| *idleRegionID101:monthID9* | *-0.04850918* | *Applicable when monthID=9 and idleRegionID=101* |
| *idleRegionID104:monthID10* | *-0.05048841* | *Applicable when monthID=10 and idleRegionID=104* |
| *idleRegionID102:monthID10* | *-0.032213346* | *Applicable when monthID=10 and idleRegionID=102* |
| *idleRegionID103:monthID10* | *-0.068309965* | *Applicable when monthID=10 and idleRegionID=103* |
| *idleRegionID101:monthID10* | *-0.052869353* | *Applicable when monthID=10 and idleRegionID=101* |
| *idleRegionID104:monthID11* | *-0.02092116* | *Applicable when monthID=11 and idleRegionID=104* |
| *idleRegionID102:monthID11* | *-0.026195031* | *Applicable when monthID=11 and idleRegionID=102* |
| *idleRegionID103:monthID11* | *-0.045139401* | *Applicable when monthID=11 and idleRegionID=103* |
| *idleRegionID101:monthID11* | *-0.046514269* | *Applicable when monthID=11 and idleRegionID=101* |
| *idleRegionID104:monthID12* | *-0.00750439* | *Applicable when monthID=12 and idleRegionID=104* |
| *idleRegionID102:monthID12* | *-0.025582194* | *Applicable when monthID=12 and idleRegionID=102* |
| *idleRegionID103:monthID12* | *-0.042625551* | *Applicable when monthID=12 and idleRegionID=103* |
| *idleRegionID101:monthID12* | *-0.047243005* | *Applicable when monthID=12 and idleRegionID=101* |

# Appendix G Example Total Idle Fraction Calculation Results

The table below shows a sample calculation of MOVES201X default total idle fractions using the coefficients in Appendix Appendix Ffor passenger cars (sourceTypeID=21) in rural counties (countyTypeID=0) in idleRegionID=101 (represented by New Jersey).

*Table 17-18 Example total idle fractions for rural New Jersey passenger cars.*

| sourceTypeID | monthID | dayID | idleRegionID | countyTypeID | TIF |
|---|---|---|---|---|---|
| 21 | 1 | 2 | 101 | 0 | 0.2670 |
| 21 | 2 | 2 | 101 | 0 | 0.2538 |
| 21 | 3 | 2 | 101 | 0 | 0.2293 |
| 21 | 4 | 2 | 101 | 0 | 0.2225 |
| 21 | 5 | 2 | 101 | 0 | 0.2164 |
| 21 | 6 | 2 | 101 | 0 | 0.2141 |
| 21 | 7 | 2 | 101 | 0 | 0.2149 |
| 21 | 8 | 2 | 101 | 0 | 0.2163 |
| 21 | 9 | 2 | 101 | 0 | 0.2155 |
| 21 | 10 | 2 | 101 | 0 | 0.2214 |
| 21 | 11 | 2 | 101 | 0 | 0.2263 |
| 21 | 12 | 2 | 101 | 0 | 0.2273 |
| 21 | 1 | 5 | 101 | 0 | 0.2782 |
| 21 | 2 | 5 | 101 | 0 | 0.2651 |
| 21 | 3 | 5 | 101 | 0 | 0.2406 |
| 21 | 4 | 5 | 101 | 0 | 0.2337 |
| 21 | 5 | 5 | 101 | 0 | 0.2276 |
| 21 | 6 | 5 | 101 | 0 | 0.2254 |
| 21 | 7 | 5 | 101 | 0 | 0.2261 |
| 21 | 8 | 5 | 101 | 0 | 0.2276 |
| 21 | 9 | 5 | 101 | 0 | 0.2268 |
| 21 | 10 | 5 | 101 | 0 | 0.2327 |
| 21 | 11 | 5 | 101 | 0 | 0.2376 |
| 21 | 12 | 5 | 101 | 0 | 0.2386 |

# Appendix H Source Masses from Previous Versions of MOVES

In MOVES201X, the source masses were unchanged from MOVES2014 for the following source type and model year combinations:

- Motorcycles, passenger cars, passenger trucks, light commercial trucks, transit buses, school buses, other buses, refuse trucks, and motor homes for all model years
- Short-haul and long-haul single-unit trucks prior to model year 2021
- Short-haul and long-haul combination trucks prior to model year 2018

This appendix describes the derivation of these source masses. Information on the updated source masses is provided in Section15.

In MOVES2010b, weight data (among other kinds of information) were used to allocate source types to source bins using a field called weightClassID. While that information is no longer used in MOVES and has not been updated, it provides a reasonable basis for estimating source mass for the MOVES source types. As described in Equation 55, each source type's source mass was calculated using an activity-weighted average of their associated source bins' midpoint weights:

$$M = \frac{\sum_a \left\{ f_a \cdot \left( \frac{\sum_b \alpha_b \cdot m}{\sum_b \alpha_b} \right) \right\}}{\sum_a f_a} \qquad \textbf{Equation 55}$$

where $M$ is the source mass factor for the source type, $f_a$ is the age fraction at age $a$, $\alpha_b$ is the source bin activity fraction for source bin $b$, and $m$ is the vehicle midpoint mass. Table 17-19 lists the vehicle midpoint mass for each weightClassID. The source bin activity fraction in MOVES2010b is a calculated value of activity based on fuel type, engine technology, regulatory class, model year, engine size, and weight class.

*Table 17-19 MOVES2010b weight classes*

| WeightClassID | Weight Class Name | Midpoint Weight |
|---|---|---|
| 0 | Doesn't Matter | [NULL] |
| 20 | weight < 2000 pounds | 1000 |
| 25 | 2000 pounds <= weight < 2500 pounds | 2250 |
| 30 | 2500 pounds <= weight < 3000 pounds | 2750 |
| 35 | 3000 pounds <= weight < 3500 pounds | 3250 |
| 40 | 3500 pounds <= weight < 4000 pounds | 3750 |
| 45 | 4000 pounds <= weight < 4500 pounds | 4250 |
| 50 | 4500 pounds <= weight < 5000 pounds | 4750 |
| 60 | 5000 pounds <= weight < 6000 pounds | 5500 |
| 70 | 6000 pounds <= weight < 7000 pounds | 6500 |
| 80 | 7000 pounds <= weight < 8000 pounds | 7500 |
| 90 | 8000 pounds <= weight < 9000 pounds | 8500 |
| 100 | 9000 pounds <= weight < 10000 pounds | 9500 |
| 140 | 10000 pounds <= weight < 14000 pounds | 12000 |
| 160 | 14000 pounds <= weight < 16000 pounds | 15000 |
| 195 | 16000 pounds <= weight < 19500 pounds | 17750 |
| 260 | 19500 pounds <= weight < 26000 pounds | 22750 |
| 330 | 26000 pounds <= weight < 33000 pounds | 29500 |
| 400 | 33000 pounds <= weight < 40000 pounds | 36500 |
| 500 | 40000 pounds <= weight < 50000 pounds | 45000 |
| 600 | 50000 pounds <= weight < 60000 pounds | 55000 |
| 800 | 60000 pounds <= weight < 80000 pounds | 70000 |
| 1000 | 80000 pounds <= weight < 100000 pounds | 90000 |
| 1300 | 100000 pounds <= weight < 130000 pounds | 115000 |
| 9999 | 130000 pounds <= weight | 130000 |
| 5 | weight < 500 pounds (for MCs) | 350 |
| 7 | 500 pounds <= weight < 700 pounds (for MCs) | 600 |
| 9 | 700 pounds <= weight (for MCs) | 700 |

The following sections detail how weight classes were assigned to the various source types in MOVES.

## Appendix H.1 Motorcycles

The Motorcycle Industry Council *Motorcycle Statistical Annual* provides information on displacement distributions for highway motorcycles for model years 1990 and 1998. These were mapped to MOVES engine displacement categories. Additional EPA certification data was used to establish displacement distributions for model year 2000. We assumed that displacement distributions were the same in 1969 as in 1990, and interpolated between the established values to determine displacement distributions for all model years from 1990 to 1997 and for 1999. Values for 2000-and-later model years are based on model year 2000 certification data.

We then applied weight distributions for each displacement category as suggested by EPA motorcycle experts. The average weight estimate includes fuel and rider. The weight distributions depended on engine displacement but were otherwise independent of model year. This information is summarized in Table 17-20.

*Table 17-20 Motorcycle engine size and average weight distributions for selected model years*

| Displacement Category | 1969 MY distribution (assumed) | 1990 MY distribution (MIC) | 1998 MY distribution (MIC) | 2000 MY distribution (certification data) | Weight distribution (EPA staff) |
|---|---|---|---|---|---|
| 0-169 cc (1) | 0.118 | 0.118 | 0.042 | 0.029 | 100%: <= 500 lbs. |
| 170-279 cc (2) | 0.09 | 0.09 | 0.05 | 0.043 | 50%: <= 500 lbs.<br>50%: 500lbs. -700lbs. |
| 280+ cc (9) | 0.792 | 0.792 | 0.908 | 0.928 | 30%: 500 lbs.-700 lbs.<br>70%: > 700lbs. |

## Appendix H.2 Passenger Cars

Passenger car weights come from the 1999 IHS dataset. The weightClassID was assigned by adding 300 lbs. to the IHS curb weight and grouping into MOVES weight bins. For each fuel type, model year, engine size, and weight bin, the number of cars was summed and fractions were computed. In general, entries for which data was missing were omitted from the calculations. Also, analysis indicated a likely error in the IHS data (an entry for 1997 gasoline-powered Bentleys with engine size 5099 and weight class 20). This fraction was removed and the 1997 values were renormalized. 1999 model year values were used for all 2000-and-later model years.

