Population and Activity of Onroad Vehicles in MOVES4

EPA United States Environmental Protection Agency

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

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List of Acronyms

AEO	Annual Energy Outlook publication
AMPO	Association of Metropolitan Planning Organizations
APU	auxiliary power unit
ARCADIS	Design & Consultancy firm for natural and built assets
ASD	average speed distribution
AVFT	Alternate Vehicle Fuel and Technology
AVGCK	VIUS broad average weight category
CAN	Controller Area Network
CARB	California Air Resources Board
CBI	confidential business information
CE-CERT	College of Engineering - Center for Environmental Research and Technology
CFR	Code of Federal Regulations
CNG	Compressed Natural Gas
CO	carbon monoxide
CO_2	carbon dioxide
CRC	Coordinating Research Council
DOT	U.S. Department of Transportation
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
ERG	Eastern Research Group, Inc.
E85	gasoline containing 70-85 percent ethanol by volume
FFV	flexible fuel vehicle
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FTA	Federal Transit Administration
GEM	Greenhouse Gas Emissions Model
GHG	Greenhouse Gases
g/hr	Grams per hour
GPO	U.S. Government Publishing Office
GPS	Global Positioning System
GVWR	Gross Vehicle Weight Rating
HC	Hydrocarbons
HD	Heavy-Duty
HDDBT	Heavy-Duty Diesel transit buses
HDV	Heavy-Duty Vehicle
HHD	Heavy-Heavy-Duty
HHDDT	Heavy-Heavy-Duty Diesel Truck
HPMS	Highway Performance Monitoring System
ID	Identification
IHS	Information Handling Services (research consulting firm)
I/M	Inspection and Maintenance program
kg/m	kilogram per meter
LD	Light-Duty

LDT	Light-Duty Truck
LDV	Light-Duty Vehicle
LHD	Light-Heavy-Duty
MAR	mileage accumulation rate
MC	Motorcycle
MD	Medium-duty
MHD	Medium-Heavy-Duty
MOBILE6	(predecessor to MOVES)
MOVES	Motor Vehicle Emission Simulator
mph	miles per hour
MPO	Metropolitan Planning Organization
MSA	Metropolitan Statistical Area (U.S. Census)
MSOD	Mobile Source Observation Database
NACFE	North American Council for Freight Efficiency
NCHRP	National Cooperative Highway Research Program
NCTCOG	North Central Texas Council of Government
NEI	National Emission Inventory
NHTS	National Household Travel Survey
NHTSA	National Highway Traffic Safety Administration
NO_x	nitrogen oxide
NPMRDS	National Performance Management Research Dataset
NREL	National Renewable Energy Laboratory
NTD	National Transit Database
NVPP	National Vehicle Population Profile
OHIM	Office of Highway Information Management
ONI	off-network idle
OPCLASS	operator classification
ORNL	Oak Ridge National Laboratory
PAMS	portable activity measurement systems
PM	Particulate Matter
$PM_{2.5}$	fine particles of particulate matter
PM_{10}	Particles of particulate matter 10 micrometers and smaller
RMAR	relative mileage accumulation rate
RPM	revolutions per minute
RT	Road Type
SBDG	Source Bin Distribution Generator
SCC	Source Classification Codes
SCR	selective catalytic reduction
SHI	source hours idle
SHO	source hours operating
SIP	State Implementation Plan
SMOKE	Sparse Matrix Operator Kernel Emissions
ST	Source Type
STP	scaled-tractive power
SUV	sport utility vehicle
SVP	Sample Vehicle Population

TDM	Travel Demand Models
TEDB	Transportation Energy Data Book
TIF	total idle fraction
TIUS	Truck Inventory and Use Survey
TRB	Transportation Research Board
TRLHP	tractive road load horsepower
TxDOT	Texas Department of Transportation
VIUS	Vehicle Inventory and Use Survey
VMT	Vehicle Miles Traveled
VSP	vehicle specific power
VTRIS	Vehicle Travel Information System
WMATA	Washington Metropolitan Area Transit Authority

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 MOVES default database. 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]

These data have been updated for MOVES4 from previous versions of MOVES. In MOVES4, we have updated vehicle activity based on newer data from Annual Energy Outlook, Highway Statistics, Transportation Energy Data Book, and School Bus Fleet Fact Book. We also updated vehicle distributions based on IHS2020 and relative mileage accumulations based on FHWA analysis. In addition, updates have been made for gliders, Class 2b and 3 light heavy-duty (LHD) vehicles, and electric vehicles for MOVES4.

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 MOVES, 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 2021.

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 significant updates made to MOVES since the MOVES2014 release were peer-reviewed under EPA's peer review guidance[3] in two separate reviews conducted in 2017, 2019, and 2020. Materials from each peer review, including peer-review comments and EPA responses are located on the EPA's science inventory webpage.[4] [5]

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
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
IdleRegion	Map of idle regions to idle region IDs.	Section 10
ModelYearGroup	A list of years and groups of years corresponding to vehicles with similar emissions performance	Section 2
MonthGroupHour	Coefficients to calculate air conditioning demand as a function of heat index	Section 16
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
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

Table 1-1 MOVES database elements covered in this report

Database Table Name	Content Summary	Report Sections
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 Section 6 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
TotalIdleFraction	Fraction of vehicle operating time when speed is zero.	Section 10
Zone	Allocation of activity to zone (county)	Section 14
ZoneRoadType	Allocation of driving time to zone (county) and road type	Section 14

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.[6] 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 cars and trucks. 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. In addition, source types have common body types, and the road load coefficients (rolling load, mechanical rotating friction, aerodynamic drag) are defined by source type as discussed in Section 15.

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 MOVES 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 MOVES

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

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 are an independent regulatory class.

Table 2-2 Regulatory Classes in MOVES

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
41	LHD2b3	Class 2b and 3 Trucks (8,500 lbs < GVWR <= 14,000 lbs)*
42	LHD45	Class 4 and 5 Trucks (14,000 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)
49	Gliders	Glider Vehicles[7]

* Class 2b trucks (GVWR 8,501-10,000 lbs) are only modeled in passenger trucks and light commercial trucks (source types 31 and 32, respectively). Class 3 trucks (GVWR 10,001-14,000 lbs) are only modeled in heavy-duty source types (buses and single unit trucks). Model year 2017-and-later engine-certified Class 3 trucks (only present within source types 52, 53, and 54) are classified as LHD45 (regclassID 42) for modeling purposes.

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 8,500-14,000 lbs. GVWR are Class 2b and Class 3 and considered light heavy-duty vehicles (LHD) in regulatory class 41.

In MOVES4, we reclassified diesel light-heavy-duty Class 3 engine-certified vehicles for model year 2017 and later years as LHD45 vehicles. The population fraction of diesel light-heavy-duty vehicles is based on data in IHS2020. The emission rates for LHD2b3 vehicles are based on the assumption that all vehicles are chassis-certified. Because Class 3 engine-certified vehicles are subject the same emission standards as Class 4 and 5 engine-certified vehicles, we reclassified these vehicles as LHD45 vehicles. Model year 2017 was selected because this is the first model year when the emission rates are different between LHD2b3 and LHD45.[11]

In the MOVES model, "Gliders" refers to post-2007 heavy-duty diesel vehicles with new chassis but with older engines that do not meet 2007 or 2010 emissions standards and thus are treated as a separate regulatory class.

Section 5.2 provides more information on the distribution of vehicles among regulatory classes. Vehicle weights in MOVES are defined by both regulatory class and source type as discussed in Section 15.

2.4.Fuel and Technology 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.[8] MOVES also allows the modeling of technology types, although these are not distinguished in MOVES output. In MOVES4, technology type is used to distinguish battery and fuel-cell electric vehicles. Table 2-3 below summarizes the fuel types and technology types populated in MOVES4. These are recorded in the default database FuelType, EngineTech and FuelEngTechAssoc tables.

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

fuelTypeID	Description	Default Fuel FormulationID[8]	EngTechID	Technology Description
1	Gasoline	10	1	Conventional Internal Combustion
2	Diesel Fuel	20	1	Conventional Internal Combustion
3	Compressed Natural Gas (CNG)	30	1	Conventional Internal Combustion
5	Ethanol (E-85)	50	1	Conventional Internal Combustion
9	Electricity	90	30	Electric
			40	Fuel Cell

It is important to note that not all fuel type/source type combinations can be modeled in MOVES. For example, MOVES cannot model gasoline-fueled long-haul combination trucks or diesel motorcycles. Similarly, flexible fuels (E85-compatible) 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.[9]

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 MOVES

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

[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.

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 speeds and acceleration patterns may run MOVES at project level where emissions can be calculated for individual links.

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[10] [11] 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 2031 vehicle belongs to the "2031" model year group for estimating running total energy consumption but belongs to the "2031-2050" 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.[10,11]

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,
- 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. MOVES 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.

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

Table Name	Key Fields*	Additional Fields	Notes
SourceTypePolProcess	sourceTypeID polProcessID	isRegClassReqd 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 modelYearID	modelYearGroupID	Assigns model years to appropriate model year groups for each polProcessID.
SampleVehiclePopulation	sourceTypeID modelYearID fuelTypeID engTechID regClassID	stmyFuelEngFraction 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 (AVFT) 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,[10,11] 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 2.4. MOVES also stores regulatory class distributions by source type in the SampleVehiclePopulation table. Table 2-7 summarizes the allowable source type-regulatory class combinations. Table 2-8 shows the full set of allowable source type, fuel type and regulatory class combinations. Also see the mapping of fuel types and technology types shown in Table 2-3. 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 MOVES4 (Allowable combinations are marked with an X)

		Source Use Type												
		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 Type		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									
Battery Electric	9		X	X	X	X	X	X	X	X	X	X	X	X
Electric Fuel Cell	9					X	X	X	X	X	X	X	X	X

Table 2-7 Matrix of the Allowable Source Type-Regulatory Class Combinations in MOVES4 (Allowable combinations are marked with an X)

		Source Use Type												
		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 Class		11	21	31	32	41	42	43	51	52	53	54	61	62
MC	10	X												
LDV	20		X											
LDT	30			X	X									
LHD2b3	41			X	X			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							
Gliders*	49												X	X

* This table was updated to fix an error in previous versions of the report. Glider assignment to sourcetypes is unchanged from MOVES3 to MOVES4.

Table 2-8 Summary of source type, fuel type, technology, and regulatory class combinations in MOVES4

sourceTypeID	fuelTypeID	engTechID	regClassID
11	1	1	10
21	1, 2, 5	1	20
	9	30	20
31, 32	1, 2	1	30, 41
	5	1	30
	9	30	30, 41
	9	40	41
41, 42	1, 2,	1	42, 46, 47
	3	1	47, 48
	9	30, 40	42, 46, 47
43	1, 2	1	41, 42, 46, 47
	3	1	47
	9	30, 40	41, 42, 46, 47
51, 52, 53, 54	1, 2	1	41, 42, 46, 47
	3	1	47
	9	30, 40	41, 42, 26, 47
61, 62	1, 9	1	46, 47
	2	1	46, 47, 49
	3	1	47
	9	30, 40	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 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 and vehicle population for every possible analysis year (1990 and 1999-2060). For national inventory runs, annual national activity is distributed temporally and spatially using allocation factors and age distributions for future years are generated from the base year distribution.

The Source Bin Distribution Generator (SBDG) uses information on model year groupings and fuel type and regulatory class distributions to estimate activity fractions of each source bin as a function of source type, model year, pollutant and process. MOVES 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. For running emissions, MOVES uses information on speed distributions and driving patterns (driving schedules) to develop operating mode fractions for each source type, road type and time of day and to calculate off-network idling activity. Similarly, other generators use MOVES inputs to develop operating mode distributions for hotelling activity, starts and vapor venting.

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,[b] 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 1999-2021)

In MOVES4, VMT estimates for the historic years 1990 and 1999-2021 come from the VM-1 table of US DOT Federal Highway Administration's (FHWA) *Highway Statistics* series.[6] In reporting years 2007 and later, the VM-1 data are calculated with an updated methodology,[12] 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 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 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

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[b] 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.

years does not fully meet the requirements of the new methodology."[c] 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-revised and 2007 and later 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.

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

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	1,943,194	10,279	70,861	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	2,555,468	13,336	107,317	168,217
2003	11,384	2,579,195	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	2,680,537	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
2016	20,445	2,849,718	16,350	113,338	174,557
2017	20,149	2,877,378	17,227	116,102	181,490
2018	20,076	2,232,588	18,303	120,699	184,165
2019	19,688	2,254,309	17,980	124,746	175,305
2020	17,632	2,568,745	15,104	124,880	177,261
2021	19,738	2,776,073	16,793	131,869	195,616

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)
2016	*Highway Statistics 2016* (May 2018)
2017	*Highway Statistics 2017* (March 2019)
2018	*Highway Statistics 2018* (March 2020)
2019	*Highway Statistics 2019* (November 2020)
2020	*Highway Statistics 2020* (December 2021)
2021	*Highway Statistics 2021* (February 2023)

3.2.Projected Vehicle Miles Traveled (2022-2060)

The *Annual Energy Outlook* (AEO)[13] 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 MOVES4, VMT for years beyond 2021 are based on the reference case VMT projections from AEO2023. 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 2021 base year HPMS data. Since AEO2023 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[iii]	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 AEO2023 Table 41: Light-Duty VMT by Technology Type
[ii] From AEO2023 Table 46: Transportation Fleet Car and Truck VMT by Type and Technology
[iii] From AEO2023 Table 49: 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 2021 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 2022-2060 by HPMS class (millions of miles)Year	Motorcycles	Light-Duty Vehicles	Buses	Single Unit Trucks	Combination Trucks
2022	20,633	2,901,945	17,214	135,406	200,278
2023	21,047	2,960,259	17,148	134,608	199,807
2024	21,197	2,981,301	17,171	134,815	200,053
2025	21,279	2,992,798	17,325	136,253	201,606
2026	21,434	3,014,635	17,561	138,444	203,994
2027	21,637	3,043,248	17,768	140,450	205,996
2028	21,825	3,069,676	17,958	142,460	207,665
2029	21,973	3,090,504	18,105	144,361	208,574
2030	22,087	3,106,420	18,240	146,472	209,036
2031	22,183	3,119,997	18,401	148,997	209,566
2032	22,267	3,131,809	18,615	152,082	210,565
2033	22,385	3,148,359	18,795	154,890	211,188
2034	22,533	3,169,199	18,971	157,678	211,738
2035	22,670	3,188,409	19,159	160,568	212,421
2036	22,782	3,204,208	19,322	163,251	212,825
2037	22,912	3,222,473	19,511	166,165	213,503
2038	23,058	3,243,010	19,696	169,004	214,176
2039	23,204	3,263,620	19,879	171,934	214,728
2040	23,372	3,287,177	20,081	175,071	215,428
2041	23,544	3,311,409	20,295	178,349	216,218
2042	23,723	3,336,548	20,505	181,564	216,996
2043	23,896	3,360,929	20,702	184,702	217,607
2044	24,075	3,386,035	20,886	187,773	218,001
2045	24,264	3,412,617	21,057	190,856	218,146
2046	24,483	3,443,472	21,255	194,304	218,439
2047	24,719	3,476,595	21,459	197,881	218,709
2048	24,960	3,510,577	21,635	201,225	218,685
2049	25,205	3,544,972	21,826	204,751	218,745
2050	25,474	3,582,818	22,086	208,966	219,456
2051	25,746	3,621,068	22,349	213,267	220,169
2052	26,021	3,659,726	22,615	217,657	220,884
2053	26,298	3,698,797	22,884	222,137	221,601
2054	26,579	3,738,285	23,156	226,709	222,321
2055	26,863	3,778,195	23,432	231,376	223,043
2056	27,150	3,818,530	23,710	236,138	223,767
2057	27,440	3,859,297	23,993	240,999	224,494

Table 3-4 VMT projections for 2022-2060 by HPMS class (millions of miles)Year	Motorcycles	Light-Duty Vehicles	Buses	Single Unit Trucks	Combination Trucks
2058	27,733	3,900,498	24,278	245,960	225,223
2059	28,029	3,942,139	24,567	251,022	225,954
2060	28,328	3,984,225	24,859	256,189	226,688

4. Vehicle Populations by Calendar Year

MOVES uses vehicle populations to characterize emissions activity that is not directly dependent on VMT. These population 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, 1999-2021)

MOVES populations for calendar years 1990 and 1999-2021 are derived primarily from registration data summarized in the Federal Highway Administration's annual *Highway Statistics* report. Motorcycle populations are from vehicle registrations reported in Table VM-1,[6] and passenger car populations are from registrations reported in Table MV-1.[14] The general categories for truck and bus registrations presented in *Highway Statistics* were allocated to specific MOVES source types as described below.

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[15,16] for calendar years 1999 and 2020. These fractions were calculated as the ratio of the total registrations by source type 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 2020. However, there are a few nuances to this analysis:

- Starting with MOVES3, the distinction between passenger light-duty trucks (31) and commercial light-duty trucks (32) was revised. Now in MOVES, 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 ratio of passenger to commercial light-duty trucks from the 2020 IHS data were used for all calendar years.
- The 2020 IHS data were unable to distinguish between short-haul (52) and long-haul (53) single-unit trucks and consequentially grouped them together. These vehicles are differentiated in MOVES4 using an earlier IHS data for 2011 which was able to differentiate between these vehicles. From the earlier data, 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.

Table 4-1 Source type distributions used to allocate truck populations in MOVES4*

Year	31/30	32/30	51/50	52/50	53/50	54/50	61/60	62/60
1990**	0.913632	0.086368	0.013311	0.767722	0.03386	0.185107	0.625648	0.374352
1999***	0.913632	0.086368	0.015472	0.791929	0.034927	0.157671	0.574437	0.425563
2000	0.913632	0.086368	0.015006	0.794353	0.035034	0.155606	0.57569	0.42431
2001	0.913632	0.086368	0.01454	0.796777	0.035141	0.153541	0.576943	0.423057
2002	0.913632	0.086368	0.014074	0.799201	0.035248	0.151476	0.578196	0.421804
2003	0.913632	0.086368	0.013608	0.801625	0.035355	0.149411	0.57945	0.42055
2004	0.913632	0.086368	0.013142	0.804049	0.035462	0.147346	0.580703	0.419297
2005	0.913632	0.086368	0.012676	0.806473	0.035569	0.145281	0.581956	0.418044
2006	0.913632	0.086368	0.01221	0.808897	0.035676	0.143216	0.583209	0.416791
2007	0.913632	0.086368	0.011744	0.811321	0.035783	0.141151	0.584462	0.415538
2008	0.913632	0.086368	0.011278	0.813746	0.03589	0.139086	0.585715	0.414285
2009	0.913632	0.086368	0.010813	0.81617	0.035997	0.137021	0.586969	0.413031
2010	0.913632	0.086368	0.010347	0.818594	0.036103	0.134956	0.588222	0.411778
2011	0.913632	0.086368	0.009881	0.821018	0.03621	0.132891	0.589475	0.410525
2012	0.913632	0.086368	0.009415	0.823442	0.036317	0.130826	0.590728	0.409272
2013	0.913632	0.086368	0.008949	0.825866	0.036424	0.128761	0.591981	0.408019
2014	0.913632	0.086368	0.008483	0.82829	0.036531	0.126696	0.593235	0.406765
2015	0.913632	0.086368	0.008017	0.830714	0.036638	0.124631	0.594488	0.405512
2016	0.913632	0.086368	0.007551	0.833138	0.036745	0.122567	0.595741	0.404259
2017	0.913632	0.086368	0.007085	0.835562	0.036852	0.120502	0.596994	0.403006
2018	0.913632	0.086368	0.006619	0.837986	0.036959	0.118437	0.598247	0.401753
2019	0.913632	0.086368	0.006153	0.84041	0.037066	0.116372	0.599501	0.400499
2020***	0.913632	0.086368	0.005687	0.842834	0.037173	0.114307	0.600754	0.399246

Note:
* Fractions may not sum to one due to rounding.
** Fractions from 1990 were retained from MOVES2014[17] with the exceptions noted in the text.
*** Fractions from 1999 and 2020 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 2002-2021 come from the *School Bus Fleet Fact Book*[18] publication series' School Transportation Statistics tables. Since these values are presented as totals corresponding to academic years (e.g., 2016-2017) 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 (2017, 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. Note that the *School Bus Fleet Fact Book* series did not publish the School Transportation Statistics tables for the academic years 2019-2020 or 2020-2021. Therefore, the school bus populations for calendar years 2020 and 2021 were linearly interpolated from the 2019 and 2022 school bus population values.
- Transit bus (42) populations were calculated from the Federal Transit Administration's National Transit Database (NTD)[19] data series on Revenue Vehicle Inventory and Rural Revenue Vehicle Inventory. See Section 5.1.4 for 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. Note that the *Highway*

Statistics series on bus populations show large changes in bus registrations for 2011, 2012, and 2016-2020, inconsistent with intermediate years as well as historic populations. Lacking evidence that these specific data reflect actual changes in the number of buses operating in the US, the bus registration values for those years were dropped and estimated instead with linear interpolation/extrapolation. Specifically, 2011 and 2012 values were linearly interpolated from 2010 and 2013 registrations, and 2016-2020 values were linearly interpolated from 2015 and 2021 registrations.

For all source type populations derived from Table VM-1, note that this registration data has the same vehicle category differences as the VMT data for reporting years prior to 2007 as described in Section 3.1. Similar to the VMT analysis, we used the FHWA-revised values for 2000-2006 and adjusted the registration data ourselves for 1990 and 1999 as described in Section 3.1.

Table 4-2 Historic source type populations for calendar years 1990 and 1999-2021

yearID	Motorcycle	Passenger Car	Passenger Truck	Light Com. Truck	Other Bus	Transit Bus	School Bus	Refuse Truck	Single Unit Short-haul	Single Unit Long-haul	Motorhome	Combination Short-haul	Combination Long-haul
1990	3,657,632	143,549,627	35,233,652	3,330,743	172,025	48,151	318,050	57,229	3,300,770	145,578	795,855	1,010,435	604,587
…													
1999	4,032,581	132,432,044	67,831,975	6,412,359	226,133	63,296	418,087	102,180	5,229,900	230,661	1,041,260	1,320,899	978,569
2000	4,346,068	133,621,420	71,372,854	6,747,089	238,473	66,750	440,902	98,708	5,225,066	230,448	1,023,540	1,387,368	1,022,554
2001	4,903,056	137,633,467	75,468,041	7,134,220	239,567	67,056	442,925	101,383	5,555,547	245,023	1,070,569	1,425,354	1,045,174
2002	5,004,156	135,920,677	76,343,163	7,216,948	243,137	68,055	449,525	98,025	5,566,262	245,496	1,054,998	1,395,588	1,018,105
2003	5,370,035	135,669,897	78,109,534	7,383,928	237,582	68,604	470,364	96,029	5,656,706	249,485	1,054,327	1,386,937	1,006,605
2004	5,780,870	136,430,651	82,631,649	7,811,417	256,107	68,796	470,371	94,274	5,767,659	254,378	1,056,953	1,393,895	1,006,464
2005	6,227,146	136,568,083	85,821,437	8,112,957	264,495	69,514	473,044	94,076	5,985,115	263,969	1,078,182	1,433,416	1,029,685
2006	6,678,958	135,399,945	89,179,459	8,430,401	274,929	70,232	476,798	94,704	6,273,755	276,699	1,110,776	1,503,506	1,074,482
2007	7,138,476	135,932,930	91,130,392	8,614,829	266,607	82,378	485,451	95,326	6,585,230	290,437	1,145,679	1,540,261	1,095,086
2008	7,752,926	137,079,843	90,786,036	8,582,276	270,188	84,739	488,381	93,477	6,744,360	297,455	1,152,754	1,514,209	1,071,021
2009	7,929,724	134,879,600	90,986,822	8,601,256	293,181	86,756	462,056	90,350	6,819,992	300,791	1,144,963	1,536,166	1,080,952
2010	8,009,503	130,892,240	90,954,042	8,598,158	284,828	89,097	472,126	85,019	6,726,539	296,669	1,108,962	1,501,651	1,051,214
2011	8,437,502	125,656,528	98,841,145	9,343,749	291,480	88,076	472,661	77,257	6,419,582	283,131	1,039,085	1,445,179	1,006,459
2012	8,454,939	111,289,906	111,893,065	10,577,586	298,491	91,912	467,980	77,108	6,744,224	297,449	1,071,506	1,458,563	1,010,530
2013	8,404,687	113,676,345	111,768,111	10,565,774	297,426	94,222	472,901	72,716	6,710,991	295,983	1,046,316	1,462,992	1,008,356
2014	8,417,718	113,898,845	115,351,838	10,904,554	289,926	98,060	484,041	70,649	6,898,626	304,259	1,055,224	1,528,882	1,048,315
2015	8,600,936	112,864,228	118,820,506	11,232,458	300,197	103,669	485,041	67,791	7,024,767	309,822	1,053,921	1,632,988	1,113,894
2016	8,679,380	112,961,266	123,051,307	11,632,408	316,227	106,871	474,194	66,042	7,287,056	321,390	1,072,030	1,639,505	1,112,538
2017	8,715,204	111,177,029	127,338,527	12,037,692	326,102	108,115	471,461	66,149	7,801,640	344,086	1,125,123	1,726,637	1,165,581
2018	8,666,185	108,570,167	129,863,323	12,276,368	331,268	106,645	476,150	68,357	8,654,635	381,706	1,223,201	1,738,513	1,167,498
2019	8,596,314	108,547,710	132,720,051	12,546,423	334,921	107,660	479,867	62,514	8,538,930	376,603	1,182,386	1,753,665	1,171,545
2020	8,347,435	105,135,300	135,714,463	12,829,494	340,474	107,199	483,161	56,346	8,351,145	368,321	1,132,597	1,796,832	1,194,130
2021	9,892,706	102,973,881	141,340,004	13,361,293	346,155	106,610	486,454	60,937	9,031,555	398,330	1,224,875	1,888,460	1,255,024

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 Appendix C.

4.2. Projected Vehicle Populations (2022-2060)

Vehicle stock estimates from the reference case of AEO2023 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 AEO2023 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 Heavy-Duty 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 AEO2020 Table 45: Light-Duty Vehicle Stock by Technology Type
[ii] From AEO2020 Table 46: Transportation Fleet Car and Truck Stock by Type and Technology
[iii] From AEO2020 Table 49: Freight Transportation Energy Use

The percent growth over time was calculated for each of the groups described above and applied to the 2021 base year source type populations. The resulting populations are presented in Table 4-4.

Table 4-4 Projected source type populations for 2022-2060

yearID	Motorcycle	Passenger Car	Passenger Truck	Light Com. Truck	Other Bus	Transit Bus	School Bus	Refuse Truck	Single Unit Short-haul	Single Unit Long-haul	Motorhome	Combination Short-haul	Combination Long-haul
2022	9,960,980	100,879,903	145,568,230	13,761,000	355,038	109,346	498,937	62,881	9,319,612	411,035	1,263,942	1,918,981	1,275,308
2023	9,980,784	98,864,871	148,495,717	14,037,744	363,032	111,808	510,171	64,581	9,571,615	422,149	1,298,119	1,948,531	1,294,946
2024	10,020,715	96,976,695	151,808,977	14,350,956	371,449	114,400	522,000	66,401	9,841,381	434,047	1,334,705	1,978,215	1,314,673
2025	10,068,231	95,019,911	155,406,263	14,691,019	380,201	117,096	534,299	68,309	10,124,111	446,516	1,373,049	2,008,353	1,334,702
2026	10,118,077	93,044,514	159,087,837	15,039,049	389,222	119,874	546,976	70,263	10,413,770	459,292	1,412,333	2,039,990	1,355,727
2027	10,163,889	91,023,562	162,716,059	15,382,035	398,448	122,715	559,941	72,244	10,707,410	472,242	1,452,157	2,073,182	1,377,786
2028	10,202,610	88,929,876	166,241,760	15,715,330	407,504	125,504	572,668	74,200	10,997,330	485,029	1,491,477	2,105,221	1,399,078
2029	10,241,184	86,849,273	169,747,957	16,046,782	415,952	128,106	584,540	76,081	11,276,029	497,321	1,529,274	2,132,446	1,417,171
2030	10,274,461	84,768,348	173,113,252	16,364,913	423,875	130,547	595,675	77,899	11,545,483	509,205	1,565,818	2,155,360	1,432,399
2031	10,302,337	82,703,488	176,315,354	16,667,617	431,222	132,809	605,999	79,616	11,800,003	520,430	1,600,337	2,175,085	1,445,508
2032	10,326,938	80,701,901	179,354,785	16,954,944	438,391	135,017	616,074	81,330	12,054,102	531,637	1,634,798	2,192,492	1,457,076
2033	10,347,718	78,770,062	182,209,219	17,224,782	444,914	137,026	625,240	82,916	12,289,045	541,999	1,666,661	2,207,104	1,466,787
2034	10,365,945	76,944,360	184,869,219	17,476,240	450,953	138,886	633,727	84,443	12,515,385	551,982	1,697,358	2,217,774	1,473,878
2035	10,387,180	75,271,063	187,427,971	17,718,126	457,036	140,760	642,277	85,970	12,741,715	561,964	1,728,053	2,229,076	1,481,389
2036	10,414,307	73,806,497	189,895,322	17,951,372	463,417	142,725	651,243	87,540	12,974,404	572,226	1,759,611	2,242,438	1,490,269
2037	10,446,868	72,549,531	192,260,465	18,174,956	469,912	144,725	660,371	89,138	13,211,315	582,675	1,791,741	2,256,034	1,499,304
2038	10,486,428	71,507,929	194,555,849	18,391,946	476,380	146,717	669,460	90,740	13,448,712	593,145	1,823,937	2,269,095	1,507,985
2039	10,532,381	70,655,368	196,796,636	18,603,774	482,531	148,612	678,104	92,319	13,682,721	603,466	1,855,674	2,278,841	1,514,462
2040	10,585,589	69,980,785	199,019,056	18,813,866	488,362	150,407	686,299	93,854	13,910,230	613,500	1,886,529	2,286,244	1,519,381
2041	10,641,874	69,428,865	201,177,470	19,017,908	493,995	152,142	694,215	95,418	14,142,009	623,723	1,917,964	2,289,512	1,521,553
2042	10,701,018	68,980,482	203,288,861	19,217,504	499,891	153,958	702,500	96,978	14,373,263	633,922	1,949,327	2,296,598	1,526,262
2043	10,761,830	68,587,840	205,378,385	19,415,033	506,440	155,975	711,703	98,681	14,625,625	645,052	1,983,552	2,305,931	1,532,465
2044	10,824,308	68,253,422	207,443,011	19,610,208	513,482	158,144	721,600	100,486	14,893,131	656,850	2,019,832	2,317,229	1,539,973
2045	10,888,569	67,967,034	209,498,009	19,804,473	520,345	160,258	731,244	102,251	15,154,826	668,392	2,055,323	2,327,904	1,547,067
2046	10,954,013	67,765,663	211,483,323	19,992,151	526,737	162,226	740,227	103,950	15,406,596	679,496	2,089,469	2,335,249	1,551,949
2047	11,019,269	67,572,902	213,453,366	20,178,385	533,008	164,158	749,040	105,664	15,660,640	690,701	2,123,923	2,340,185	1,555,230
2048	11,083,706	67,405,457	215,371,446	20,359,706	539,141	166,046	757,658	107,373	15,913,938	701,872	2,158,276	2,343,428	1,557,385
2049	11,148,959	67,255,915	217,289,944	20,541,068	544,712	167,762	765,487	108,989	16,153,368	712,432	2,190,748	2,343,352	1,557,334

yearID	Motorcycle	Passenger Car	Passenger Truck	Light Com. Truck	Other Bus	Transit Bus	School Bus	Refuse Truck	Single Unit Short-haul	Single Unit Long-haul	Motorhome	Combination Short-haul	Combination Long-haul
2050	11,217,514	67,150,524	219,243,961	20,725,787	549,881	169,354	772,752	110,555	16,385,455	722,668	2,222,224	2,340,070	1,555,153
2051	11,286,490	67,045,298	221,215,550	20,912,167	555,100	170,962	780,085	112,143	16,620,877	733,051	2,254,152	2,336,793	1,552,975
2052	11,355,891	66,940,237	223,204,868	21,100,223	560,368	172,584	787,489	113,754	16,859,681	743,584	2,286,539	2,333,520	1,550,800
2053	11,425,718	66,835,341	225,212,076	21,289,971	565,686	174,222	794,962	115,389	17,101,916	754,267	2,319,391	2,330,252	1,548,628
2054	11,495,975	66,730,609	227,237,334	21,481,424	571,054	175,875	802,506	117,047	17,347,632	765,104	2,352,716	2,326,988	1,546,459
2055	11,566,664	66,626,041	229,280,804	21,674,600	576,474	177,544	810,122	118,728	17,596,878	776,097	2,386,519	2,323,729	1,544,293
2056	11,637,787	66,521,637	231,342,651	21,869,512	581,944	179,229	817,810	120,434	17,849,705	787,248	2,420,808	2,320,475	1,542,130
2057	11,709,348	66,417,397	233,423,039	22,066,177	587,467	180,930	825,572	122,164	18,106,164	798,559	2,455,589	2,317,225	1,539,971
2058	11,781,349	66,313,320	235,522,135	22,264,611	593,042	182,647	833,406	123,920	18,366,309	810,032	2,490,870	2,313,979	1,537,814
2059	11,853,792	66,209,406	237,640,108	22,464,830	598,670	184,381	841,315	125,700	18,630,190	821,671	2,526,658	2,310,739	1,535,660
2060	11,926,681	66,105,655	239,777,127	22,666,848	604,352	186,130	849,300	127,506	18,897,864	833,476	2,562,961	2,307,502	1,533,509

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.[20] [21] 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 MOVES 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.”[22] 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.[22] For consistency with vehicle emission standards, the category also includes some small crossover vehicles.[23] 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, most sport utility vehicles (SUVs) and vans.[22] 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; with the exception of Class 2b trucks (8,500 to 10,000 lbs) with two axles or more and at least six tires, colloquially known as “duallies”, which FHWA classifies into the single-unit truck category.

In MOVES, a light-duty truck is considered a passenger truck (sourceTypeID 31) if it is registered to an individual, or a light-duty commercial truck (sourceTypeID 32) if it is registered to an organization or business.

Because the Class 2b trucks with only 2 axles and only 4 tires are classified in the light-duty source types, sourceTypeIDs 31 and 32 contain vehicles in both the light-duty truck regulatory class (regClassID 30) and the Class 2b and 3 truck regulatory class (regClassID 41) as discussed in Section 5.2.3.

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.[24]

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.[25]

Any other buses that do not fit into the transit or school bus categories are modeled in MOVES as "other" buses.[d] 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

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

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 are often purchased in secondary markets, such as for drayage applications, after being used primarily for long-haul trips.[26]

5.2.Sample Vehicle Population

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

The stmyFraction represents the default national fuel type, EngTech, and regulatory class allocation for each source type and model year. We define the stmyFraction as shown in Equation 5-1.

$$f(stmy)_{st,my,ft,et,rc} = \frac{N_{st,my,ft,et,rc}}{\sum_{\substack{ft \in FT \\ et \in ET \\ rc \in RC}} N_{st,my,ft,et,rc}} \qquad \textbf{Equation 5-1}$$

where the number of vehicles N in a given source type st, model year my, fuel type ft, EngTech et, and regulatory class rc is divided by the sum of vehicles across the set of all fuel types FT, EngTechs ET, and regulatory classes RC. That is, the denominator is the total number of vehicles in 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 fuel types with their associated EngTechs, and regulatory classes 30 and 41. A value of zero indicates that the MOVES default population of vehicles of that source type, model year, fuel type, EngTech, and regulatory class is negligible in the national population or does not exist.

Because a modeler may modify fuel type and EngTech distributions by source type and model year to simulate local conditions through the Alternative Vehicle Fuel and Technology (AVFT) table—but is not expected to modify regulatory class distributions—the SampleVehiclePopulation table also contains the stmyFuelEngFraction. When a modeler supplies an AVFT table, MOVES will use the stmyFuelEngFraction to apply a default regulatory class distribution to the user-supplied fuel type and EngTech distributions, regardless of whether these vehicles exist in the default. Similar to the stmyFraction above, we define stmyFuelEngFraction as shown in Equation 5-2.

$$f(stmyfueleng)_{st,my,ft,et,rc} = \frac{N_{st,my,ft,et,rc}}{\sum_{rc\epsilon RC} N_{st,my,ft,et,rc}}$$ **Equation 5-2**

for number of vehicles N in a given source type st, model year my, fuel type ft, EngTech et, regulatory class rc, and the set of all regulatory classes RC. In this case, the denominator is the total for a given source type, model year, fuel type, and EngTech, and so the stmyFuelEngFraction must sum to one for each combination of source type, model year, fuel type, and EngTech.

For a concrete example of how stmyFraction and stmyFuelEngFraction are used in MOVES, take the example of MY2030 combination long-haul trucks. The stmyFraction assigns the default fuel, EngTech, and regulatory classes to the population of MY2030 combination long-haul trucks, which is nearly all HHD class 8 diesel. However, a modeler could create a future scenario in which there is a high penetration of fuel cell electric trucks. The stmyFuelEngFraction allows MOVES to assign vehicles to regulatory classes without also requiring the modeler to supply future weight class distributions.