## Appendix H.3 Light-Duty Trucks

Determining weight categories for light trucks was fairly complicated. The VIUS1997 data combines information from two different survey forms. The first form was administered for VIUS "Strata" 1 and 2 trucks: pickup trucks, panel trucks, vans (including mini-vans), utility type vehicles (including jeeps) and station wagons on truck chassis. The second form was administered for all other trucks. While both surveys requested information on engine size, only the second form requested detailed information on vehicle weight. Thus for Strata 1 and 2 trucks, VIUS classifies the trucks only by broad average weight category (AVGCK): 6,000 lbs. or less, 6,001-10,000 lbs., 10,001-14,000 lbs., etc. To determine a more detailed average engine size and weight distribution for these vehicles, we used an Oak Ridge National Laboratory (ORNL) light-duty vehicle database, compiled from EPA test vehicle data and Ward's Automotive Inc.[104] data, to correlate engine size with vehicle weight distributions by model year.

In particular, for source types 31 and 32 (Passenger Trucks and Light Commercial Trucks):

- VIUS1997 trucks of the source type in Strata 3, 4, and 5 were assigned to the appropriate MOVES weight class based on VIUS detailed average weight information.
- VIUS1997 trucks of the source type in Strata 1 and 2 were identified by engine size and broad average weight category.
- Strata 1 and 2 trucks in the heavier (10,001-14,000 lbs., etc.) VIUS1997 broad categories were matched one-to-one with the MOVES weight classes.
- For trucks in the lower broad categories (6,000 lbs. or less and 6001-10,000 lbs.), we used VIUS1997 to determine the fraction of trucks by model year and fuel type that fell into each engine size/broad weight class combination (the "VIUS fraction").

- We assigned trucks in the ORNL light-duty vehicle database to a weightClassID by adding 300 lbs. to the recorded curb weight and determining the appropriate MOVES weight class.
- For the trucks with a VIUS1997 average weight of 6,000 lbs. or less, we multiplied the VIUS1997 fraction by the fraction of trucks with a given weightClassID among the trucks in the ORNL database that had the given engine size and an average weight of 6,000 lbs. or less. Note, the ORNL database did not provide information on fuel type, so the same distributions were used for all fuels.

  Because the ORNL database included only vehicles with a GVW up to 8500 lbs., we did not use it to distribute the trucks with a VIUS1997 average weight of 6,001-10,000 lbs. Instead these were distributed equally among the MOVES weightClassID 70, 80, 90 and 100.

## Appendix H.4 Heavy-Duty Trucks

In MOVES2014, the heavy-duty truck source masses were updated with 2011 Weigh-in-Motion (WIM) data made available through FHWA's Vehicle Travel Information System (VTRIS).[105] This section first describes the original derivation of the single-unit truck and combination truck source masses as used in MOVES2010b and then describes the adjustments made for MOVES2014.

## Appendix H.5 Single-Unit Trucks

Source types 52 and 53 (long- and short-haul single-unit trucks) also included some trucks in VIUS1997 Strata 1 and 2, thus a similar algorithm as the one used for light-duty trucks was applied.

- VIUS1997 trucks of the given source type in Strata 3, 4, and 5 were assigned to the appropriate MOVES weight class based on VIUS1997 detailed average weight information.
- VIUS1997 trucks of the given source type in Strata 1 and 2 were identified by engine size and broad average weight category.
- Strata 1 and 2 trucks in the heavier (10,001-14,000 lbs., etc.) VIUS1997 broad categories were matched one-to-one with the MOVES weight classes.
- For trucks in the lower broad categories (6,000 lbs.-or-less and 6001-10,000 lbs.), we used VIUS1997 to determine the fraction of trucks by model year and fuel type that fell into each engine size/broad weight class combination (the "VIUS fraction").
- We did not believe the ORNL light-duty vehicle database adequately represented single-unit trucks. Thus, the trucks with a VIUS1997 average weight of 6,000 lbs. or less and an engine size less than 5 liters were distributed equally among the MOVES weight classes 20, 25, 30, 35, 40, 45, 50, and 60. Because no evidence existed of very light trucks among the vehicles with larger engines (5 liter or larger), these were equally distributed among MOVES weight classes 40, 45, 50 and 60.
- The trucks with a VIUS1997 average weight of 6,001-10,000 lbs. were distributed equally among the MOVES weight classes 70, 80, 90 and 100.

### Appendix H.6 Combination Trucks

Long- and short-haul combination trucks (source types 61 and 62) did not include any vehicles of VIUS1997 Strata 1 or 2. Thus we used the detailed VIUS1997 average weight information and engine size information to assign engine size and weight classes for all of these trucks.

When VIUS2002 became available, we updated values that had been based on VIUS1997. The VIUS2002 contains an estimate of the average weight (vehicle weight plus cargo weight) of 1998-2002 model year vehicle or vehicle/trailer combination as it was most often operated when carrying a typical payload during 2002. These estimates were used to determine the MOVES weightClassID categories for these trucks. Any vehicles with a zero or missing value for the average weight and without a weight classification in the WeightAvgCK field were excluded from the analysis for determining the average weight distributions.

Since there is a smaller number of gasoline trucks among the single-unit and refuse trucks, all model years (1998-2002) were combined to determine a single weight distribution to use for these model years. The VIUS1997 based estimates were retained for light-duty trucks (source types 31 and 32) and for all model years prior to 1998.

In cases where distributions were missing (no survey information), distributions from a nearby model year with the same source type was used. Weight distributions for all 2003 and newer model years were set to be the same as for the 2002 model year for each source type.

#### Appendix H.6.1 Weigh-in-Motion Adjustment

FHWA compiles truck weight data by axle configuration and roadway type from individual states' Weigh-in-Motion (WIM) programs. The average weights for single-unit trucks and combination trucks were determined from FHWA's Vehicle Travel Information System (VTRIS) W-3 Tables using data collected in 2011. These data are available by state, road type, and HPMS truck type (single-unit or combination). The national average mass by truck type was calculated by weighting the masses with VMT by state and road type using FHWA's 2011 *Highway Statistics* Table VM-2.

Because the WIM data did not distinguish by source type, the source type masses in MOVES2010b were updated for MOVES2014 using the percent difference between the average WIM HPMS vehicle type mass and the average MOVES2010b HPMS vehicle type mass.[q] The percentage difference for single-unit trucks was applied to the source masses of short-haul single-unit trucks, long-haul single-unit trucks, refuse trucks, and motor homes. Likewise, the percentage difference for combination trucks was applied to the source masses of short-haul and long-haul combination trucks. Finally, the source masses for heavy-duty model year 2014-2050 vehicles were updated to account for HD GHG Phase 1.

[q] Source masses in MOVES2010b were calculated by source type, as described in the above sections. Average HPMS masses were calculated for both single unit trucks and combination trucks by weighting the source type masses with the 2011 source type VMT as calculated by running a draft version of MOVES2014.

## Appendix H.7 Buses

For the non-transit, non-school "other buses", we used information from Table II-7 of the FTA 2003 Report to Congress[29] that specified the number of buses in various weight categories. This information is summarized in below in Table 17-21. Note that the FTA term "over-the-road bus" was applied to the MOVES other bus category. The FTA weight categories were mapped to the equivalent MOVES weight classes.

*Table 17-21 FTA estimates of bus weights*

| Weight (lbs.) | MOVES Weight ClassID | MOVES Weight Range (lbs.) | Number of buses (2000) | Bus type |
|---|---|---|---|---|
| 0-20,000 | | | 173,536 | school & transit |
| 20,000-30,000 | | | 392,345 | school & transit |
| 30,000-40,000 | 400 | 33,000-40,000 | 120,721 | school & transit & other |
| 40,000-50,000 | 500 | 40,000-50,000 | 67,905 | other |
| total | | | 754,509 | |

*Table 17-22 1999 bus population comparisons by data source*

| Data Source | Total Buses | Other Buses | Transit Buses | School Buses |
|---|---|---|---|---|
| FHWA MV-1 | 732,189 | | | |
| FHWA MV-10 (excludes PR) | 728,777 | | | 592,029* |
| FHWA adjusted for PR | | | | 594,800 |
| FTA NTD | | | 55,706 | |
| APTA[106] *** | | | 75,087 | |
| IHS (Polk) TIP® | | | | 460,178 |
| School Bus Fleet Fact Book | | | | 429,086 |
| Motorcoach Census[28]** | | 44,200 | | |

* Includes some church & industrial buses.
** Includes Canada.
*** Includes trolleybuses.

Using the 1999 bus population estimates in Table 17-22, we were able to estimate the fraction of all buses that were other buses and then to estimate the fraction of other buses in each weight bin. In particular:

Estimated number of other buses in 2000:

$$754{,}509 * (84{,}454/(84{,}454+55{,}706+592{,}029)) = 87{,}028$$

Estimated number of other buses 30,000-40,000 lbs.:

$$87{,}028 - 67{,}905 = 19{,}123$$

Estimated other bus weight distribution:

$$\text{Class } 400 = 19{,}123/87{,}028 = 22 \text{ percent}$$
$$\text{Class } 500 = 67{,}905/87{,}028 = 78 \text{ percent}$$

This distribution was used for all model years.

For transit buses, we took average curb weights from Figure II-6 of the FTA Report to Congress[29] and added additional weight to account for passengers and alternative fuels. The resulting in-use weights were all in the range from 33,850 to 40,850. Thus all transit buses were assigned to the weight class "400" (33,000 - 40,000 lbs.) for all model years. This estimate could be improved if more detailed weight information for transit buses becomes available.

For school buses, we used information from a survey of California school buses. While this data is older and may not be representative of the national average distribution, it was the best data source available. The California data[107] provided information on number of vehicles by gross vehicle weight class and fuel as detailed in Table 17-23.