As noted in Section 2.4, these fuel type fractions indicate the fuel capability of the vehicle, which is not necessarily 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—they describe vehicles that 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.[8]

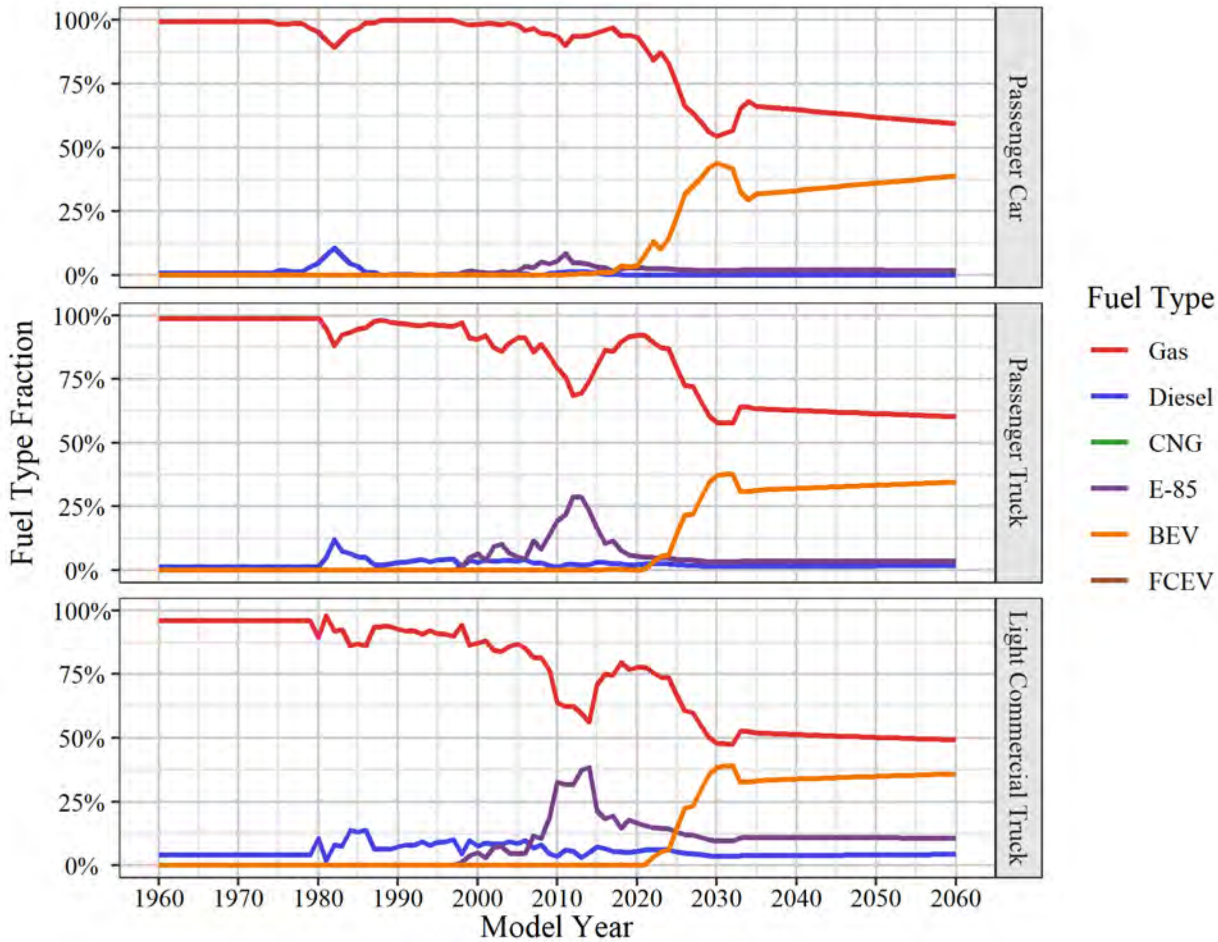

Figure 5-1 Default fuel fractions for light-duty source types in MOVES4

In MOVES4, both the stmyFractions and the stmyFuelEngFractions were primarily calculated using 2014 and 2020 IHS data[15] [16] as explained below. Electric vehicle fleet fraction in MOVES were based on analysis for EPA rulemaking, considering costs, consumer preferences, and CARB regulatory programs; see details in each vehicle type section below.

For model years 2000-2013, the 2014 IHS data were used to calculate fuel type, regulatory class, and EngTech distributions. Values for model years 2014 to 2019 were calculated using the 2020 IHS data. As the 2020 IHS data does not contain complete information on model year 2020 and later vehicles, we held regulatory class distributions for these vehicles constant at the model year 2019 values, except where noted below.

Before the fuel type and regulatory class distributions could be calculated from the 2014 and 2020 IHS data, the data needed to be cleaned. For the source type field, there were many Class 3 trucks that were classified as light-duty; 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). Additionally, some compact SUVs were originally classified as light trucks where EPA emission certification data showed that those makes and models were regulated as cars;[23] we re-classified these vehicles as passenger cars. 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, it was set to be the most common fuel type for the vehicle’s source type and model year. Any remaining vehicles with 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 dropped from the data.

Each of the subsections below describe in more detail which data sources were applied to which model years for each source type.

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

All passenger cars fall into the light-duty vehicle regulatory class (regClassID 20). IHS data provided the split between gasoline, diesel, electricity, and E-85 capable cars in the SampleVehiclePopulation table. For model years 2000 through 2013, the 2014 IHS data were used, while for model years 2014 to 2019, the 2020 IHS data were used.

In MOVES4 national defaults, for model years prior to 2023, electric passenger cars were modeled with market shares from the 2022 EPA Trends report.[27] For model years 2023 and later, the electric passenger car sales fractions are based on light-duty electric vehicle cost and consumer preferences as modeled in EPA OMEGA (Optimization Model for reducing Emissions of Greenhouse Gases from Automobiles) model.[28]

The fuel type distributions for gasoline, diesel, and E-85 capapable passenger cars for model years 2022 and later were derived from Department of Energy car sales projections from AEO2023’s table “Light-Duty Vehicle Sales by Technology Type”.[13] Fuel type distributions for MY2020-MY2021 were not available in AEO2023, so we used AEO2021 and AEO2022 for those model years, respectively.

Note that MOVES may be run at the county or project scale with local information to accurately capture EV market penetration and other fuel type variation by geographic region. As explained in the MOVES Technical Guidance,[2] this can be done through the AVFT importer in the MOVES interface. MOVES cannot model CNG or fuel cell electric 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 41. Light-duty trucks in the 2020 IHS data with a GVWR class of 1, 2, or 2a were classified as regulatory class 30, and Class 2b trucks were classified as regulatory class 41. IHS data provided the split between gasoline, diesel, electricity, and E-85 capable trucks. Note that all E-85 light-duty trucks are modeled as regulatory class 30.

For model years 2000 through 2013, the 2014 IHS data were used to calculate fuel type and regulatory class distributions; for model years 2014 to 2019, the 2020 IHS data were used.

In MOVES4 national defaults, for model years prior to 2023, electric passenger trucks were modeled with market shares from the 2022 EPA Trends report.[29] For model years 2023 and later, light-duty (regClassID 30) electric passenger truck and light commercial truck sales fractions are based on light-duty electric vehicle cost and consumer preferences as modeled in EPA OMEGA (Optimization Model for reducing Emissions of Greenhouse Gases from Automobiles) model.[30] Projections for battery electric Class 2b trucks (regClassID 41) were based on OMEGA outputs and an analysis of the national impact of CARB's Advanced Clean Trucks regulation.[31]

The fuel type distributions for light-duty gasoline, diesel, and E-85 capable trucks for model years 2022 and later were derived from Department of Energy light truck and light commercial truck sales projections from AEO2023's tables "Light-Duty Vehicle Sales by Technology Type" and "Transportation Fleet Car and Truck Sales by Type and Technology".[13] Fuel type distributions for MY2020-MY2021 were not available in AEO2023, so we used AEO2021 and AEO2022 for those model years, respectively.

Note that MOVES may be run at the county or project scale with local information to accurately capture fuel distribution and EV market penetration variation by geographic region. As explained in the MOVES Technical Guidance,[2] this can be done through the AVFT importer in the MOVES interface. MOVES cannot model CNG or fuel cell electric passenger trucks or light commercial trucks.

5.2.4. Buses

MOVES4 can model diesel, gasoline, CNG and electric buses, but cannot model E-85 buses.

Since school buses have a distinguishing characteristic in their VIN and they are well represented in the 2014 and 2020 IHS data, we were able to calculate their fuel type and regulatory class distributions, with model years 2000-2013 based on the 2014 IHS data and model years 2014-2019 based on the 2020 IHS data. All CNG school buses are assigned to regulatory class 47.

On the other hand, transit buses and "other buses" are not distinguished from each other in the 2014 and 2020 IHS datas. The National Transit Database is a potential alternate data source for transit buses, but since it lacks weight class information, it could not be used to calculate regulatory class distributions. Instead, considering that the vehicles in the transit and "other bus" categories may overlap, we grouped these categories together when 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.[32] 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 as regulatory class 47. Additionally, MOVES can only model CNG other buses in regulatory class 47. For model years 2013 and earlier, the 2014 IHS data were used to calculate fuel type and regulatory class distributions; for model years 2014 to 2019, the 2020 IHS data were used.

For all bus source types, for model years 2022 and later, we used Department of Energy heavy-duty sales projections from AEO2023's "Freight Transportation Energy Use"[13] table to derive year-over-year growth for all heavy-duty gasoline, diesel, CNG, battery electric, and fuel cell electric vehicles. Data for MY2020-MY2021 were not available in AEO2023, so we used AEO2021 and AEO2022 for those model years, respectively. We applied the year-over-year growth in vehicle sales to the model year 2019 bus counts in the 2020 IHS data in order to derive future year fuel type and regulatory class distributions. Battery electric bus projections in AEO2023 were adjusted for model years 2024 and later based on an analysis of the national impact of CARB's Advanced Clean Trucks regulation.[31]

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 fuels based on IHS data. The IHS data 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, 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. As with the other heavy-duty vehicles, MOVES can only model CNG single-unit trucks in regulatory class 47. MOVES cannot model E-85 single-unit trucks.

The ability to model electric single unit trucks was added in MOVES4.

For single unit short-haul and long-haul trucks (sourceTypeIDs 52 and 53), the 2014 IHS data were used to calculate fuel type and regulatory class distributions for model years 2000-2013, and the 2020 IHS data were used for model years 2014-2019.

For refuse trucks (sourceTypeID 51), we use the 2014 and 2020 IHS data for model years 2000-2013 and 2014-2019, respectively. However, we found that electric refuse trucks were not well represented in the IHS data, so we used electric refuse truck counts reported to EPA from the 2019 Annual Production Volume Reports into Engine and Vehicle Compliance Information System[33] instead of the electric refuse truck counts in the IHS data.

For motor homes (sourceTypeID 54), we used the 2014 IHS data for all model years 2013 and earlier, and the 2020 IHS data for model years 2014-2019.

For all single unit trucks model years 2020 and later (including refuse trucks and motorhomes), we used Department of Energy heavy-duty sales projections from AEO2023's "Freight Transportation Energy Use"[13] table to derive year-over-year growth for light heavy-duty and medium heavy-duty gasoline, diesel, CNG, battery electric, and fuel cell electric vehicles. Data for MY2020-MY2021 were not available in AEO2023, so we used AEO2021 and AEO2022 for those model years, respectively. We applied the year-over-year growth in vehicle sales to the model year 2019 single unit truck counts (from the sources described above) to derive future year fuel type and regulatory class distributions. Battery electric and fuel cell electric vehicle projections in AEO2023 were adjusted for model years 2024 and later based on an analysis of the national impact of CARB's Advanced Clean Trucks regulation.[31]

5.2.6. Combination Trucks

Combination trucks consist mostly of Class 8 trucks in the MOVES HHD regulatory class (regClassID 47) but also include Class 7 trucks in the MHD regulatory class (regClassID 46) and glider trucks (regClassID 49).

Almost all combination trucks are diesel-fueled, but MOVES4 also can model CNG and electric combination trucks, as well as gasoline short-haul combination trucks. Combination trucks were split between long-haul and short-haul by IHS using vehicle registration characteristics. As with the other heavy-duty vehicles, MOVES does not model E-85 combination trucks.

For combination short-haul trucks (sourceTypeID 61), the 2014 IHS data were used to calculate fuel type and regulatory class distributions for model years 2000-2013, and the 2020 IHS data were used for model years 2014-2019. However, we found that battery electric combination trucks were not well represented in the IHS data, so we used electric combination truck counts reported to EPA from the 2019 Annual Production Volume Reports into Engine and Vehicle Compliance Information System[33] instead of the battery electric combination truck counts in the IHS data.

For combination long-haul trucks (sourceTypeID 62), the 2014 IHS data were used to calculate fuel type and regulatory class distributions for model years 2000-2013, and the 2020 IHS data were used for model years 2014-2019.

For model years 2020 and later, we used Department of Energy heavy-duty sales projections from AEO2023's "Freight Transportation Energy Use"[13] table to derive year-over-year growth for heavy heavy-duty gasoline, diesel, CNG, battery electric, and fuel cell electric vehicles. Data for MY2020-MY2021 were not available in AEO2023, so we used AEO2021 and AEO2022 for those model years, respectively. We applied the year-over-year growth in vehicle sales to the model year 2019 combination truck counts in the 2020 IHS data in order to derive future year fuel type and regulatory class distributions. Battery electric and fuel cell electric vehicle projections in AEO2023 were adjusted for model years 2024 and later based on an analysis of the national impact of CARB's Advanced Clean Trucks regulation.[31] [e]

5.2.6.1. Glider Truck Populations

"Glider trucks" in MOVES refers to vehicles with new chassis but with older engines that do not meet MY 2007 or 2010 emissions standards (Section 2.3). Most glider trucks are Class 8 vehicles that use diesel heavy heavy-duty engines. For simplicity, in MOVES, we assume that all glider vehicles are HHD but modeled as a separate regulatory class (regClassID 49) and are only populated within the combination short- and long-haul truck source types (sourceTypeID 61 and 62, respectively).

We used sales data from both glider kit manufacturers and glider assembler manufacturers to estimate glider truck populations in MOVES. The glider kits contain the vehicle chassis and cab, but lack the engine and transmission. Glider assembler manufacturers (referred heareafter as "glider assemblers") assemble the glider vehicle by installing the engine and transmission into the glider kit produced by the glider kit manufacturer. Most glider assemblers are small businesses that sell less than 10 glider vehicles per year. However, most of the glider vehicles made from 2016 to 2020 have been produced by a handful of large glider assemblers.

We estimated the glider population based on annual glider production volume (sales) data for model years 2010 to 2016 shared as claimed confidential business information (CBI) from the two major glider kit manufacturers.[34] For use in MOVES, we assumed annual sales of 500 for glider vehicles for years prior to 2010 and rounded the reported production volumes in the years 2010 to 2016 to the nearest thousand, as shown in Table 5-1. The rounded values reflect the uncertainty regarding the number of gliders in the fleet, including the contribution of small volume glider manufacturers and the number used in single-unit vehicles.[f]

Table 5-1: Annual Glider Vehicle Sales Estimates Applied in MOVES Based on Claimed CBI Data Shared by Manufacturers

MY	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Glider Population	500	500	1000	3000	4000	5000	8000	12000	7000	7500	3500	1500	0	0

[e] We made the simplifying assumption that all electric short-haul trucks are battery EVs and all electric long-haul trucks are fuel cell EVs. However, there were no fuel cell EV combination trucks in production in our base year of 2020, so we could not directly apply year-over-year growth in AEO to project future distributions. Instead, we calculated the ratio of AEO2023's HHD fuel cell EV sales to HHD battery EV sales and applied this ratio as a scaling factor to the battery EV short-haul truck projections to estimate future year fuel cell EV long-haul truck counts. We then derived future year fuel type and regulatory class distributions from these counts.

[f] In 2017, glider manufacturers are limited to producing their maximum production between MYs 2010 and 2014. See 81 FR 73478 for more information.

For estimating the glider sales for 2017 and 2018, we did not have data from the two glider kit manufacturers, but we have data from the glider assemblers. As part of EPA's Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles – Phase 2 rulemaking (Phase 2)[91], the agency adopted new rules for glider kits, glider vehicles and glider engines. Starting in model year 2018, a glider assembler could continue to sell glider vehicles, without limit, if the glider engine was from a 2010 or later model year. If a glider assembler wishes to sell glider vehicles with earlier model year engines, they are limited to the lesser of 300 per year or the number of glider vehicles they sold in calendar year 2014. The regulation requires glider assemblers to report their sales data to EPA, including their 2014 sales to identify their individual sales allowances. The number of manufacturers who reported glider sales data to EPA for 2014, 2017, 2018, and 2019 are shown in Table 5-2, and the reported sales are displayed in Figure 5-2. Prior to the 2018 model year, more than 260 glider assemblers reported their sales data, including five manufacturers which produced more than 300 gliders and whose sales were capped starting in 2018. The reported sales from the glider assemblers in 2014 was close to 9,000 vehicles, which compares well to the 8,000 glider kit sales reported for 2014 shown in Table 5-1.

Table 5-2. Number of Glider Assemblers that reported to EPA, grouped by glider production in 2014

Glider Production in 2014	Manufacturers reporting in 2014	Manufacturers reporting in 2017	Manufacturers reporting in 2018	Manufacturers reporting in 2019
<=10	208	70	73	21
10-50	53	23	23	6
51-300	8	5	5	0
300 +	5	2	2	0
Total	274	100	103	27

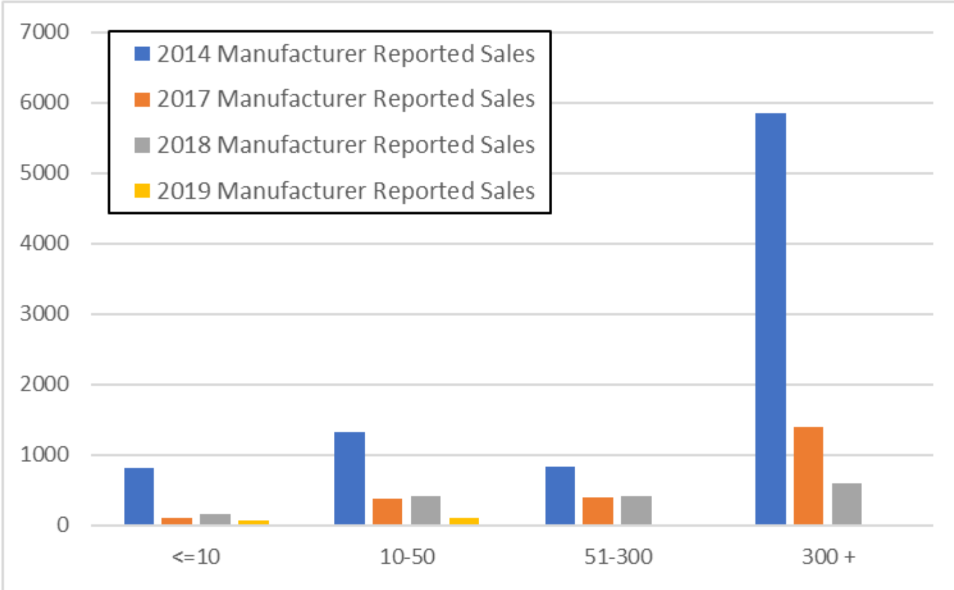

Figure 5-2. Reported Glider Sales by Glider Assemblers for Calendar Year 2014, 2017, 2018, and 2019.

The total number of glider sales by glider assemblers is significantly reduced in 2017, 2018, and 2019 as shown in Figure 5-2. One reason for the decrease is that we only received reported sales from a subset of the assemblers who reported their sales in 2014. For the assemblers who reported sales in 2017, we calculated the ratio of sales to the number of sales these assemblers reported in 2014. For the assemblers who reported sales in 2018 and 2019, we calculated the ratio of the sales to maximum allowable (the smaller of their sales in 2014 or 300 glider vehicles). As shown in Table 5-3, the larger glider assemblers tended to produce more gliders in comparison to the 2014 sales and their maximum allowable sales.

Table 5-3. Ratio of 2017, 2018, and 2019 Glider Sales to 2014 Sales or the Maximum Allowable Sales (2017 and 2018) from Reporting Glider Assemblers

	A	B	C
Glider Production in 2014	Ratio of 2017 sales to 2014 sales for assemblers that reported in 2017	Ratio of 2018 sales to maximum allowable for assemblers that reported in 2018	Ratio of 2019 to 2014 sales to maximum allowable for assemblers that reported in 2019
<=10	0.30	0.46	0.62
10-50	0.57	0.63	0.70
51-300	0.68	0.71	
300 +	1.02	1.00	

To estimate the number of glider sales in 2017, we multiplied the ratios in Column (A) of Table 5-3 by total number of gliders sales by glider assembler size reported in 2014. This is under the assumption that the sale growth/reduction rate from 2014 to 2017 is the same between reported glider assemblers and the overall glider assemblers. And similarly, to estimate the number of glider sales in 2018, we multiplied the ratios in Column (B) by the maximum allowable of all glider assembler manufacturers who reported in 2014. When rounded to the nearest 500, this yielded total glider sales estimates of 7,500 in 2017 and 3,500 in 2018 as shown in Table 5-1.

To estimate 2019 sales, we had limited data from the glider assembler manufacturers (only 27 assembler manufacturers reported 2019 sales at the time of the analysis, all of which sold less than 50 gliders per manufacturer). The two major glider kit manufacturers informed EPA that they had stopped production of glider kits in 2018. As such, we assumed that the 2019 glider vehicles would be 1500 vehicle sales, which is calculated from 50 gliders per manufacturer and 27 reported assembler manufacturers, rounded to the nearest 500. We assumed zero sales for 2020 and later model years. Assuming an insignificant number of gliders in future years is appropriate due to decreasing availability of pre-2010 engines and requirements for 2021 and later model year glider vehicles to meet the Medium and Heavy-duty Greenhouse Gas Phase 2 emissions and fuel economy standards.[83]

We calculated the fraction of gliders (stmyFraction) by dividing the estimated glider production by the number of age-0 combination trucks for each model year using Equation 5-3. We applied this fraction to both short-haul combination (sourceTypeID 61) and long-haul combination trucks (sourceTypeID 62). Note all gliders are regclass 49 diesel trucks.

$$f(stmy)_{regclass\ 49, model\ year\ i,} = \frac{Gliders_i}{Combination\ Trucks_{soucetype\ 61+62,i}}$$ **Equation 5-3**

5.2.7. Older Model Years

For pre-2000 model years, most SampleVehiclePopulation values are based on combining 1999 and 2011 IHS vehicle registration data with data from the 1997 and 2002 Vehicle Inventory and Use Survey (VIUS).[g] The documentation of the pre-2000 model years may be found in Appendix A. Note that there are two exceptions to our reliance on the VIUS-based analysis for model years before 2000:

- For passenger trucks and light commercial trucks, we used the 2014 IHS data for model years 1981-2000 because the MOVES definition of these vehicle types is no longer consistent with the VIUS definition. Unfortunately, the data are too scarce in 2014 IHS and later for pre-1981 model years, so we continue to rely on the previous analysis as described in Appendix A analysis for those model years.
- We also relied exclusively on the 2014 and 2020 IHS data for all model years of transit buses, other buses, and motor homes.

6. Vehicle Age-Related Characteristics

[g]At this writing, VIUS 2002 is the latest VIUS available. DOT has begun collecting data for the 2021 VIUS and we hope to incorporate data from this survey in future versions of MOVES.

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.[10,11] This section describes vehicle age distributions and relative mileage accumulation rates by source type.

6.1. Age Distributions

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 MOVES4 only contains registration-based age distributions for two analysis years: 1990 and 2020. The age distributions for all other analysis years in MOVES4 were projected forwards or backwards from the 2020 base age distribution. All default age distributions are available in the SourceTypeAgeDistribution table in MOVES database.

The rest of this section details the derivation of the base 2020 age distribution and the forwards and backwards projections for all years other than 1990. The 1990 age distributions are discussed in Appendix B.

6.1.1. Base Age Distributions

The 2020 base age distributions for cars and trucks were primarily derived from the 2020 IHS data and the 2017 National Transit Database (NTD). The 2020 IHS data 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 2020 IHS data did not capture all vehicles sold in 2020. Vehicle sales by source type in 2020 were calculated from a variety of sources as described in Appendix C.2. The source type sales were divided by the 2020 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 is only used in MOVES to determine vehicle distributions, not for vehicle populations.

Figure 6-1shows the fraction of vehicles by age and source type for calendar year 2020, which formed the basis for forecasting and back-casting age distributions as described in the following sections. Please note that since all vehicles age 30 and older are grouped together, there is an uptick in this age bin for most source types.

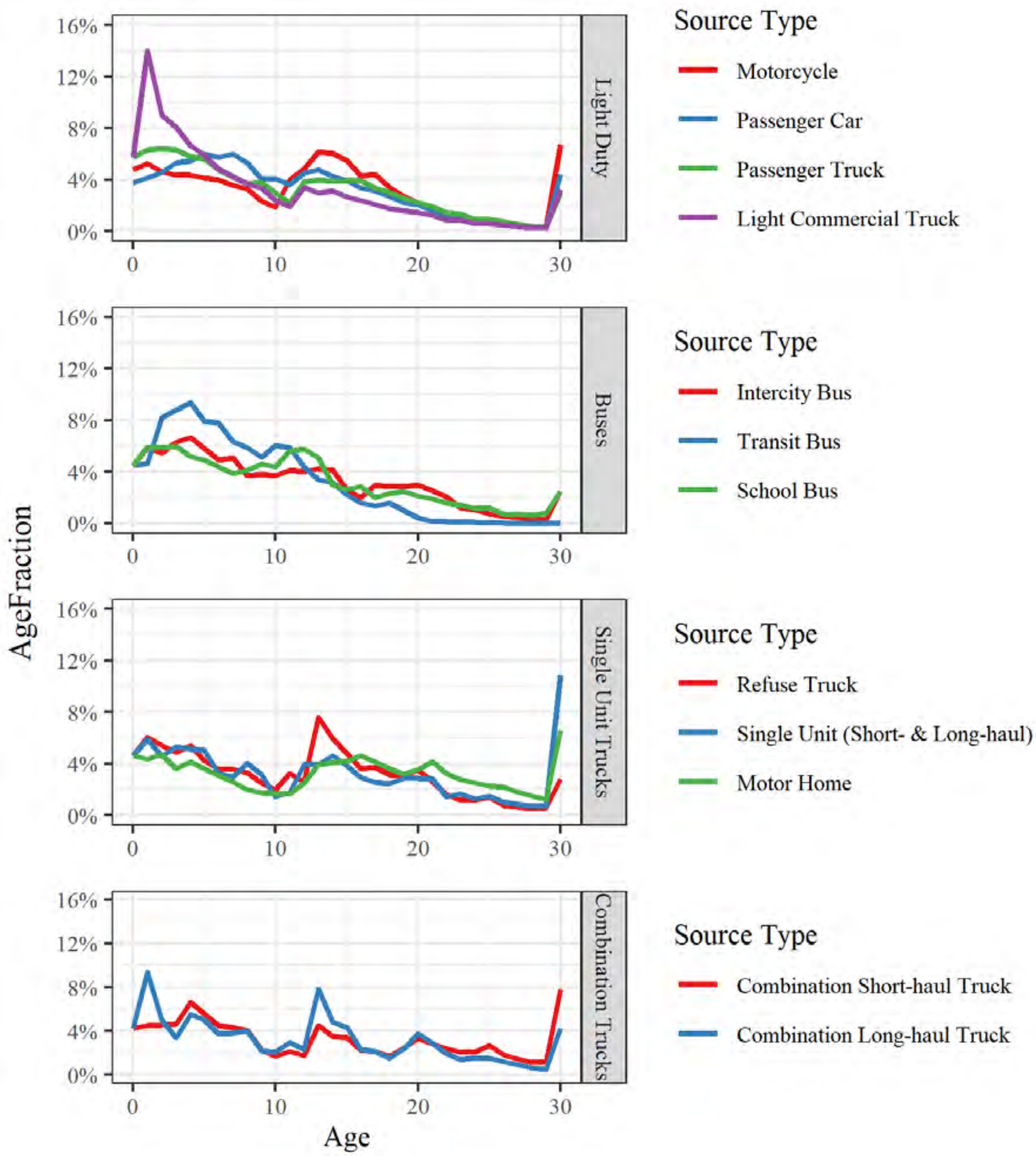

Figure 6-1 2020 age distributions by source type in MOVES4

6.1.2. Historic Age Distributions

The 2000-2019 age distributions were backcast from the 2020 base age distribution using historic population and sales estimates. Age distributions are calculated from population counts, if the populations are known by age:

$$f_{a,y} = \frac{p_a}{P_y} \qquad \textbf{Equation 6-1}$$

In Equation 6-1, $f_{a,y}$ 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 6-2:

$$\overrightarrow{P_{y-1}} = \overrightarrow{P_y} - \overrightarrow{N_y} + \overrightarrow{R_{y-1}} \qquad \textbf{Equation 6-2}$$

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 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 6-1.
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 is 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 2021-2060 age distributions from the 2020 distribution is similar to the backcasting method described above. To forecast an age distribution one year, Equation 6-2 of the previous section can be rewritten as Equation 6-3:

$$\overrightarrow{P_{y+1}} = \overrightarrow{P_y} - \overrightarrow{R_y} + \overrightarrow{N_{y+1}}$$

Equation 6-3

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 6-1.
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 historic national default age distributions in MOVES.

In addition to producing the default projected age distributions, this algorithm was implemented in the spreadsheet-based Age Distribution Projection Tool.[35] 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 4) and age distributions described in Section 6.1 to 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 (Light-duty vehicles, HPMSVTypeID 25). As described below in Section 6.2.1.1, new (age 0) passenger trucks and light commercial trucks are defined to have a RMAR of one (1.0)[h] and new passenger cars have a RMAR of 0.95. This means that when MOVES allocates the VMT assigned to the light-duty vehicle HPMS class to passenger cars, passenger trucks and light commercial trucks, a passenger car of age 0 will be assigned only 95 percent of the annual VMT assigned to a passenger truck or light commercial truck of age 0. The RMAR values used in MOVES4 are shown in Figure 6-2.

[h] 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.

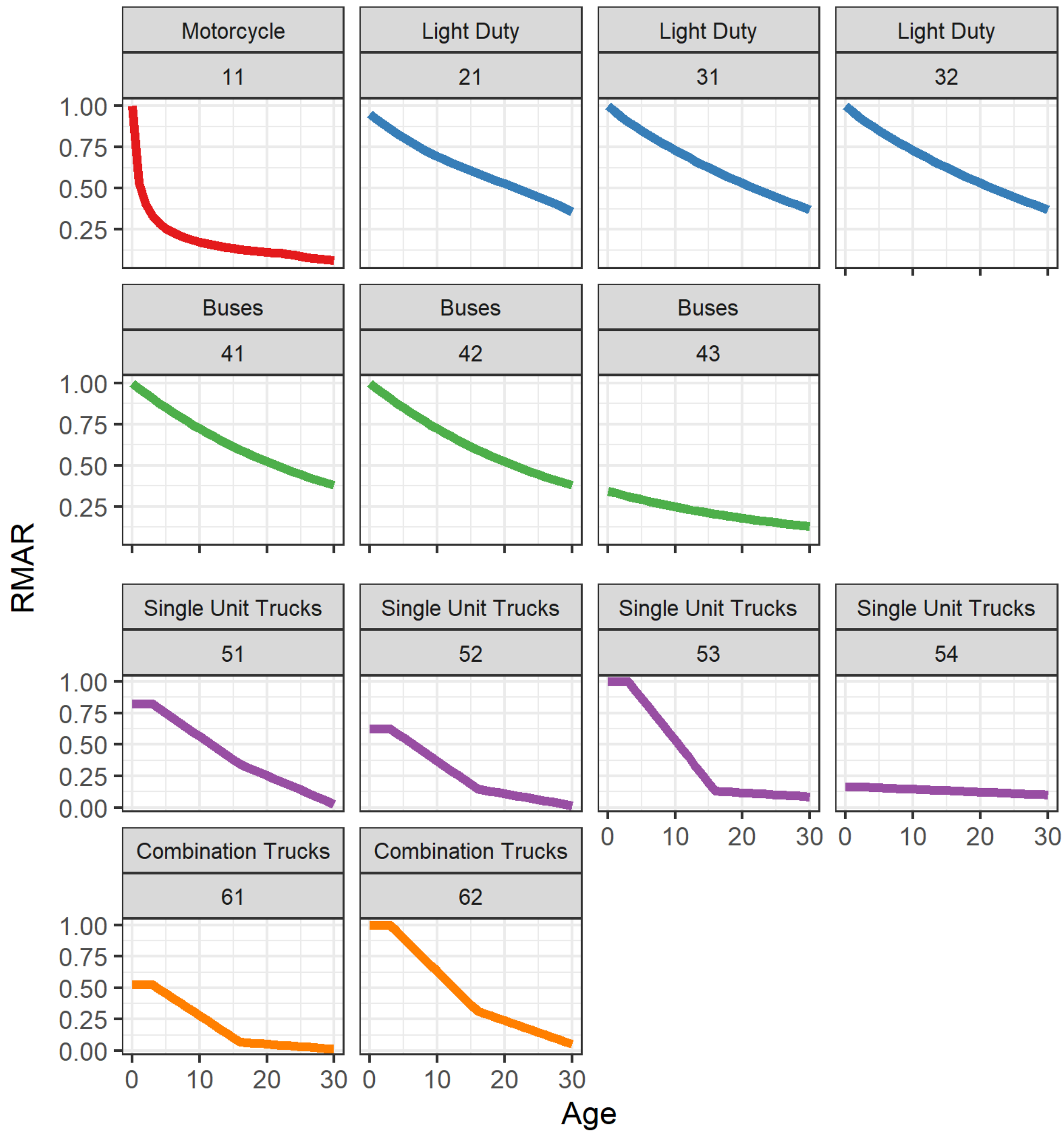

Figure 6-2. Relative Mileage Accumlation Rates (RMAR) by HPMS Class and SourceTypeID

The derivation of the RMAR values for each sourcetype and HPMS class are discussed in the following subsections.

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.[36]

6.2.1.1. Passenger Cars, Passenger Trucks and Light-Commercial Trucks

In earlier versions of MOVES, 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.[112] In that NHTSA analysis, annual mileage by age was determined for cars and for trucks using data from the 2001 National Household Travel Survey.

For MOVES4, we updated the RMAR values for passenger cars, passenger trucks and light commercial trucks (sourcetypeID 21, 31, and 32). We leveraged the vehicle miles traveled analysis done by NHTSA for their CAFE standards for MY 2024-2026 presented in their Technical Support Documentation.[37] NHTSA used a random national sample of one million vehicles based on data from IHS-Polk for 2016, which provides a longitudinal dataset with information on individual vehicles over time, providing data on vehicle mileage as they age. The smoothed annual mileage schedules used by NHTSA are presented in Table 6-1:

Table 6-1 VMT Annual Mileage Schedules Derived by NHTSA and Weights Used to Generate LDT Mileage for MOVES

Vehicle Age	Cars	Vans/SUVs	Pickups	Weight 31	Weight 32
0	15,922	16,234	18,964	0.831	0.169
1	15,379	15,805	17,986	0.884	0.116
2	14,864	15,383	17,076	0.896	0.104
3	14,378	14,966	16,231	0.900	0.100
4	13,917	14,557	15,449	0.905	0.095
5	13,481	14,153	14,726	0.917	0.083
6	13,068	13,756	14,060	0.924	0.076
7	12,677	13,366	13,448	0.918	0.082
8	12,305	12,982	12,886	0.915	0.085
9	11,952	12,605	12,372	0.930	0.070
10	11,615	12,234	11,903	0.928	0.072
11	11,294	11,870	11,476	0.940	0.060
12	10,986	11,512	11,088	0.945	0.055
13	10,690	11,161	10,737	0.945	0.055
14	10,405	10,816	10,418	0.947	0.053
15	10,129	10,477	10,131	0.944	0.056
16	9,860	10,146	9,871	0.942	0.058
17	9,597	9,820	9,635	0.943	0.057
18	9,338	9,501	9,421	0.946	0.054
19	9,081	9,189	9,226	0.944	0.056
20	8,826	8,883	9,047	0.946	0.054
21	8,570	8,583	8,882	0.946	0.054
22	8,313	8,290	8,726	0.950	0.050
23	8,051	8,004	8,577	0.957	0.043
24	7,785	7,724	8,433	0.962	0.038
25	7,511	7,450	8,290	0.964	0.036
26	7,229	7,183	8,146	0.965	0.035
27	6,938	6,923	7,998	0.968	0.032
28	6,635	6,669	7,842	0.971	0.029
29	6,319	6,421	7,676	0.984	0.016
30	5,988	6,180	7,497	0.831	0.169

We derived RMAR values using the same methodology used for previous MOVES versions.[38] Passenger cars, passenger trucks and light commercial trucks were 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. Analysis of the data determined that new passenger cars (age 0) accumulate 95 percent of the annual miles accumulated by new light-duty trucks.
We chose to continue using the same RMAR for all light trucks rather than deriving individual mileage accumulation rates for sourceTypeID 31 and 32 because the NHTSA results did not distinguish passenger and commercial trucks. However, rather than computing a simple

arithmetic average of the annual mileage for the SUV/Van and Pickup categories, we weighted these values using factors from a separate IHS-Polk sample obtained by EPA for 2017 in five states: Colorado, Georgia, New Jersey, California, and Illinois. We originally purchased this sample to update the RMAR for light-duty vehicles but given the availability of a national sample with similar longitudinal characteristics, we opted to use the NHTSA mileage schedules as our main data source. EPA's five-state sample did, however, classify vehicles to MOVES sourcetypes based on body shape, GVWR and personal vs commercial registration type. We calculated weights for SUV/Vans and Pickups based on the five-state samples for sourcetype 31 and 32, respectively, and applied them to the NHTSA schedules (see Table 6-1), assuming that the SUV/Van category loosely mapped to passenger vehicles while the Pickup category mapped to light commercial trucks and assuming no significant difference between the populations in 2016 and 2017. The resulting weighted mileages for LDV and LDT are shown in Figure 6-3.