*Table 17-23 California school bus study weight classes and fuel types*

| | Gas | Diesel | Other | Total |
|---|---|---|---|---|
| LHDV | 2740 | 4567 | 8 | 7315 |
| MHDV | 467 | 2065 | 2 | 2534 |
| HHDV | 892 | 11639 | 147 | 12678 |
| Total | 4099 | 18271 | 157 | |

To estimate the distribution of average weights among the MOVES weight classes, we assumed that the Light Heavy-Duty (LHDV) school buses were evenly distributed among weightClassIDs 70, 80, 90, 100, and 140. Similarly, we assumed the Medium Heavy-Duty (MHDV) school buses were evenly distributed among weightClassIDs 140, 160, 195, 260, and 330 and the Heavy Heavy-Duty (HHDV) school buses were evenly distributed among weightClassIDs 195, 260, 330, and 440.

The final default weight distributions for buses are summarized in Table 17-24.

*Table 17-24 Weight distributions for buses by fuel type*

| | Other Buses (41) | Transit Buses (42) | School Buses (43) | |
|---|---|---|---|---|
| **Weight Class** | **Diesel** | **Diesel & Gas** | **Diesel** | **Gas** |
| 70 | | | 0.0500 | 0.1337 |
| 80 | | | 0.0500 | 0.1337 |
| 90 | | | 0.0500 | 0.1337 |
| 100 | | | 0.0500 | 0.1337 |
| 140 | | | 0.0726 | 0.1565 |
| 160 | | | 0.0226 | 0.0228 |
| 195 | | | 0.1819 | 0.0772 |
| 260 | | | 0.1819 | 0.0772 |
| 330 | | | 0.1819 | 0.0772 |
| 400 | 0.2197 | 1.0000 | 0.1593 | 0.0544 |
| 500 | 0.7800 | | | |

## Appendix H.8 Refuse Trucks

Because the sample of Refuse Trucks in VIUS was small, the weight distributions were calculated for model year groups rather than individual model years, shown below in Table

17-25. As for other trucks, the WeightClass was determined from the VIUS reported average weight.

*Table 17-25 Refuse truck SizeWeight fractions by fuel type*

| **Gasoline** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Engine Size** | **Weight (lbs.)** | **Pre-1997** | **1997 and Newer** | | | | |
| 3-3.5L | 5000-6000 | 0.009074 | 0 | | | | |
| >5L | 7000-8000 | 0.148826 | 0 | | | | |
| >5L | 9000-10000 | 0.070720 | 0 | | | | |
| >5L | 10000-14000 | 0.135759 | 0.324438 | | | | |
| >5L | 14000-16000 | 0.199961 | 0.593328 | | | | |
| >5L | 16000-19500 | 0.055085 | 0 | | | | |
| >5L | 19500-26000 | 0.205341 | 0 | | | | |
| >5L | 26000-33000 | 0.022105 | 0 | | | | |
| >5L | 33000-40000 | 0.153129 | 0 | | | | |
| >5L | 50000-60000 | 0 | 0.082234 | | | | |
| **Sum** | | **1.000000** | **1.000000** | | | | |
| | | | | | | | |
| **Diesel** | | | | | | | |
| **Engine Size** | **Weight (lbs.)** | **Pre-1998** | **1998** | **1999** | **2000** | **2001** | **2002 and Newer** |
| 3.5-4L | 10000-14000 | 0.007758 | 0 | 0 | 0 | 0 | 0 |
| 4-5L | 10000-14000 | 0 | 0 | 0 | 0 | 0 | 0.006614 |
| 4-5L | 14000-16000 | 0 | 0 | 0 | 0.015505 | 0 | 0 |
| 4-5L | 16000-19500 | 0 | 0 | 0 | 0 | 0.011670 | 0 |
| >5L | 9000-10000 | 0.006867 | 0.009593 | 0 | 0 | 0 | 0 |
| >5L | 10000-14000 | 0.011727 | 0 | 0 | 0 | 0.019438 | 0 |
| >5L | 14000-16000 | 0.022960 | 0 | 0 | 0 | 0 | 0 |
| >5L | 16000-19500 | 0.063128 | 0 | 0.011367 | 0.047200 | 0 | 0 |
| >5L | 19500-26000 | 0.099782 | 0.035378 | 0.026212 | 0.052132 | 0.018329 | 0.026079 |
| >5L | 26000-33000 | 0.102077 | 0.019625 | 0.067419 | 0.072106 | 0.043877 | 0 |
| >5L | 33000-40000 | 0.237485 | 0.103922 | 0.088975 | 0.085991 | 0.042678 | 0.046966 |
| >5L | 40000-50000 | 0 | 0.283642 | 0.275467 | 0.165624 | 0.266357 | 0.194716 |
| >5L | 50000-60000 | 0.336484 | 0.338511 | 0.326902 | 0.384612 | 0.315133 | 0.474469 |
| >5L | 60000-80000 | 0.111730 | 0.196424 | 0.193238 | 0.176831 | 0.282517 | 0.224995 |
| >5L | 80000-100000 | 0 | 0 | 0.010420 | 0 | 0 | 0.013081 |
| >5L | 100000-130000 | 0 | 0.012904 | 0 | 0 | 0 | 0.013081 |
| **Sum** | | **1.000000** | **1.000000** | **1.000000** | **1.000000** | **1.000000** | **1.000000** |

## Appendix H.9 Motor Homes

No detailed information was available on average engine size and weight distributions for motor homes. We assumed all motor home engines were 5 L or larger. As a surrogate for average weight, we used information on gross vehicle weight provided in the IHS (Polk) TIP® 1999 database by model year and mapped the IHS GVW Class to the MOVES weight bins. These values are likely to overestimate average weight. The IHS (Polk) TIP® information did not specify fuel type, so we assumed that the heaviest vehicles in the IHS database were diesel-powered and the remainder were powered by gasoline. This led to the weight distributions in Table 17-26 and Table 17-27.

*Table 17-26 Weight fractions for diesel motor homes by model year*

| **Polk GVW bin** | **3** | **4** | **5** | **6** | **7** | **8** |
|---|---|---|---|---|---|---|
| **MOVES weight class** | **140** | **160** | **195** | **260** | **330** | **400** |
| **Model Year** | **Diesel** | | | | | |
| 1975-and-earlier | 0.171431 | 0.792112 | 0.029828 | 0 | 0.006629 | 0 |
| 1976 | 0.637989 | 0.340639 | 0.018755 | 0.000436 | 0.002181 | 0 |
| 1977 | 0.68944 | 0.292308 | 0.012168 | 0.000277 | 0.005531 | 0.000277 |
| 1978 | 0.423524 | 0.574539 | 0 | 0.000387 | 0.00155 | 0 |
| 1979 | 0.096922 | 0.899344 | 0 | 0.001067 | 0.002667 | 0 |
| 1980 | 0.462916 | 0.537084 | 0 | 0 | 0 | 0 |
| 1981 | 0 | 0.941973 | 0 | 0.030174 | 0 | 0.027853 |
| 1982 | 0 | 0.868333 | 0 | 0.049 | 0.03 | 0.052667 |
| 1983 | 0 | 0.912762 | 0.000203 | 0.014845 | 0.030096 | 0.042094 |
| 1984 | 0 | 0.932659 | 0.000835 | 0.009183 | 0.036732 | 0.020592 |
| 1985 | 0 | 0.881042 | 0.001474 | 0.010761 | 0.083285 | 0.023438 |
| 1986 | 0 | 0.855457 | 0.013381 | 0.022962 | 0.089534 | 0.018667 |
| 1987 | 0 | 0.791731 | 0.085493 | 0.022498 | 0.087164 | 0.013113 |
| 1988 | 0 | 0.72799 | 0.148917 | 0.015469 | 0.093335 | 0.014289 |
| 1989 | 0 | 0.73298 | 0.128665 | 0.043052 | 0.082792 | 0.012511 |
| 1990 | 0 | 0.173248 | 0.614798 | 0.043628 | 0.149939 | 0.018387 |
| 1991 | 0 | 0 | 0.619344 | 0.063712 | 0.296399 | 0.020545 |
| 1992 | 0 | 0 | 0.551548 | 0.01901 | 0.385085 | 0.044356 |
| 1993 | 0 | 0 | 0.345775 | 0.471873 | 0.144844 | 0.037509 |
| 1994 | 0 | 0 | 0.45546 | 0.354386 | 0.159622 | 0.030531 |
| 1995 | 0 | 0 | 0.635861 | 0.163195 | 0.17468 | 0.026264 |
| 1996 | 0 | 0 | 0.553807 | 0.229529 | 0.184208 | 0.032456 |
| 1997 | 0 | 0 | 0.666905 | 0.193167 | 0.111299 | 0.028628 |
| 1998 | 0 | 0 | 0.267 | 0.335069 | 0.357508 | 0.040423 |
| 1999+ | 0 | 0 | 0 | 0.736656 | 0.233886 | 0.029458 |

*Table 17-27 Weight fractions for gasoline motor homes by model year*

| **IHS GVW bin** | **3** | **4** | **5** | **6** | **7** | **8** |
|---|---|---|---|---|---|---|
| **MOVES weight class** | **140** | **160** | **195** | **260** | **330** | **400** |
| **Model Year** | **Gasoline** | | | | | |
| 1975-and-earlier | 1 | 0 | 0 | 0 | 0 | 0 |
| 1976 | 1 | 0 | 0 | 0 | 0 | 0 |
| 1977 | 1 | 0 | 0 | 0 | 0 | 0 |
| 1978 | 1 | 0 | 0 | 0 | 0 | 0 |
| 1979 | 1 | 0 | 0 | 0 | 0 | 0 |
| 1980 | 1 | 0 | 0 | 0 | 0 | 0 |
| 1981 | 0.747723 | 0.252277 | 0 | 0 | 0 | 0 |
| 1982 | 0.732235 | 0.267765 | 0 | 0 | 0 | 0 |
| 1983 | 0.714552 | 0.285448 | 0 | 0 | 0 | 0 |
| 1984 | 0.641577 | 0.358423 | 0 | 0 | 0 | 0 |
| 1985 | 0.692314 | 0.307686 | 0 | 0 | 0 | 0 |
| 1986 | 0.720248 | 0.279752 | 0 | 0 | 0 | 0 |
| 1987 | 0.606635 | 0.393365 | 0 | 0 | 0 | 0 |
| 1988 | 0.459429 | 0.540571 | 0 | 0 | 0 | 0 |
| 1989 | 0.551601 | 0.448399 | 0 | 0 | 0 | 0 |
| 1990 | 0.543354 | 0.456646 | 0 | 0 | 0 | 0 |
| 1991 | 0.612025 | 0.322022 | 0.065952 | 0 | 0 | 0 |
| 1992 | 0.54464 | 0.373999 | 0.081361 | 0 | 0 | 0 |
| 1993 | 0.583788 | 0.361277 | 0.054935 | 0 | 0 | 0 |
| 1994 | 0.481099 | 0.361146 | 0.157755 | 0 | 0 | 0 |
| 1995 | 0.52997 | 0.198479 | 0.271551 | 0 | 0 | 0 |
| 1996 | 0.435959 | 0.289453 | 0.274588 | 0 | 0 | 0 |
| 1997 | 0.221675 | 0.433334 | 0.344991 | 0 | 0 | 0 |
| 1998 | 0.288222 | 0.581599 | 0.13018 | 0 | 0 | 0 |
| 1999+ | 0.170133 | 0.392451 | 0.288411 | 0.149004 | 0 | 0 |

# Appendix I Freeway Ramp Contribution at the County-Scale

MOVES201X removed the capability to model ramp emissions separately from freeways (Rural restricted and Urban restricted roadtypes). This appendix contains summary of the analysis used to evaluate the emission consequences of removing the ramp roadtype from MOVES.

We analyzed vehicle activity on ramps and freeways from a study using portable activity measurement systems (PAMS) conducted in the Detroit metropolitan area on 12 light-duty vehicles[108]. From the PAMS measurements, we calculated MOVES running operating mode distributions for each of the 62 highway trips using two scenarios: 1) we included the on and off ramp as part of each highway trip 2) we excluded the ramp activity from the highway trips.

Using MOVES2014a, we calculated the emission rates (g/hr and g/mile) from the two scenarios.. The overall emission rates calculated from all 62 trips (in both g/hr and g/mile) ramps are higher than emissions estimated from MOVES highway driving cycles for all speeds greater than 20 mph. Thus, it is reasonable to expect that removing ramps could decrease the g/mile estimates for exhaust pollutants, which it did for HC, CO, and PM. Whereas, NOx and $CO_2$ were only increased slightly (<1.1 percent), which may be attributed to the lower g/mile emission rates observed on off-ramps compared to highway driving.

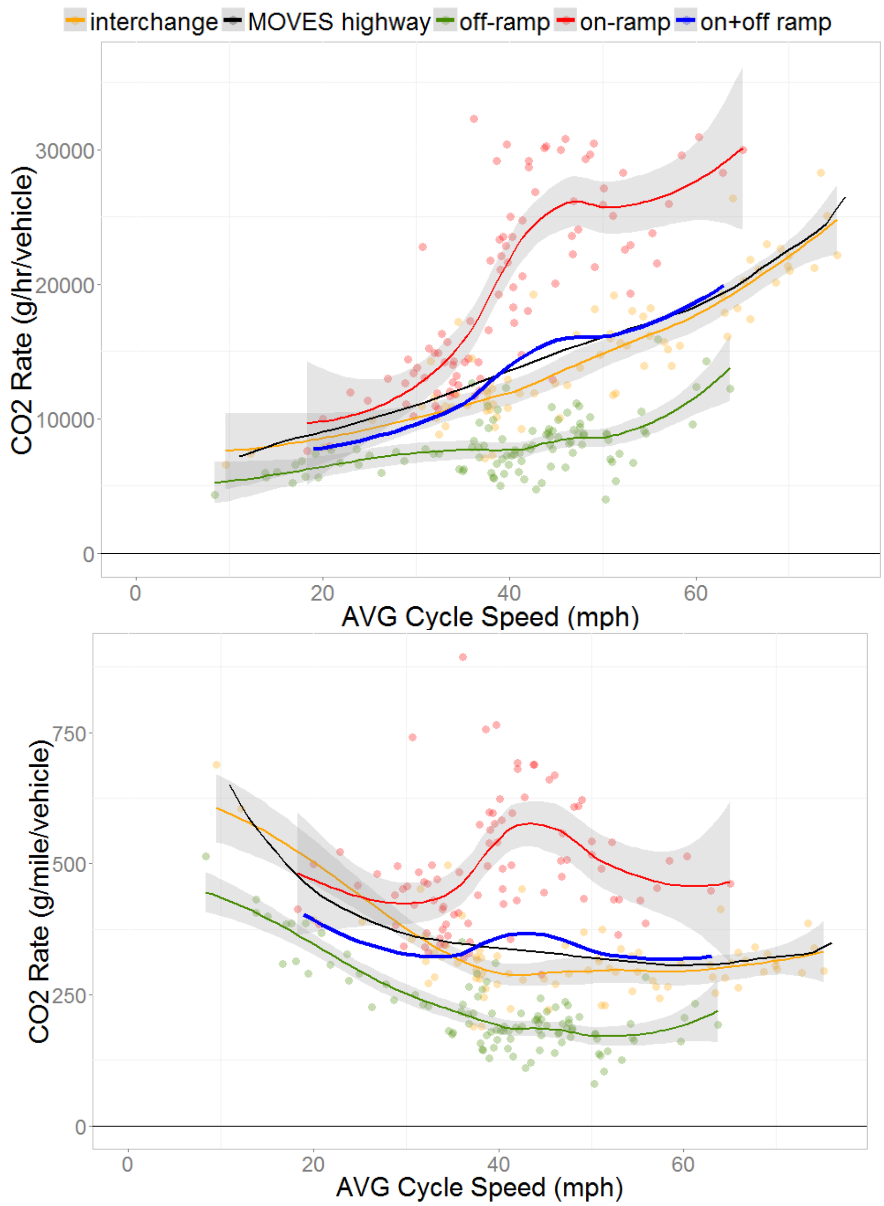


*Figure 17-4. Comparison of g/hr and g/mile across cycle average speed estimated from MOVES for vehicles operating on ramps measured in the Detroit PAMS study on on-ramps (red), off-ramps (green), and interchange ramps (orange) The MOVES highway (black line) plots the estimated emissions using the default MOVES driving cycles which do not include ramp activity.*

For estimating the impact of removing ramp in MOVES, the g/hr difference is used. This is because MOVES estimates emissions by multiplying emission rates (g/hr) by source hours operating (SHO). The calculation of SHO on restricted access highways is not affected with the removal of ramps in MOVES201X, because the inputs to calculate SHO on restricted access roadways (VMT and average speed) in both MOVES2014 and MOVES201X include all the activity on restricted access roadways, including the ramp activity.

Brake wear emissions exhibit a different behavior than the tailpipe emissions. The brakewear emissions from the trips that exclude ramps are 44 percent (g/hr) and 33 percent (g/mile) lower than the trips that contain the on and off ramp activity. These results are intuitive as off-ramps should contain a large percentage of the deceleration that occurs on each highway trip. Tire wear emissions were not estimated from the two scenarios, but are anticipated to differ only slightly, because MOVES tire wear emissions are a function of speed and not acceleration.

We estimated the impact of excluding ramps from onroad mobile source emissions inventories for three urban counties across five different calendar years. We first estimated the mobile emissions by roadtype using MOVES2014a without any ramp activity (ramp fraction = 0). Then we adjusted the restricted access roadtype emissions to account for ramp activity based on the g/hr values in Figure 17-4 estimated from the Detroit Light-duty PAMS study. As stated earlier, we used the g/hr values because we assume the average speed and VMT by MOVES user is unchanged for restricted access roadtypes, to isolate the impact of changing only the operating mode distribution of the roadtypes. We applied the percentage differences to all sourcetypes, assuming that the values derived from light-duty vehicles can be extended to all vehicle types. Using these assumptions, we calculated the emissions impact of excluding ramp activity from the highway driving cycles as shown in Table 17-28. By treating ramp VMT as non-ramp freeway VMT, the mobile-source emissions inventories are reduced by less than 3 percent for NOx, and less than 1 percent for HC, CO, and Primary $PM_{2.5}$ exhaust. Brakewear particulate is reduced by <9 percent.

*Table 17-28. Estimated Emissions Inventory impact from excluding ramp activity from highway driving cycles*

| Pollutant | County | 2011 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| HC | A | 0.24% | 0.24% | 0.22% | 0.21% | 0.19% |
| | B | 0.40% | 0.39% | 0.33% | 0.31% | 0.30% |
| | C | 0.19% | 0.18% | 0.15% | 0.14% | 0.13% |
| CO | A | 0.39% | 0.40% | 0.40% | 0.40% | 0.40% |
| | B | 0.69% | 0.73% | 0.74% | 0.75% | 0.76% |
| | C | 0.37% | 0.39% | 0.42% | 0.43% | 0.42% |
| NOx | A | 2.48% | 2.63% | 2.73% | 2.71% | 2.64% |
| | B | 3.00% | 3.05% | 3.01% | 2.91% | 2.78% |
| | C | 1.95% | 2.00% | 1.97% | 1.92% | 1.82% |
| Primary Exhaust PM2.5 | A | 0.26% | 0.27% | 0.26% | 0.25% | 0.23% |
| | B | 0.33% | 0.33% | 0.32% | 0.30% | 0.29% |
| | C | 0.19% | 0.20% | 0.19% | 0.18% | 0.16% |
| Brake wear Particulate | A | -5.73% | -5.99% | -5.95% | -5.92% | -5.88% |
| | B | -8.51% | -8.73% | -8.74% | -8.74% | -8.72% |
| | C | -4.66% | -4.75% | -4.72% | -4.70% | -4.69% |

# Appendix J MOVES Highway Ramp Operating Mode Distribution Tool: User Guide and Technical Documentation

## Appendix J.1 Introduction

For project-level analyses of air pollution emissions from cars, trucks, and other onroad mobile sources, it is important to be able to model the location of elevated emissions, such as exhaust emissions on an aggressive on-ramp, or brake and tire wear emissions on an off-ramp. The Highway Ramp Operating Mode Distribution Tool is designed to provide users of the EPA Motor Vehicle Emission Simulator (MOVES) model with the inputs needed for this analysis.