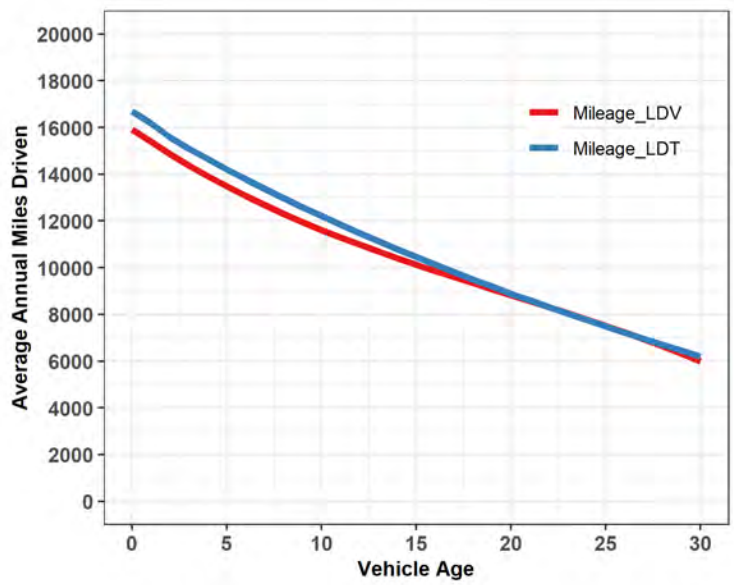

Figure 6-3 Annual Mileage for LDV and LDT

The updated RMARs are presented in Figure 6-4 and shown in comparison to the relative MAR for light-duty vehicles used in MOVES3. For cars, the new curves suggest an increase in miles driven across the age range in comparison to MOVES3, but particularly for vehicles between 15-25 years old. For LDT, there is a small reduction in miles driven for younger trucks up to 10 years old and a reduction for the oldest trucks (27 years old and later), while an increase in miles driven is observed between the age range 12-27 years. Furthermore, the relationship between LDV and LDT in MOVES4 shows how both groups have increasingly similar driving patterns compared to earlier data.

Emissions sensitivity analysis at the national level indicates that the updated RMARs for light-duty vehicles results in an increase in the light-duty inventory of one to three percent depending on the pollutant and calendar year, with smaller increases further in the future. Because vehicle populations and the total miles for HPMS vehicle class 25 were held constant in this testing, the emissions change is caused by the shift in VMT to older ages.

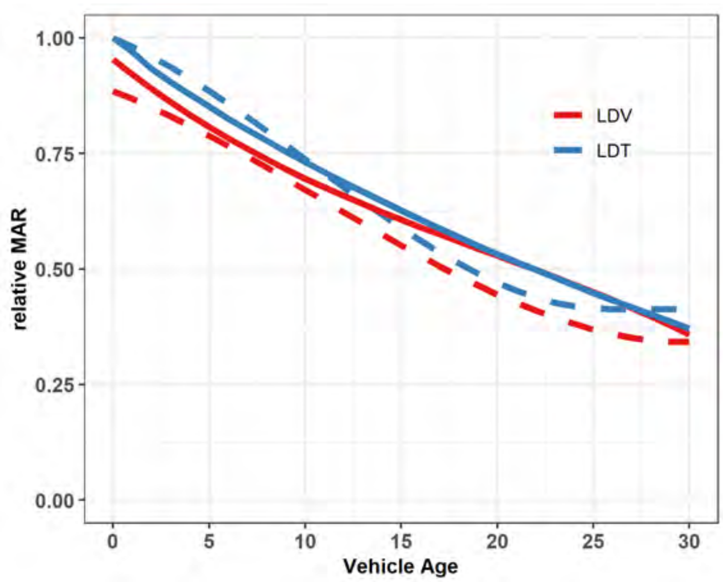

Figure 6-4 LDV and LDT relative MAR for MOVES4 (solid lines) and MOVES3 (dashed lines)

6.2.2. Buses

In MOVES4, the RMARs for Buses are unchanged from MOVES3.

The transit bus (sourceTypeID 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 as shown in Table 6-3 and a smoothing function applied to remove the variability in the data.[39] The MOBILE6 results were extended to calculate values for ages 26 through 30.

For MOVES3, we redefined source type 41 as "other bus" (sourceTypeID 41) and assigned the same RMAR as the transit bus (sourceTypeID 42).

The school bus (sourceTypeID 43) annual mileage accumulation rate (9,939 miles per year) is derived from the 1997 School Bus Fleet Fact Book.[18] For MOVES3, we updated the RMAR for school buses such that it has the same shape as the transit bus RMAR, but adjusted down such that year 0 is based on the 9,939 miles per year from the School Bus Fleet Fact Book. The same relative shape is evident in of the Bus RMAR in Figure 6-2.

Table 6-2 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					

6.2.3. Other Heavy-Duty Vehicles

In MOVES4, the RMARs for other HD vehicles are unchanged from MOVES3.

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).[40] The total reported annual miles traveled by truck in each source type by age, as shown in Table 6-3, was divided by the vehicle population by age to determine the average annual miles traveled per truck by source type.

Table 6-3 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	60,654	109,418
1	2001	32,391	22,755	28,168	59,790	128,287
2	2000	31,210	24,446	30,139	61,651	117,945
3	1999	31,444	23,874	49,428	62,865	110,713
4	1998	31,815	21,074	33,266	55,113	99,925
5	1997	28,450	21,444	23,784	54,263	94,326
6	1996	25,462	16,901	21,238	40,678	85,225
7	1995	30,182	15,453	27,562	38,797	85,406
8	1994	20,722	13,930	21,052	33,485	71,834
9	1993	25,199	13,303	11,273	30,072	71,160
10	1992	23,366	11,749	18,599	27,496	67,760
11	1991	18,818	13,675	15,140	24,175	80,207
12	1990	12,533	11,332	13,311	22,126	48,562
13	1989	15,891	9,795	9,796	21,225	64,473
14	1988	19,618	9,309	12,067	21,163	48,242
15	1987	12,480	9,379	16,606	20,772	58,951
16	1986	12,577	4,830	8,941	11,814	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 reach 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.[41]

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. The average mileage accumulation rate of ages 0 to 3 were used for age 3 in the regression. The resulting coefficients are summarized in Table 6-4,
3) Age 30 uses the 1992 TIUS relative mileage accumulation rate for age 30. These relative mileage accumulation rates were allocated to the MOVES source types from the MOBILE6 mileage accumulation rates, they were converted to mileage based on the mileage data used in MOVES, then converted back to an RMAR consistent with the other ages.
4) Ages 17 through 29 use values from interpolation between the values in age 16 and age 30.

Table 6-4 Regression coefficients 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]	30,437	23,250	37,069	61,240	116,591
Slope[b]	-1,361	-1,368	-2,476	-4,092	-6,418
Age 30 RMAR	0.027	0.0115	0.086	0.015	0.052

[a] Average sample annual miles traveled for ages 0 through 3.
[b] Intercept at age 3; slope from ages 4 through 16.

The RMAR values for heavy-duty were updated for MOVES3. The resulting relative mileage accumulation rates are shown in Table 6-5 below and Figure 6-2 above. As in previous versions of MOVES, the first four ages (age 0 to 3) are identical and then decline linearly to age 16 and then linearly to age 30 with a different slope.

6.2.4. Motor Homes

For MOVES3, we updated the RMAR values and added a decreasing trend with age. Data from the 2017 National Household Travel Survey[42] was used for the motor home RMAR calculation. The calculation methodology is different from the other heavy-duty trucks. The same average annual mileage accumulation rate was used for age 0-3 motor homes. Age 4 through 30 used mileage accumulation rates that were calculated using a linear regression of the National Household Travel Survey data.

Based on this data, the average annual vehicle miles of travel per vehicle for age 0 to 3 is 6003. In the regression analysis, this value was used as intercept at age 3. The slope from age 4 through 30 was calculated at -83 miles/year. The motor home mileage accumulation values were then converted to RMARs by dividing by the average mileage for age 0-3 long-haul single-unit trucks (37,069).

The resulting relative mileage accumulation rates of motor homes are shown in Table 6-5 below and Figure 6-2 above. Note that first four ages are identical and then decline linearly to age 30 since the 2017 National Household Travel Survey has data available from age 0 to 30.

Table 6-5 Relative mileage accumulation rates for heavy-duty trucks in MOVES

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	0.8211	0.6272	1.0000	0.1620	0.5253	1.0000
1	0.8211	0.6272	1.0000	0.1620	0.5253	1.0000
2	0.8211	0.6272	1.0000	0.1620	0.5253	1.0000
3	0.8211	0.6272	1.0000	0.1620	0.5253	1.0000
4	0.7844	0.5903	0.9332	0.1597	0.4902	0.9473
5	0.7477	0.5534	0.8664	0.1575	0.4551	0.8945
6	0.7110	0.5165	0.7996	0.1552	0.4200	0.8418
7	0.6743	0.4796	0.7328	0.1529	0.3849	0.7891
8	0.6376	0.4427	0.6660	0.1507	0.3498	0.7363
9	0.6009	0.4058	0.5992	0.1484	0.3147	0.6836
10	0.5642	0.3689	0.5323	0.1462	0.2796	0.6309
11	0.5275	0.3320	0.4655	0.1439	0.2445	0.5781
12	0.4908	0.2950	0.3987	0.1417	0.2094	0.5254
13	0.4541	0.2581	0.3319	0.1394	0.1743	0.4727
14	0.4174	0.2212	0.2651	0.1372	0.1392	0.4199
15	0.3807	0.1843	0.1983	0.1349	0.1041	0.3672
16	0.3440	0.1474	0.1315	0.1327	0.0690	0.3145
17	0.3214	0.1380	0.1282	0.1304	0.0652	0.2957
18	0.2987	0.1285	0.1249	0.1282	0.0613	0.2769
19	0.2761	0.1191	0.1216	0.1259	0.0575	0.2581
20	0.2535	0.1097	0.1184	0.1236	0.0536	0.2394
21	0.2309	0.1002	0.1151	0.1214	0.0498	0.2206
22	0.2083	0.0908	0.1118	0.1191	0.0460	0.2018
23	0.1857	0.0814	0.1085	0.1169	0.0421	0.1830
24	0.1631	0.0719	0.1052	0.1146	0.0383	0.1642
25	0.1405	0.0625	0.1019	0.1124	0.0344	0.1454
26	0.1179	0.0530	0.0986	0.1101	0.0306	0.1267
27	0.0953	0.0436	0.0954	0.1079	0.0267	0.1079
28	0.0727	0.0342	0.0921	0.1056	0.0229	0.0891
29	0.0500	0.0247	0.0888	0.1034	0.0191	0.0703
30	0.0274	0.0153	0.0855	0.1011	0.0152	0.0515

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 MOVES4 were derived to reflect the VMT data included in the 2017 National Emission Inventory (NEI) Version 2.[43] 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 Highway Statistics[44] 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 Freeways and Expressways	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 Major Collector	5	Urban Unrestricted Access
Urban Minor 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.

Note that because it is difficult to distinguish single unit 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.

Table 7-2 MOVES4 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	0.0825631	0.267313	0.198403	0.451721	1.000
21	Passenger Car	0.08177	0.204595	0.259544	0.454091	1.000
31	Passenger Truck	0.0958223	0.265213	0.222866	0.416098	1.000
32	Light Commercial Truck	0.0839972	0.217512	0.262385	0.436105	1.000
41	Other Bus	0.131819	0.246451	0.222309	0.399421	1.000
42	Transit Bus	0.122177	0.232623	0.259237	0.385963	1.000
43	School Bus	0.133622	0.290446	0.202762	0.37317	1.000
51	Refuse Truck	0.133744	0.281628	0.244409	0.340218	1.000
52	Single-Unit Short-Haul Truck	0.133827	0.290565	0.233264	0.342345	1.000
53	Single-Unit Long-Haul Truck	0.124627	0.288468	0.224945	0.36196	1.000
54	Motor Home	0.146173	0.297276	0.211836	0.344715	1.000
61	Combination Short-Haul Truck	0.172224	0.327849	0.244772	0.255155	1.000
62	Combination Long-Haul Truck	0.338174	0.240709	0.256685	0.164432	1.000

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

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

As described below, the default average speed distributions for all sourcetypes were updated in MOVES3 using the telematics data. There were no updates for MOVES4.

8.1. Description of Telematics Dataset

In a study done by the Coordinating Research Council (CRC A-100)[45], the GPS data collected by StreetLight Data were used to develop inputs for the 2014 National Emissions Inventory. The dataset consists of data from billions of trips derived from smart phone applications, in-dashboard car navigation systems and commercial fleet management systems on vehicles operating over a period of 12 consecutive months between September 2015 and August 2016 at a high temporal and spatial resolution.

The data included latitude, longitude and timestamps corresponding to the instantaneous position that each vehicle sends to a central server. StreetLight overlays the coordinates on their roadway network to determine distance traveled between consecutive points. From the distance and time between points, average speeds were calculated and further classified by month, day of the week and hour. The dataset also was able to discriminate between personal vehicles, medium-duty commercial trucks (Class 6 and lower) and heavy-duty commercial trucks (Class 7 and 8). The personal dataset was available at high resolution (1 Hz) and low resolution (one point every 10 or 30 seconds) while the commercial dataset was available at a lower resolution with one point every 60 or 180 seconds. The data included a GIS shapefile containing road information classified into the four MOVES road types and a second shapefile containing county boundaries to generate data with the appropriate mapping.

Note that since the CRC A-100 project was developed to improve inputs used in the NEI, the definitions of urban and rural applied to the CRC study were consistent with the requirements of EPA's platform modeling for the NEI and regulatory impact analyses[46], which follow the definitions established by the U.S. Census Bureau. This is inconsistent with the urban-rural roadtype definitions used in MOVES, which follow those established by FHWA. The main difference in the definitions established by the U.S. Census Bureau and FHWA is the population threshold used to distinguish between urban and rural. The U.S. Census Bureau defines an urban area as areas with a population of 2500 or more, whereas the FHWA defines an urban area as areas with a population of 5000 or more. Therefore, telematics speed data gathered by StreetLight Data in some areas that are considered rural by FHWA and MOVES may have been assigned to "urban" roadtypes. For MOVES modeling purposes, this discrepancy implies that the average speed distributions derived from this dataset could be biased high by some degree, since vehicles on rural roads generally spend more time traveling at faster speeds than those on urban roads.

Due to restrictions in time and resources, the final dataset consisted of only 1/16th of the information available to StreetLight Data. This aggregated subset totaled 250 million records classified into 3 vehicle categories:

- Personal Passenger vehicles
- Medium-Duty commercial trucks (under 26,000 lbs of GVWR)
- Heavy-Duty commercial trucks (over 26,000 lbs of GVWR)

The final dataset contains information for the three vehicle categories mentioned above across 3,109 counties in the mainland US. The dataset was classified into MOVES roadtypes and MOVES speedbins, for 12 months of the year, seven days of the week and 24 hours of the day. For further details, see the CRC A-100 report.[45]

A single set of default national average speed distributions for the MOVES default database were developed using the national database which contains average speed distributions for each county and hour of the day, for weekday/weekend, varying by road type and source type. Additionally, we used activity (VMT and average speed by county, fuel, source type and road type) from the beta version of the NEI collaborative 2016 modeling platform[47]. The following section describes the procedure to generate the average speed distributions included in MOVES.

8.2. Derivation of Default National Average Speed Distributions

The general steps for the derivation of default average speed distributions were:

1. Calculation of source hours operating (SHO) for each source type on each road type aggregated over all counties to represent the entire U.S.

2. Calculation of average speed distributions for each hour of the day, day of the week, road type and source type, weighted by the fraction of SHO in each county in reference to the national SHO for a given source type and road type combination.

For the first step, we used county-specific annual VMT classified by fuel, source type and road type as well as county-specific annual average speed values classified by source type and road type. Both data files were used in the development of activity for the NEI collaborative 2016 beta modeling platform and are based on FHWA and CRC A-100 information (where available), respectively. We calculated a county-specific annual value of source-hours operating (SHO) for each source type – road type combination, as shown in Equation 8-1, by adding all the VMT assigned to different fuels (*i*) for each source type (ST) - road type (RT) combination in each county (Co) and dividing by the corresponding annual average speed:

$$Annual\ SHO_{ST,RT,Co} = \frac{\sum_{i=fuel} Annual\ VMT_{STi,RT,i,Co}}{Annual\ Average\ Speed_{ST,RT,Co}} \left[\frac{miles}{miles/hour}\right] \quad \textbf{Equation 8-1}$$

Then, we aggregate over all counties *i* to obtain a national annual SHO for each source type (ST) – road type (RT) combination following Equation 8-2:

$$National\ Annual\ SHO_{ST,RT} = \sum_{i=Co} Annual\ SHO_{(ST,RT)i}\ \ [hours] \quad \textbf{Equation 8-2}$$

In the second step, we used a data file from the CRC A-100 project containing average speed distributions by hour of the day and day typefor each source type – road type combination for each county. These values were weighted togheter using the SHO for each county developed in Equation 8-1 divided by the national annual SHO determined in Equation 8-2. This results in average speed distributions (ASD) weighted by the national activity for a given source type – road type combination for each hour (h) of each weekday/weekend (d). This is summarized in Equation 8-3:

$$ASD_{h,d,ST,RT} = \sum_{i=16} \frac{AverageSpeedFraction_{i,h,d,ST,RT,Co} \times Annual\ SHO_{ST,RT,Co}}{National\ Annual\ SHO_{ST,RT}} = 1 \quad \textbf{Equation 8-3}$$

Note that the sum over all 16 speed bins should be equal to 1 for each hour and type of day for a given source type and road type combination.

For the default national average speed distributions used in MOVES4, we used the same mapping of telematics data to MOVES source type used in the NEI to maintain consistency. For buses, refuse trucks, and motor homes for which no direct mapping was provided, we assigned the medium-duty commercial profile. The final mapping is detailed in Table 8-2:

Table 8-2 Map of MOVES Source Types to telematics data vehicle type

MOVES Source Type ID	MOVES Source Type Name	Telematics Vehicle Type
11	Motorcycle	Personal
21	Passenger Car	Personal
31	Passenger Truck	Personal
32	Light Commercial Truck	Medium-Duty Commercial
41	Intercity Bus	Medium-Duty Commercial
42	Transit Bus	Medium-Duty Commercial
43	School Bus	Medium-Duty Commercial
51	Refuse Truck	Medium-Duty Commercial
52	Single Unit Short-haul Truck	Medium-Duty Commercial
53	Single Unit Long-haul Truck	Heavy-Duty Commercial
54	Motor home	Medium-Duty Commercial
61	Combination Unit Short-haul Truck	Heavy-Duty Commercial
62	Combination Unit Long-haul Truck	Heavy-Duty Commercial

8.3. Updated average speed distributions

As an example, the resulting default average speed distributions for different vehicle types are shown in Figure 8-1 for all road types and day types at 5 pm.

- Differences between Personal, Medium-Duty and Heavy-Duty commercial are most noticeable on rural restricted roads, where the Personal category (mapped to Passenger Cars, Passenger Trucks and Motorcycles) shows notably more time traveling at speeds above 75 mph.
- For all vehicle types, weekday-weekend differences between average speed profiles are generally small; the exception is for urban restricted access roads, reflecting the expected difference between weekend and weekday traffic volumes at 5 pm on urban freeways.

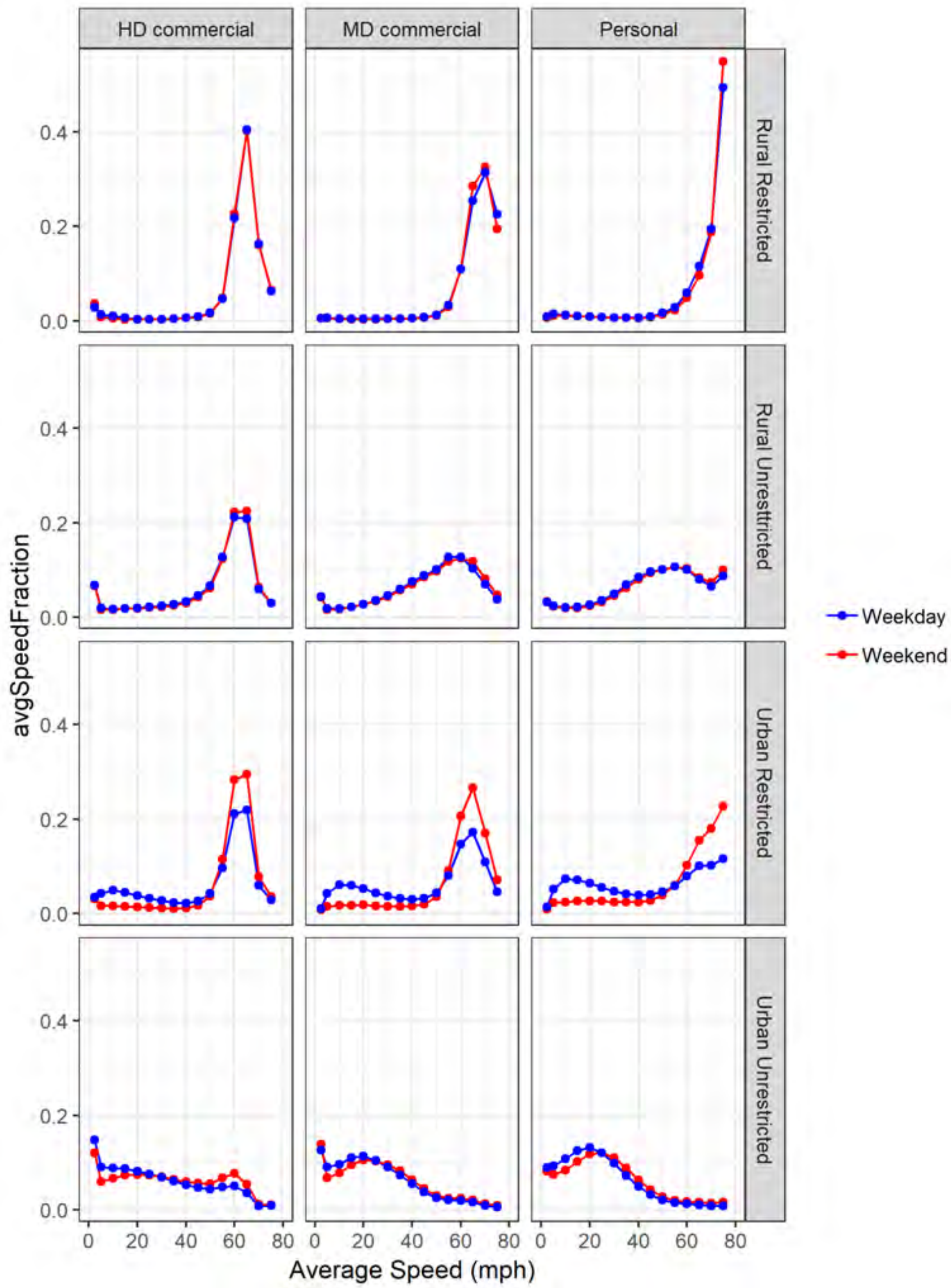

Figure 8-1 Average speed distributions for 5pm (hourID 17) on the different MOVES road types. For mapping between MOVES source types and telematics vehicle types, see Table 8-2.

The StreetLight data improves on previous estimates, with more data and enough detail to differentiate between Personal, Medium-Duty and Heavy-Duty vehicle types. However, it does not provide information to differentiate between vocation-specific trucks or buses. As new datasets beome available, we will continue to update and improve these inputs.

9. Driving Schedules and Ramps

Drive schedule refers to a second-by-second vehicle speed trajectory. The drive schedules in MOVES are intended to include all vehicle operation from the time the engine starts until the engine is keyed off, both driving (travel) and idling time.[i] 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 MOVES4 are unchanged from MOVES3 and are mostly the same as those in MOVES2014, with the exception of drive schedules for transit and school buses, as described below, and the handling of ramps as described in Section 9.2.

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 many schedules to represent driving patterns across source type, road type and average speed. For the national default case, MOVES uses 49 drive schedules with various average speeds, mapped to specific source types and road types.

MOVES stores all 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 these cases, for example, at extreme congestion or unimpeded high speeds, we assume that the road type itself has little impact on the expected driving behavior (driving

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

schedule). 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.[48] “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,[49] 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.[111] These cycles were selected to best cover the range of road types and average speeds modeled in MOVES.

The driving schedules (ID 201-206, 251-255, 397, and 398) used for all buses (41,42,43) are borrowed directly from driving schedules used for single-unit trucks. The "New York City Bus"[50] and "WMATA Transit Bus"[51] drive schedules are included for urban driving that includes transit-type bus driving behavior. The "CRC E55 HHDDT Creep"[52] 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 based on Ann Arbor Transit Authority buses instrumented in Ann Arbor, Michigan.[53] 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. The "Bus Low Speed Urban" bus cycle (ID 401) is the last 450 seconds of the standard New York City Bus cycle.

For MOVES3 and later versions of MOVES, we revised the handling of bus speeds; we changed the driving cycle mapping in the DriveSchedule table to be the actual speed for all bus drive cycles. Consistent with our changes, users should input the actual average speed distribution for transit buses.

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 data from 150 medium- and heavy-duty vehicles instrumented to gather instantaneous speed and GPS measurements.[54] The drive cycle data were segregated into restricted access and unrestricted access driving for medium- and heavy-duty vehicles and then further stratified by 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 developed schedules 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 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 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)[55] 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 could follow the speed demands of the proposed driving cycles without exceeding maximum torque or power.

We compared the operating mode distrition estimated for a national scale run in MOVES to the operating mode distribution measured from the Heavy-Duty In-Use Testing (HDIUT) program in the Appendix G of the heavy-duty exhaust report. Overall, the operating mode distributions compare well. One notable differene is, for a national scale run, MOVES estimates a higher percentage of activity in the highest power, high speed operating mode bins.[11] This may be reasonable because the manufactur-run testing for the HDIUT data are expected to under-represent high power operation due to steep grades, high speeds, and heavy-pay loads (e.g., multiple trailers, over-weight trailers) compared to the in-use fleet. Or perhaps, the discrepancy could be due in part to the high-speed driving cycle being overly aggressive compared to in-use driving. As mentioned in the Conclusions section, we suggest that a further evaluation of the in-use operating mode distributions and heavy-duty driving cycles be considered for future work for MOVES.

9.2.Modeling of Ramps in MOVES

For MOVES3 and later versions of MOVES, we simplified the modeling of emissions on restricted access roadways by modeling ramps as part of highway driving. The MOVES3 Population and Activity Report has a detailed discussion of this change.[38] 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.

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[56] and brake emissions. Users can continue to estimate ramps as individual links in project-scale. Preferably, project-level users can characterize the specific operating mode or driving cycle of the ramps they are evaluating.

10. Off-Network Idle Activity

To better account for observed levels of idling, we added a new emission calculation to MOVES3 for County and National Scale runs[j] allowing the model to estimate idle emissions that occur off the road network (i.e., on roadTypeID=1) for all soucetypes. We have made no updates for MOVES4. This section summarizes the new calculation methodology employed by MOVES and then provides information on the idling data available for both light-duty and heavy-duty vehicles.

10.1. Off-Network Idle Calculation Methodology and Definitions

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 below. 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 source hours idle ($SHI_{2\text{-}5}$) during normal daily vehicle operation for each of the four onroad 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 (see Section 11). Total idle fractions are stored in the new TotalIdleFraction table in the MOVES default database.

Since the estimates of TIF are greater than the idle time accounted for in the MOVES driving schedules ($SHI_{2\text{-}5}$), we also need to increase MOVES' estimate of total source hours operating (SHO). In particular, the off-network idle (ONI) time is defined as the additional idle hours that need to be added to the on-network source hours operating ($SHO_{2\text{-}5}$) in order to account for the additional idle time. The on-network $SHO_{2\text{-}5}$ is derived from the VMT and speed distribution. Starting with MOVES3, the additional ONI hours are assigned to the running exhaust process (processID=1) for the off-network road type (roadTypeID=1).

In MOVES2014, total SHO was calculated from vehicle miles traveled (VMT) and average speed for all onroad roadTypeIDs 2, 3, 4 and 5. Starting with MOVES3, we renamed this value as on-network $SHO_{2\text{-}5}$ to indicate that additional time needs to be added to account for off-network idle time. The SHO for all road types will now include the "extra" operating time (ONI) implied by the larger total idle fraction value:

$$SHO = \left(\sum_{i=2}^{5} SHO_i\right) + ONI \qquad \textbf{Equation 10-1}$$

Where i = *roadTypeID*

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[j] In Project Scale, MOVES does not adjust activity to account for off-network idling. Instead, the user can provide location-specific idling activity as appropriate.

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

$$\boldsymbol{SHI} = \left(\sum_{i=2}^{5} \boldsymbol{SHI_i}\right) + \boldsymbol{ONI} \qquad \textbf{Equation 10-2}$$

Where i = *roadTypeID*

All running exhaust activity for roadTypeID=1 is idle, so SHO_1=SHI_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:

$$\boldsymbol{SHI} = \boldsymbol{TIF} \times \boldsymbol{SHO} \qquad \textbf{Equation 10-3}$$

Thus, from Equation 10-1, Equation 10-2 and Equation 10-3:

$$TIF = \frac{\left(\sum_{i=2}^{5} SHI_i\right) + ONI}{\left(\sum_{i=2}^{5} SHO_i\right) + ONI} \qquad \textbf{Equation 10-4}$$

And, by by re-arranging Equation 10-4 and using the TIF, on-network source hours operating ($SHO_{2\text{-}5}$) and on-network source hours idling ($SHI_{2\text{-}5}$) from the four network road types, MOVES can calculate the hours for off-network idle (ONI):

$$\mathrm{ONI} = \frac{\left(\sum_{i=2}^{5} \mathrm{SHO}_i\right) \times \mathrm{TIF} - \sum_{i=2}^{5} \mathrm{SHI}_i}{(1 - \mathrm{TIF})} \qquad \textbf{Equation 10-5}$$

Where i = *roadTypeID*

As an example, the default values of TIF for light-duty vehicles in idleRegionID=101 (New Jersey) are presented in Table E-2 in Appendix E.

In cases where the ONI is calculated to be less than zero, the ONI will be set to zero. This is currently true for motorcycles and motorhomes.

Off-network idle emissions are calculated for each hour by using the corresponding emission rate (grams per hour) for opModeID=1 for that hour. All of the adjustments (e.g., fuel effects, air condition effects) made to the emission rates for opModeID=1 for other road types apply to off-network idle emissions as well. MOVES3 separately reports the emissions from the off-network idle hours in the movesOutput table as exhaust running process (processID=1) for road type “off-network” (roadTypeID=1).

10.2. Light-Duty Off-Network Idle

10.2.1. Verizon Telematics Data

MOVES defaults for light-duty off network idling continues to rely on our MOVES3 analysis. In developing MOVES3, Verizon Telematics data for light-duty vehicles was purchased only for the following five states due to costs – California, New Jersey, Illinois, Georgia and Colorado. These states were selected for a variety of reasons, including geographic coverage, urban and rural mix, use of inspection and maintenance programs, and number of vehicles participating in the program. The data were collected August 2015 through August 2016 using on-board diagnostic data loggers under contracts with State Farm insurance, Mercedes-Benz and Volkswagen. The data includes vehicles from model year 2017 back to model year 1996, which is also the first year manufacturers were required to equip all vehicles with on-board diagnostic (OBD) systems.[57] Vehicle owners allowed their vehicles to be measured for a variety of reasons and the data cannot be considered a random sample. The Verizon Telematics data were used as a primary data source for the light-duty off-network idle defaults described in this section and also for the soak and start defaults described in Section 12.1 The data characteristics and pre-processing steps for both analyses are described here.

The Verizon data includes activity information gathered on vehicles for all or some subset of the entire year. 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 a fraction 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, the 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, all of the activity by vehicles was assumed to occur within the county in which they were registered. 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 having a State Inspection and Maintenance (I/M) program or not.

10.2.2. 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%

* 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. To distinguish infrequently used vehicles from those that had left the program, we developed an algorithm to extract 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 only if 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 and month derived using this sampling approach. Appropriate weighting was then applied to the monthly results to generate annual averages.

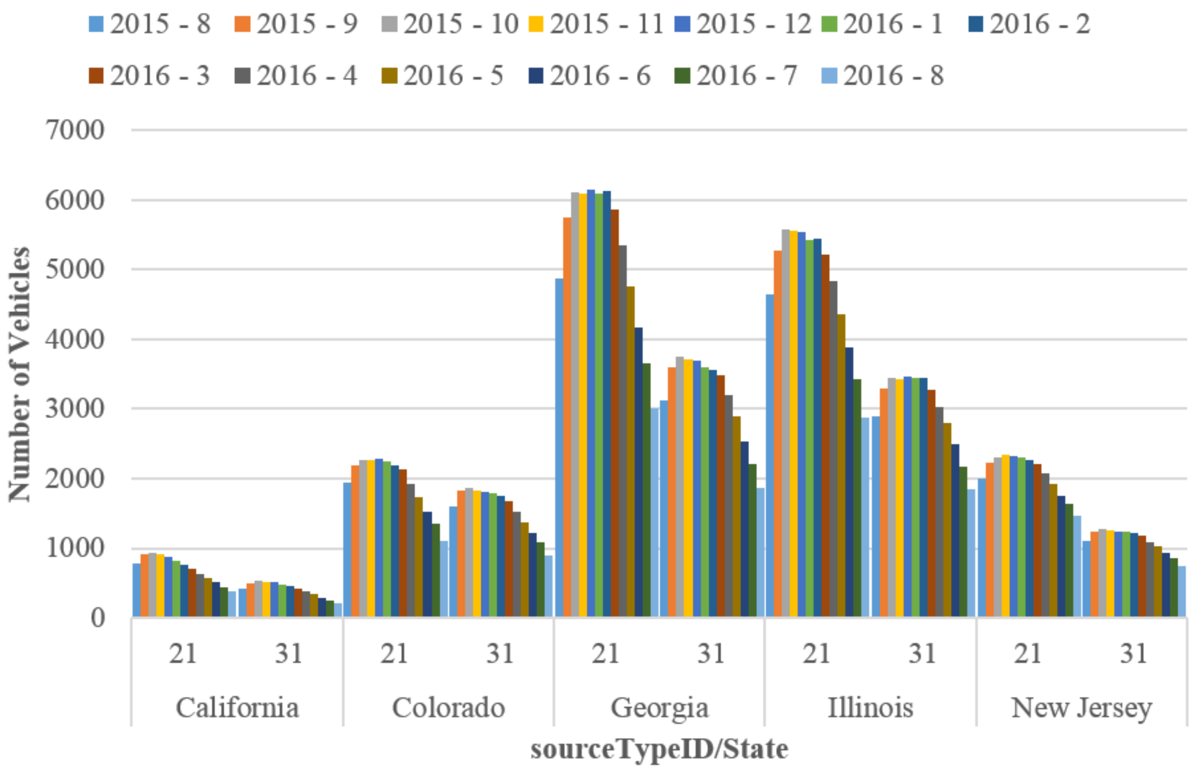

Figure 10-1 Sample vehicle population in the Verizon Telematics data by month, state and sourceType. Note: the legend indicates the "year-month" of the data collection.

There were a few instances where the trip time was less than 1 second, or the soak time was less than two seconds, for example, when a vehicle crossed into a different time zone or when the data logger recorded erroneous trip starts at midnight for trips that included midnight driving. 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 were used to analyze engine starts and soaks (see the "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.

10.2.3. Estimating MOVES National Defaults from Verizon Telematics Data

The Verizon Telematics data covered only five states, but 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. Table 10-2 lists the vehicle populations used for computing national averages. Figure 10-2 shows how we mapped individual states to the Verizon data. We grouped the states qualitatively, considering proximity and climate. Climate was considered because the monthly patterns varied between areas with large temperature shifts between seasons (Colorado, Illinois) and states with moderate seasonal changes (California and Georgia). The weighted average results for the light-duty passenger trucks (indicated in the data as sourceTypeID 31) were used for light-duty commercial trucks (sourceTypeID 32) as well. Due to lack of data, motorcycle idle fractions were set to zero. This results in the same roadway (drivecycle-based) idling as before and no off-network idle.

Table 10-2 2014 Vehicle populations of the idle regions

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

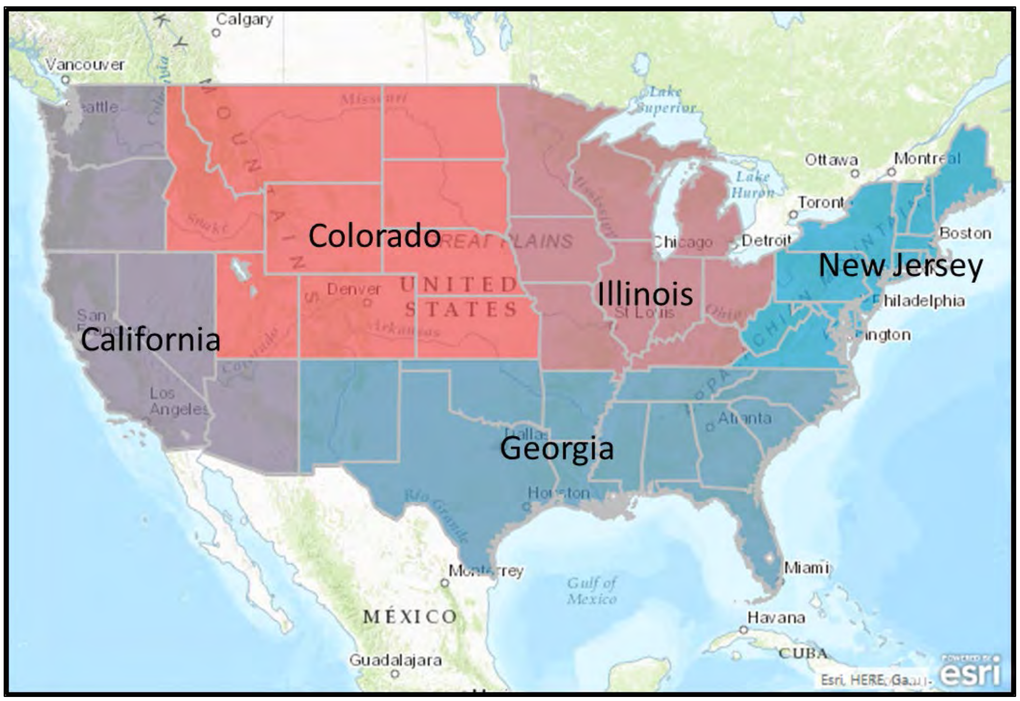

Figure 10-2 Default Regions for Weighting Light-Duty Activity[k]

In addtion to region, the Verizon Telematics data analysis suggested that the following factors are important when estimating total idling fraction:

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

- Month of the year (which depends on the region)
- 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. A simplified linear regression model was built to capture the variability of the total idle fraction (TIF) across different variables (dayID, sourceTypeID, countyTypeID, idleRegionID and monthID). MOVES3 default values for TIF were calculated based on the equation below:

$$TIF = dayID_i + sourceTypeID_j + countyTypeID_k + idleRegionID_l + monthID_m + idleRegionID_l \times monthID_m + n$$

Equation 10-6

where, *i, j, k, l,m* are coefficient values for the combinations of dayID (2=Weekend,5=Weekday), sourceTypeID, countyTypeID, idleRegionID and monthID and *n* is the intercept (a constant) for Equation 10-6 above. The regression model handled ordinal categorical variables as independent variables. The full set of coefficients are available in Appendix E.

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

In MOVES, we use the model fit TIF values from the multi-variable linear model (Equation 10-6, rather than using the averages from the Verizon Telematics data, mainly to smooth the variation in the Verizon Telematics data. Figure 10-3 below illustrates the model fit against actual values. TIF model results are represented by solid lines versus average values from the Verizon Telematics data, shown as dashed lines. As expected, Region 105 (California) which has the smallest sample size also shows the most variation and deviation from the regression results. For example, for Region 105 (California), passenger trucks (sourceTypeID 31), weekdays (dayID 5), the model fit smooths out the abnormally high idle fraction measured for July (monthID 7).

We also use the model estimated TIF values to estimate values that were not measured by Verizon. Note that there was no data available for New Jersey from Verizon Telematics for rural counties (i.e., countyTypeID=0) as shown in Figure 10-3. However, the regression model applies the rural/urban effect without regard to region. Appendix E shows a sample calculation using MOVES3 default values for passenger cars in rural counties in idleRegionID=101 (New Jersey).

The model fit TIF values apply to all calendar years in MOVES. Note that idleRegionID and countyTypeID vary depending on the county location. Each state is assigned an idleRegionID in the MOVES State table as shown in Figure 10-2. Each county is assigned an “urban” or “rural” countyTypeID in the MOVES County table based on the MSA designation. As discussed earlier, the results for the light-duty passenger trucks (indicated in the data as sourceTypeID 31) are also used for light-duty commercial trucks (sourceTypeID 32).

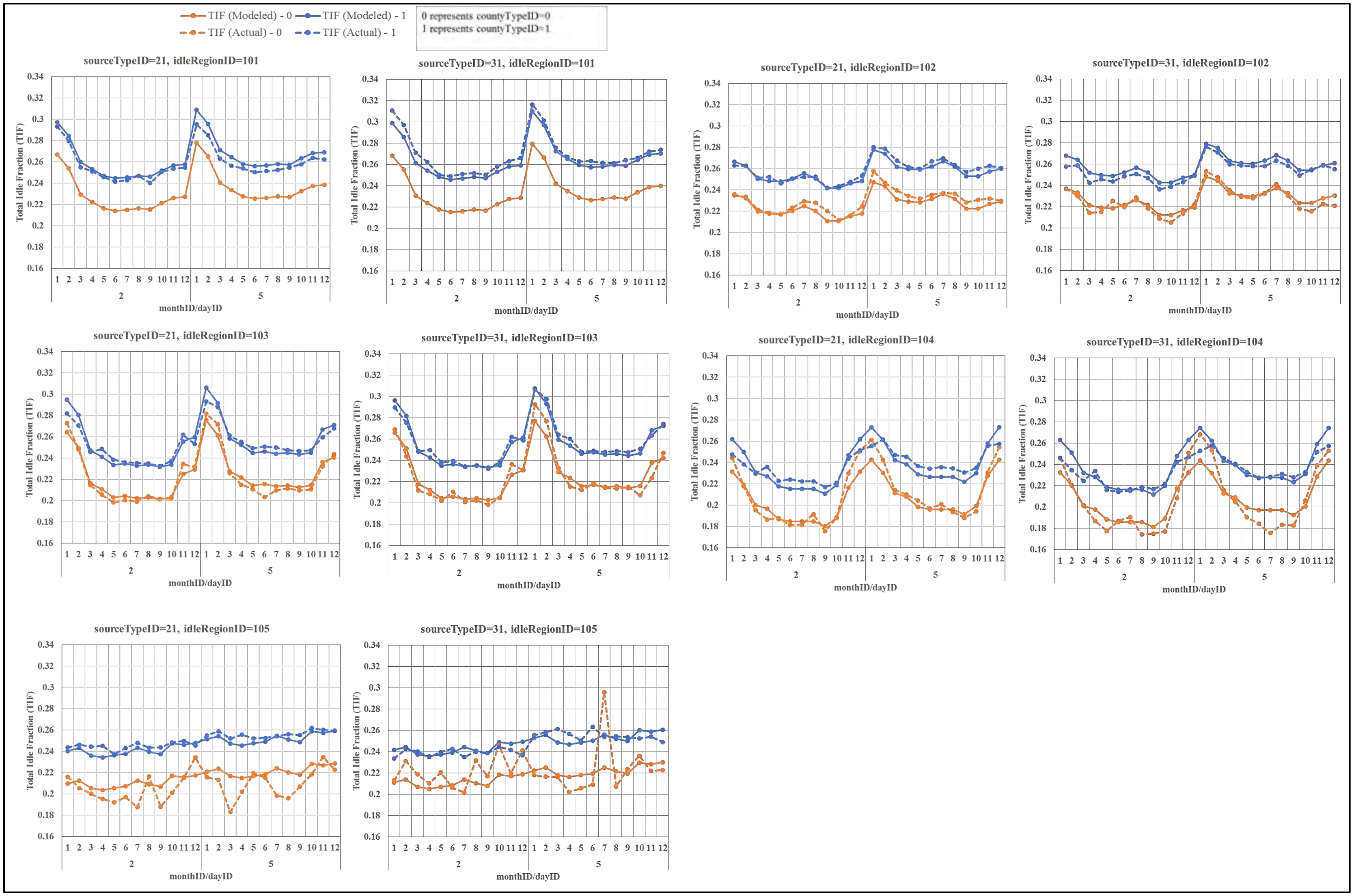

Figure 10-3: TIF model results compared to the values from the Verizon Telematics data

10.3. Heavy-Duty Off-Network Idle

The Verizon Telematics data exclusively covered light-duty vehicles. Heavy-duty vehicles are spread across a wide range of vocations and have activity patterns that are distinctly different from light-duty. Currently, the idling captured in the MOVES driving cycles represents the idling at intersections and on congested highways, but do not include a full estimate of “workday idle” that many commercial heavy-duty trucks experience in their daily operation, such as queuing at distribution centers, or loading and unloading payload. Off-network idle is also intended to address these gaps in idle activity modeling.

The heavy-duty off-network idle defaults were derived from the National Renewable Energy Laboratory (NREL) Fleet DNA clearinghouse of commercial fleet vehicle operating data. The data processing applied to the Fleet DNA dataset is described in this section. This analysis has not been updated since MOVES3. However, the University of California Riverside’s Bourns College of Engineering Center for Environmental Research and Technology (CE-CERT) has concluded their data collection for a study to evaluate the selective catalytic reduction (SCR) behavior of heavy-duty vehicles. We hope to apply the same processing steps to the latest CE-CERT dataset and expect to combine the results the with Fleet DNA data in a future MOVES update.

The same Fleet DNA dataset and pre-processing steps described in this section were used for the soak and start defaults described in Section 12.2

10.3.1. NREL Fleet DNA Database

We partnered with NREL to make use of their expansive Fleet DNA database[58] 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 devices to record 1-Hz telematics and CAN (controller area network[59]) 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. This analysis used data from 415 conventional heavy-duty vehicles with over 120,000 hours of operation, providing a diverse data encompassing 23 vehicle vocations in 36 states. The number of conventional vehicles in the Fleet DNA database by MOVES source type are shown in Table 10-3. The table also includes the number of states with activity in each Fleet DNA sample. The geographic distribution could influence average idle emission rates, due to differences in congestion, topography and regional policies.[l] [60] However, as presented in the NREL project report,[61] truck idling and start activity was observed to be largely a function of the truck vocation, rather than the US state of operation. Likely a larger sample size of vehicles across vocations and states would be needed to elucidate geographic differences in truck activity.

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	Number of States with Recorded Activity
41	Other Buses (non-school, non-transit)	0	0
42	Transit Buses	16	3
43	School Buses	7	1
51	Refuse Trucks	37	4
52	Single-Unit Short-Haul Trucks	119	8
53	Single-Unit Long-Haul Trucks	0	0
54	Motor Homes	0	0
61	Combination Short-Haul Trucks	105	8
62	Combination Long-Haul Trucks	131	32
	Total	**415**	

Note: The number of trucks operating in each US state is listed in the NREL project report[61]

Table 10-4 shows the vocational distribution of the short-haul source types (single unit and combination short-haul trucks) and the sample size of each vocation category. A complete description of the Fleet DNA dataset, additional pre-processing performed, and analyses not discussed in this report can be found in the NREL report.[61]

[l] For example, California has a regulation prohibiting idling for more than five minutes for vehicles that are not California clean idle certified.[1] However, other states, counties and cities also have idling regulations. In addition, most recent heavy-duty vehicles are California clean-idle certified. For example, all fourteen of the MY 2008 and later heavy heavy-duty tractors tested for extended idling emission rates (produced from four major engine manufacturers) were all clean idle certified.[5]

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

Combination Short-Haul Vehicle Vocation	Number of Vehicles in Fleet DNA	Single-Unit Short-Haul Vehicle Vocation	Number of Vehicles in Fleet DNA
Beverage Delivery	10	Warehouse Delivery	9
Food Delivery	13	Parcel Delivery	39
Drayage	28	Linen Delivery	17
Transfer Truck	28	Food Delivery	30
Local Delivery	7	Snow Plow	11
Regional Haul	7	Towing	4
Dump Truck	4	Concrete	3
Parcel Delivery	5	Delivery	1
Dry Van	3	Shredder	1
		Propane Tank	1
		Dump Truck	3

10.3.2. CE-CERT Study

The California Air Resources Board (CARB) contracted with CE-CERT to conduct 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. EPA supported the test program by providing data loggers and data quality analysis through a Cooperative Research and Development Agreement with CE-CERT. Most of these vehicles were registered in California and traveled a majority of their miles in-state. The study did include some out-of-state vehicles in the line-haul and pick-up/delivery categories. Almost all 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 the buses were CNG fueled. In addition, some of the vehicles in the study were hybrids. We hope to incorporate data from the CE-CERT study in future versions of MOVES.

10.3.3. Heavy-Duty Off-network Idle Data Processing

The NREL Fleet DNA data were preprocessed to identify starts and idle periods for the analysis. Two key parameters are engine speed (revolutions per minute [rpm]) and wheel speed (miles per hour [mph]). An engine speed greater than zero indicates that the vehicle engine is running and a wheel speed greater than zero mph signifies that the vehicle is in motion. In this analysis, vehicle starts are calculated by identifying the transition from an engine speed of zero to greater than zero. Vehicle soak is defined as the length of time between engine off (engine speed of zero) and the next time it is started (engine speed greater than zero). A vehicle is considered to be idling when its wheel speed is less than one mph and the engine speed is greater than zero. The total operating time (engine RPM > 0) occurring within each dayID is also calculated.

Periods of contiguous idle are identified by length and the dayID corresponding to the start of the idle. If an idle period started during one dayID and ended on another, the idle time was only counted for the dayID in which the trip started. Idle periods longer than an hour were categorized separately as “extended idle” for long-haul combination trucks (sourceTypeID 62) and not included in the average idle time of the off-network idle fraction calculation below.

Vehicle activity values in MOVES represent average activity at a national scale. MOVES uses “total idle fraction” to quantify off-network idle. In this analysis, total idle fraction was calculated by first summing the daily average idle time for each individual vehicle across all vehicles within the same vehicle (sourceType) and day type (dayID) classification. Those summed idle times were then divided by the sum of the daily average operating time for each individual vehicle across all vehicles within the same vehicle and day type. This sum-over-sum approach normalizes the recorded activity by the amount of time each vehicle was instrumented and weights the average idle fraction towards the vehicles with the most daily-average activity.[m]

[m] We evaluated several approaches for calculating average idle fraction using the Fleet DNA data. The approach presented here (Equation 10-7) is equivalent to Equation 17-23 (Method 3 “normalized sum over sum”) in Appendix I. Appendix I includes an overview of each approach and a comparison between calculation approaches.

Equation 10-7 shows the calculation of the total idle fraction for each source type and specific day type (weekday or weekend).

$$Idle\ fraction_{s,d} = \frac{\sum \left({idle\ hours_i}/{days_i} \right)}{\sum \left({operating\ hours_i}/{days_i} \right)} \quad \textbf{Equation 10-7}$$

Where:
i = individual vehicle ID
s = source type ID
d = day type ID

10.3.4. Heavy-duty Off-network Idle Results

As seen in Table 10-3, several heavy-duty source types were not available in the Fleet DNA database at the time of this report. Additionally, none of the school buses instrumented for this dataset operated on the weekend, so there is no data for dayID 2. We hope to have more of the source types and dayID's covered when we process the CE-CERT dataset and combine it with the Fleet DNA dataset in a future version of MOVES. In the interim, we assumed the idle behavior of the missing vehicles closely matched others. We chose to use the transit bus (sourceTypeID 42) to represent other buses (sourceTypeID 41), applied the weekday data from the school bus (sourceTypeID 43) for the missing weekend data, used the single-unit short-haul data (sourceTypeID 52) to represent the single-unit long-haul trucks (sourceTypeID 53). Lacking data for motorhomes (sourceTypeID 54), we set their total idle fraction to zero. This will result in the same roadway (drivecycle-based) idling as in MOVES2014 and no off-network idle. While this is an area that would benefit from more research, we think it is unlikely for motorhomes to idle significantly when they are not on roadways since they are equipped with APUs and often park where auxiliary power is available.

Figure 10-4 and Figure 10-5 show the idle fraction values for weekends and weekdays, respectively. In both figures, the solid blue bars represent the off-network idle for each heavy-duty vehicle sourceType. The hashed bars represent the extended idle portion, which is only available to the long-haul combination trucks (sourceTypeID 62). The specific values added to the MOVES TotalIdleFraction database table for this update are shown in Table 10-5.

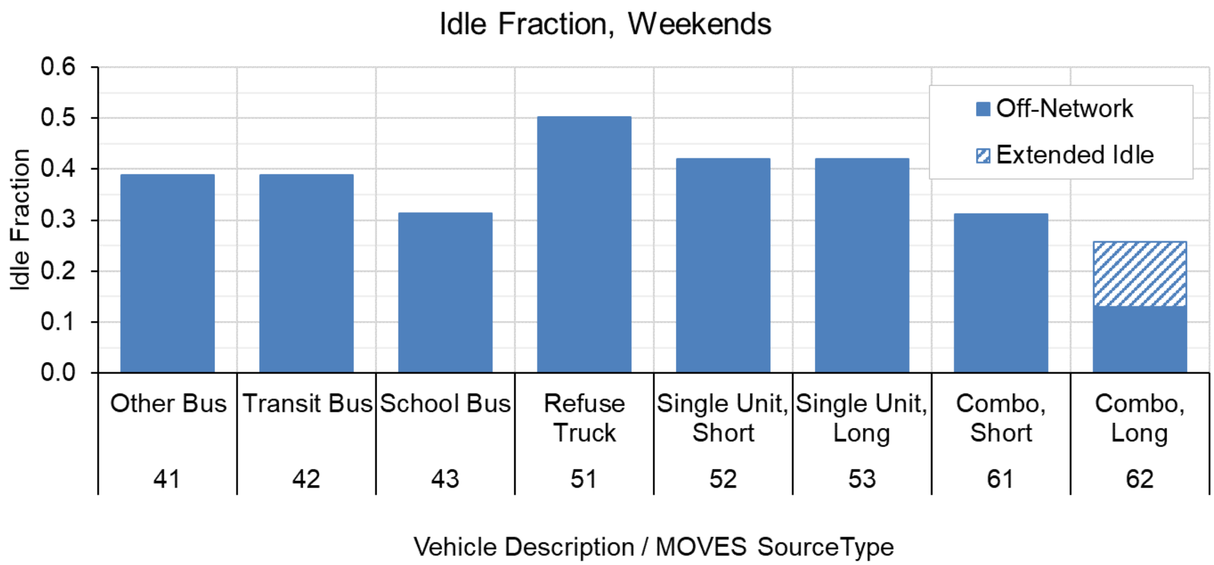

Figure 10-4 Weekend idle fractions for heavy-duty vehicle sourceTypes based on data from NREL's Fleet DNA database

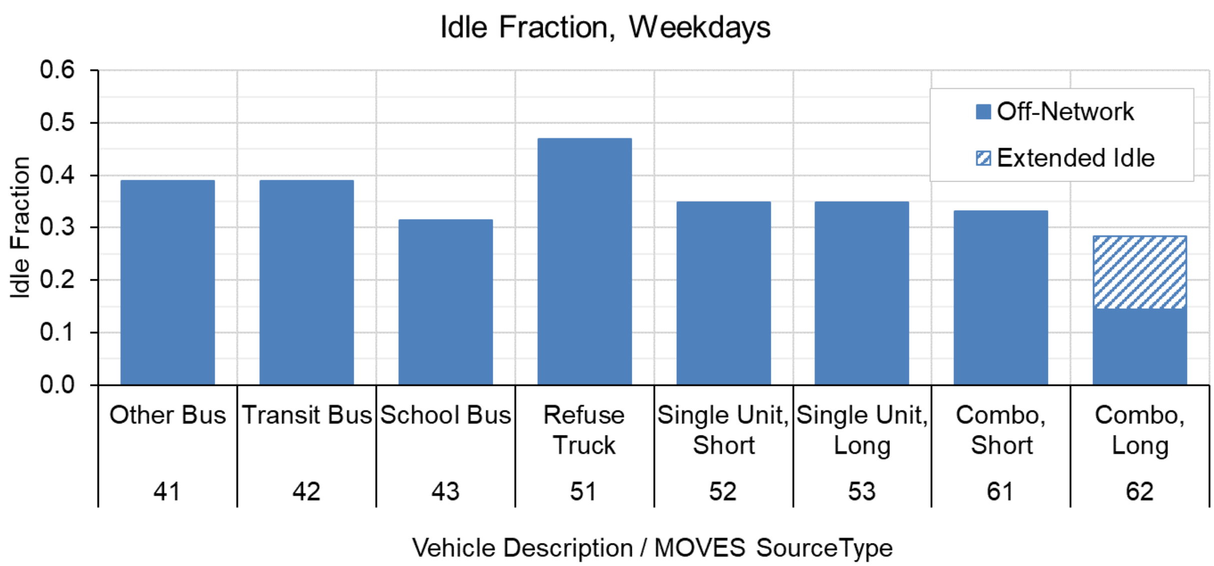

Figure 10-5 Weekday idle fractions for heavy-duty vehicle sourceTypes based on data from NREL's Fleet DNA database

Table 10-5 Idle fraction values for heavy-duty sourceTypes based on data from NREL's Fleet DNA database

SourceType	Vehicle Description	Weekend Idle Fractions		Weekday Idle Fractions	
		Off-Network	Extended	Off-Network	Extended
41	Other Bus	0.388	0.000	0.390	0.000
42	Transit Bus	0.388	0.000	0.390	0.000
43	School Bus	0.314	0.000	0.314	0.000
51	Refuse Truck	0.503	0.000	0.469	0.000
52	Single Unit, Short	0.420	0.000	0.348	0.000
53	Single Unit, Long	0.420	0.000	0.348	0.000
61	Combo, Short	0.312	0.000	0.332	0.000
62	Combo, Long	0.130	0.127	0.145	0.138

10.4. Off-network Idling Summary

Figure 10-6 displays the off-network idling fraction and the on-network idling fraction for an urban county in the midwestern idle region. The off-network idling accounts for most of the idling for most source types. Note that the idle fraction, and subsequently, the off-network idling fraction changes significantly between January and July for the light-duty vehicles. However, it is unchanged for the heavy-duty vehicles. Also, note that the idling fraction for long-haul combination trucks is lower than for other vehicles because long-duration idling (> 1 hour) for long-haul combination trucks is modeled as hotelling activity discussed in the Section 11.

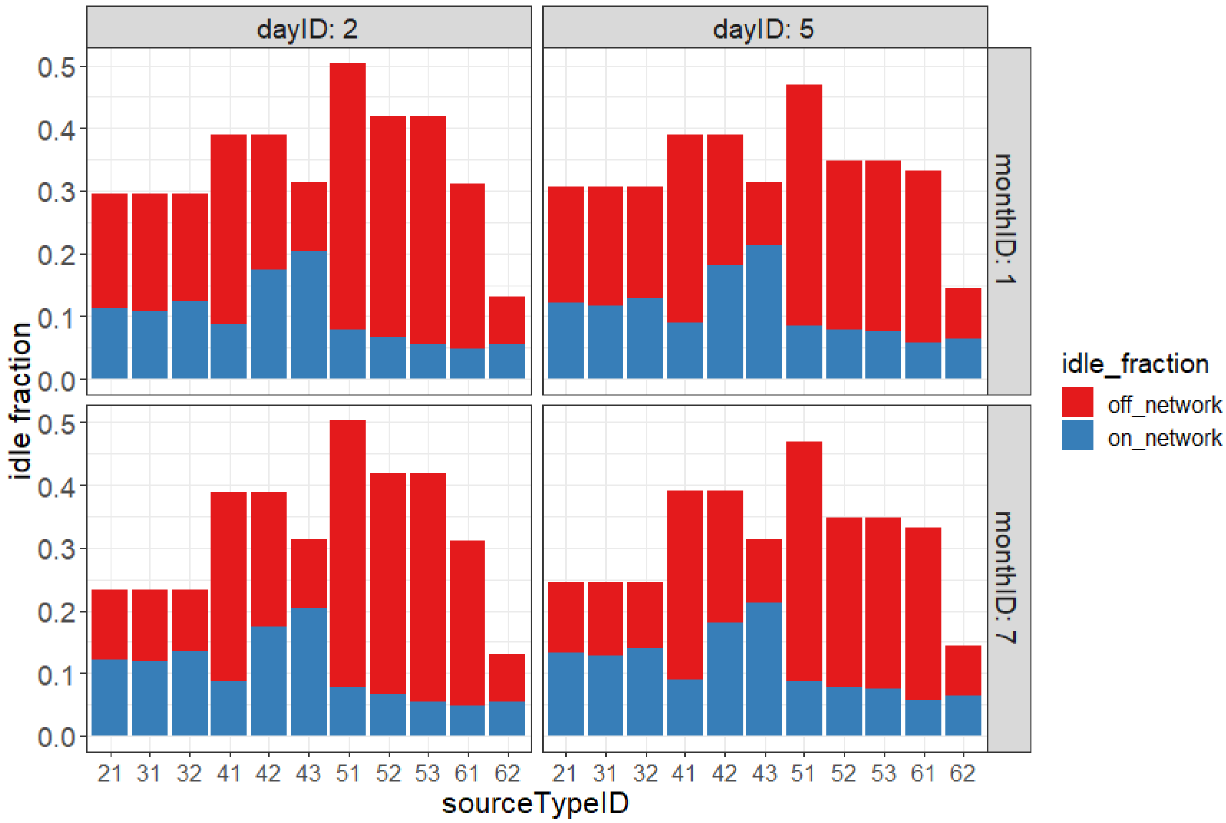

Figure 10-6. On-network idle and Off-network idle fractions for an Urban County in the Midwestern Region

11.Hotelling Activity

MOVES defines "hotelling" as any long period of time (e.g., > 1 hour) that drivers spend in their vehicles during mandated rest times during long distance deliveries by tractor/trailer combination heavy-duty trucks. During the mandatory rest time, drivers can stay in motels or other accommodations, but most of these trucks have sleeping berths built into the cab of the truck and drivers stay in their vehicles.

Hotelling hours are included in MOVES to account for the energy used and pollutants generated to power air conditioning, heat and other amenities. 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 the rest time may occur without the use of amenities at all.

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

11.1. 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. Table 11-1 shows the hotelling operating modes available in MOVES.

Table 11-1 Hotelling activity operating modes in MOVES

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

The hotelling activity distributions in MOVES are consistent with the hotelling assumptions used in EPA's Heavy-Duty Greenhouse Gas Phase 2 rulemaking, which included increasing adoption of battery or electric supplemental power.[62] Additionally, we updated the model to include a fraction of hotelling time when the driver did not require any supplemental power. Starting in 2011, the hours-of-service regulations from the Federal Motor Carrier Safety Administration (FMCSA) were updated to encourage longer periods of rest.[63] Drivers could split their 10 hours of mandated off-duty time between the sleeper berth for at least 8 hours and another location for the remaining 2 hours. We assume the drivers do not require power when not in the sleeper berth and applied a constant 20 percent of hotelling time to represent the 2 hours off-duty time not in the sleeper berth for all years.

The HotellingActivityDistribution table, shown in Table 11-2, contains the MOVES default values for the distribution of hotelling activity to the operating modes. For model years before 2010, we assume 80 percent of time is extended idling and 20 percent does not require supplemental power, as mentioned previously. Starting with the 2010 model year, an increased number of trucks equipped with APUs are expected as a result of the Phase 1 Heavy Duty Greenhouse Gas Standards[64] and a fraction of the time that previously was assigned to extended idle is now assigned to opModeID 201 (the use of APUs). In later model years, we continue to assume a constant fraction of time with no supplemental power and distribute the remaining time among extended idle, APU use and increasing 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 Phase 2, with stepwise increases in model years 2021, 2024 and 2027.[65] Similar to pre-2010 model years, we assumed drivers would not require supplemental power 20 percent of the time for model years 2010 and later.

Alternative fueled long-haul trucks are assumed to have the same hotelling activity distribution as diesel trucks as described above with the following adjustments:

- CNG trucks are assumed to not have diesel APUs and instead rely on the main engine idling.
- Fuel Cell EVs are assumed to use shore power for the 80 percent time in sleeper berth.

Table 11-2 Default hotelling activity distributions

Fuel Type	beginModelYearID	endModelYearID	opModeFraction for given opModeID			
			200	201	203	204
			Idle	APU	Shore Power	Battery/Off
Diesel	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	0.00	0.28
	2024	2026	0.40	0.32	0.00	0.28
	2027	2060	0.36	0.32	0.00	0.32
CNG	1960	2020	0.80	0.00	0.00	0.20
	2021	2026	0.72	0.00	0.00	0.28
	2027	2060	0.68	0.00	0.00	0.32
Fuel Cell EV	1960	2060	0.00	0.00	0.80	0.20

Based on peer-review comments on the above analysis for diesel trucks in 2017, we reevaluated our assumptions about APU and hotelling battery penetration rates. The diesel APU usage assumptions for model year 2010 through 2020 in Table 11-2 are qualitatively consistent with two fleet surveys: NACFE 2018 Annual Fleet Fuel Study[66] [n] and Shoettle et al. (2016).[67] [o] On the other hand, both surveys suggested a higher (non-zero) penetration of hotelling battery units in 2010-2020, as well as projecting a higher penetration in future years. However, given concerns about the representativeness of the surveys, we have decided to retain the current assumption regarding fleet-average APU and battery usage in MOVES4 and recognize that the current hotelling battery usage may be a low estimate. Future MOVES updates could utilize instrumented truck and APU measurements to replace these projections.

11.2. National Default Hotelling Rate

To estimate hotelling activity, MOVES uses a hotelling rate. As shown in Equation 11-1, the default 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).

$$Hotelling\ Rate = \frac{Hotelling\ Hours}{Total\ Restricted\ Miles\ Traveled} \qquad \textbf{Equation 11-1}$$

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 MOVES.

[n] NACFE (2018) reported increasing diesel APU and and battery penetration rates for model year 2010-2016 vehicles. The diesel APU values span the MOVES values for model year 2010-2020. The NACFE 2013 Annual Fleet Fuel Study reports survey values from 20 participating fleets, which are likely earlier adopters and may not be representative of the entire fleet.

[o] Shoettle et al. reports that 38.7 percent of fleets use auxiliary power sets and 30.1 percent use battery packs based on a survey of 96 heavy-duty fleet managers. However, information regarding the percentage of vehicles within a fleet is not provided.

The hotelling rate is used to estimate hotelling in different calendar years and to spatially allocate hotelling to counties across the US. The hotelling rate is based on travel on rural and urban restricted access roads (freeways), because this is where long-haul trucks are most frequently operated and most hotelling occurs at locations near those roadways (i.e., rest stops or truck stops).

For MOVES3 and later versions of MOVES, the national default hotelling rate is based on data collected and analyzed by the National Renewable Energy Laboratory (NREL) Fleet DNA[61] as discussed in Section 10.3.1. For the hotelling analysis, NREL analyzed data collected from 131 long-haul combination diesel trucks operating in the United States. The 131 trucks had broad coverage across the United States, with home bases in 32 states.

Because the NREL data did not include information on all operating modes of hotelling activity, we back-calculated the hours of hotelling from the data on extended idling using Equation 11-2.

First, we estimated the extended idle hours per mile from the NREL data. Vehicles were assumed to be extended idling (hotelling with the main engine running in idle), if the vehicle speed = 0 and the duration of the idling was > 1 hour. For the 131 long-haul trucks, the trucks averaged 3.45 extended idle hours for every 1,000 miles driven. Then, we calculated a ratio of total miles traveled to restricted access miles using the MOVES national default values presented in Table 7-2 (the rural restricted VMT fraction = 0.34 and urban restricted VMT fraction = 0.26). This allows better spatial allocation of hoteling activity to counties with freeways. Finally, we multiply the extended idle hours by the ratio of hotelling hours to the extended idle hours. We did not have information from NREL about use of auxiliary power units from any of the trucks in the Fleet DNA data, so we used the 80 percent extended idling value for pre-2010 model year trucks which assumes no APU usage as presented in Table 11-2.

$$Hotelling\ Rate =$$

$$= \left(\frac{Extended\ Idle\ Hours}{Total\ Miles\ Traveled}\right)\left(\frac{Total\ Miles\ Traveled}{Restricted\ Access\ Miles\ Traveled}\right)\left(\frac{Hotelling\ Hours}{Extended\ Idle\ Hours}\right)$$

$$= \left(\frac{3.45}{1000}\right)\left(\frac{1}{0.34 + 0.26}\right)\left(\frac{1}{0.8}\right)$$

Equation 11-2

$$= \left(\frac{3.45}{1000}\right)\left(\frac{1}{0.6}\right)\left(\frac{1}{0.8}\right)$$

$$= \frac{7.2\ Hotelling\ Hours}{1000\ Restriced\ Access\ Miles\ Traveled}$$

Figure 11-1 compares the hotelling rate in MOVES3 derived from NREL Fleet DNA, with the default value used in MOVES2014 for the 2014 NEI version 2[68] and two other studies. Lutsey et al.[69] presented data from a nationwide truck survey[p] and NCHRP 08-101[70] conducted an analysis of an instrumented truck dataset with 300 trucks.[q] The hotelling rate was unchanged between MOVES3 and MOVES4.

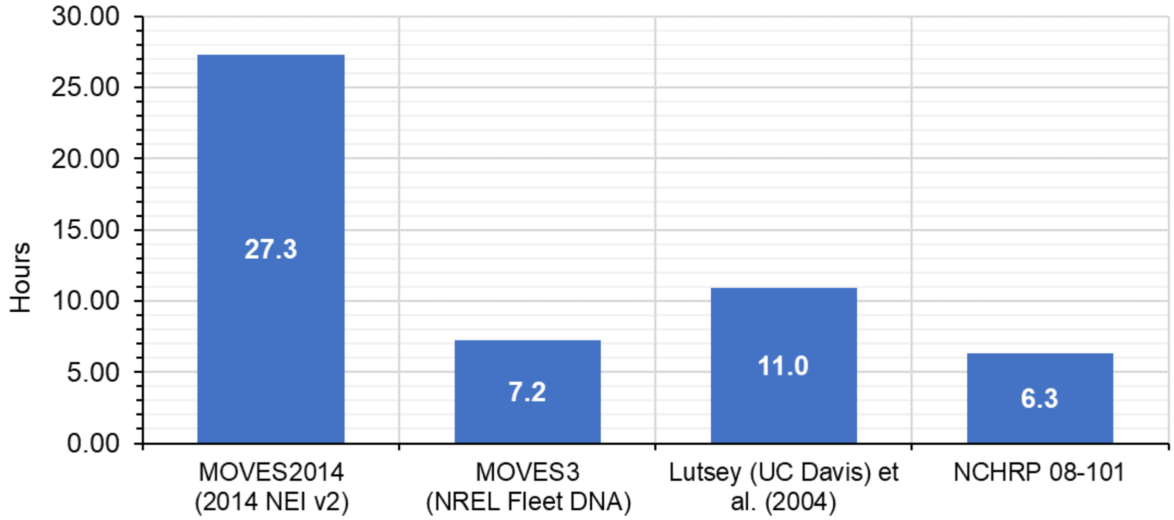

Figure 11-1. Hotelling hours per 1000 miles driven on freeways compared across different datasets.

In MOVES, the national rate of hotelling hours per mile of restricted access roadway VMT is stored in the HotellingCalendarYear table for each calendar year. 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. In MOVES, the national rate of hotelling hours per mile of restricted access roadway VMT is stored in the HotellingCalendarYear table for each calendar year. 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 other users 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.

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[p] Lutsey reported average idling hours and driving hours per day. Using default national hours driving and restricted access miles driven reported in Table 11-1 of the MOVES2014 Population and Activity Report, we derived an estimate of extended idle hours per restricted access miles. We also used the ratio of hotelling hours to extended idle hours as was done in Equation 11-2.

[q] Equation 11-2 was also used to calculate the hotelling rates from the data reported from NCHRP 08-101. The definition of hotelling for the NCHRP 08-101 data was idling between 8 and 16 hours of duration, which is different than used by the NREL analysis.

12.Engine Start Activity

Immediately following the start of an internal combustion engine, fuel is inefficiently burned due to the relatively cool temperature of the engine and the need to provide excess fuel to 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. 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) as discussed in the light-duty[10] and heavy-duty[11] emission rate reports. 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.

MOVES uses the following set of tables in the default database to determine the default number of starts, soak times and their temporal distributions:

- StartsPerDayPerVehicle
- StartsAgeAdjustment
- StartsHourFraction
- StartsMonthAdjust
- StartsOpModeDistribution

The StartsPerDayPerVehicle table contains a factor (startsPerDayPerVehicle) which, when multiplied by the total number of vehicles of a given source type calculates the number of starts in a day. The startsPerDayPerVehicle factor represents the average starts per day for each sourcetype and day type (weekday/weekend)

Starting with MOVES3, starts vary by source type, day type and vehicle age to account for the lower average start activity that is expected to occur as vehicles age (see Section 12.1.1 for light-duty and Section 12.2.3 for heavy-duty). Figure 12-1 shows the calculation of starts per day per vehicle by vehicle age for light-duty vehicles. Note that the age 0 starts per day are greater than the fleet-average starts per day, and the starts at age 30 are lower than the fleet-average starts per day.