MOVES estimates air pollution emissions from onroad vehicles based, in part, on their speed and acceleration as defined by operating modes. This tool estimates the fraction of time spent in each MOVES-defined operating mode on highway on-ramps and off-ramps based on user-provided information about average speed, road type and vehicle type. Modelers could use this tool in the absence of other data (e.g. traffic observation, traffic simulation) regarding the vehicle operation on the ramp link. However, the tool has limitations that should be considered before it is used in a project-level analysis.

This document provides information on the use of the Highway Ramp Operating Mode Distribution Tool, limitations associated with the tool, instructions, and information about the data and analysis that went into the tool.

More information on using MOVES is available on the MOVES web page, https://www.epa.gov/moves.  Addition information on doing project-level conformity and hot-spot analysis is available at https://www.epa.gov/state-and-local-transportation/project-level-conformity-and-hot-spot-analyses.

## Appendix J.2 Using the Highway Ramp Operating Mode Distribution Tool

For project-level analysis in MOVES, users can specify the driving behavior of vehicles on individual roadway links by inputting one of three types of data: 1) drive cycle, 2) operating mode distribution, or 3) average speed. When users input average speed and road type, MOVES assigns operating modes by selecting driving cycles with corresponding average speeds and road types as documented in Section 9. However, because highway on-ramp and off-ramps are defined as part of the restricted access road types in MOVES201X, using the average speed approach to estimate emissions for an on-ramp or off-ramp link leads to modeling the operating conditions for highway driving activity without ramps.

The purpose of the Highway Ramp Operating Mode Distribution Tool is to estimate average vehicle operating conditions on ramps in the absence of other data. The tool was designed for users who otherwise would have estimated the operating mode distribution on a freeway ramp using average speed and the default highway driving cycles in MOVES. In cases, where the average speed and default highway cycles were used to characterize ramp activity, the tool should provide a significant improvement. Even so, the users of the tool should recognize the limitations of the tool, and exercise judgment about whether the tool should be used for their emissions modeling purposes.

The tool is an Excel spreadsheet that provides operating mode distributions for three source types in MOVES: passenger cars, passenger trucks and light-commercial trucks. The tool provides operating mode distributions for ramps with average speeds between 18 and 50 mph only. It is equipped to calculate an operating mode distribution for all pollutants associated with running emissions on highway ramps. This includes running exhaust, brake wear, tire wear, and crankcase running exhaust.

The tool contains a lookup table of ramp operating mode distributions based on data from instrumented light-duty vehicles in the Detroit, Michigan area during 2012. The lookup table stores operating mode distribution by source type, ramp type, day type, hour, and four average speed bins. Based on user inputs, the tool outputs an appropriate operating mode distribution as interpolated between the distributions stored in the lookup table.

### Appendix J.2.1 Step-by-Step Instructions

1. Open the Highway Ramp Operating Mode Distribution Tool using Excel.
2. In "Table 1" of the tool, select ramp type, days, and hour of MOVES analysis as defined in the MOVES run specification.
3. Enter a link ID. A unique link ID should be used for each ramp within one MOVES project level run.
4. Enter average speed in miles per hour.
    a. This value is the average speed on the individual ramp you are analyzing
    b. If "N/A" appears in Table 2, entered speed is either:
        i. Not a valid input (non-numerical)
        ii. Outside of the expected average ramp speed range (18-50 miles per hour)
5. Save the tool as an .xls file.
6. Using MOVES, import the 'opModeDistribution' worksheet from the .xls file into the MOVES project data manager under the 'Operating Mode Distribution' tab.
    a. The tool will provide the operating mode distribution for all possible light duty source types and all pollutant processes. After being imported into the project data manager, the user will see an "extra data imported but not used" error if the user is not analyzing all pollutant processes and/or source types in their run spec. This will not affect results of the MOVES run.
7. Repeat steps 1-5 for each ramp being analyzing in the same project level run spec.
    a. For each new ramp in a run spec, the link ID should be updated. The ramp type and average speed should be updated if they are different for each ramp. Hour and days should remain constant within each run spec.
8. DO NOT DELETE, RENAME OR OTHERWISE ALTER ANY ROWS, COLUMNS, OR WORKSHEETS IN THE TOOL.

### Appendix J.3 Limitations

One limitation of the Highway Ramp Operating Mode Distribution Tool is that it is intended to provide operating mode distributions that can be applied to represent an average of many different on and off-ramp geometries and traffic conditions. In the tool, average speed is used to represent both congestion levels and the associated design properties of a ramp. (e.g. the data at lower speeds include a higher sampling of cloverleaf ramps, while the higher speed operating modes include more diamond ramps). Thus, we would not expect the tool to provide useful results in modeling speed changes when no change was made to the geometry of the ramps.

In addition, the tool does not account for other factors that could impact emissions from the ramps such as road grade, length of the ramp, ramp geometry, number of lanes, traffic volume, and whether the connection of the ramp to a local arterial is a free-flowing intersection or a stopped intersection. In addition, the ramp operating mode distributions were based on driving in the Detroit metropolitan area during the summer. Different areas of the country, particularly areas with ramp meters and toll booths, may have significantly different ramp operating conditions.

Another limitation of the tool is that it only provides operating mode distributions for average speeds between 18 and 50 mph. Finally, another key limitation of the tool is that it only applies to light-duty vehicles (passenger vehicles, passenger trucks, and light-commercial trucks). Users should provide their own data, or make their own assumptions about operating mode distributions for average speeds and vehicle types not covered by the tool.

We encourage future work to develop additional data sets and tools that would help users address these limitations.

### Appendix J.4 Technical Background

This tool was created using data collected in the Detroit, Michigan area during 2012.[108] Light duty cars were equipped with portable activity measurement systems (PAMS), which recorded second-by-second speed and position data. This allowed EPA to isolate vehicle activity on highway ramps. The vehicle activity that occurred on each ramp type (on or off) for each trip was identified, as described in Liu et al., 2016.[108] We used the PAMS data on the vehicle's instantaneous speed and engine load, along with MOVES road-load coefficients and average vehicle weights, to calculate vehicle specific power discussed in Section 15 to assign each second of data to an operating mode. Although the vehicles measured were all passenger cars, we also applied the MOVES road-load coefficients and average vehicle weights to estimate the operating modes for passenger trucks and light-commercial trucks, assuming that the speed traces are the same for these vehicles. We did not have grade data for the trips, and assumed a grade of zero for calculating vehicle specific power using **Equation 22**. The operating modes used in this tool are described in Table 17-29 below. Operating modes 0 through 40, used for exhaust and brake-wear emissions, are a function of instantaneous speed and vehicle specific power. Operating modes 400 through 416, used for tire wear emission rates, are a function of instantaneous speed only. Operating mode 501 is used when vehicle speed = 1 mph for brake wear emissions. Otherwise, operating mode 1 is used for the exhaust pollutants.

*Table 17-29 MOVES Operating Modes Relevant for Ramps*

| Op Mode ID | Description | VSP | Speed Range |
|---|---|---|---|
| 0 | Deceleration/Braking | | |
| 1 | Idle | | 0 ≤ v < 1 |
| 11 | Coast | VSP < 0 | 1 ≤ v < 25 |
| 12 | Cruise/Acceleration | 0 ≤ VSP < 3 | 1 ≤ v < 25 |
| 13 | Cruise/Acceleration | 3 ≤ VSP < 6 | 1 ≤ v < 25 |
| 14 | Cruise/Acceleration | 6 ≤ VSP < 9 | 1 ≤ v < 25 |
| 15 | Cruise/Acceleration | 9 ≤ VSP < 12 | 1 ≤ v < 25 |
| 16 | Cruise/Acceleration | 12 ≤ VSP | 1 ≤ v < 25 |
| 21 | Coast | VSP < 0 | 25 ≤ v < 50 |
| 22 | Cruise/Acceleration | 0 ≤ VSP < 3 | 25 ≤ v < 50 |
| 23 | Cruise/Acceleration | 3 ≤ VSP < 6 | 25 ≤ v < 50 |
| 24 | Cruise/Acceleration | 6 ≤ VSP < 9 | 25 ≤ v < 50 |
| 25 | Cruise/Acceleration | 9 ≤ VSP < 12 | 25 ≤ v < 50 |
| 27 | Cruise/Acceleration | 12 ≤ VSP < 18 | 25 ≤ v < 50 |
| 28 | Cruise/Acceleration | 18 ≤ VSP < 24 | 25 ≤ v < 50 |
| 29 | Cruise/Acceleration | 24 ≤ VSP < 30 | 25 ≤ v < 50 |
| 30 | Cruise/Acceleration | 30 ≤ VSP | 25 ≤ v < 50 |
| 33 | Cruise/Acceleration | VSP < 6 | 50 ≤ v |
| 35 | Cruise/Acceleration | 6 ≤ VSP < 12 | 50 ≤ v |
| 37 | Cruise/Acceleration | 12 ≤ VSP <18 | 50 ≤ v |
| 38 | Cruise/Acceleration | 18 ≤ VSP < 24 | 50 ≤ v |
| 39 | Cruise/Acceleration | 24 ≤ VSP < 30 | 50 ≤ v |
| 40 | Cruise/Acceleration | 30 ≤ VSP | 50 ≤ v |
| 400 | Tirewear; Idle | | v = 0 |
| 401 | Tirewear | | 0 < v < 2.5 |
| 402 | Tirewear | | 7.5 ≤ v < 12.5 |
| 403 | Tirewear | | 12.5 ≤ v < 17.5 |
| 404 | Tirewear | | 17.5 ≤ v < 22.5 |
| 405 | Tirewear | | 22.5 ≤ v < 27.5 |
| 406 | Tirewear | | 27.5 ≤ v < 32.5 |
| 407 | Tirewear | | 32.5 ≤ v < 37.5 |
| 409 | Tirewear | | 37.5 ≤ v < 42.5 |
| 410 | Tirewear | | 42.5 ≤ v < 47.5 |
| 411 | Tirewear | | 47.5 ≤ v < 52.5 |
| 412 | Tirewear | | 52.5 ≤ v < 57.5 |
| 413 | Tirewear | | 57.5 ≤ v < 62.5 |
| 414 | Tirewear | | 62.5 ≤ v < 67.5 |
| 415 | Tirewear | | 67.5 ≤ v < 72.5 |
| 416 | Tirewear | | 72.5 ≤ v |
| 501 | Brakewear; Stopped | | v = 0 |