MOVES accounts for the effect of age using the ageAjustment factors stored in the StartsAgeAdjustment table. This table stores the number of starts by vehicle age within each sourcetype, relative to the number of starts at age 0. All of the ageAdjustment factors in MOVES are based on the mileage accumulation rates (discussed in Section 6.2). By using the mileage accumulation rates to derive the start ageAdjustement factors, we are assuming that the starts per mile is constant over the life of the vehicle. In other words, as vehicles travel fewer miles per day as they age, they similarly conduct fewer starts. The ageAdjustment factors for each source type are set equal to one at age zero, and decrease from one as the age increases, reflecting relatively lower starts as the vehicles age. MOVES does not use the absolute values in this table, but scales the ageAdjustment factors in conjunction with the source type age distributions of the MOVES run (Section 6.1) such that the average starts reported in in the StartsPerDayPerVehicle table is conserved. Using this method, MOVES estimates starts by vehicle age without having the default or input age distribution impact the estimated number of starts. However, the StartsPerDayPerVehicle factor value stored in the startsPerDayPerVehicle is intended to be representative of the fleet-average starts, and we consider the age distributions when estimating these fleet-average starts as discussed in the following subsections.

The StartsMonthAdjust table contains the monthAdjust factor which adjusts the starts per day to reflect monthly variation in the number of engine starts (see Section 12.1.2.2 for light-duty and Section 12.2.3.2 for heavy-duty). The monthAdjustment is used as a raw multiplicative factor, with values greater and less than one. Unlike the startsageadjustment table, MOVES does not scale the monthAdjustment factors to conserve starts for each model year. The average monthAdjust values across all 12 months is one, so the annual number of starts estimated by MOVES is consistent with the values in the startsPerDayPerVehicle table. However, the numbers of starts for a given month vary from the values in the startsPerDayPerVehicle table according to the monthAdjustment factors.

The StartsHourFraction distributes the starts in a day to the hours of the day. The allocationFraction value varies by source type, day type and hour of the day (see Section 12.1.2.1 for light-duty and Section 12.2.3.1 for heavy-duty).

The StartsOpModeDistribution table contains the distribution of engine start soak times for each source type, age, day type and hour of the day (see Section 12.1.3 for light-duty and Section 12.2.4 for heavy-duty).

MOVES allows users to update the starts table if they have more representative data for their purposes. MOVES provides additional start input tables and flexibilities for entering starts as described in the Technical Guidance[2].

The data inputs for motorcycles and motorhomes for the four start tables are discussed in Section 12.3.

As discussed in Section 13.4, the MOVES2014 SampleVehicleTrip table is still used in MOVES4 for estimating evaporative emission activity. Thus, the number and time of starts used to estimate start emissions is inconsistent with the trips and parking time used for evaporative emissions in MOVES3 and later versions. While we think the impact of these inconsistencies is small, we plan to address this conflict in future versions of MOVES.

12.1. Light-Duty Start Activity

For MOVES4, light-duty start activity are calculated from the same sample of vehicles from the Verizon Telematics data discussed in Section 10.2.1.

12.1.1. Starts Per Day Per Vehicle

The vehicle starts input format was substantially updated for MOVES3 to better allow inputs based on the summary activity from large telematic datasets. In addition, the start inputs have been updated to account for differences in start activity by month, day type, hour of day, and vehicle age. To calculate the national average light-duty starts per day for MOVES, we calculated the average starts from a set of telematics data obtained from Verizon (discussed in Section 10.2.1) and adjusted this average to account for vehicle age. There were no additional updates for MOVES4.

Table 12-1 below shows the starts per day per vehicle derived from the Verizon telematics dataset for passenger cars (sourceTypeID 21) and passenger trucks (sourceTypeIDs 31) and by weekend days (dayID 2) and weekdays (dayID 5). We calculated a weighted-average starts per day per vehicle from the Verizon dataset using the regional populations from each state sampled (California New Jersey, Illinois, Georgia and Colorado) as documented in Table 10-2. The values shown for passenger trucks (sourceTypeID 31) are also being used for light commercial trucks (sourceTypeID 32).

Next, we calculated the average age of the vehicles in the Verizon dataset, using the model year for each vehicle stored in the the vehicle metadata file from all the vehicles in the Verizon dataset. We assumed the base year = 2015.6 (5 months of the Verizon dataset were in 2015 and 6 months occurred in 2016). We calculated the average vehicle age for each vehicle using Equation 12-1.

$$Age = \ Base\ Year\ (2015.6) - Average\ Model\ Year \qquad \textbf{Equation 12-1}$$

We then calculated the average age for each state included in the dataset and then calculated a Verizon weighted-average shown in Table 12-1 using the regional populations used previously (Table 10-2)

Table 12-1 National Average Starts per Day per Vehicle for Light-duty Vehicles based on Verizon Telematics data per Vehicle

Source Type	Source-TypeID	Verizon weighted average age (years)	MOVES3 CY 2016 average age (years)	Day of the Week	Verizon weighted average starts per vehicle per day	Calculated national average starts per day per vehicle
Passenger Cars	21	7.3	9.55	Weekend	3.36	3.13
				Weekday	3.96	3.68
Passenger Trucks	31	8.54	10.1	Weekend	3.49	3.32
				Weekday	4.09	3.89
Light-Commercial Trucks	32	8.54	8.47	Weekend	3.49	3.52
				Weekday	4.09	4.13

Next, we adjusted the starts for each vehicle age. We could not use the Verizon data directly because it did not include a full range of vehicle ages. Instead, we used factors derived from the mileage accumulation rates as discussed in the beginning of Section 12. We scaled the age adjustment factors, such that at the average age (e.g., 7.3 years for passenger cars), the starts per day is equal to the average estimated from Verizon (e.g., 3.96 per day for weekdays for passenger cars). The resulting starts per day by age for light-duty vehicles are presented in Figure 12-1. The starts per day for age 0 are higher than the Verizon weighted average starts per day, while the starts at age 30 are substantially lower.

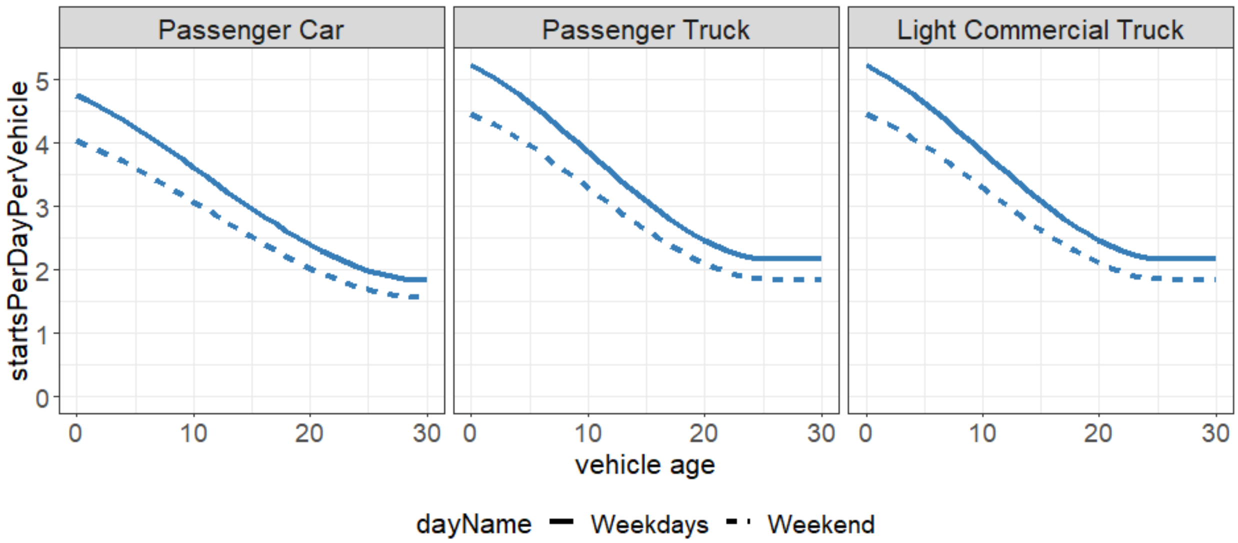


Figure 12-1. Starts per day per vehicle by vehicle age calculated from the Verizon dataset and MOVES ageAdjustment factors

We then used Equation 12-2 to calculate the MOVES age-weighted average starts per vehicle per day using the starts per day per vehicle by age calculated in Figure 12-1 and the 2016 default age distributions in MOVES. The purpose of this calculation is to adjust the average starts per day from the Verizon sample to represent the nation, given that the national age distribution is different than the age distribution of vehicles sampled in the Verizon datasets. As shown in Table 12-1Figure 12-1, the age in MOVES for CY 2016 passenger cars and passenger trucks is older than in the Verizon dataset, while the average age of light commercial trucks is slightly older in MOVES than in the Verizon dataset. We adjusted the average starts using the 2016 default age distribution because the Verizon dataset was conducted in 2015-2016.

$$National\ Average\ Starts\ per\ Vehicle\ per\ Day = \sum_{age=0}^{30} (Starts\ per\ Day\ Per\ Vehicle)_{age} \times ageFraction_{age}$$

Equation 12-2

Table 12-2 demonstrates the calculation of Equation 12-2 for passenger cars on weekdays. Table 12-1 shows the calculated national average starts per vehicle per day which are used in MOVES.

The national average starts per vehicle day in 12-1 are used to estimate the average starts for these source types and day types for all calendar years in MOVES.

Table 12-2. Calculation of the National Average Starts per Vehicle per Day for Passenger Cars (SourceType21) on Weekdays (DayID 5)

Vehicle age (ageID)	Starts per Day Per Vehicle by Age	CY 2016 Age Distribution (ageFraction)	Starts per Day per Vehicle × ageFraction
0	4.76	0.061	0.29
1	4.67	0.066	0.31
2	4.57	0.067	0.31
3	4.47	0.062	0.28
4	4.36	0.056	0.24
5	4.24	0.043	0.18
6	4.12	0.044	0.18
7	4.00	0.040	0.16
8	3.87	0.050	0.19
9	3.74	0.055	0.21
10	3.61	0.051	0.19
11	3.48	0.050	0.17
12	3.35	0.046	0.15
13	3.22	0.045	0.15
14	3.09	0.040	0.12
15	2.97	0.034	0.10
16	2.84	0.033	0.09
17	2.72	0.025	0.07
18	2.61	0.021	0.05
19	2.50	0.017	0.04
20	2.39	0.013	0.03
21	2.30	0.012	0.03
22	2.21	0.009	0.02
23	2.12	0.007	0.01
24	2.05	0.006	0.01
25	1.99	0.005	0.01
26	1.93	0.004	0.01
27	1.89	0.003	0.01
28	1.86	0.003	0.00
29	1.84	0.002	0.00
30	1.84	0.030	0.05
National Age-Weighted Average Starts per Vehicle per Day =			3.68

12.1.2. Temporal Distributions
There were no updates to default temporal distibutions in MOVES4.

12.1.2.1. Hourly Distribution

The number of starts varies by hour of day. National values for the distribution of starts per day by hour for passenger cars and light-duty trucks were calculated from the five-state Verizon sample data described above in Section 10.2.1. The resulting national defaults for start distribution in MOVES3 and later are illustrated in Figure 12-2. The start fraction values for hourIDs 1 through 24 sum to 1.0 for a given sourceTypeID and dayID combination. The start distribution curve in MOVES3 is much smoother than the start distribution based on the SampleVehicleTrip table in MOVES2014 owing to the larger sample size of the Verizon data. However, the overall trends are similar.

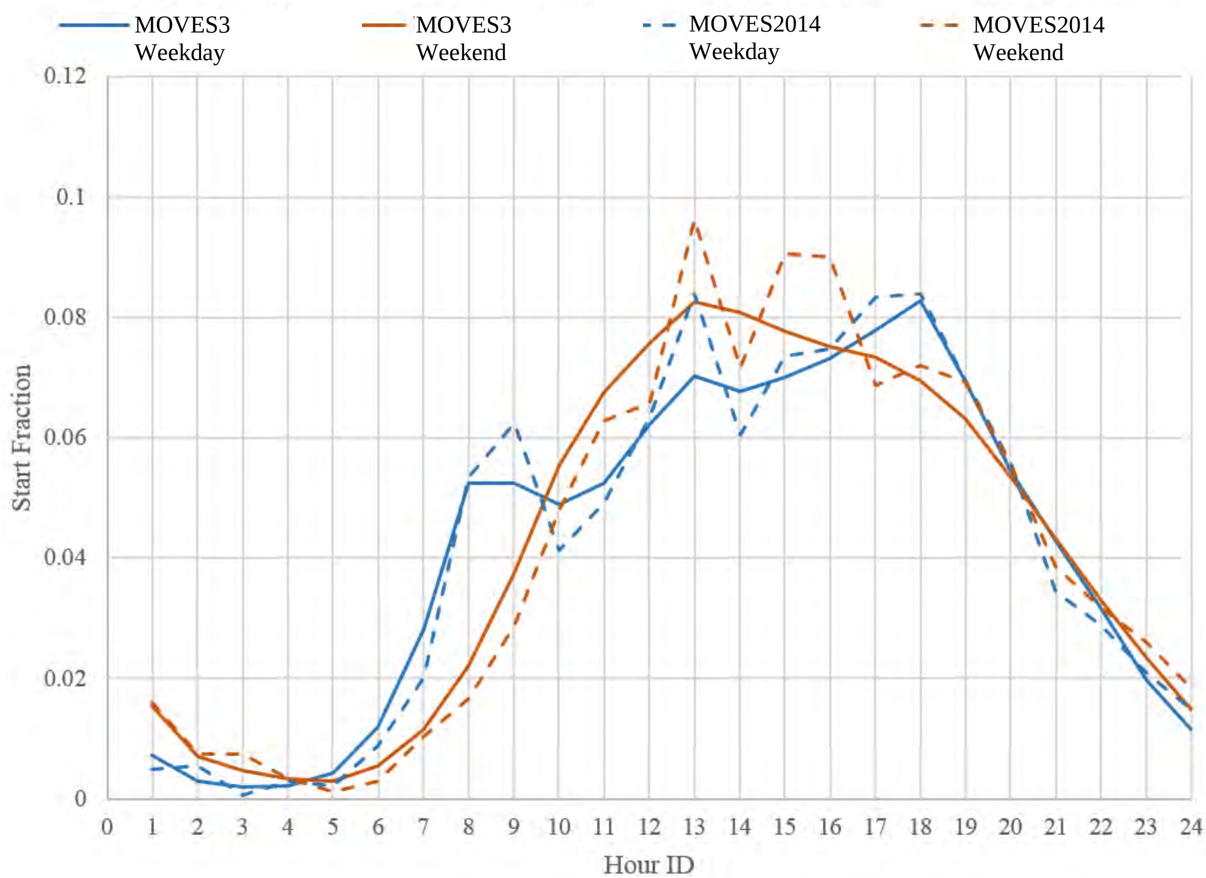


Figure 12-2 Start distribution for source type 21: MOVES3 derived from Verizon data vs. MOVES2014

12.1.2.2. Monthly Distribution
For MOVES, we assume that the starts/mile is the same across months. We use the same monthly distribution for starts in the MonthAdjust table as for VMT in the MonthVMTFraction

table discussed in Section 13.1. Light-duty vehicles and all other source types (except motorcycles) follow the same monthly variation, with slightly elevated starts during the summer months, and corresponding decrease in starts in the winter.

12.1.3. Start Soak Distributions

As discussed in the beginning of Section 12, soak times are binned into different operating modes, shown in Table 12-3. The fraction of starts assigned to each soak bin is the "soak distribution." The light-duty soak distributions derived from Verizon differ by source type, day type and hour of the day.

The engine soak time distributions for all source types are available in the OpModeDistribution table of the default database (see Section 10.2) 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 MOVES national default soak distribution for a weekday for passenger cars (sourceTypeID 21).

Table 12-3 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

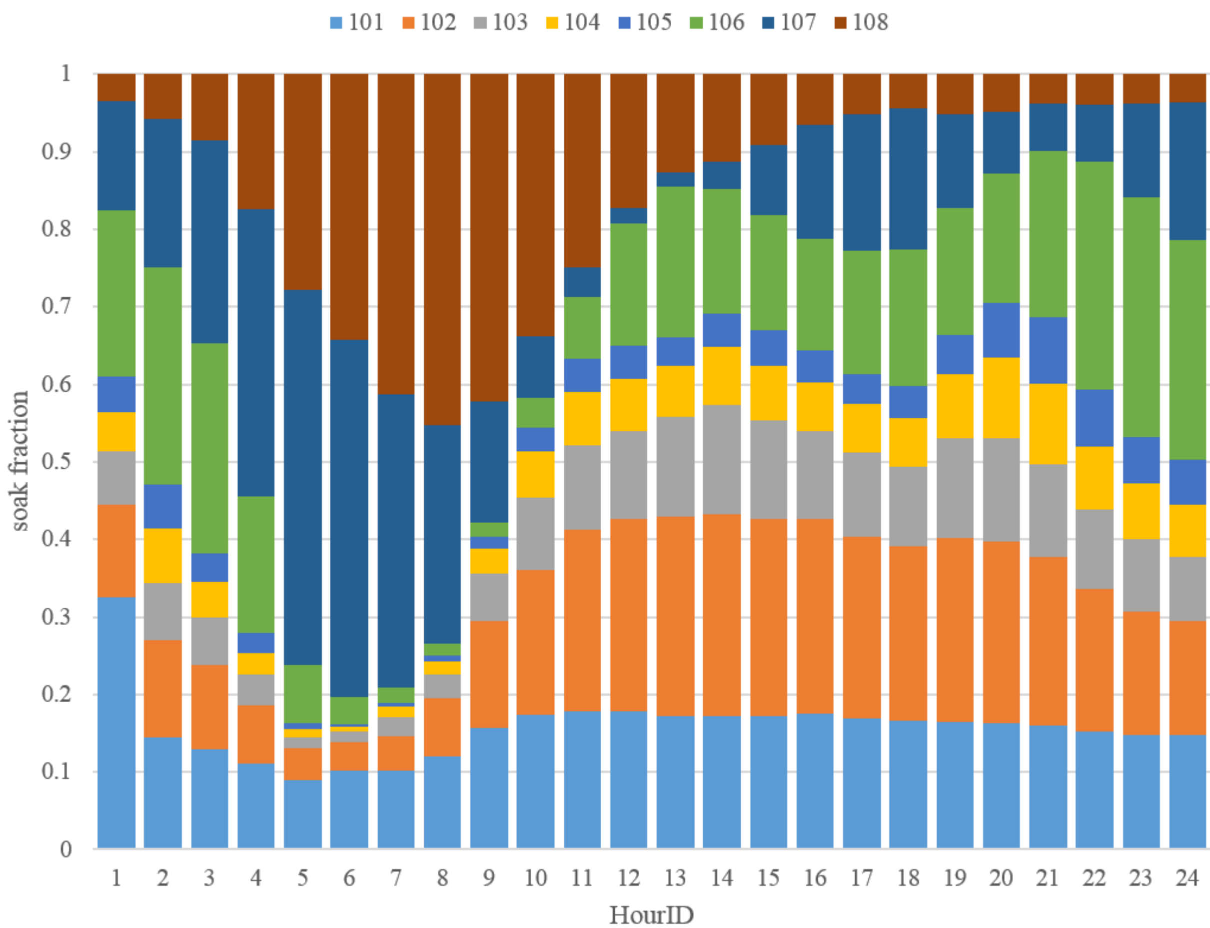


Figure 12-3 MOVES national average engine soak distribution for source type 21 and weekday

MOVES has the capability to model different soak distributions by vehicle age, but we are currently using the same soak distribution across all vehicle ages. In general, as vehicles age, we would expect less vehicle starts on average and a soak distribution to shift towards longer soak times. Access to a large data covering a wider range of ages would help us better quantify this.

12.2. Heavy-Duty Start Activity

Like light-duty vehicles, starts from heavy-duty vehicles can be an important contributor to emission inventories (e.g., THC and NOx). Additionally, heavy-duty diesel aftertreatment technologies such as selective catalytic reduction (SCR) systems are also not fully active at controlling NOx emissions below the catalyst light-off temperature.

Compared to light-duty vehicles, less data are available on heavy-duty vehicle start activity and there are more subgroups of vehicles with potentially unique activity patterns. For example, delivery vehicles have different start and soak patterns than long-haul trucks. For MOVES3 and later, data that covers a wider range of heavy-duty vocations was available. The engine start analysis below was applied to the same NREL Fleet DNA dataset used in the off-network idle analysis discussed in Section 10. We are aware of the additional heavy-duty activity data collected by CE-CERT (also described in Section 10) and we expect to incorporate the data in a future version of MOVES.

12.2.1. Heavy-Duty Engine Start Activity Data Processing

Starts were identified in the data using the data channel for engine speed, measured in revolutions per minute (RPM). All the instances when the engine speed transitioned from zero to greater than zero were considered new starts. If the data logger was installed but did not record any activity, the start fraction is zero; however, if the data logger was not installed on a specific day type, those values were denoted as "nan" (not-a-number) and were removed from the analysis. The sum of the hourly fractions across all hours of the day is one.

The number of starts per day was calculated on a per vehicle basis and averaged equally across all vehicles as shown in Equation 12-3. Thus, vehicles that start frequently or infrequently are equally weighted in the average starts per day.

Similar to the off-network idle discussion in Section 10, we applied a sum-over-sum approach to our hourly start fractions. Using Equation 12-4, a start fraction for each hour was calculated by dividing the daily average starts-per-hour by the average starts-per-day for each combination of sourceType and dayID. This sum-over-sum approach normalizes the recorded start activity by the amount of time each vehicle was instrumented and weights the average start fraction towards the vehicles with the most daily-average starts.[r]

$$Starts\ Per\ Day_{s,d} = \frac{\sum \left({starts_i}/{days_i} \right)}{n}$$

Equation 12-3

i = Vehicle ID within a given sourceType, s
$days_i$ = days within a given dayID, d, when $vehicle_i$ is instrumented
n = number of VehicleIDs withing a given sourceType, s

$$Start\ fraction_{h,s,d} = \frac{\sum \left({starts_{h,i}}/{days_i} \right)}{\sum \left({starts_i}/{days_i} \right)}$$

Equation 12-4

h = hour of the day
i = Vehicle ID within a given sourceType, s

[r] We evaluated several approaches for calculating average start and soak fractions using the Fleet DNA data. The equations presented in this section are equivalent to the equations labeled "Method 3 'normalized sum over sum'" in Appendix I. Appendix I includes an overview and a comparison of the calculation approaches.

$days_i$ = days within a given dayID, d, when $vehicle_i$ is instrumented

Vehicle soak is defined as the time difference between when an engine stops and the next time the engine starts, as shown in Equation 12-5. The engine stop is defined as the time when engine speed transitions from greater than zero to zero and engine start is defined as the time when engine speed transitions from zero to greater than zero.

$$soak\ time = engine\ stop\ time - engine\ start\ time$$ **Equation 12-5**

Every start was assigned a soak opModeID based on the definitions in Table 12-3.[s] We then calculated the average soak fraction, using a normalized sum-over-sum approach like we did for the start fraction.[r] For each vehicle, hour and daytype, an average number of starts by soak length was calculated by summing the number of starts matching each soak opModeID for each hourID and dayID and dividing by the number of unique days of measurement for that vehicle. The hourly soak fraction distribution for each opModeID, sourceType and dayID was then calculated using Equation 12-6. The sum of the eight opModeID soak fractions will equal 1.0 for each combination of dayID, hourID and sourceTypeID.

$$Soak\ fraction_{h,o,s,d} = \frac{\sum \left({starts_{h,i,o}}/{days_i} \right)}{\sum \left({starts_{h,i}}/{days_i} \right)}$$

Equation 12-6

h = hour of the day
i = Vehicle ID within a given sourceType, s
o = operating mode/soak length
$days_i$ = days within a given dayID, d, $vehicle_i$ is instrumented

12.2.2. Starts Per Vehicle Per Day

[s] The first start identified for each vehicle was not considered when calculating soak time due to lack of a previous recorded stop time.

As seen in Table 10-3, several heavy-duty source types were not available in the Fleet DNA database at the time of this analysis. In the future, we hope to update the analysis using both Fleet DNA and CE-CERT datasets. In the interim, we assumed the start behavior of the missing vehicles closely matched others. We chose to use the transit bus (sourceTypeID 42) to represent other bus (sourceTypeID 41), used the single-unit short-haul data from the weekend (sourceTypeID 52) to represent both the weekday and weekend data of the single-unit long-haul trucks (sourceTypeID 53) and continued to use the same starts per day for motorhomes (sourceTypeID 54) as in MOVES2014 (See Table 13-8).

None of the school buses (sourceTypeID 43) instrumented in the Fleet DNA dataset operated on the weekend, so there is no data for that dayID. In Section 10, we applied the weekday school bus off-network idle data for the weekend data, assuming the idle behavior of buses was similar regardless of day type. We opted to retain the zero starts-per-day value for weekends (dayID 2), assuming the frequency of school bus starts differed between weekends and weekdays.

Figure 12-4 and Figure 12-5 show the starts-per-day values for weekends and weekdays, respectively.

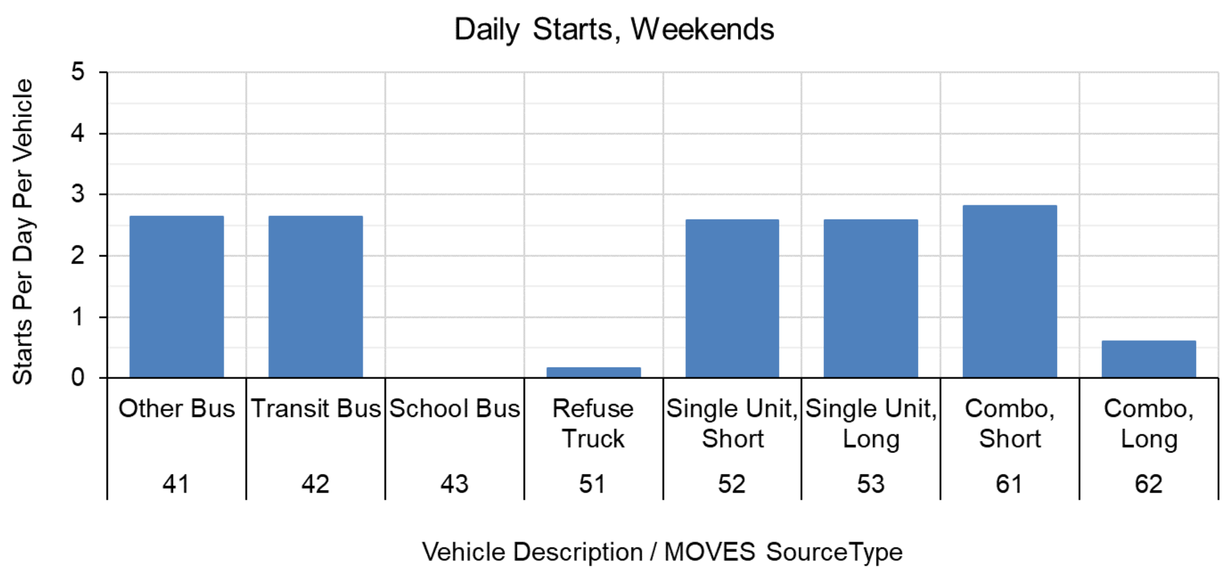


Figure 12-4 Weekend starts per day for heavy-duty source types based on data from NREL's Fleet DNA database

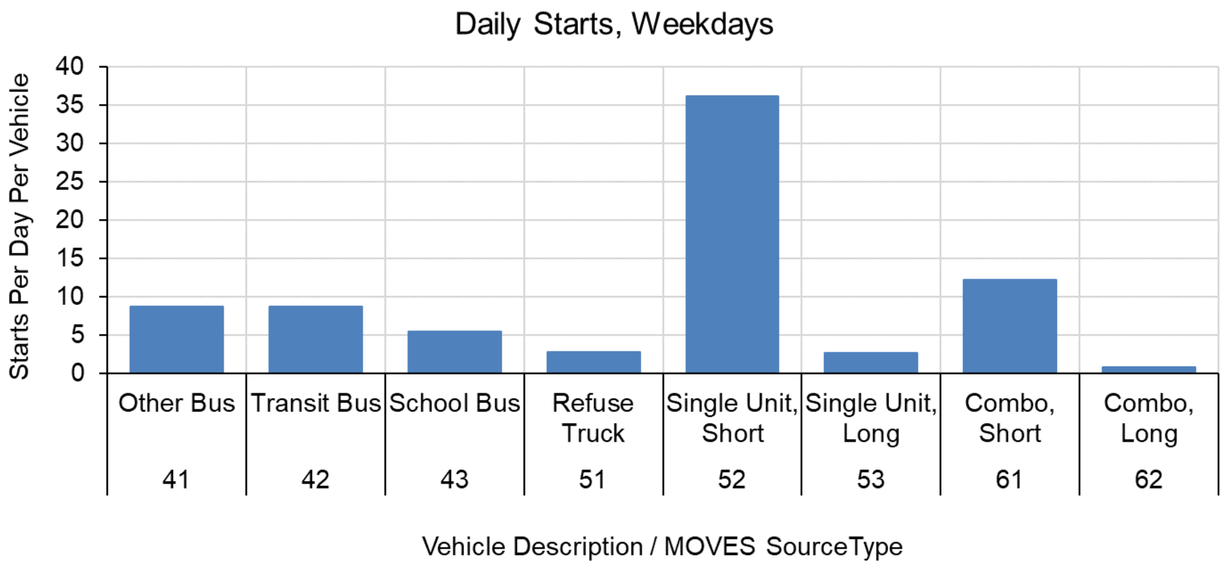


Figure 12-5 Weekday starts per day for heavy-duty source typesbased on data from NREL's Fleet DNA database

As shown in Figure 12-5, the single-unit short-haul trucks (sourceTypeID 52) have significantly more starts on weekdays. To understand this, we evaluated the impact of the vehicles' vocations on their start behavior. Figure 12-6 shows that the parcel delivery vocation contributes many more starts than the other vocations. While we did see differences in starts activity due to vehicle vocation, we did not account for vocation differences when calculating starts for MOVES because we could not identify a means to map the vocations represented in this dataset to a nationally-representative population of vocations. We plan to revisit these estimates in future versions of MOVES.

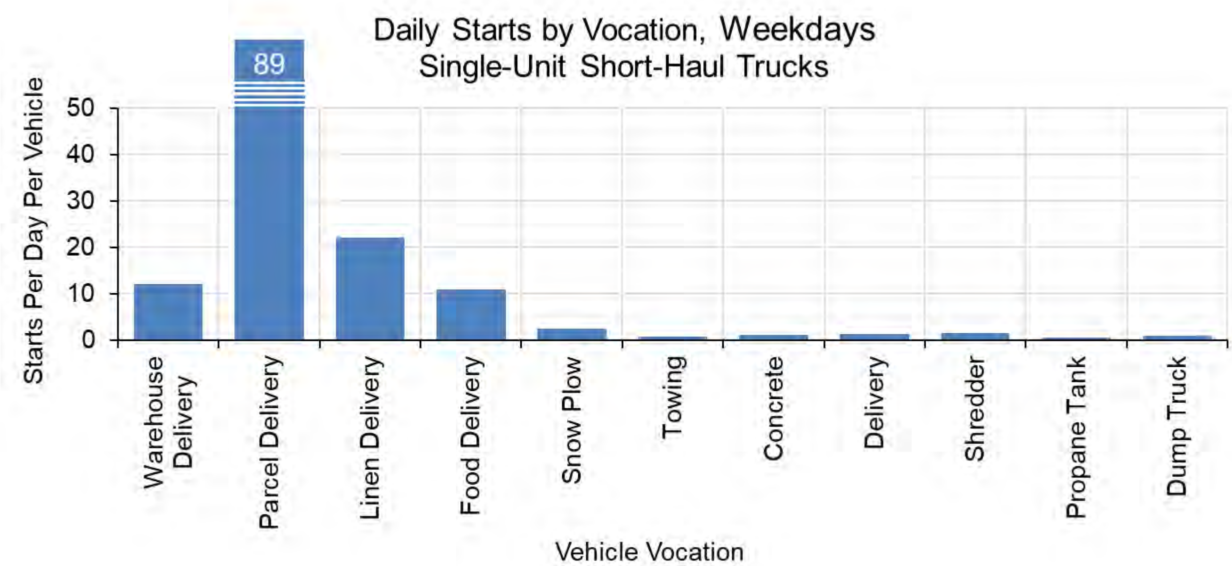


Figure 12-6 Vocation impacts on weekday starts-per-day for heavy-duty, single-unit short-haul vehicles (sourceType 52) based on data from NREL's Fleet DNA database

As discussed in the beginning of Section 12, the startsPerDayPerVehicle factor stored in the MOVES startsPerDayPerVehicle table represents the national average starts per day by sourcetype and day of the week. We developed adjusted the starts measured from Fleet DNA to be consistent with the national average age distribution in MOVES.

First, we adjusted the heavy-duty start values obtained from Fleet DNA using the ageAdjustment factors (derived from the mileage accumulation rates in Section 6.2), by assuming that the Fleet DNA starts are representative of vehicles at age 0. We assumed the Fleet DNA starts are representative of activity at age 0 because:

- Of the vehicles with a recorded age (112 out of 415 vehicles in the Fleet DNA database), most are younger than 3 years of age.
- NREL has informed the US EPA that vehicles chosen to be instrumented in the Fleet DNA database tend to be active vehicles.

Figure 12-7 displays the resulting starts per day per vehicle across all ages for heavy-duty vehicles calculated using these assumptions. Note that the starts per day per vehicle at age 0 are equivalent to the average values reported from the Fleet DNA database, while the starts per day for age 30 source types are significantly lower.

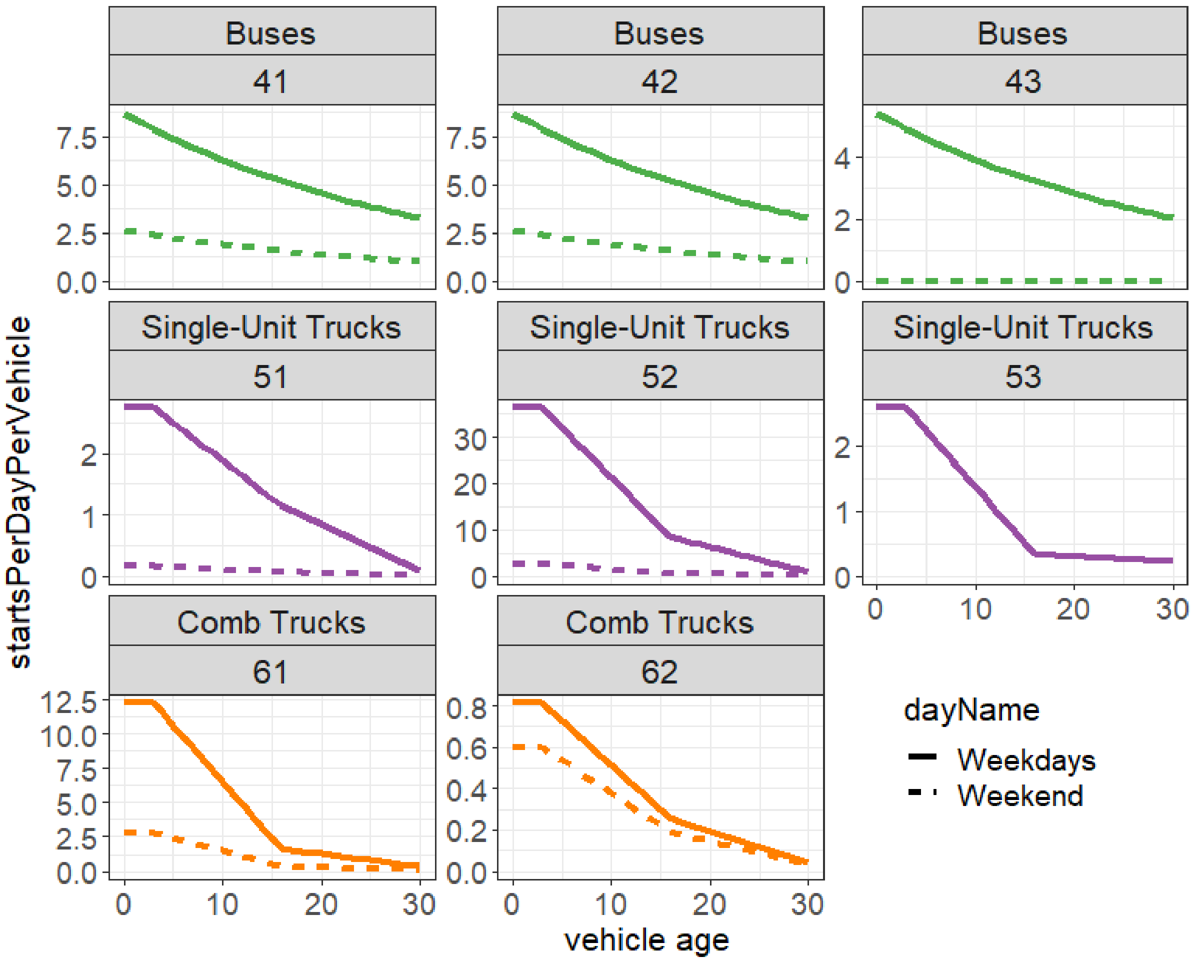


Figure 12-7. Starts per day per vehicle by vehicle age calculated from the Fleet DNA dataset and MOVES ageAdjustment factors

Next, we calculated the national average starts per day for heavy-duty vehicles using Equation 12-2 with the starts per day per vehicle by age in Figure 12-7 and the 2014 heavy-duty default age distributions in MOVES. We used the 2014 age distributions because it was the calendar year with the most vehicle measurements in the FleetDNA dataset; the average age from the MOVES 2014 age distributions are shown in Table 12-4. The resulting national average starts per day per vehicle are also displayed in Table 12-4, which are significantly lower than the average starts per day as measured from the FleetDNA database.

Table 12-4 National Average Starts Per Day Per Vehicle for Heavy-duty Vehicles based on data from NREL's Fleet DNA database

Source Type	SourceTypeID	MOVES3 CY 2014 Average Age (years)	Day of the Week	FleetDNA Starts per day per vehicle	Calculated national average starts per day per vehicle
Other Bus	41	10.4	Weekend	2.64	1.93
			Weekday	8.70	6.38
Transit Bus	42	6.5	Weekend	2.64	2.16
			Weekday	8.70	7.13
School Bus	43	10.3	Weekend	0.00	0.00
			Weekday	5.41	3.98
Refuse Truck	51	11.7	Weekend	0.16	0.10
			Weekday	2.74	1.71
Single Unit Short-haul	52	11.8	Weekend	2.58	1.41
			Weekday	36.26	19.86
Single Unit Long-haul	53	11.8	Weekend	2.58	1.33
			Weekday	2.58	1.33
Combination Short-haul	61	12.0	Weekend	2.82	1.35
			Weekday	12.25	5.87
Combination Long-haul	62	10.5	Weekend	0.60	0.37
			Weekday	0.81	0.51

12.2.3. Temporal Distribution

12.2.3.1. Hourly Distribution

This section describes the temporal distribution of starts (also referred to as the start fractions) for heavy-duty vehicles in MOVES based on data from NREL's Fleet DNA. As seen in Table 10-3, several heavy-duty source types were not available in Fleet DNA at the time of the analysis. We expect data collected by CE-CERT to cover more of the source types and dayIDs and we hope to update the analysis using both Fleet DNA and CE-CERT datasets. In the interim, we assumed the start behavior of the missing vehicles closely matched others, as described when the figures are presented below.

The Fleet DNA dataset did not conain any information from buses meeting the MOVES definition of "other buses." We assumed the start distributions from transit bus (sourceTypeID 42) represented other buses (sourceTypeIDs 41) for both weekends and weekdays. Figure 12-8 shows the resulting starts distribution for these two bus types.

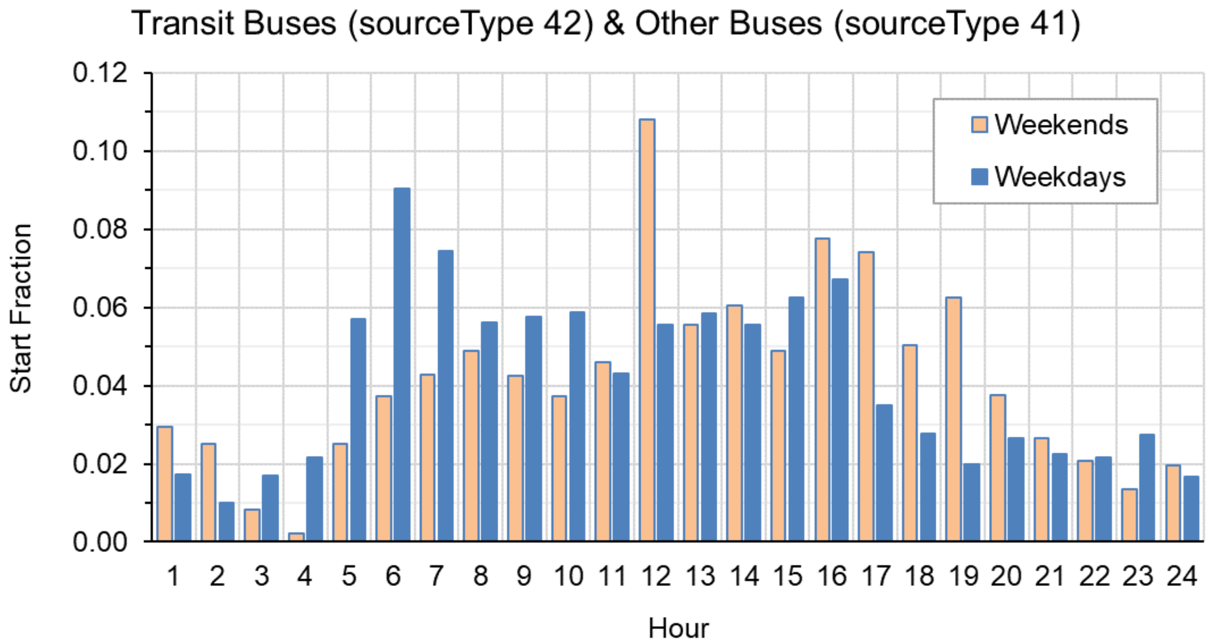


Figure 12-8 Start fraction temporal distribution for transit buses (sourceType 42) and other buses (sourceType 41) based on data from NREL's Fleet DNA database

The school buses and refuse vehicles in the Fleet DNA dataset did not operate during certain hours of the day. To avoid tables with zero values for those hours, we averaged adjacent blocks of time, so those zeros were replaced with very small, nonzero values. The school buses in this dataset did not operate from the hours of 8:00 PM to 6:00 AM on weekdays. We replaced the zeros in those hours with 0.0008, which was the average start fraction from 6:00 PM through 6:00 AM, as depicted by the red boxes in Figure 12-9. The refuse trucks did not operate on weekends from 7:00 PM to 4:00 AM and no data were collected in the hour between 6:00 AM and 7:00 AM. The missing night hours' data were replaced with 0.01 (the average of the data for 7:00 PM to 4:00 AM) and the missing 6:00 AM data point was replaced with 0.07 (the average of the 4:00 AM to 7:00 PM data). For each case, we renormalized the results once the zeros were replaced, so the start fractions across all 24 hours of the day continued to sum to 1.0.

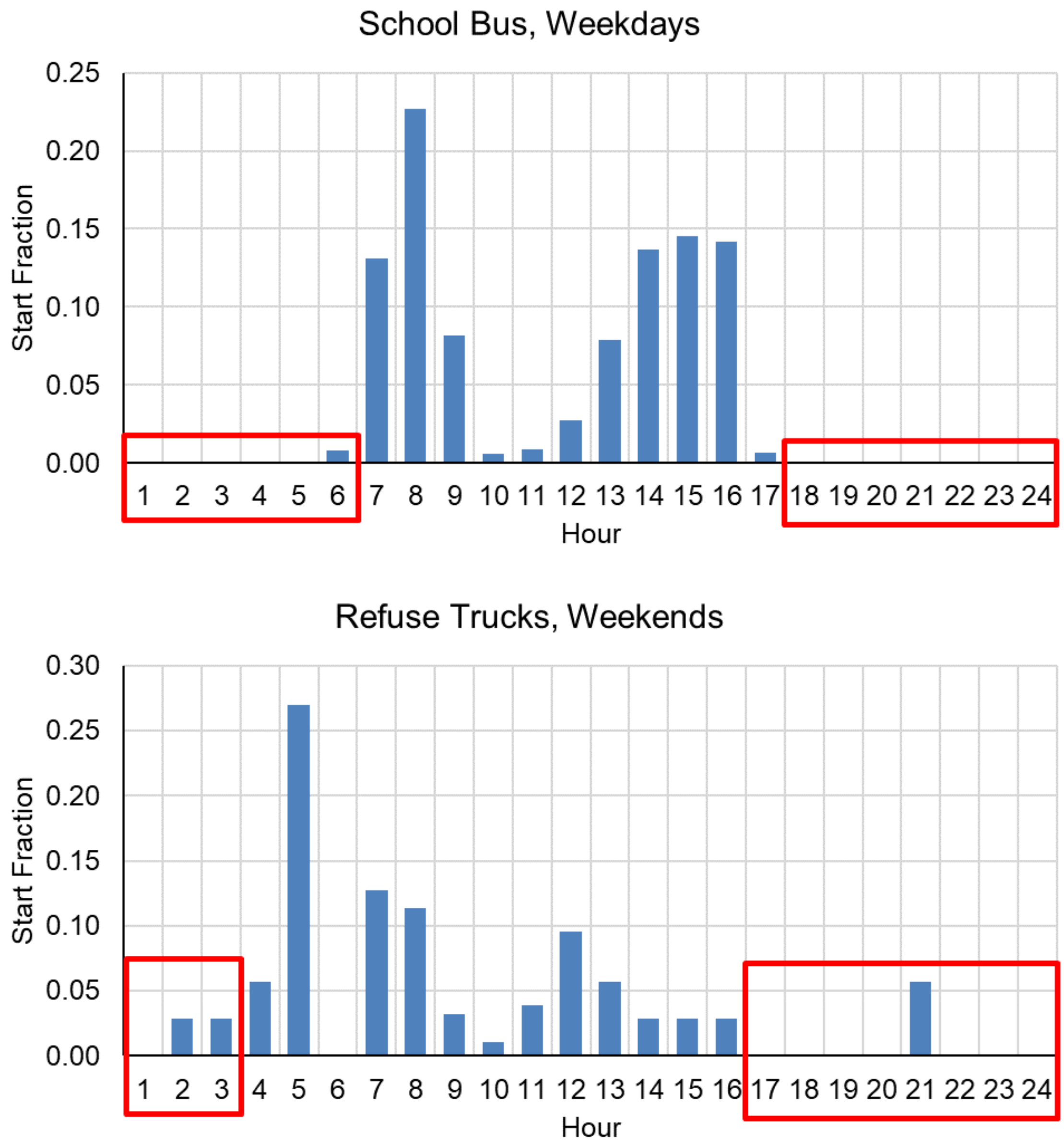


Figure 12-9 Approach for renormalizing the start fraction results to avoid zeros in hours when no data were collected. The zero-value start fraction in the red boxes were replaced with the average start fractions from the range of hours in the red boxes. For refuse trucks, the 6:00 AM missing datapoint was replaced with an average of the hours not outlined in red boxes.

Figure 12-10 and Figure 12-11 show the resulting start fractions by hour for school buses and refuse trucks, respectively. Note that, in MOVES, school buses (sourceTypeID 43) have zero starts per day on weekends, and none of the school buses instrumented in the Fleet DNA dataset operated on the weekend, so we applied the start fractions from the weekday school bus data to weekends.

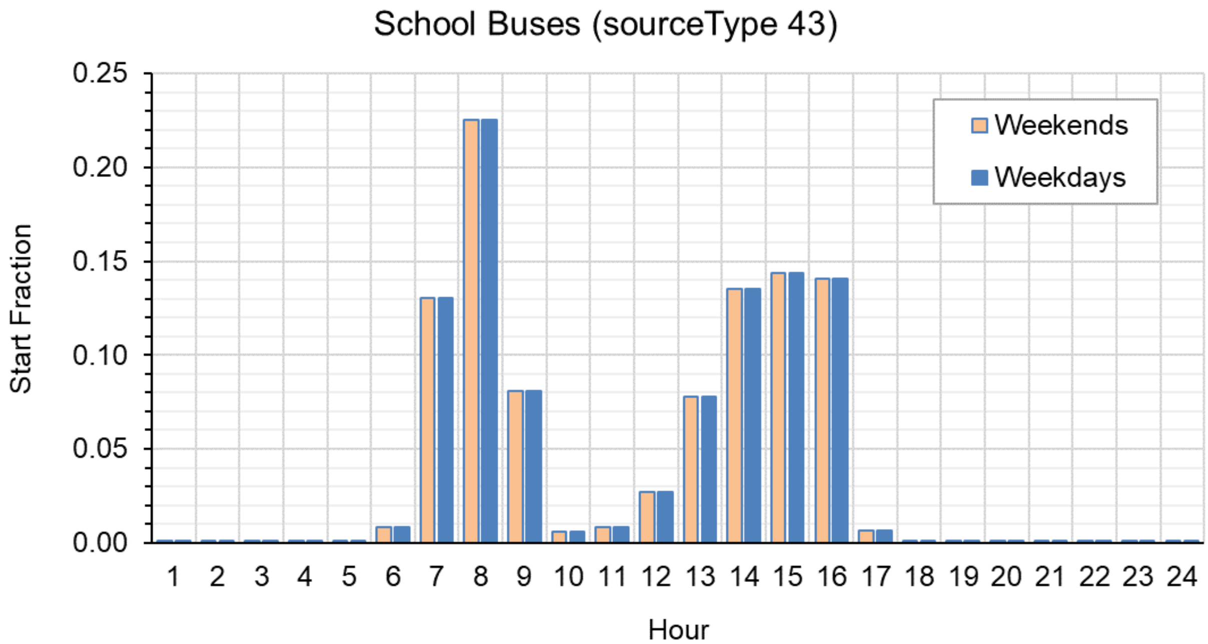


Figure 12-10 Start fractions by hour for school buses (sourceType 43) based on data from NREL's Fleet DNA database

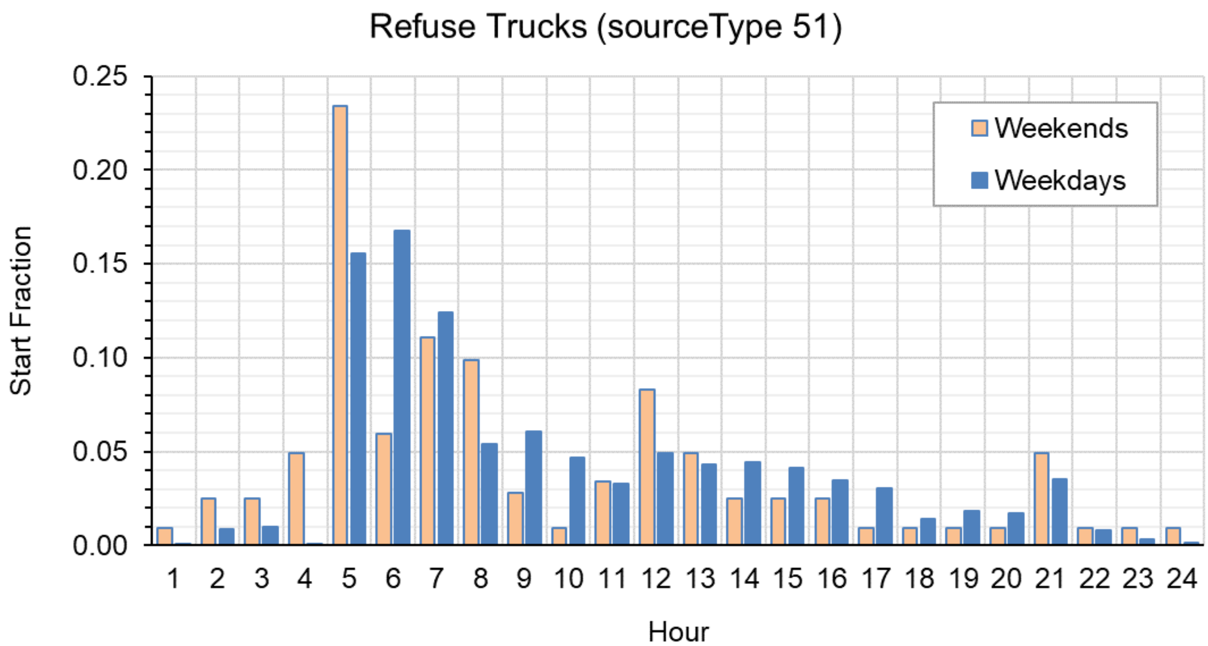


Figure 12-11 Start fractions by hour for refuse trucks (sourceType 51) based on data from NREL's Fleet DNA database

The Fleet DNA dataset did not contain any single-unit long-haul trucks (sourceType 53) so we assumed their start distribution was similar to the single-unit short-haul trucks (sourceType 52).

Figure 12-12 shows the start distribution applied to both single-unit truck types for weekends and weekdays.

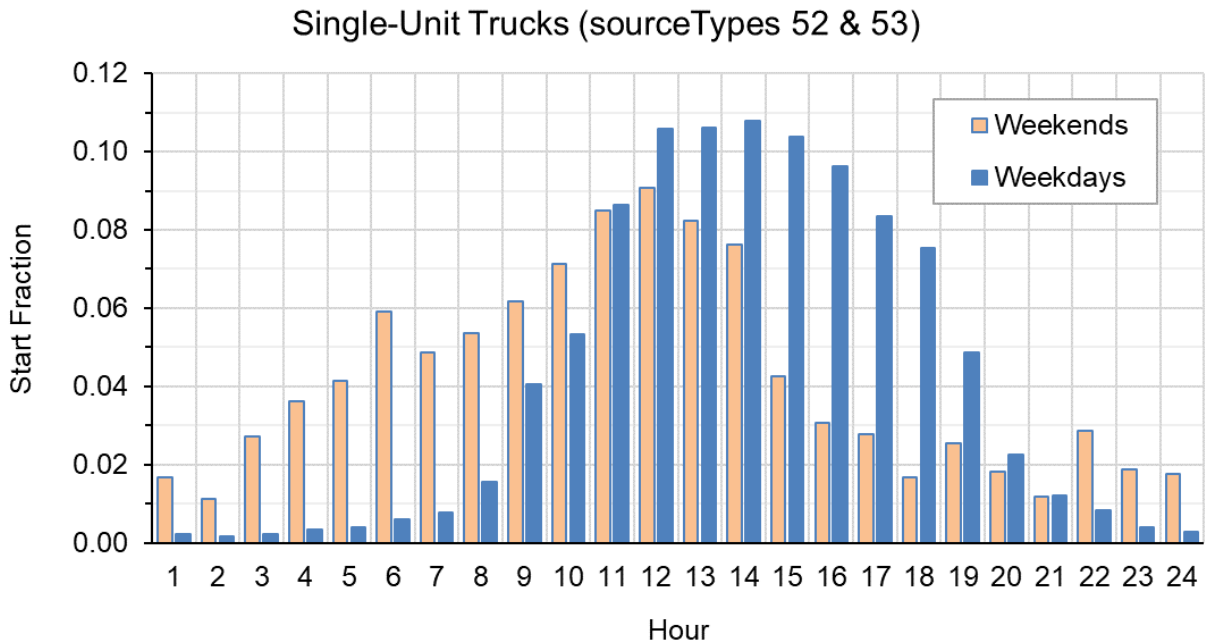


Figure 12-12 Start fraction by hour for single-unit short-haul trucks (sourceType 52) and single-unit long-haul trucks (sourceType 53) based on data from NREL's Fleet DNA database

Additional consideration was given before using the FleetDNA data to populate the hourly fraction tables. The Fleet DNA dataset contained many combination long-haul trucks (sourceType 62) and NREL staff are confident that the average idle data described in Section 10 and average starts-per-day data described earlier in this section represent the activity of combination long-haul trucks. However, NREL believes there was a time zone-related logging error when the data were reported to NREL. Most of the data from the 131 combination long-haul trucks in the Fleet DNA dataset were collected by an industry partner and NREL was unable to accurately confirm which time zone the activity was recorded in. The data consistently showed that the trucks operated more at night with hotelling during the day, which conflicted with other data sources as discussed in Section 13.5. Figure 12-13 shows the original Fleet DNA data for long-haul combination trucks that was not applied in MOVES due to the possible time misalignment. Instead, we assumed the start distribution from short-haul combination trucks was a better representation. Figure 12-14 shows the starts distribution that was applied in MOVES for both short- (sourceType 61) and long-haul combination trucks (sourceType 62).

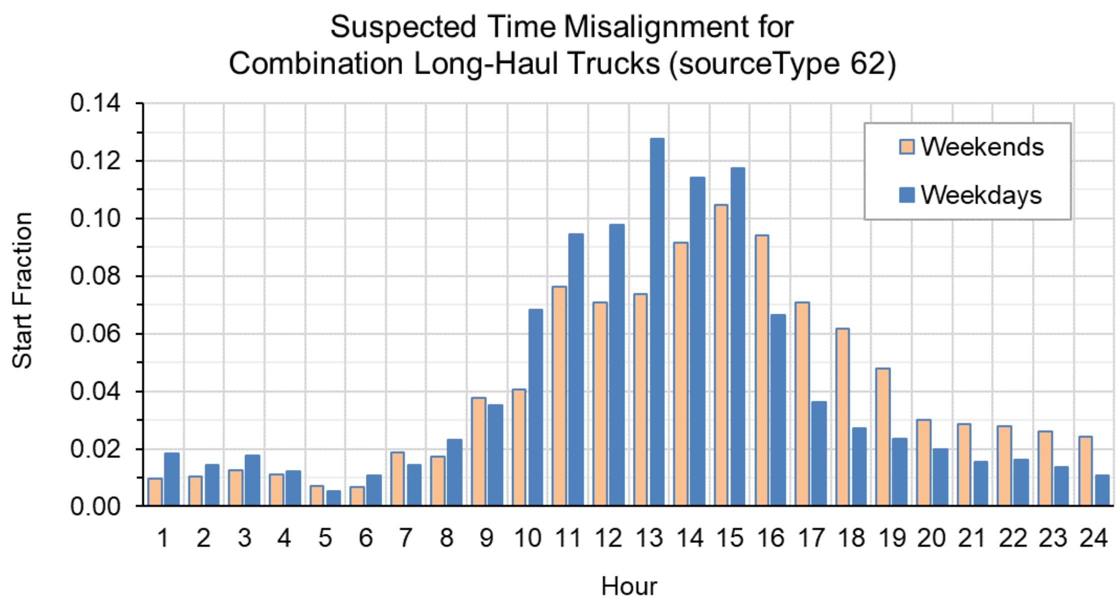


Figure 12-13 Start fractions from on NREL's Fleet DNA database that were <u>not</u> applied for combination long-haul trucks (sourceType 62); we suspect a time misalignment in the the data

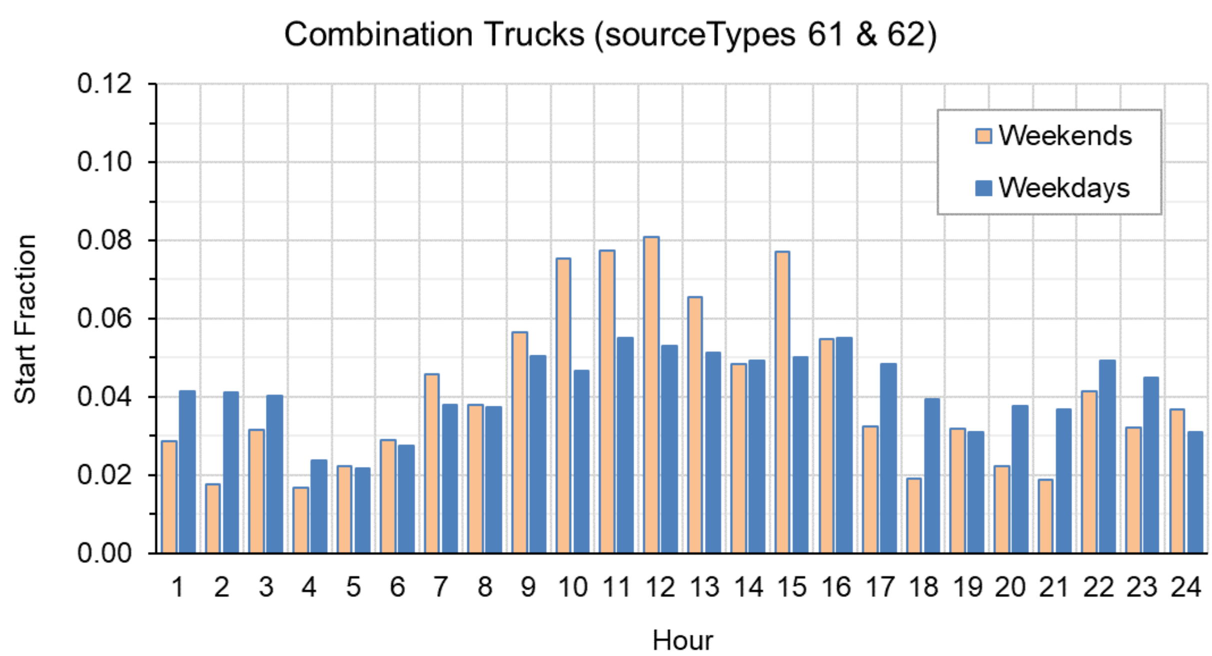


Figure 12-14 Start fraction temporal distribution for combination short-haul trucks (sourceType 61) and combination long-haul trucks (sourceType 62) based on data from NREL's Fleet DNA database

12.2.3.2. Monthly Distribution

In MOVES, we assume that the starts/mile is the same across all months. We use the same monthly distribution for starts in the MonthAdjust table as for the VMT in the MonthVMTFraction table discussed in Section 13.1. Heavy-duty vehicles follow the same monthly variation as light-duty vehicles, with slightly elevated starts during the summer months, and corresponding decrease in starts in the winter.

12.2.4. Start Soak Distributions

This section describes the heavy-duty vehicles' soak distributions in MOVES. As seen in Table 10-3, several heavy-duty source types were not available in the Fleet DNA database at the time of this analysis. We hope to update the analysis using both Fleet DNA and CE-CERT datasets. In the interim, we applied several assumptions for the soak behavior as described below.

The Fleet DNA dataset did not contain any information from buses meeting the MOVES definition of "other buses". We assumed the start distributions from transit bus (sourceTypeID 42) represented other buses (sourceTypeIDs 41) for both weekends and weekdays. Figure 12-15 and Figure 12-16 show the resulting starts distributions for these two bus types on weekends and weekdays, respectively.

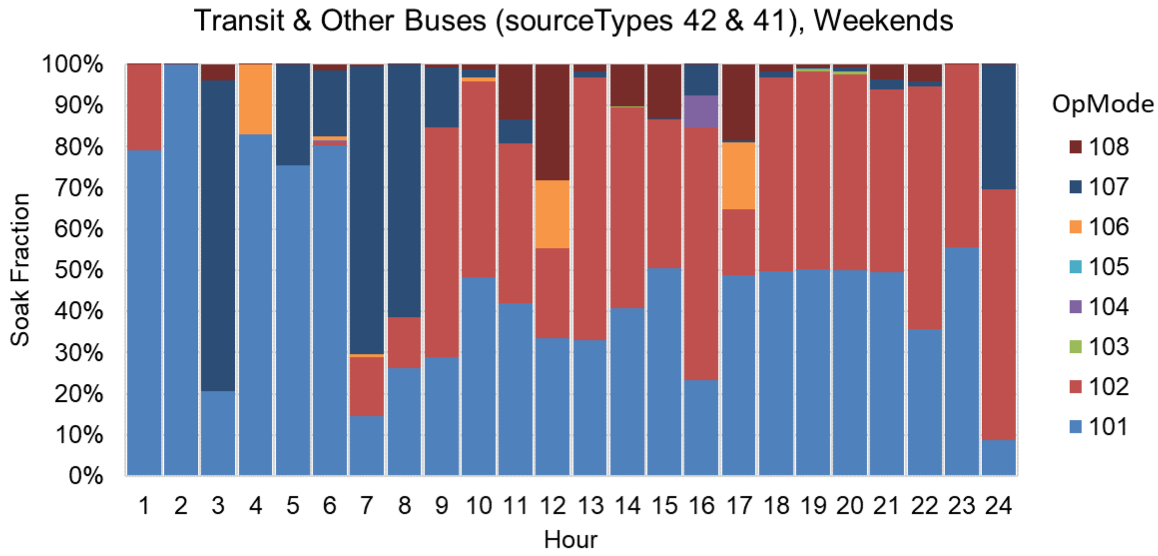


Figure 12-15 Weekend soak distributions transit buses (sourceType 42) and other buses (sourceType 41) based on data from NREL's Fleet DNA database

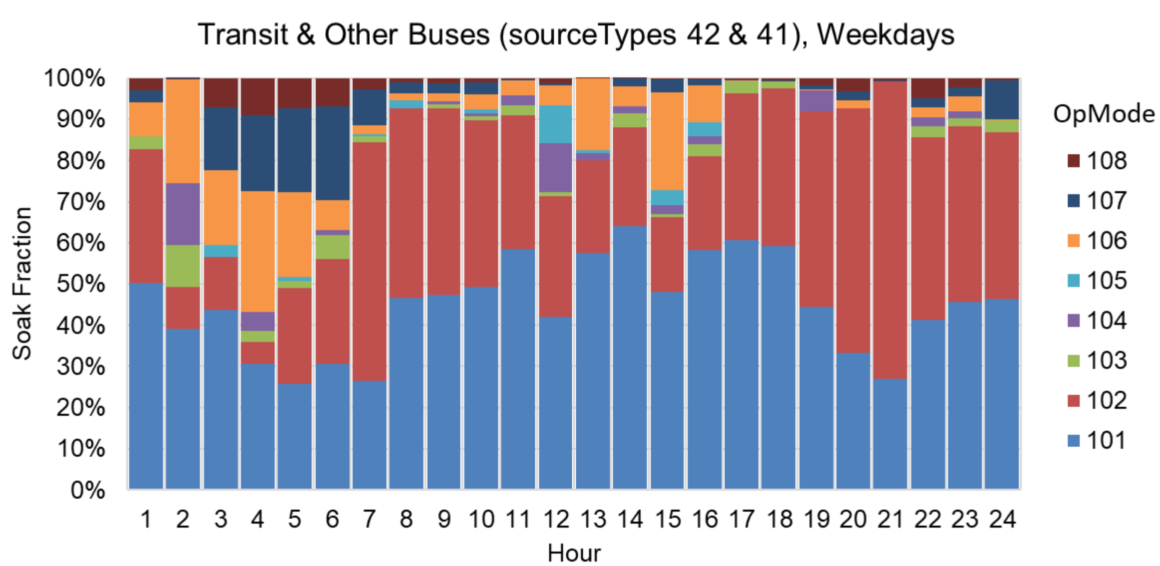


Figure 12-16 Weekday soak distributions transit buses (sourceType 42) and other buses (sourceType 41) based on data from NREL's Fleet DNA database

As mentioned previously in the start distribution discussion, school buses (sourceTypeID 43) in this dataset did not operate from 8:00 PM to 6:00 AM on weekdays. For soak distribution, we replaced these hours with the average hourly soaks over the period from 6:00 PM through 6:00 AM. The school buses in the Fleet DNA dataset did not operate on the weekends, so we applied the weekday school bus soak distribution to weekends. Figure 12-17 shows the soak distribution applied to school buses for both weekends and weekdays.

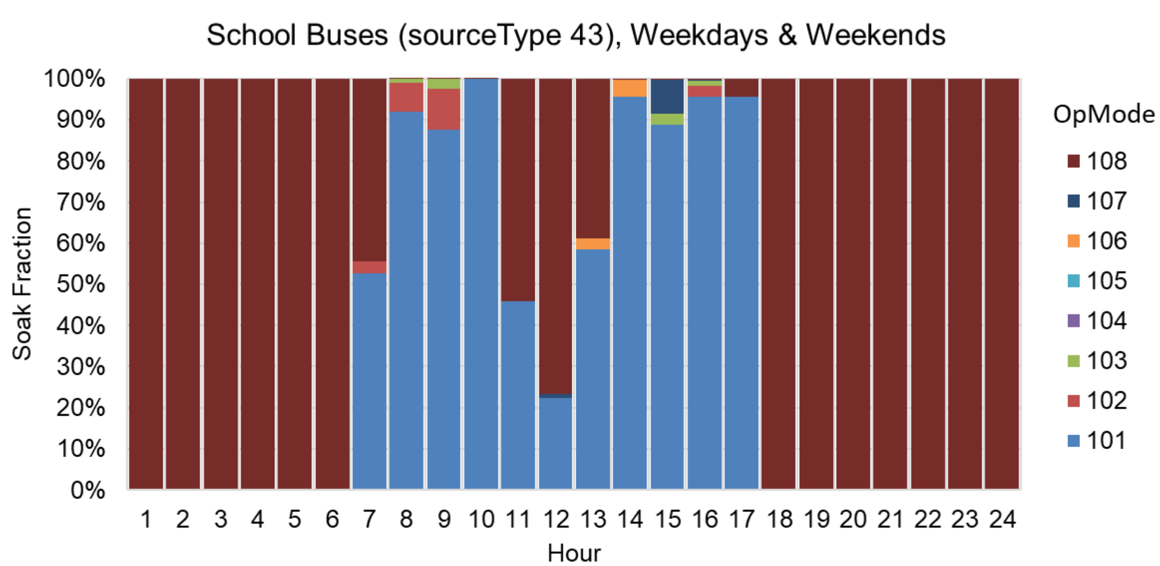


Figure 12-17 Weekend and weekday soak distributions for school buses (sourceType 43) based on data from NREL's Fleet DNA database

Refuse trucks (sourceType 51) in the Fleet DNA dataset did not operate on weekends from 7:00 PM to 4:00 AM and no data were collected in the hour between 6:00 AM and 7:00 AM. The missing night hours' data were replaced with the average hourly soaks over the period from 7:00 PM to 4:00 AM and the missing 6:00 AM data point was replaced with the average hourly soaks from 4:00 AM to 7:00 PM. Figure 12-18 and Figure 12-19 show the soak distributions for refuse trucks on weekends and weekdays, respectively.

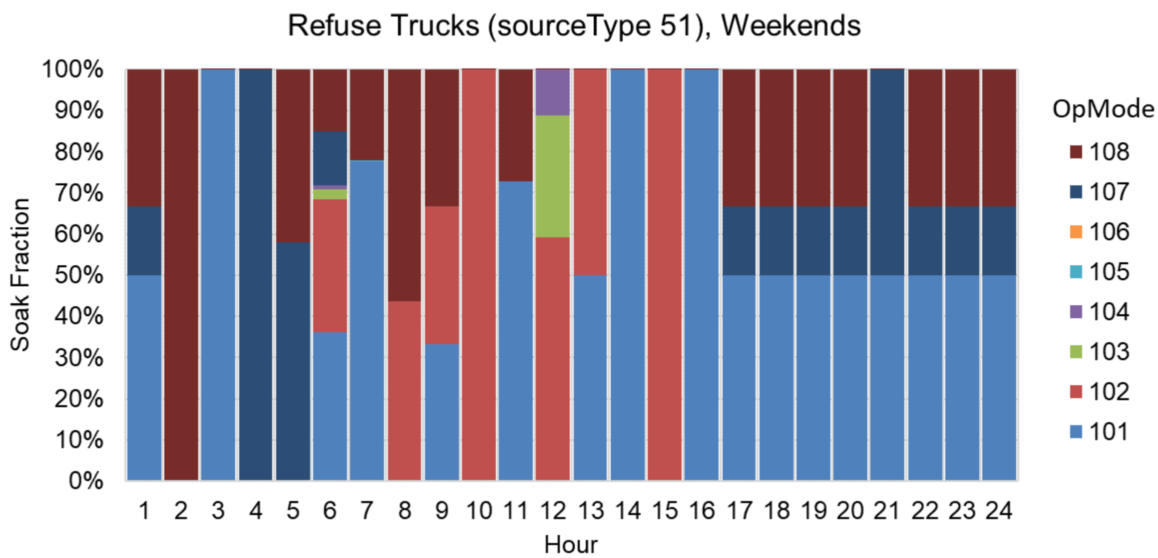


Figure 12-18 Weekend soak distributions for refuse trucks (sourceType 51) based on data from NREL's Fleet DNA database

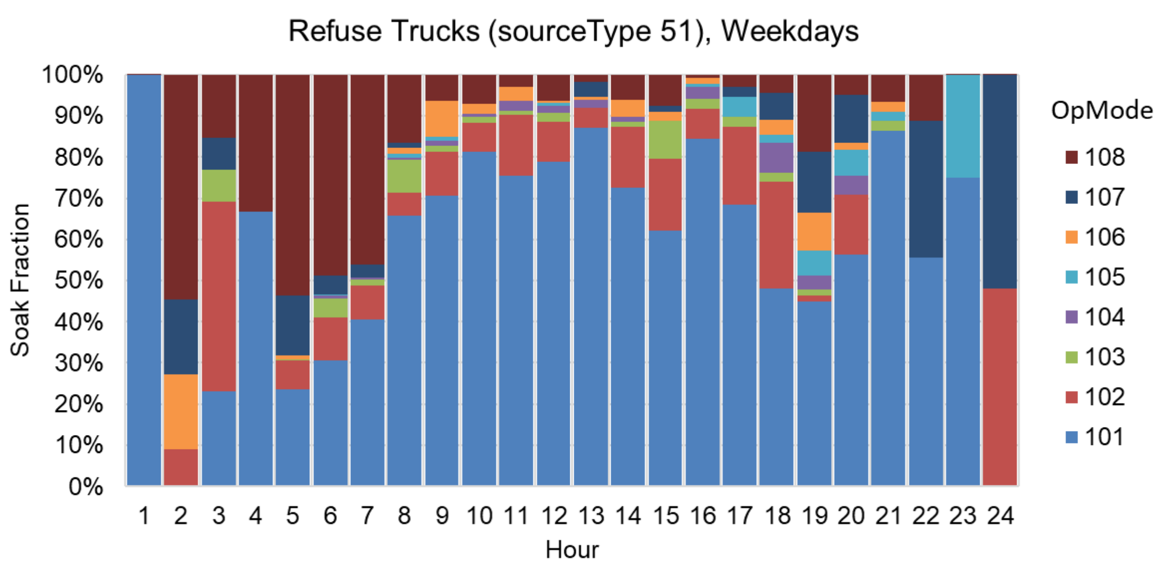


Figure 12-19 Weekday soak distributions for refuse trucks (sourceType 51) based on data from NREL's Fleet DNA database

The Fleet DNA dataset did not contain any single-unit long-haul trucks (sourceType 53) and we assumed their soak distribution was similar to the single-unit short-haul trucks (sourceType 52).