After calculating the operating mode distributions for each ramp trip, we used the MOVES emission rates to inform the averaging of the operating mode distributions. We calculated fleet-average MOVES g/hr emission rates by operating mode using a MOVES run for Wayne County (Detroit, Michigan) for July 2015.[108] We assigned an emission rate to each second of operation of the ramps, and calculated the average speed of each ramp trip. Ramp trips were then sorted, according to average ramp speed, into 16 five mph speed bins. The average HC, CO, NOx, $PM_{2.5}$, $PM_{10}$, $CO_2$, and brake wear emission rates for each speed bin were calculated using the trip data within each bin. We then aggregated the 16 mph speed bins into four larger speed bins, such that the average g/hr emission rates tended to increase with increasing speed, and the speed bins showed significant differences in the average emission rates. The process is shown in Figure 17-5 below.

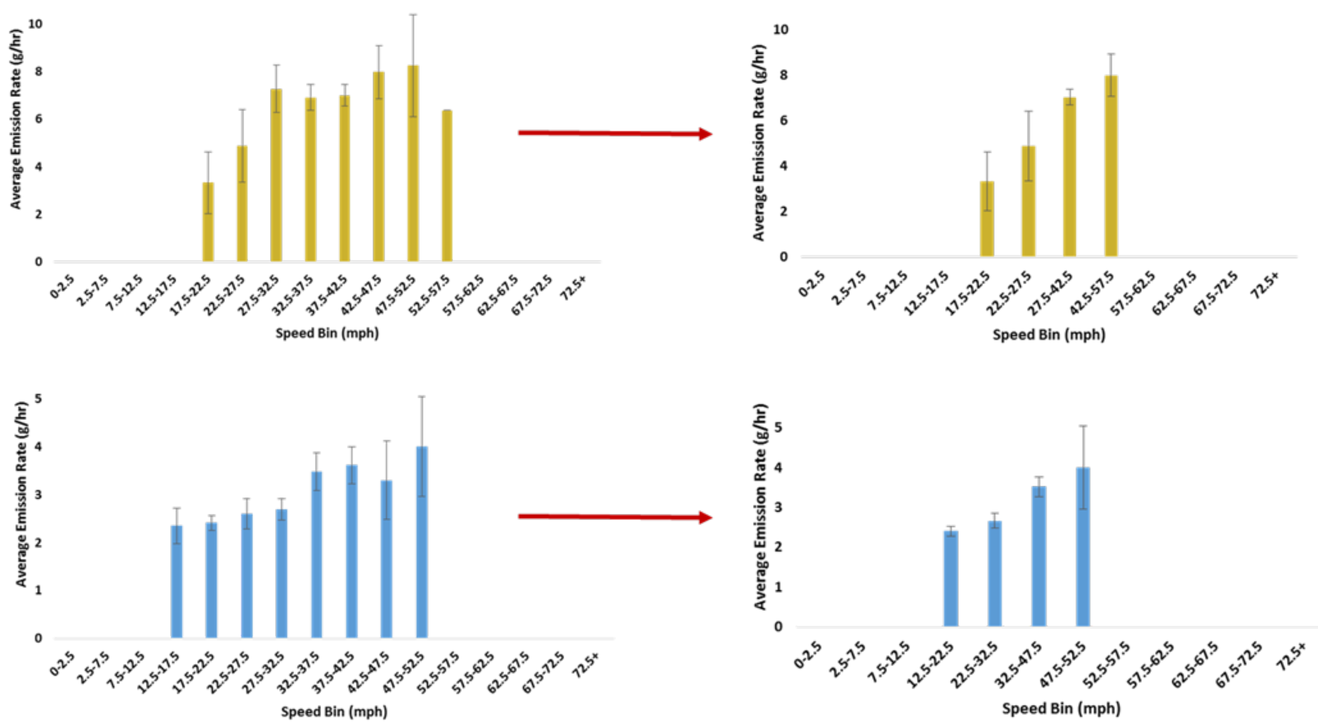


*Figure 17-5. Example of aggregation of speed bins to yield monotonically increasing HC emission rates (g/hr) and statistically significant differences between the speed bin ranges. Example shown for HC emissions for on-ramps (top panel) and off-ramps (bottom-panel).*

The final speed averages resulted in four grouped speed bins for each ramp type as shown in Table 17-30. Figure 17-6 shows the average emission rates based on the aggregated speed, compared to the individual predictions based on the operating mode distributions for each ramp trace.

*Table 17-30 Grouped Speed Bins and Average Speeds for On- and Off-ramps*

| *On-ramps* | | | | *Off-ramps* | | |
|---|---|---|---|---|---|---|
| *Average Speed in Data (mph)* | *Grouped Speed Bin* | *Trip Counts* | *Speed Range (mph)* | *Trip Counts* | *Grouped Speed Bin* | *Average Speed in Data (mph)* |
| | | | *12.5 - 17.5* | *4* | *1* | *18.92* |
| *20.39* | *1* | *2* | *17.5 - 22.5* | *12* | | |
| *23.58* | *2* | *5* | *22.5 - 27.5* | *13* | *2* | *29.24* |
| *36.77* | *3* | *16* | *27.5 - 32.5* | *22* | | |
| | | *21* | *32.5 - 37.5* | *21* | *3* | *40.36* |
| | | *28* | *37.5 - 42.5* | *19* | | |
| *47.53* | *4* | *11* | *42.5 - 47.5* | *4* | | |
| | | *7* | *47.5 - 52.5* | *7* | *4* | *49.52* |
| | | *1* | *52.5 - 57.5* | | | |

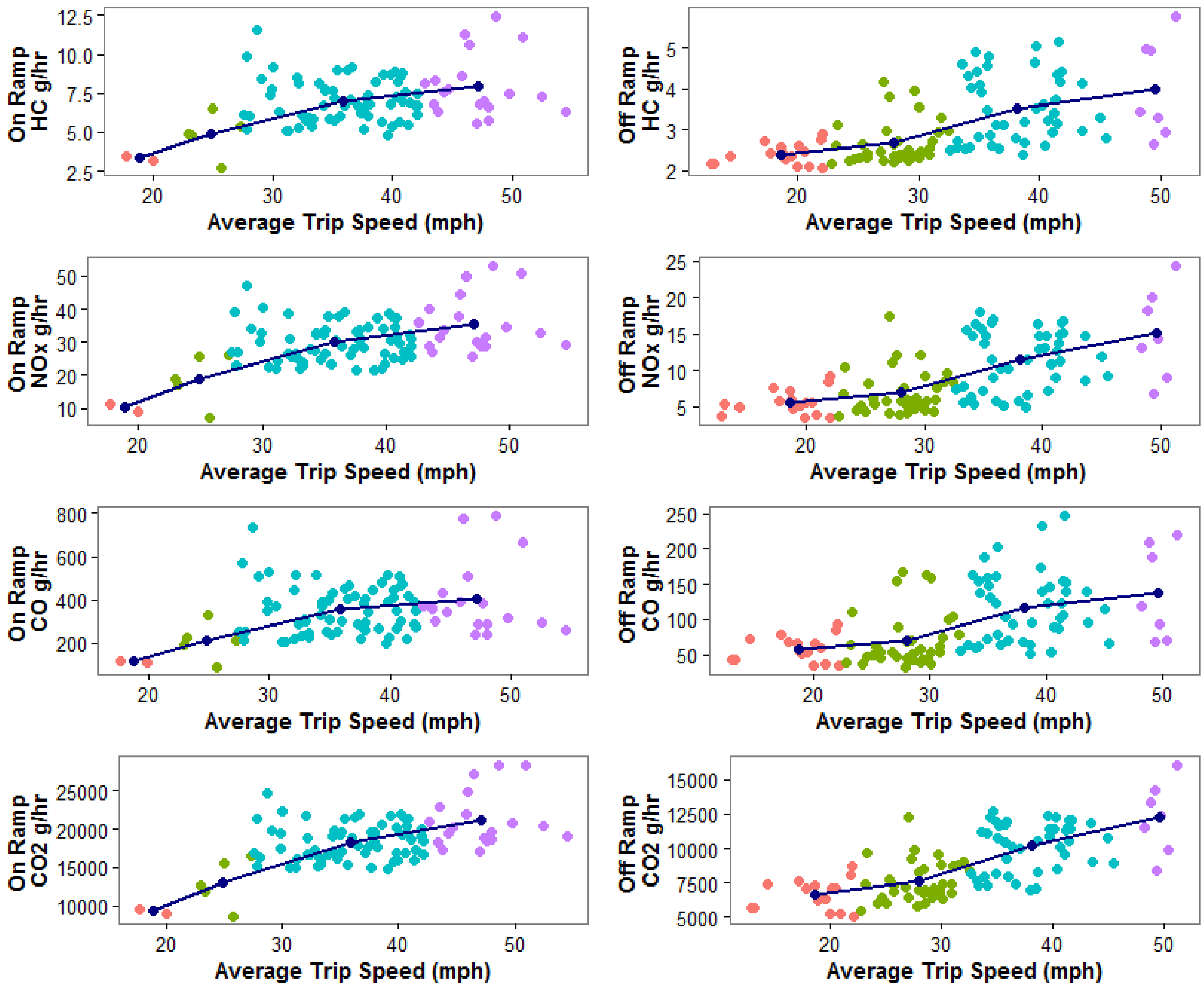


*Figure 17-6. Ramp emission rates vs. average ramp speeds and grouped speed bins for HC, NOx, CO, and CO2 emissions*