Figure 12-20 and Figure 12-21 show the soak distributions applied to both single-unit truck types for weekends and weekdays, respectively.

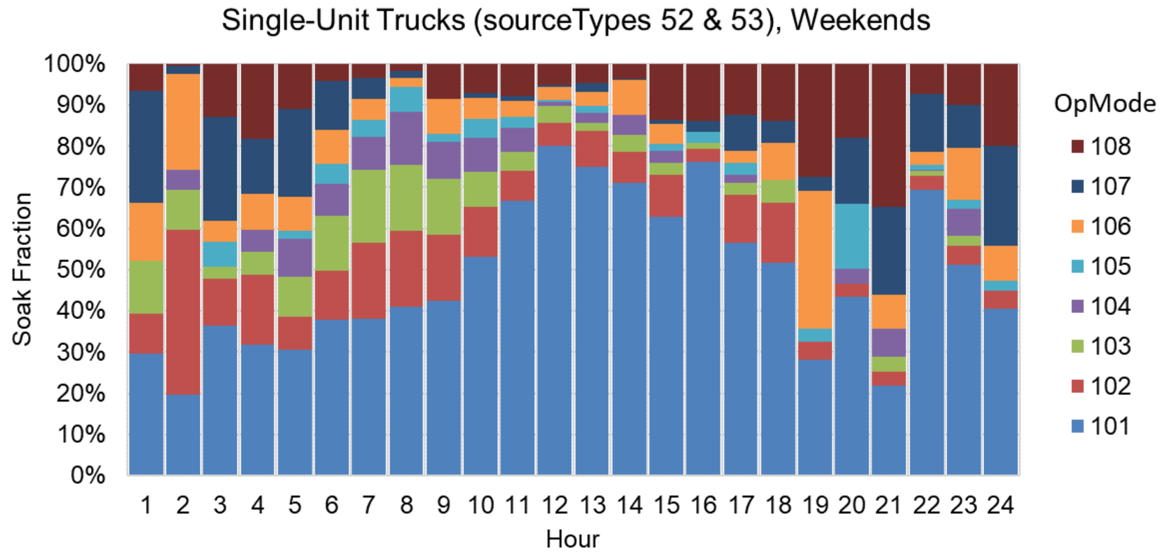


Figure 12-20 Weekend soak distributions for single-unit short-haul trucks (sourceType 52) and single-unit long-haul trucks (sourceType 53) based on data from NREL's Fleet DNA database

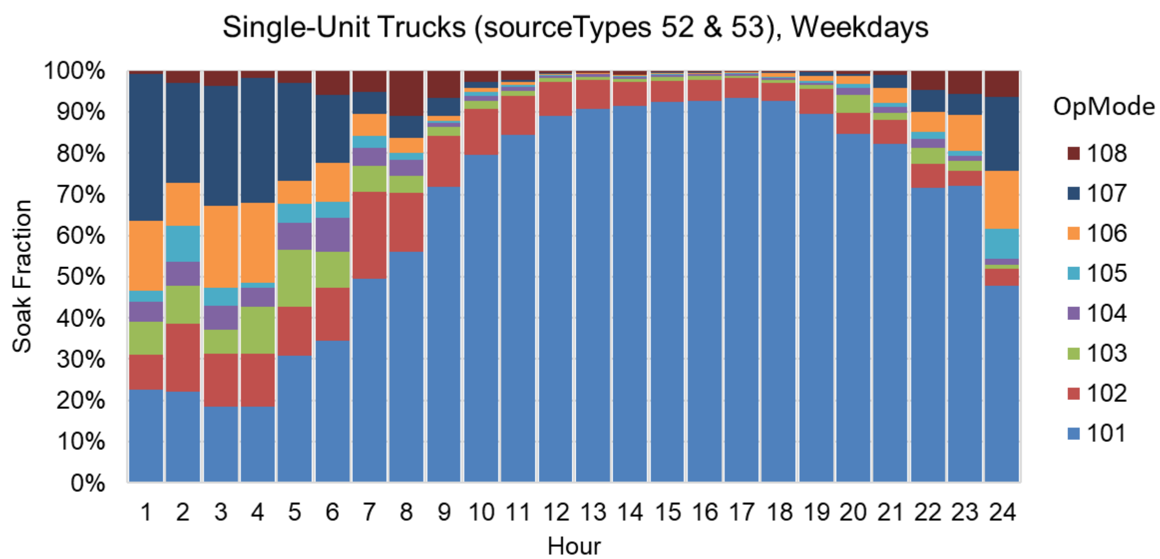


Figure 12-21 Weekday soak distributions for single-unit short-haul trucks (sourceType 52) and single-unit long-haul trucks (sourceType 53) based on data from NREL's Fleet DNA database

Figure 12-22 shows the weekend soak distribution that was applied in MOVES for combination short-haul trucks (sourceType 61). Figure 12-23 shows the weekday soak distribution for the same vehicles.

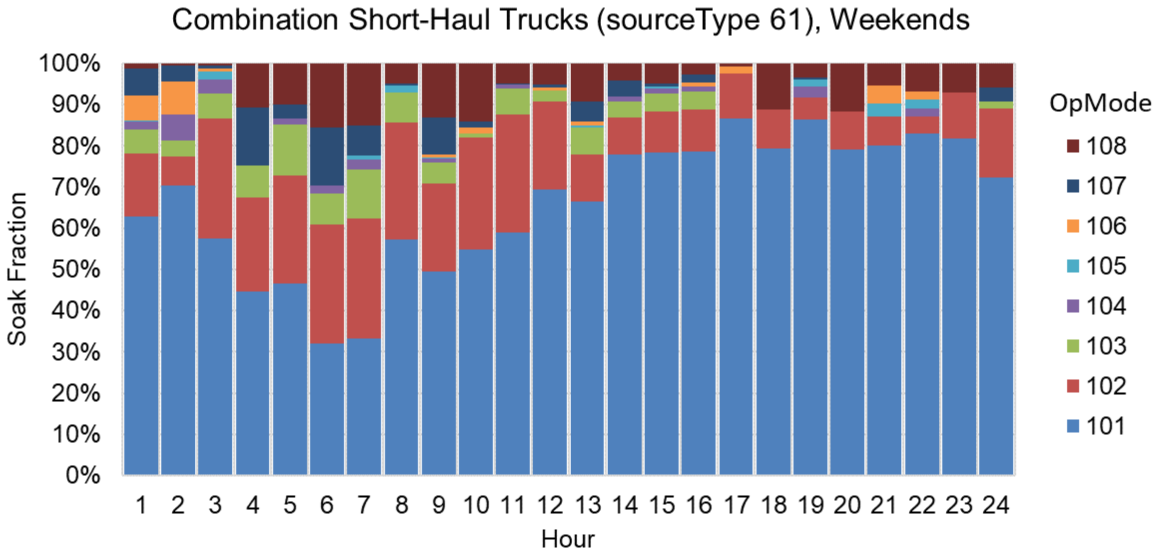


Figure 12-22 Weekend soak distributions for combination short-haul trucks (sourceType 61) based on data from NREL's Fleet DNA database

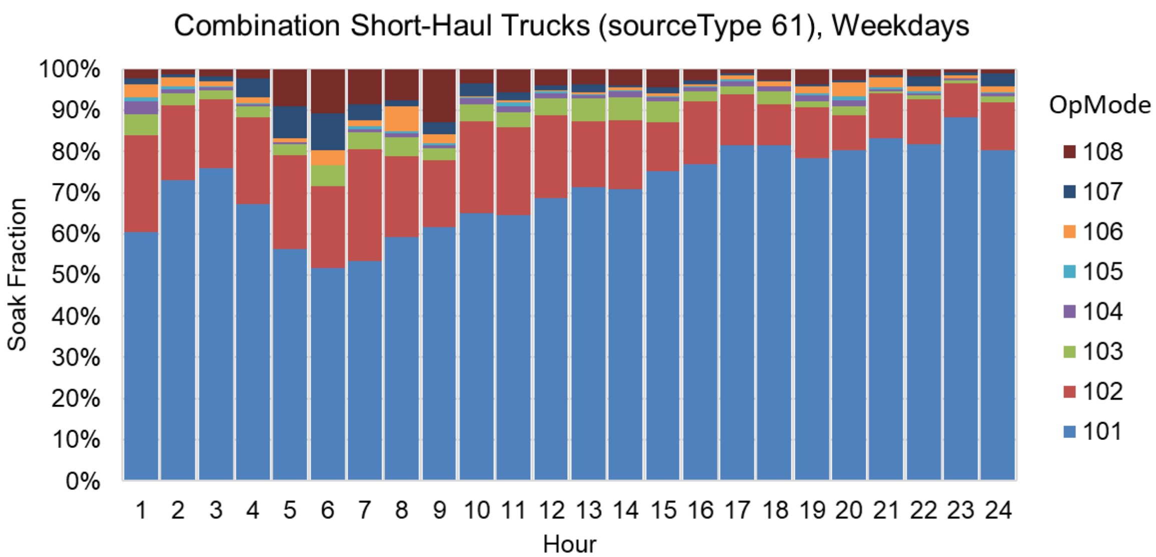


Figure 12-23 Weekday soak distributions for combination short-haul trucks (sourceType 61) based on data from NREL's Fleet DNA database

As mentioned in the start distribution section, we believe there was a time zone-related logging error for many of the combination long-haul trucks (sourceType 62) in the Fleet DNA dataset. Consequently, we opted to apply the same average hourly soak distribution from each day type across all hours of the day. The soak distributions applied for combination long-haul trucks on weekends are shown in Figure 12-24. The weekday soak distrbituions are in Figure 12-25.

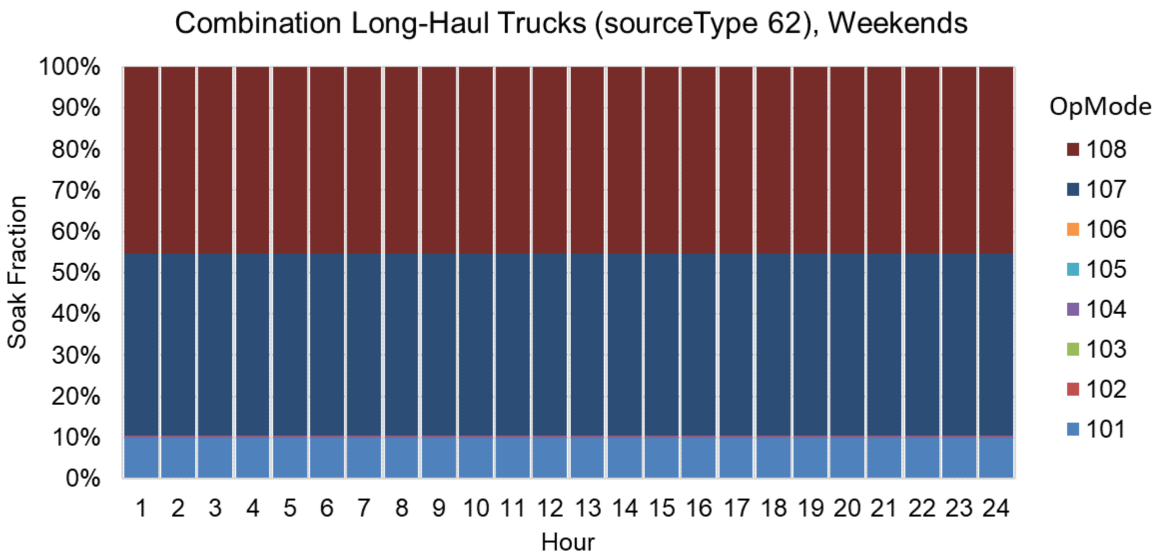


Figure 12-24 Weekend soak distributions for combination long-haul trucks (sourceType 62) applying the average hourly soak distribution from NREL's Fleet DNA database across all hours of the day

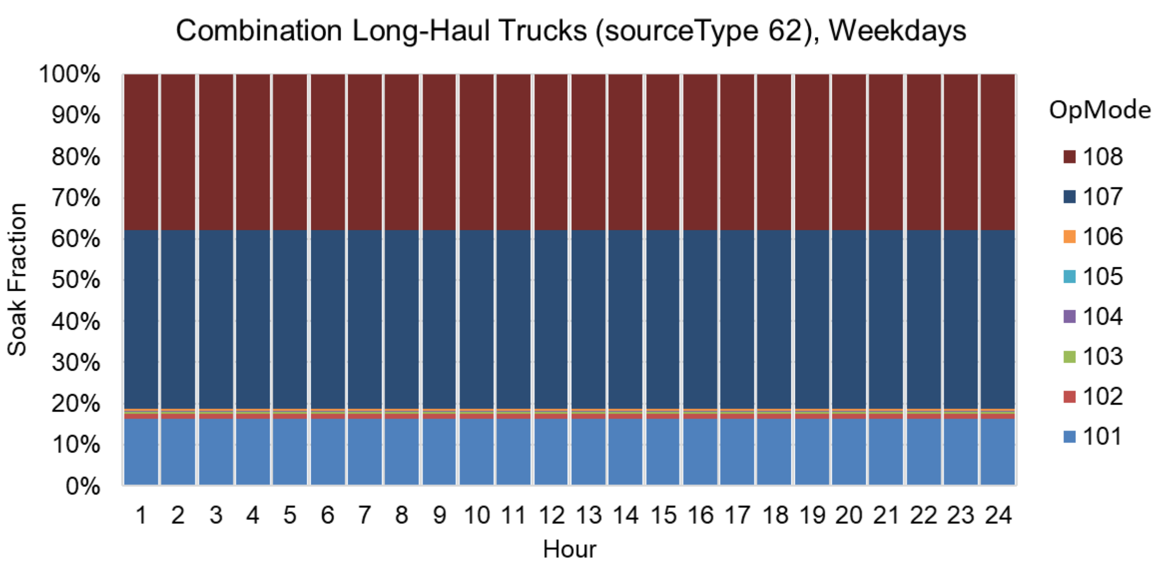


Figure 12-25 Weekday soak distributions for combination long-haul trucks (sourceType 62) applying the average hourly soak distribution from NREL's Fleet DNA database across all hours of the day

As mentioned for light-duty vehicles, MOVES has the capability to model different soak distributions by vehicle age. We are currently using the heavy-duty soak distribution estimated from Fleet DNA across all vehicle ages. In general, as vehicles age, we would expect fewer vehicle starts and a soak distribution shift towards longer soak times. However, the available data on heavy-duty vehicles at older ages is much more limited. Future work could evaluate the dependency of soak distributions on vehicle age.

12.3. Motorcycle and Motorhome Starts

Motorcycle and motorhome data are not captured in the Verizon and Fleet DNA datasets used to update the other source types. The data we used to model starts from motorcycles and motorhomes is outlined in Table 12-5.

Table 12-5. Motorcycle and Motorhome Start Data

MOVES Table	Motorcycles (SourceTypeID 11)	Motorhomes (SourceTypeID 54)
startsPerDayPerVehicle	Starts from Table 13-8 adjusted to represent CY 2014 age distribution	Table 13-8 adjusted to represent CY 2014 age distribution
startsHourFraction	Passenger Cars (21)	Passenger Trucks (31)
startsOpmodeDistribution (soaks)	Passenger Cars (21)	Passenger Trucks (31)
startsMonthAdjust	Table 13-2	Table 13-1

For national average starts per day per vehicle, we used the starts per day estimated in MOVES2014 as presented in Table 13-8. Because these start rates were calculated from instrumented vehicle data, we assume these start rates are respresentative of active, age 0 vehicles. We thus followed similar steps to calculate national average starts per day per vehicle as was conducted for heavy-duty vehicles above which used the same assumptions. We calculated starts per day by vehicle age by applying the ageAdjustment factors to the start data as shown in Figure 12-26.

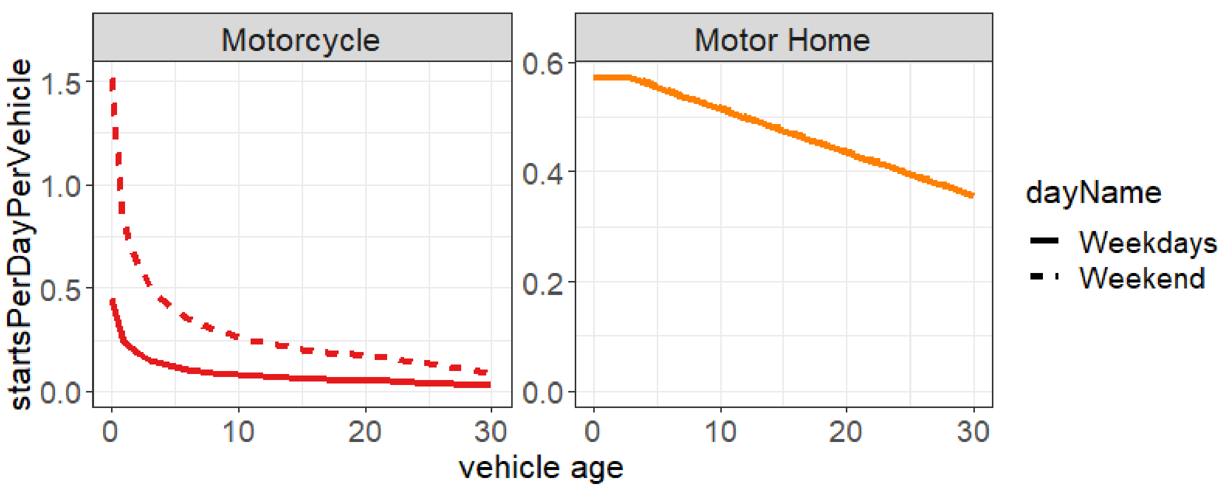


Figure 12-26. Starts per day per vehicle by vehicle age for motorcycles and motorhomes calculating using MOVES ageAdjustment factors

We then calculated the national average starts per day for motorcycles and motorhomes using Equation 12-2 with the starts per day per vehicle by age in Figure 12-26, Figure 12-7 and the

2014 heavy-duty default age distributions in MOVES3. We used the 2014 age distributions because it is the year from which the source type age distributions are based in MOVES3 (Section 6.1). The resulting national average starts per day per vehicle for motorcycles and motorhomes are displayed in Table 12-4, which are significantly lower than the age zero start rate.

Table 12-6. National Average Starts Per Day Per Vehicle for Motorcycles and Motorhomes

Source Type	SourceTypeID	MOVES3 CY 2014 Average Age (years)	Day of the Week	Starts per day per vehicle at age 0	Calculated national average starts per day per vehicle
Motorcycle	11	10.5	Weekend	1.52	0.37
			Weekday	0.45	0.11
Motorhome	54	15.0	Weekend	0.57	0.48
			Weekday	0.57	0.47

The hourly distribution of starts (stored in the startsHourFraction table) for motorcycles is assumed to be the same as for passenger cars. For motorhomes, the hourly distribution of starts is assumed to be the same as for passenger trucks, both of which are estimated from the Verizon database.Motorcyles soak distributions are the same as passenger cars and motorhomes are the same as passenger trucks. We assume that the montly pattern of starts (stored in the startsMonthAdjust table) follows the same pattern as VMT as described in in Section 13.1. Thus, motorcycle have a pronounced increase in starts during summer months. Motorhomes starts follow the monthly variation of all other source types, which are only slightly elevated during the summer months.

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).[71] 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 MOVES3 or MOVES4.

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 VMT on restricted access road types 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, 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 MOVES 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 temporal 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. When EPA runs MOVES for air quality modeling purposes, we use local activity data including temporal allocations as explained in EPA technical support documents.[46] EPA plans to update the temporal allocations currently in MOVES using more recent data sources, such as telematics data, as they become available.

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 to fit MOVES specifications. Table 13-1 shows VMT/day taken from the OHIM report (Figure 2.2.1 "Travel by Month, 1970-1995"), normalized to one for January. The VMT per day in Table 13-1 were used to calculate the fraction of total annual VMT in each month using the number of days in each month, assuming 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.[72] 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.

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.[71]

The DayVMTFraction needed for MOVES has only two categories: weekdays (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	0.762365
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.

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

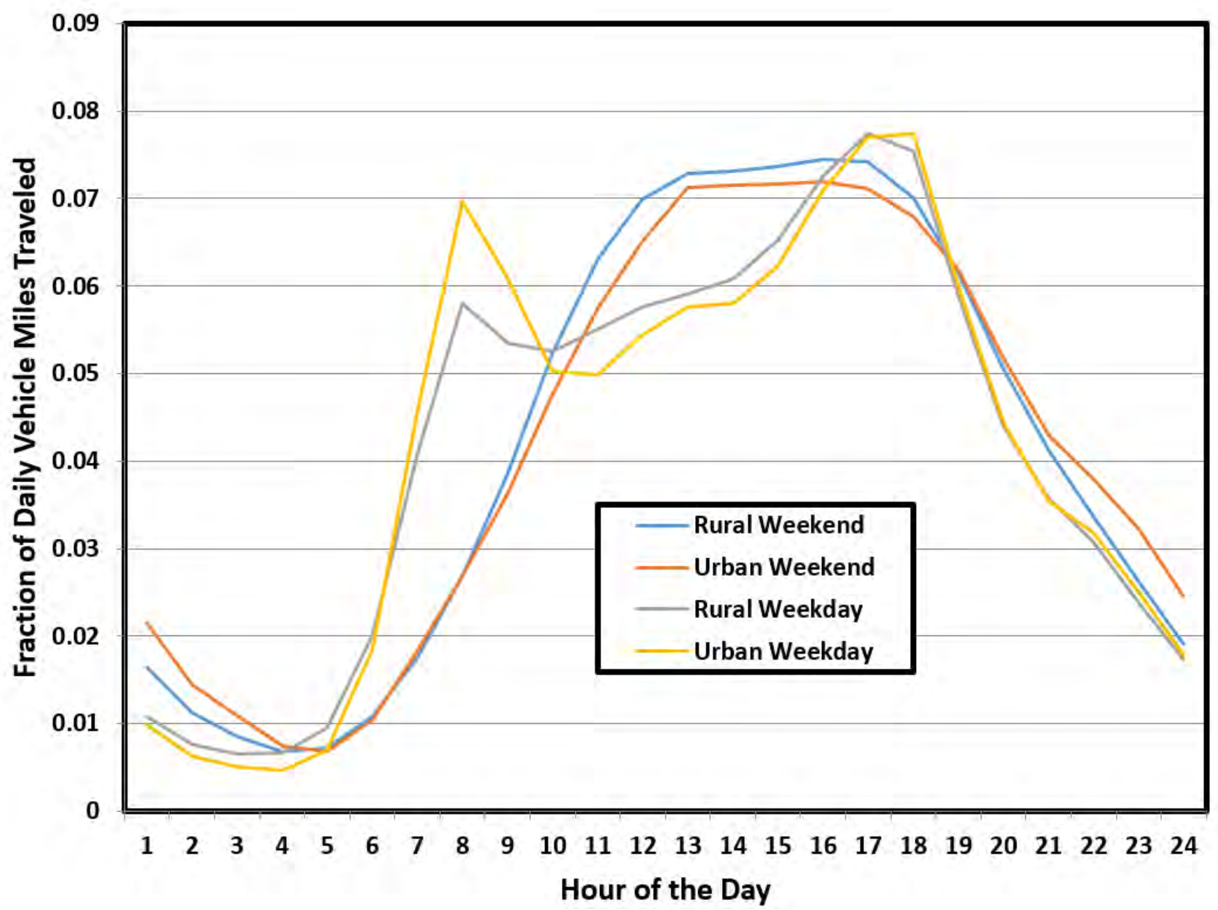


Figure 13-1 Hourly VMT fractions by day type and road type

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. For example, an analysis by CRC has made county specific hourly VMT distributions available for calendar year 2014.[46]

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, since updating the activity data in these tables was beyond the scope of more recent MOVES updates.[t] 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.[73] This analysis is described in greater detail in the report describing evaporative emissions in MOVES.[74]

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

[t] Updating the sampleVehicleTrip table to use the data also used to update starts is not straightforward. For example, the current SampleVehicleTrip table used for evaporative emissions currently contains 37,216 vehicle trips, whereas the Verizon light-duty database used for starts contains millions of trips. Another approach would be to change the MOVES algorithm to calculate evaporative emissions based on summarized trip information (as was done for start emissions) but creating this new algorithm would be a significant programing effort.

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.[75,76] The data come from a variety of instrumented vehicle studies, summarized in Table 13-6. These data were 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[77] 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 Trip per day by source type used for evaporative emissions activity

Source Type	Weekday	Weekend
Motorcycles	0.45	1.52
Passenger Cars	5.38	4.99
Passenger Trucks	5.58	4.7
Light Commercial Trucks	6.02	5.06
Other Buses	2.88	1.19
Transit Buses	4.75	4.93
School Buses	5.88	1.64
Refuse Trucks	3.85	1.28
Single-Unit Short-Haul Trucks	7.14	1.67
Single-Unit Long-Haul Trucks	4.45	1.74
Motor Homes	0.57	0.57
Combination Short-Haul trucks	6.07	1.6
Combination Long-Haul trucks	4.29	1.29

The trip activity used for determination of emissions resulting from parked vehicles differs from the activity used to determine engine start emissions, described in Section 12. Ideally, trips, engine soak periods, and parking hours would be consistent. However, since both approaches, although different, are describing the same vehicle activity, the differences are not expected to have a negative impact on total emission estimates.

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.[76]

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 (see 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

In Section 11, we updated the hotelling activity rate based on instrumented truck data from the NREL Fleet DNA database. However, this dataset was not deemed appropriate for updating the hourly hotelling activity.[u] As discussed below, we found that the hotelling hourly distribution assumed in MOVES2014 compared well to other datasets. Thus, the hourly hotelling activity is unchanged from MOVES2014.

To derive the hotelling hour distribution in MOVES, we used the assumption that 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*[54] 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.

[u] The NREL long-haul dataset yielded an hourly hotelling distribution with most of the activity occuring during the daytime hours, while the MOVES2014, NCHRP 08-101 and truck survey data suggests that most occurs during the nighttime. As discussed in Section 12, NREL could not confirm the time stamp of the data for the long-haul trucks in the FleetDNA was the local time, or a reference time because the long-haul truck was provided by an industry partner, not collected by NREL. For these reasons, we decided not to use the FleetDNA data to update the hotelling hourly distributions.

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[78] 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 hotelling 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 hotelling time period 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[79] 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 using 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.

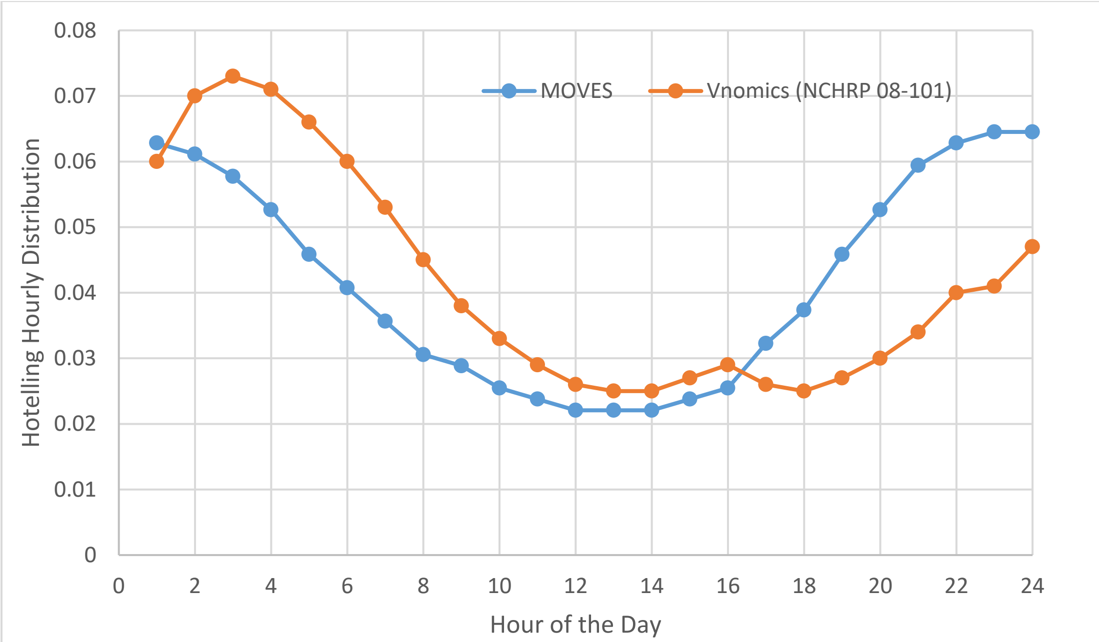


Figure 13-2 Truck hotelling distribution by hour of the day in MOVES

In Figure 13-2, we also compare the hotelling distribution to hotelling activity derived from the Vnomics data analyzed by the NCHRP 08-101 project.[70] As shown, it provides a constent diurnal pattern, with most of the hotelling activity occuring during the nighttime hours. This is a consistent pattern displayed by truck parking results at unofficial locations and truck stops reported by the Federal Highway Administration.[80] The data from the NCHRP 08-101 project was used only for comparison purposes and not used dirctly to update the hotelling hourly distribution, because NCHRP 08-101 utilized different definitions of hotelling activity than MOVES.[v]

[v] The definition of hotelling used in the draft NCHRP 08-101 project estimates idling activity with duration > 8 hour, whereas in Section 11 we used an idle duration of > 1 hour.

14. Geographical Allocation of Activity

The vehicle miles traveled (VMT) and vehicle populations contained in the default database (see Section 3 and Section 4, respectively) are for all 50 states and Washington D.C. However, MOVES can estimate activity in individual states or counties (including Puerto Rico and the Virgin Islands) when running at Default Scale using geographic allocation factors stored in two tables: Zone and ZoneRoadType. The geographic allocations in MOVES4 are based on the 2020 NEI[81] distribution of VMT by county.

In MOVES4, 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). Similarly, engine starts are calculated based on county vehicle populations and are not allocated from national estimates, although county vehicle populations themselves are calculated using allocation factors (SHO and SHP as explained in the sections below).

Note that the MOVES design only allows for one set of geographic allocations to be stored in the default database. While real-world geographic allocations 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.

For MOVES4, we updated the default list of counties (and therefore zones) to incorporate changes in the state of Alaska that went into effect in January 2019 when the Valdez-Cordova census area (FIP 02261) was divided into two new census areas: Chugach Census Area (FIP 02263) and Copper Census Area (FIP 02066). For the default database, we split the activity existing in the zone and zoneroadtype tables for the original Valdez-Cordova Census Area and allocated it to the new census areas using the population estimate reported in the 2020 US Census[82] for these new areas.

14.1. Source Hours Operating Allocation to Zones

The national total source hours of operation (SHO) are calculated from the estimates of VMT as described in sections above. This total VMT for each road type is allocated to county using the SHOAllocFactor field in the ZoneRoadType table. Although the field is named “source hours operating”, it is used only for allocating VMT and not hours of operation.

The 2020 NEI VMT was aggregated into the annual sum for the four MOVES road types in each county and nationally and used to calculate the SHOAllocFactor using Equation 14-1.

$$SHOAllocFactor_{RoadTypeID} = \frac{CountyVMT_{RoadTypeID}}{NationalVMT_{RoadTypeID}}$$ **Equation 14-1**

The county allocation values for each roadway type sum to one (1.0) over all 50 states and Washington D.C. 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. 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 a VMT-based allocation.

The allocation is determined using the VMT estimates for each county in each state as calculated using Equation 14-2, where i represents each individual county and I is the set of all US counties.

$$SHPAllocFactor_i = \mathrm{CountyVMT}_i \Big/ \sum_{i \epsilon I} \mathrm{CountyVMT}_i$$ **Equation 14-2**

The county allocation values for parking hours sum to one (1.0) over all 50 states and Washington D.C. 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.

Note that the same allocation values are used for the StartAllocFactor column, also saved in the Zone table.

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 the motorcycle, light-duty vehicles and light-duty truck regulatory classes 10, 20, and 30 and STP is used for heavy-duty regulatory classes.

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 combination of source type and regulatory class averaged over all ages. In MOVES2014, the SourceUseTypePhysics table varied only by source type. However, regulatory class and model year were added in MOVES3 as one of the key changes to model the Heavy-Duty Greenhouse Gas Phase 2 rule[83] which anticipates improvements to vehicle and trailer design. MOVES uses values in the SourceUseTypePhysics table to calculate VSP and STP for each source type/regulatory class combinations according to Equation 15-1 and Equation 15-2:

$$VSP = \frac{Av + Bv^2 + Cv^3 + M \cdot (a + g \cdot sin\theta) \cdot v}{M}$$ **Equation 15-1**

$$STP = \frac{Av + Bv^2 + Cv^3 + M \cdot (a + g \cdot sin\theta) \cdot v}{f_{scale}}$$ **Equation 15-2**

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 $\mathrm{m/s^2}$, $\sin\theta$ is the (fractional) road grade[w] and f_{scale} is a scaling factor. Note that the only difference between the VSP and STP equations is the term in the denominator. For light-duty vehicles using VSP, the power is normalized by the mass of the vehicle ($f_{scale} = M$). For heavy-duty vehicles, the f_{scale} is similar, but not equal to the average source mass of the vehicle source type ($f_{scale} \neq M$).

When conducting light-duty emissions analysis, emissions data from individual vehicles are assigned to VSP operating mode bins using Equation 15-1, with the individual vehicle's

[w] MOVES does not model grade at the national and county scale. Road grade may be entered at the project scale.

measured weight as the source mass (hence the term "vehicle-specific"). When developing emissions rates for MOVES, the emissions from individual vehicles are averaged across operating mode bins to calculate average emission rates for each regulatory class. Because individual vehicle weights within the same regulatory class vary, the absolute tractive power produced by individual vehicle activity assigned to the same VSP-defined operating mode also varies. In contrast, when MOVES calculates VSP from driving cycles and assigns operating modes for an entire source type, the average source type mass is used instead.

For heavy-duty vehicles, STP is calculated with Equation 15-2, which is very similar to the VSP equation except the tractive power is normalized by a fixed f_{scale} values for all vehicles within the same regulatory class and model year group. The f_{scale} is used to bring the numerical range of tractive power from heavy-duty vehicles into the same numerical range as the VSP values when assigning operating modes. When developing emission rates for MOVES, operating modes are assigned to individual vehicles using both the individual truck weight, and the common f_{scale} value used for all heavy-duty vehicles from the same regulatory class, source type and model year group. Because a common f_{scale}value is used, individual vehicles assigned to the same STP-defined operating mode bin are producing the same absolute tractive power, regardless of differences in their individual source masses. When MOVES estimates STP and assigns operating mode distributions for the heavy-duty fleet, it uses the average source type mass (M) for each regulatory class, source type, and model year group in the numerator and uses the common f_{scale} value which was used in the emission rate analysis.

Additional discussion regarding VSP and STP (including the selection of f_{scale} values) are provided in the MOVES light-duty[10] and heavy-duty[11] exhaust emission rate reports, respectively.

In both cases, MOVES derives operating mode distributions 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 15-1 and Equation 15-2.

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 vehicles of a given regulatory class within a source type, which includes the weight of the vehicle, occupants, fuel and payload (M in Equation 15-1 and Equation 15-2) and the fixed mass factor represents the STP scaling factor (f_{scale} in Equation 15-2). The mass factors in the SourceUseTypePhysics table are in units of metric tons (1000 kilograms). The source masses are reported in this section both in units of weight in lbs (used in the regulatory class defintions), and mass in kilograms (used in MOVES calculations).

In MOVES4, the source masses of light-duty vehicles were unchanged from previous versions of MOVES, as presented in Table 15-1 and documented in Appendix F.

Table 15-1. Average Vehicle Weight and Mass for Motorcycles, Light-duty Vehicles, and Light-duty Trucks Regulatory Classes

Source Type (sourceTypeID)	Regulatory Class (regClassID)	Average Vehicle Weight (lbs)	Average Vehicle Mass (kg)
Motorcycle (11)	Motorcycle (10)	628	285
Passenger Car (31)	Light-duty Vehicle, LDV (20)	3,260	1,479
Passenger Truck (31)	Light-duty Truck, LDT (30)	4,116	1,867
Light Commercial Truck (32)	Light-duty Truck, LDT (30)	4,541	2,060

The source masses for light heavy-duty trucks are based on a report from the National Research Council.[84] This report included data on empty vehicle weight ranges, typical payload capacity and annual fleet VMT by truck class. For light heavy-duty trucks, the average source mass was assumed to be the midpoint of the empty vehicle weight range plus 50 percent of the typical payload capacity. The source mass for passenger trucks and light commercial trucks in regulatory class 41 was calculated using the data presented for class 2b trucks only. A VMT-weighted average mass was calculated for single-unit trucks in regulatory class 41 using data for class 2b and 3 trucks, and single-unit trucks in regulatory class 42 were assigned a VMT-weighted average for class 4 and 5 trucks.

Table 15-2. Average Vehicle Weight Mass for LHD2b3 and LHD45 Regulatory Classes by Source Type

Source Type (sourceTypeID)	Regulatory Class (regClassID)	VMT-weighted Average Vehicle Weight (lbs)	VMT-weighted Average Vehicle Mass (kg)
Passenger Truck (31) Light Commercial Truck (32)	LHD2b3 (41)	7,500	3,402
Refuse Truck (51) Single-unit Short-haul Truck (52) Single-unit Long-haul Truck (53) Motor Home (54)	LHD2b3 (41)	7,879	3,574
	LHD45 (42)	12,716	5,768

The source masses for medium and heavy heavy-duty single-unit trucks and combination trucks were estimated based on weigh-in-motion data made available through FHWA's Vehicle Travel Information System (VTRIS).[85] This data source presents average gross vehicle weights by truck type (single unit, single trailer and multi-trailer), axle count and state. An approximate mapping between MOVES source types/regulatory classes and the VTRIS truck types/axle counts is presented in Table 15-3. National average masses were calculated for regulatory classes 46, 47 and 49 in the single-unit truck and combination truck source types using 2013 VTRIS data, weighted by VMT data for the same year by state, as presented in *Highway Statistics* Table VM-2.