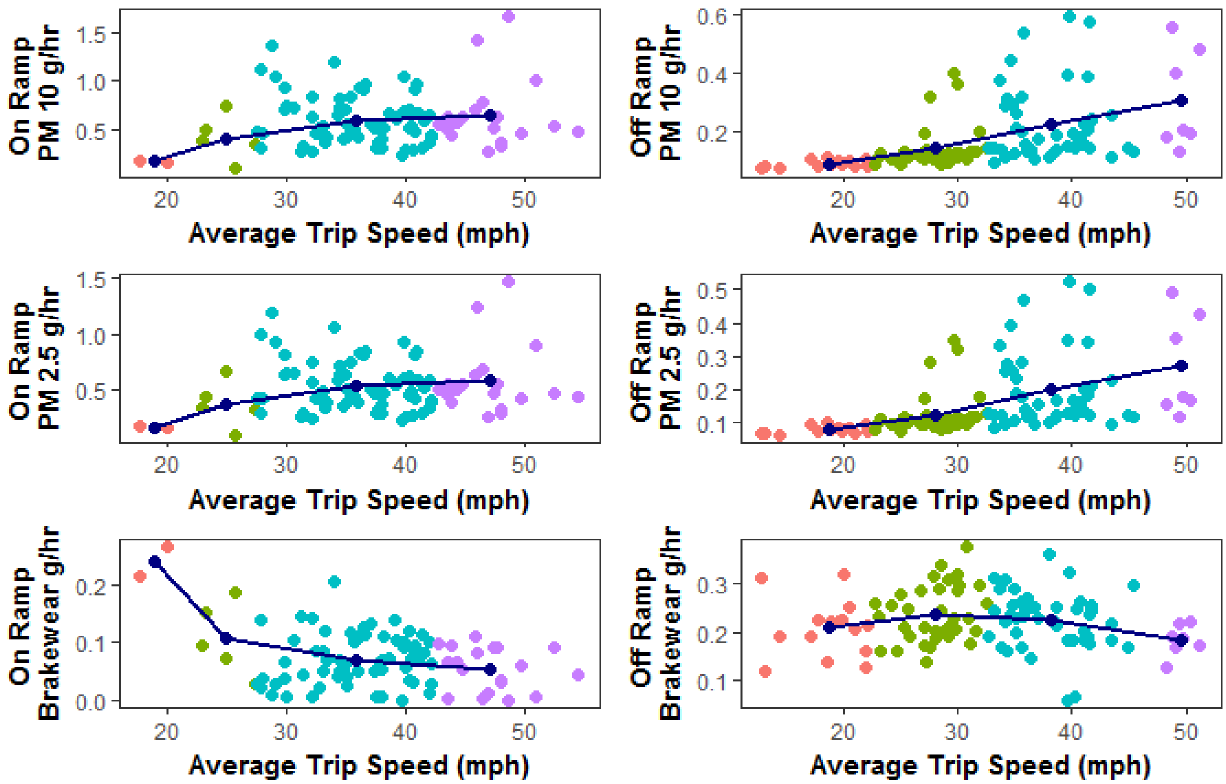


*Figure 17-7. Plots of emission rates vs. average ramp speeds and group speed bins for $PM_{2.5}$ exhaust, $PM_{10}$ exhaust, and brakewear PM emissions*

Each ramp type has four average speeds, which were the result of grouping speed bins together and averaging the speeds for trips within those bins. Therefore, the average bin speed is not necessarily the midpoint of the speed range for that bin. Each average speeds represent driving patterns that are significantly different from each other in terms of operating mode distribution, and, thus, produce significantly different emissions.

These operating mode distributions were found by calculating the fraction of time spent in each operating mode with respect to the total amount of trip time within a grouped speed bin. Since operating modes were initially assigned for three vehicle types, there is an operating mode distribution for each vehicle type at each average speed.

When the user enters a speed in the ramp tool, the tool will find the difference between the entered speed and the two closest defined average speeds. Using those differences, a weighted average for each operating mode will be calculated and displayed. For example, if a user selects ramp type “OFF”, enters an average speed of “25” mph, chose to simulate weekends between 3-3:59pm (15:00-15:59) and sets LinkID to “2”, the following processes will take place:

1. In Table 1, user chooses RAMP TYPE from drop down list, inputs a valid AVERAGE SPEED between 18 and 50 mph, selects DAYS and HOUR from drop down lists that correspond to MOVES run spec parameters, and inputs the ramp’s LINK ID as defined by run spec:

Table 1

| | |
|---|---|
| RAMP TYPE | OFF |
| AVERAGE SPEED | 25 |
| DAYS | Weekend |
| HOUR | 15:00 - 15:59 |
| LINK ID | 2 |

2. The tool finds nearest average speeds in a corresponding ramp type table for each vehicle type.

3. The difference between average speeds and input speed is calculated, and is multiplied by the operating mode distribution for each nearest average speed (average $\text{speed}_n$) in order to get individual operating mode distributions:

$$\left(\left(\frac{|input\ speed - average\ speed_1|}{|average\ speed_1 - average\ speed_2|}\right) \times op\ mode\ distribution_1\right) + \left(\left(\frac{|input\ speed - average\ speed_2|}{|average\ speed_1 - average\ speed_2|}\right) \times op\ mode\ distribution_2\right) = operating\ mode\ distribution_{calculated}$$

4. The operating mode distribution for all vehicle types and pollutant processes will be displayed in ‘opModeDistribution’ tab.

# Appendix K NREL Fleet DNA Preprocessing Steps

Appendix K discusses the preprocessing steps undertaken on the NREL's Fleet DNA database, which is used to derive default activity for heavy-duty vehicles, including idle fractions (see Section 10) and starts activity (see Section 12).

Prior to calculation and preprocessing, the data is collected from the database which involves loading and combining all of the 1 Hz data from Fleet DNA into a single 1-dimensional data array for each parameter. Each data file is arranged in the database by vehicle, day and parameter as shown in Figure 2.1. To create one contiguous array per parameter, the processing script loads each parameter and appends it to the parameter from the previous day resulting in five 1-D arrays of equal length which can be joined on index.

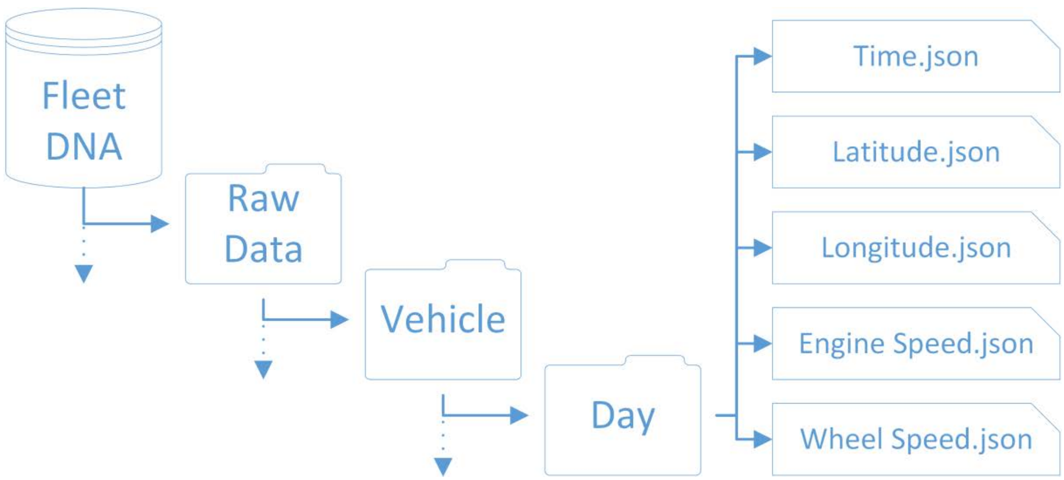


**Figure 2.1. Diagram of Fleet DNA database file structure**

After collecting the data, a processing step is performed to ensure the data is an accurate representation of a vehicle's activity. Two of the key activity analyses from this report are vehicle soak lengths and starts which are defined by the engine speed parameter that indicates if the vehicle is running or not. A start is calculated by identifying a transition of the engine speed from 0 to greater than zero, and a soak is the length of time the engine was off before it is started. Both parameter calculations depend on the engine being off; however, in some instances the data logger will shut off before recording a zero for engine speed raising the concern that starts and soak times may be missed or not accurately categorized.

To account for these instances in data preprocessing an algorithm was developed to look at the time stamp and identify large leaps or gaps from one data point to the next. If the algorithm finds a gap, the engine speed is replaced with a zero at that point to indicate the vehicle's engine has shut off.

One of the major questions with this time gap method is what time length would constitute an engine-off event. If the selected time length is too short, then instances such as the logger updating it's timestamp from the GPS may be characterized as a start. Conversely, if the time length is too long, starts and vehicle soaks may be missed. A possible scenario resulting in a mischaracterization of starts could be when the GPS updates the data logger's clock while crossing a time zone or the logger pausing its recording for a few seconds when creating a new log file. Depending on the type of data logger used, some will create a new file at a specified time interval or when a file size limit is reached requiring the logger to shift computing power to saving the file to memory. If the gap length is set to an hour or less, the algorithm may count these normal logger operations as vehicle starts. Similarly, if the logger was taken off of a vehicle on the west coast and placed on a vehicle on the east coast, the timestamp may jump 3 hours should the GPS update the internal clock to local time.

To avoid these types of timestamp jumps which may show for soak operation modes 101 through 106, the gap length was set to 6 hours for this analysis. Plots of vehicle soak distribution weighted by start fraction for various gap lengths are provided in Figure 17-8 and Figure 17-9 to demonstrate what effect changes in gap length might have. Finally, after running the gap filling routine, the first and last days of data are eliminated to avoid counting incomplete or unrepresentative operation when the data logger is being installed or removed.

Plots of vehicle soak distribution weighted by start fraction for gap lengths varying between 1 second and 30 hours are provided in Figure 17-8 and Figure 17-9 to demonstrate what effect changes in gap length might have. Figure 17-8 provides the distributions for source type 62 which consists of combination long-haul trucks that have very few starts per day, and Figure 17-9 provides the distributions for source type 52 which consists of single-unit short-haul trucks that have a large number of starts per day. Intuitively the gap length algorithm had the most noticeable effect on source type 62 due to the high weighting placed on each start as a result of having very few starts per day.

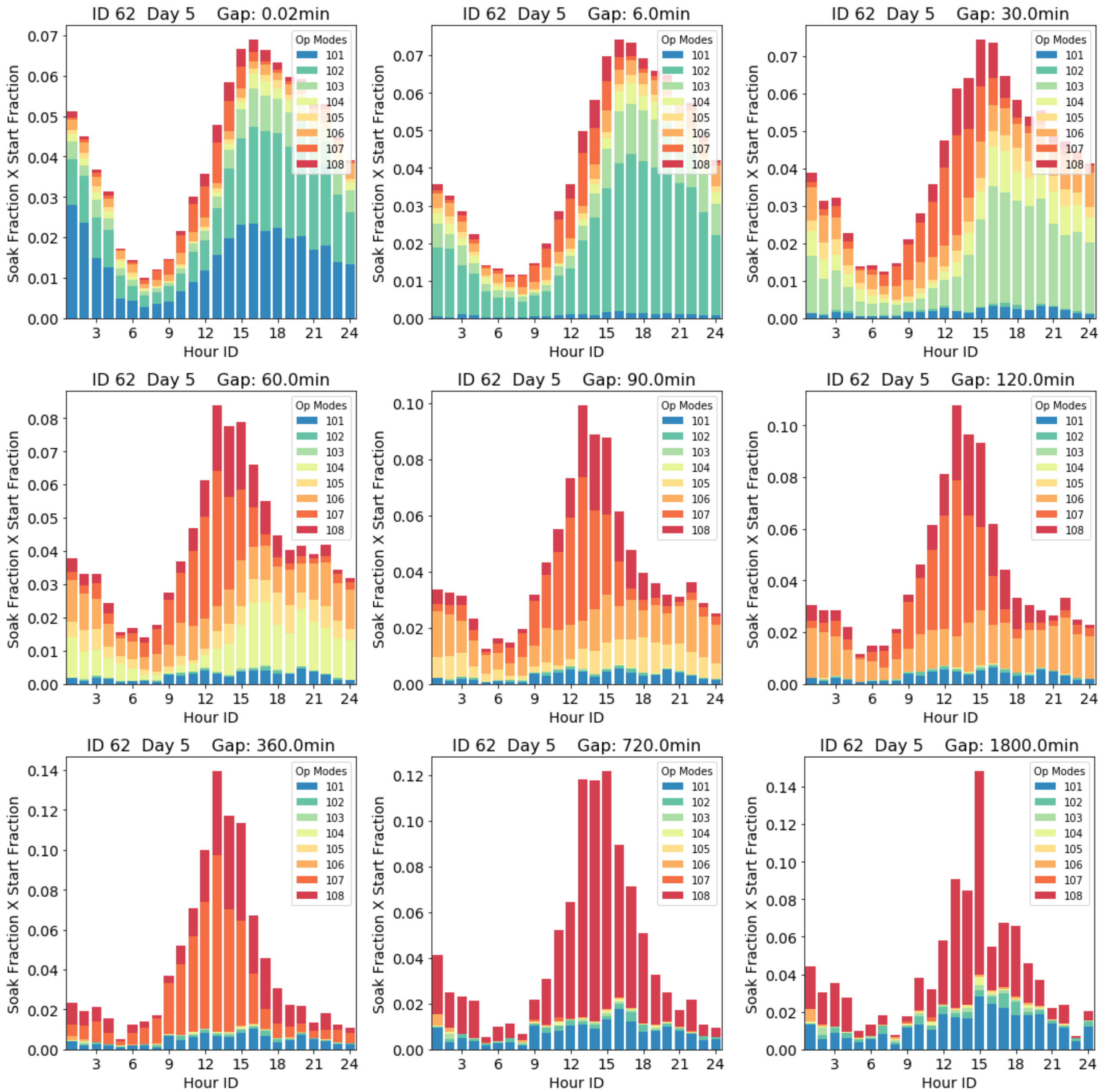


*Figure 17-8. Start fraction weights soak distribution weighted by gap length: source type 62*

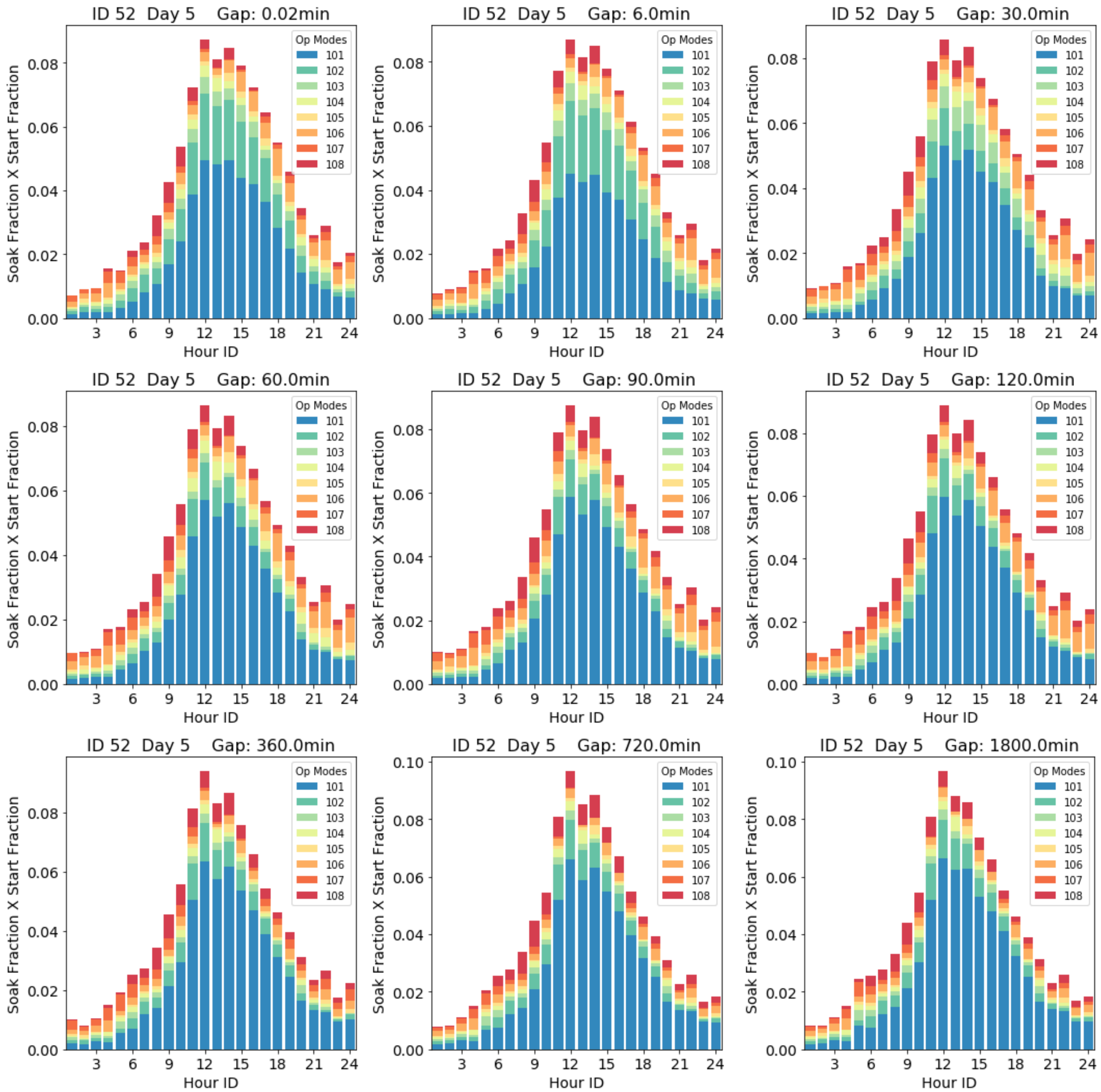


*Figure 17-9 Start fraction weights soak distribution weighted by gap length: source type 52*

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