Table 15-3 Average Vehicle Weight and Mass for MHD, HHD and Glider Regulatory Classes and Source Type and VTRIS Vehicle Classes and Axle Count

Source Type (sourceTypeID)	Regulatory Class (regClassID)	VTRIS Vehicle Class and Axle Count	VMT-weighted Average Vehicle Weight (lbs)	VMT-weighted Average Vehicle Mass (kg)
Refuse Truck (51)	MHD (46)	Single-unit Trucks: 3-axle	30,424	13,800
	HHD (47)	-	45,645	20,704
Single-unit Short-haul Truck (52) Single-unit Long-haul Truck (53) Motor Home (54)	MHD (46)	Single-unit Trucks: 3-axle	30,424	13,800
	HHD (47)	Single-unit Trucks: 4-axle	55,221	25,048
Combination Short-haul Truck (61) Combination Long-haul Truck (62)	MHD (46)	Single Trailer Trucks: 4-axles or less	30,891	14,012
	HHD (47)	Single Trailer Trucks: 5-axle, 6-axle, or more	54,741	24,830
		All Multi-trailer Trucks		
	Glider (49)	Single Trailer Trucks: 5-axle, 6-axle, or more	54,741	24,830
		All Multi-trailer Trucks		

The exception to the single-unit truck analysis described above is the average source mass for class 8 (HHD) refuse trucks because these trucks are subject to a lower Federal weight limit due to their typical vehicle length and axle configuration.[86] These vehicles are assumed to have an average source mass of 45,645 lbs, based on several studies of in-use refuse truck activity.[87] [88] [89] [90]

The medium heavy- and heavy heavy-duty truck source masses were adjusted from the baseline masses as calculated above to account for expected changes by model year due to both the Heavy-Duty GHG Phase 1 and Phase 2 rules. With the Phase 1 rule, decreases were expected for combination trucks. With the Phase 2 rule, weight reductions were also expected for single-unit trucks. The changes in source masses from the baseline masses reflecting the Phase 1 and 2 rules are shown in Table 15-4. The details of the analyses used to estimate the changes in source masses can be found in the Phase 1 Regulatory Impact Analysis[91] and in the docket for the Phase 2 rule.[92] [93]

Table 15-4 MHD and HHD Changes in Vehicle Weight by Model Year

Source Type*	Model Years	Change in Vehicle Weight from Baseline (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	2014+	-321
Combination Long-haul Truck	2014+	-400

* No change in vehicle weights is modeled for other sourcetypes.

The source masses for all medium heavy-duty and heavy heavy-duty buses are based on a report from the American Public Transit Association (APTA).[94] This report included data on the ranges of seating capacity, curb weight and fully-loaded weight for different types and lengths of buses. Lacking specific data on in-use bus masses, we assume that the average source mass is the mid-point between the curb weight and fully-loaded weight. We also assume that seating capacity is the driving variable for the curb weight and fully-loaded weight of a bus. Under this simplifying assumption, linear functions of seating capacity for average and fully-loaded masses were determined by bus type and length using the ranges presented in the APTA report.

To calculate national average source masses for medium heavy-duty and heavy heavy-duty buses, the mass functions derived from the APTA report were weighted by bus activity data from FTA's 2017 National Transit Database (NTD).[19] The NTD contains estimates of transit bus populations and VMT and also includes data on seating capacity, bus type and vehicle length. For each entry in the NTD that described a type of bus, double decked bus or articulated bus, we calculated an average mass and a fully-loaded mass based on seating capacity, bus type and vehicle length. We assigned vehicles with fully-loaded masses between 19,500 and 33,000 lbs to the medium heavy-duty regulatory class (regClassID 46) and vehicles above 33,000 lbs were assigned to the heavy heavy-duty regulatory class (regClassID 48 for diesel and CNG transit buses and regClassID 47 for all the remaining bus source type and fuel type combinations). Using these regulatory class assignments, we calculated VMT-weighted average masses for regulatory classes 46, 47, and 48 and applied them to all bus source types (i.e., sourceTypeIDs 41, 42, and 43). In the future, we will consider updating the bus mass estimates to incoporate data on mile-weighted average passenger load.

Because the APTA report did not include data for light heavy-duty buses, we calculated source mass based on a number of assumptions regarding vehicle parameters from manufacturer specifications for the most popular vehicle models in the NTD with a bus type of cutaway. Specifically, we assumed the following:

- The fully-loaded vehicle mass is at the upper bounds of allowable GVWR for each class (i.e., 14,000 lbs for regClassID 41 and 19,500 lbs for regClassID 42).
- Passenger capacity is 15 for regClassID 41 and 25 for regClassID 42 and the average passenger weighs 175 lbs.
- Fuel tank capacity is 50 gallons (gasoline).

If the average operating conditions for these vehicles are at 50 percent passenger and 50 percent fuel capacity, then the average vehicle mass for LHD2b3 (regClassID 41) buses can be calculated as 12,531 lbs and LHD45 (regClassID 42) buses as 17,156 lbs. The average weights and source masses are shown in Table 15-5.

Table 15-5. Bus Weights and Mass by Regulatory Classes by Source Type

Source Type (sourceTypeID)	Regulatory Class (regClassID)	Vehicle Weight (lbs)	Vehicle Mass (kg)
Other Bus (41) School Bus (43)	LHD2b3 (41)	12,531	5,684
Other Bus (41) Transit Bus (42) School Bus (43)	LHD45 (42)	17,156	7,782
Other Bus (41) Transit Bus (42) School Bus (43)	MHD (46)	25,060	11,367
Other Bus (41) Transit Bus (42) School Bus (43)	HHD (47)	34,399	15,603
Transit Bus (42)	Urban Bus (48)	34,399	15,603

The complete list of sourceMass and fixedMassFactor in MOVES4 is presented in Appendix J.

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 15-3 through Equation 15-5, were empiricially derived in accordance with standard practice:[95,96]

$$A = 0.088 \cdot M$$ **Equation 15-3**

$$B = 0$$ **Equation 15-4**

$$C = 0.00026 + 0.000194 \cdot M$$ **Equation 15-5**

For light-duty vehicles, the road load coefficients were calculated according to Equation 15-6 through Equation 15-8:[97]

$$A = \frac{0.7457}{50 \cdot 0.447} \cdot 0.35 \cdot TRLHP_{@50\text{mph}} \qquad \textbf{Equation 15-6}$$

$$B = \frac{0.7457}{(50 \cdot 0.447)^2} \cdot 0.10 \cdot TRLHP_{@50\text{mph}} \qquad \textbf{Equation 15-7}$$

$$C = \frac{0.7457}{(50 \cdot 0.447)^3} \cdot 0.55 \cdot TRLHP_{@50\text{mph}} \qquad \textbf{Equation 15-8}$$

In the three equations above, the first factor is the appropriate unit conversion to allow A, B and C to be used in Equation 15-1 and Equation 15-2, 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)[98] to Equation 15-6 through Equation 15-8. 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.[99] 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,[100] as shown in Table 15-6. 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[x]. 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. The road load parameters for combination trucks have been revised for model years 1960-2060 using the methods described in Section 15.2.2.2. The

[x] The A and C coefficients were derived in MOVES2010 based on the equations in Table 15-3 and the population fraction of regulatory classes within the sourcetypes in MOVES2010. For MOVES2014 and MOVES3, we updated the vehicle source masses, and we scaled the A coefficients from MOVES2010 according to the changes in vehicle mass, because there is a direct relationship between rolling resistance and vehicle weight. In contrast, for all but the combination trucks, the aerodynamic drag coefficients, C, are unchanged from MOVES2010 because we lacked new data and there is not a direct relationship between arodynamic drag and vehicle weight.

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 15-6 Road Load Coefficients for MY 1960-2013 Buses, Motor Homes and Single-Unit Heavy-duty Trucks

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
$C\left(\frac{kW\text{-}s^3}{m^3}\right)$	$0.00147 + 5.22 \times 10^{-5} \cdot M$	$0.00193 + 5.90 \times 10^{-5} \cdot M$	$0.00289 + 4.21 \times 10^{-5} \cdot M$	$0.0032 + 5.06 \times 10^{-5} \cdot M$

15.2.2.1. Incorporation of Heavy-Duty Greenhouse Gas Standards in MOVES

EPA set greenhouse gas (GHG) emission standards for heavy-duty vehicles in two separate rulemakings, refered to in this report as the Phase 1[101] and Phase 2[102] HD GHG rules. The Phase 1 rulemaking became effective for the 2014 model year. The Phase 2 rulemaking became effective in 2021 model year and is fully phased-in by the 2027 model year.

The road load coefficients in MOVES reflect the projected improvements to the vehicles in different model year groups. The first model year 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 over this time period, 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 standards are phased-in using model year groups 2021-2023, 2024-2026 and 2027-and-later. To account for the improvements due to the HD GHG rules, road load forces were separated into individual road load coefficients 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 MOVES4 as a result of information on Phase 2 HD GHG rule implemention.[y]

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

[y] Due to a 2021 appeals court ruling vacating the portions of the Heavy-duty Greenhouse Gas Phase 2 standards (HDGHG2) that apply to trailers, we revised MOVES inputs that describe weight, aerodynamics, rolling resistance and "other efficiency" improvements for combination trucks of model year 2018 and later to better represent the implemented program.

$$F_{aero} = \frac{1}{2}\rho C_d A_f v_{air}^2$$ **Equation 15-9**

where ρ 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:

$$STP_{aero} = \left(\frac{1}{f_{scale}}\right) \cdot \frac{1}{2}\rho C_d A_f v^3$$ **Equation 15-10**

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

$$C = \frac{1}{2}\rho C_d A_f$$ **Equation 15-11**

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:

$$A = C_{RR}M_g$$ **Equation 15-12**

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 MOVES. Section 15.2.2.3 describes 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 MOVES can be found in the MOVES Heavy-Duty Emission Rates Report.[11]

While we expect road load coefficients for Heavy-Duty Pickups and Vans (regclassID 41) to improve over time due to the Phase 1 and Phase 2 HD GHG rules, the impact of these changes have been directly incorporated into the emission and energy rates.[11] 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

MOVES3 included updates to both the aerodynamic and rolling resistance components of the overall road load reflecting the greenhouse gas emissions standards for combination trucks. An aerodynamic assessment of all model years of combination trucks was conducted to utilize a consistent method in MOVES, and the aerodynamic values were updated for all model years to reflect the aerodynamic technology analysis and projections in HD GHG Phase 2 rulemakings. These values were further updated in MOVES4 to reflect the HD GHG Phase 2 rulemaking as implemented. The average road load coefficients are updated by source type and regulatory class through the beginModelYearID and endModelYearID fields in the SourceUseTypePhysics table.

Appendix J describes how the aerodynamic improvements were developed as part of the rulemaking and how they were used to update MOVES.

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 and Phase 2 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.[103]

The final road load coefficients for all regulatory classes and sourcetypes in MOVES4 are shown in Appendix J.

16. Air Conditioning Activity Inputs

This section 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 remain the same as in earlier versions of MOVES. More information on air conditioning effects and how air conditioning affects Electric Vehicle energy consumption is provided in the MOVES technical report on adjustment factors.[104]

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.[105] 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 1995 for cars and 1975-1995 for light trucks. Rates in the first few years of available data were 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 were 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. Air Conditioning Activity Demand

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*.[105] 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.

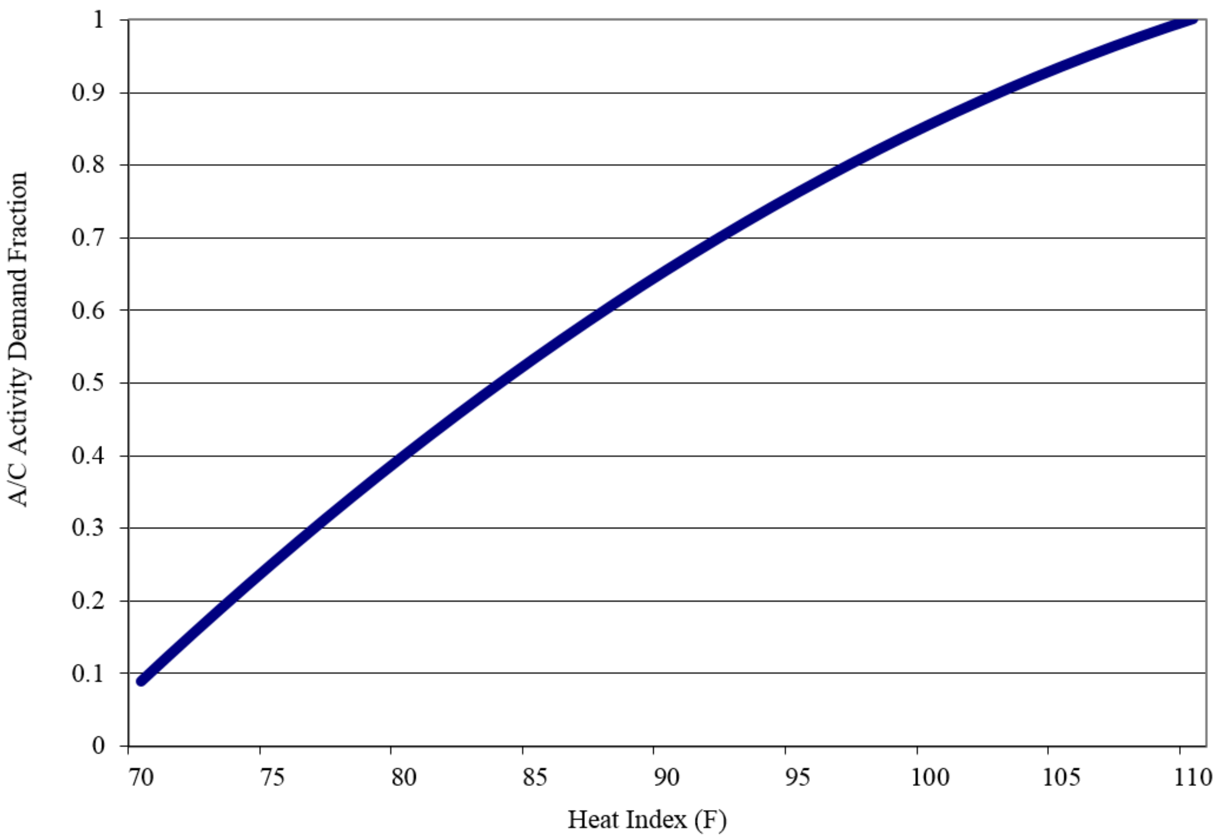


Figure 16-1 Air conditioning activity demand as a function of heat index

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 MOVES4 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.

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 recommended to replace many of the MOVES fleet and activity defaults with local data when available 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 MOVE3 were developed for a 2017 base year and much of the source data is from 2017 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.

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 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;
- Updated real-world highway driving cycles and operating mode distributions, including incorporating ramp activity into the default highway driving cycles and accounting for grade;

- 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, and variation in operating modes for different vehicle fuel types and technologies;
- 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;
- Updated information on light-duty vehicle mass;
- Information on shifts in vehicle activity patterns with population shifts to electric, shared, connected and automated vehicles.

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 the current version of MOVES, 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.

A1. Distributions for Model Years 1960-1981

The fuel type distributions between 1960 and 1981 for each source type have been summarized in Table A-1 and Table A-2. Truck diesel fractions in Table A-1 were derived using the 1999 IHS vehicle registrations and the 1997 VIUS,[106] 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 A-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

*All other trucks are assumed to be gasoline-powered. Motor homes values were estimated as described in Section 5.2.

For the non-truck source types, school bus fuel type fractions were reused from MOBILE6,[77] originally based on 1996 and 1997 IHS data, and passenger cars were split between gasoline and diesel for 1960-1981 using the 1999 IHS vehicle registrations data. As in previous versions of MOVES, motorcycles were assumed to be all gasoline.

Table A-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

*All other vehicles are assumed to be gasoline-powered. Values for Transit Buses and Other Buses were estimated as described in Section 5.2.

The 1960-1981 regulatory class distributions were derived from the 1999 IHS data 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 A-3.

Table A-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 A-4 below. All 1960-1981 gasoline-fueled single-unit and combination trucks fall into the medium heavy-duty (MHD) regulatory class (regClassID 46).

Table A-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%

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

A2. 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 A-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 A-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

* 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.

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.

Light-Duty Trucks

Light-duty trucks include pickups, sport utility vehicles (SUVs) and vans.[22] 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.

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 MOVES3, only school bus distributions for model years prior to 2000 were retained in the current version of MOVES. 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.

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 were not retained in the current version of MOVES, and therefore these vehicles are not discussed further in this section.

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.[107]

Fuel Type and Regulatory Class Distributions

The SampleVehiclePopulation table fractions were developed by EPA using the sample vehicle counts data, 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 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 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 A-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 A-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

*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,[108] summarized in Table A-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 regulatory class 41.

Table A-7 Fractions used to distribute Class 2a and 2b trucks

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, 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. Table A-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 A-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.

Table A-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 were first assigned to MOVES source types using the constraints in Table A-5**,** and then to MOVES regulatory classes using the mapping described in Table A-6, including the allocation between Class 2a and 2b trucks from the ORNL study in Table A-7. Similar to our fuel type mapping of the IHS dataset, we chose to omit alternative fuel vehicles, as summarized below in Table A-9.

Table A-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 A-1:

$$f(VIUS)_{i,j,k,l} = \frac{N_{i,j,k,l}}{\sum_{l \epsilon L} N_{i,j,k,l}}$$ **Equation A-1**

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. Expressed in Equation A-2, the sample vehicle counts are:

$$N(SVP)_{i,j,k,l} = P(Polk)_{i,j,k,l} \cdot f(VIUS)_{i,j,k,l},$$ **Equation A-2**

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.

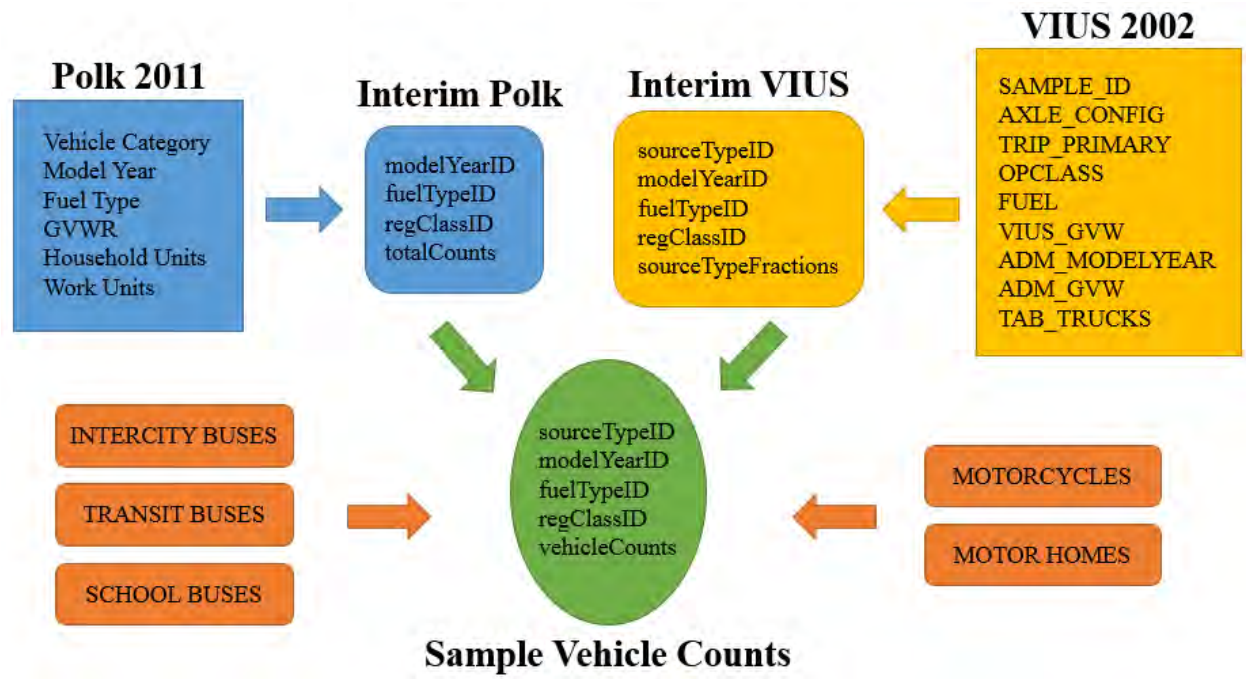


Figure A-1 Flowchart of data sources of fuel and regulatory class distributions for model years 1982-1999

These sample vehicle counts by source type were then utilized to calculate the sample vehicle population fractions, stmyFraction and stmyFuelEngFraction, as defined above. For simplicity, we also moved the small number of LHD45 (regClassID 42) vehicles in combination truck source types to MHD (regClassID 46). The source mass and road-load coefficients for combination trucks are only developed for MHD, HHD and Glider 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 the current version of MOVES. 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 A-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.[109] The school bus regulatory class distributions were also derived from 2011 FHWA data[110] as listed in Table A-11, which were applied to model years prior to 2000 for both gasoline and diesel.

Table A-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 A-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 the current version of MOVES, 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 MOVES may be found in Appendix C.

B1. 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.

B2. 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.

B3. 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 B-1. 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 B-1 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

B4. 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.

B5. 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.

B6. 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 1st 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 B-2 presents the equations used to create the age distribution and the years in which the equations were used.

Table B-2 Curve fit equations for registration distribution data by age

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

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 6.1 and presented below 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 the analysis presented in this appendix, 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.

C1. Vehicle Survival by Source Type

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.[111] Survival rates for passenger cars, passenger trucks and light commercial trucks came from NHTSA's survivability Table 3 and Table 4.[112] 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 σ_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 C-1 through Equation C-3 below:

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

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

Ages 2-30: $$s_a = s_{2\ldots30} = \frac{\sigma_{a-1}}{\sigma_{a-2}}$$ **Equation C-3**

With limited data available on heavy-duty vehicle scrappage, survivability for all other source types came from the *Transportation Energy Data Book*.[113] We used the heavy-duty vehicle survival rates for model year 1980 (TEDB40, Table 3.17). 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 C-1. Please note that since MOVES 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 the table header.

Table C-1 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	0.300	0.300	0.300	0.300

C2. 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 MOVES doesn't calculate age distributions at run time, this information isn't stored in the default database.[z] However, sales data are used in the age distribution backcasting and projection algorithms, which are described

[z] Early versions of MOVES calculated age distributions at 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 current MOVES default database.

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.

Historic motorcycles sales came from the Motorcycle Industry Council's 2015 *Motorcycle Statistical Annual*,[114] which contains estimates of annual on-highway motorcycle sales going back to 1989. Sales for calendar years 2015-2020 were estimated as a constant proportion of the total motorcycle stock, using the ratio of 2014 sales to population.

Historic passenger car sales came from the TEDB40 Table 4.6 estimate for total new retail car sales.

Historic light truck sales came from the TEDB40 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, 2020, and 2023 publications of *School Bus Fleet Fact Book*.[18] Each publication contains estimates for 10 years of historic annual national sales. Sales for before 1990 were estimated as a constant proportion of the total school bus stock, using the ratio of 1999 sales to population.

Historic transit bus sales were calculated from the Federal Transit Administration's National Transit Database (NTD)[19] 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 C-1. 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, sales for 1990 and 1999-2001 were estimated as a constant proportion of the total transit bus stock, using the ratio of 2002 sales to population.

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 C-4 below. The historic populations for each of the bus source types were determined as described in Section 4.1.

$$Sales_{other} = \frac{Sales_{school} + Sales_{transit}}{Pop_{school} + Pop_{transit}} \cdot Pop_{other}$$ **Equation C-4**

Historic sales for heavy-duty trucks were derived from the TEDB40 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 2020 IHS data. Since the 2020 IHS data 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 AEO2023. 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 4.2for the derivation of projected populations). Since AEO2023 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 C-2 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 Section4.2. 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 to derive projected sales for each source type.

Table C-2 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 AEO2023 Table 39: Light-Duty Vehicle Sales by Technology Type
[ii] From AEO2023 Table 45: Transportation Fleet Car and Truck Sales by Type and Technology
[iii] From AEO2023 Table 50: Freight Transportation Energy Use

C3. Base Year Age Distributions

Table C-3 2020 age fractions by MOVES source type

Age	11	21	31	32	41	42	43	51	52	53	54	61	62
0	0.047761	0.037546	0.057107	0.057107	0.045031	0.045031	0.045031	0.046470	0.046470	0.046470	0.046470	0.042869	0.042869
1	0.052400	0.041352	0.063106	0.140304	0.058830	0.046336	0.058979	0.060318	0.059067	0.059067	0.043827	0.045291	0.093437
2	0.046272	0.045642	0.064161	0.090038	0.054369	0.082068	0.058866	0.053975	0.045495	0.045495	0.047319	0.046055	0.050051
3	0.043723	0.052911	0.063062	0.080902	0.062808	0.087860	0.059606	0.049131	0.053115	0.053115	0.036305	0.046192	0.033916
4	0.043596	0.054667	0.057843	0.066182	0.066487	0.093850	0.052028	0.054158	0.051697	0.051697	0.041262	0.066533	0.054979
5	0.041426	0.059893	0.056042	0.059659	0.058041	0.079109	0.049169	0.042716	0.050433	0.050433	0.036367	0.055583	0.050492
6	0.039651	0.057165	0.047868	0.048493	0.049059	0.077841	0.043786	0.035514	0.032395	0.032395	0.031091	0.045340	0.037899
7	0.035567	0.060114	0.042031	0.042520	0.050891	0.063694	0.038647	0.035715	0.029942	0.029942	0.026107	0.043162	0.038171
8	0.033039	0.053182	0.036813	0.036637	0.037046	0.058783	0.041379	0.033047	0.040353	0.040353	0.019478	0.040796	0.039936
9	0.023515	0.040409	0.037550	0.033283	0.037753	0.051184	0.045872	0.024895	0.031275	0.031275	0.017785	0.022894	0.021830
10	0.018800	0.040849	0.029931	0.023765	0.037120	0.060321	0.043788	0.019612	0.014166	0.014166	0.017084	0.017332	0.020730
11	0.039971	0.036269	0.022443	0.018943	0.041298	0.058819	0.055923	0.032297	0.017457	0.017457	0.016419	0.021724	0.029756
12	0.048526	0.045040	0.038133	0.033914	0.039965	0.043701	0.057422	0.025863	0.039435	0.039435	0.024859	0.017525	0.023289
13	0.061493	0.047569	0.039925	0.029767	0.042408	0.033745	0.050565	0.075982	0.039150	0.039150	0.039191	0.045234	0.078008
14	0.060752	0.042595	0.039050	0.031243	0.040985	0.031658	0.029630	0.059385	0.046464	0.046464	0.041087	0.035303	0.048212
15	0.054562	0.039156	0.039375	0.026351	0.026023	0.022260	0.026323	0.047669	0.038304	0.038304	0.042110	0.033956	0.043353
16	0.042953	0.033351	0.039205	0.024091	0.020094	0.015748	0.028503	0.036373	0.029104	0.029104	0.046490	0.022496	0.023612
17	0.044374	0.031378	0.033688	0.020613	0.029568	0.013383	0.019932	0.037159	0.025630	0.025630	0.041247	0.021725	0.021740
18	0.033927	0.026976	0.030265	0.017589	0.028384	0.015676	0.023235	0.031347	0.024356	0.024356	0.036265	0.016992	0.014959
19	0.027320	0.022473	0.025473	0.016038	0.028227	0.009650	0.024495	0.030762	0.028509	0.028509	0.031719	0.024432	0.024225
20	0.021720	0.020538	0.022595	0.014391	0.029434	0.004137	0.021260	0.034838	0.028612	0.028612	0.035780	0.033098	0.037675
21	0.016109	0.015239	0.019057	0.012273	0.025464	0.001592	0.019068	0.026211	0.027957	0.027957	0.041354	0.028281	0.029096
22	0.011883	0.012193	0.014233	0.008508	0.020482	0.001241	0.015783	0.015993	0.014209	0.014209	0.032232	0.023972	0.019881
23	0.009585	0.009815	0.013347	0.008593	0.012043	0.000953	0.014303	0.011716	0.016581	0.016581	0.027771	0.021106	0.014253
24	0.008580	0.007195	0.009032	0.005820	0.010606	0.000666	0.011697	0.011972	0.012626	0.012626	0.024841	0.020950	0.016126
25	0.007140	0.006689	0.008858	0.005957	0.007381	0.000234	0.012115	0.013910	0.014881	0.014881	0.022691	0.026790	0.015148
26	0.005851	0.004924	0.007553	0.005018	0.005601	0.000225	0.006658	0.007677	0.010121	0.010121	0.021594	0.018307	0.011944
27	0.005229	0.004031	0.005211	0.003611	0.004737	0.000072	0.007233	0.006233	0.008673	0.008673	0.018133	0.014518	0.009581
28	0.003769	0.003459	0.003903	0.003003	0.002651	0.000027	0.006134	0.005228	0.007137	0.007137	0.015002	0.011214	0.006814
29	0.003161	0.003253	0.003326	0.002686	0.002428	0.000018	0.007586	0.005831	0.007758	0.007758	0.012387	0.011864	0.005461
30+	0.067345	0.044129	0.029811	0.032701	0.024786	0.000117	0.024985	0.028002	0.108627	0.108627	0.065731	0.078464	0.042557

C4. 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 6-1.
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.

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

$$\overrightarrow{P_{y-1}} = \overrightarrow{P_y} - \overrightarrow{N_y} + \overrightarrow{R_{y-1}} \qquad \textbf{Equation 6-2}$$

Unfortunately, as described in Section C1, 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 C-5 Note that the open circle operator ($\circ$) 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.

$$\overrightarrow{R_{y-1}} = k_{y-1} \cdot \left(1 - \overrightarrow{S_0}\right) \circ \overrightarrow{P_{y-1}} \qquad \textbf{Equation C-5}$$

Substituting Equation C-5 into Equation 6-2 yields Equation C-6:

$$\overrightarrow{P_{y-1}} = \overrightarrow{P_y} - \overrightarrow{N_y} + k_{y-1} \cdot \left(1 - \overrightarrow{S_0}\right) \circ \overrightarrow{P_{y-1}} \qquad \textbf{Equation C-6}$$

To solve for k_{y-1}, Equation C-6 can be transformed into Equation C-7 using known total populations and sales:

$$P_{y-1} = P_y - N_y + k_{y-1} \cdot \sum_a \left(\left(1 - \overrightarrow{S_0}\right) \circ \overrightarrow{P_{y-1}} \right) \qquad \textbf{Equation C-7}$$

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 C-7, 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 C-7 and then a guess for $\overrightarrow{P_{y-1}}$ is calculated from Equation C-6. 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 1×10^{-6}, which occurred within 10 iterations for most source types and calendar years.

This algorithm was then repeated for each historic year from 2019 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 C1.
- Vehicle sales N_y as described in Section C2.
- Base age distributions $\overrightarrow{f_{2020}}$ 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 1999-2019 are stored in the SourceTypeAgeDistribution table of the default database.

C5. 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 6-1.
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):

$$\overrightarrow{P_{y+1}} = \overrightarrow{P_y} - \overrightarrow{R_y} + \overrightarrow{N_{y+1}} \qquad \textbf{Equation 6-3}$$

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 6-3 and Equation C-5 can be combined into Equation C-8:

$$\overrightarrow{P_{y+1}} = \overrightarrow{P_y} - k_y \cdot (1 - \overrightarrow{S_0}) \circ \overrightarrow{P_y} + \overrightarrow{N_{y+1}} \qquad \textbf{Equation C-8}$$

To solve for k_y, Equation C-8 can be transformed into Equation C-9 using the population and sales totals:

$$P_{y+1} = P_y - k_y \sum_a \left((1 - \overrightarrow{S_0}) \circ \overrightarrow{P_y} \right) + N_{y+1} \qquad \textbf{Equation C-9}$$

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 back-casting 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 C-8 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 2021 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 C1.
- Vehicle sales N_{y+1} as described in Section C2.
- Base age distributions $\overrightarrow{f_{2020}}$ 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 2021-2060 and are stored in the SourceTypeAgeDistribution table of the default database. An illustration of passenger car age distributions is presented in Figure C-1. For clarity, only four years are shown: 2014, 2020, 2030 and 2040.

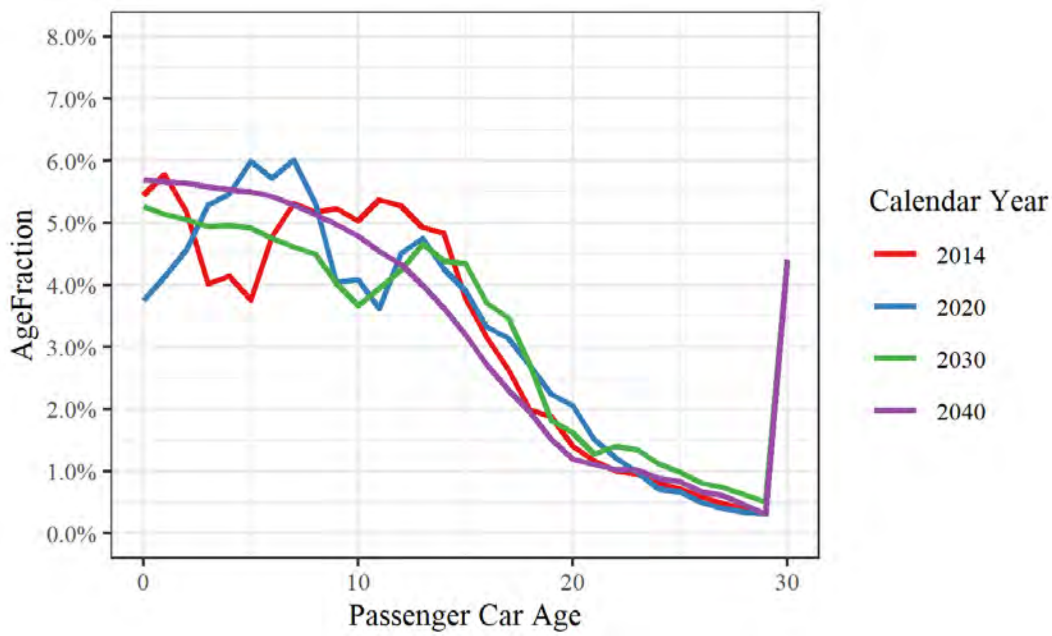


Figure C-1 Selected age distributions for passenger cars in MOVES4

Appendix D 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, MOVES4 employs 49 drive schedules with various average speeds, mapped to specific source types and roadway types. These are unchanged from MOVES2014.

Table D-1 below lists the driving schedules used in MOVES. 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 D-1 MOVES 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
397	MD High Speed Freeway Plus 5mph	77.8	85.40	0	0.0%	103.363	4782.00	79.70	1.328

Drive Schedule ID	Drive Schedule Name	Avg Speed	Max Speed	Idle Time (sec)	Percent of Time Idling	Miles	Time (sec)	Minutes	Hours
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 E Total Idle Fraction Regression Coefficients

Table E-1 displays the regression coefficients for the linear model used to estimate variation in total idle fraction for light-duty vehicles presented in Equation 10-6 discussed in Section 10.2.3.

Table E-1 Total idle fraction regression coefficients for light-duty vehicles trucks in urban counties for weekdays

Variable	Coefficients	Comments
(Intercept)	0.20977	
dayID5	0.011262	Applicable when dayID=5
sourceTypeID31	0.001329	Applicable when sourceTypeID=31
countyTypeID1	0.03058	Applicable when equation is used for an urban county (countyTypeID=1)
idleRegionID104	0.021342	Applicable when idleRegionID=104
idleRegionID102	0.026097	Applicable when idleRegionID=102
idleRegionID103	0.05461	Applicable when idleRegionID=103
idleRegionID101	0.057216	Applicable when idleRegionID=101
monthID2	0.002789	Applicable when monthID=2
monthID3	-0.00429	Applicable when monthID=3
monthID4	-0.00609	Applicable when monthID=4
monthID5	-0.00412	Applicable when monthID=5
monthID6	-0.00264	Applicable when monthID=6
monthID7	0.002914	Applicable when monthID=7
monthID8	-0.00066	Applicable when monthID=8
monthID9	-0.00296	Applicable when monthID=9
monthID10	0.007288	Applicable when monthID=10
monthID11	0.00585	Applicable when monthID=11
monthID12	0.007586	Applicable when monthID=12
idleRegionID104:monthID2	-0.01478	Applicable when monthID=2 and idleRegionID=104
idleRegionID102:monthID2	-0.00664	Applicable when monthID=2 and idleRegionID=102
idleRegionID103:monthID2	-0.0173	Applicable when monthID=2 and idleRegionID=103
idleRegionID101:monthID2	-0.01595	Applicable when monthID=2 and idleRegionID=101
idleRegionID104:monthID3	-0.02666	Applicable when monthID=3 and idleRegionID=104
idleRegionID102:monthID3	-0.01167	Applicable when monthID=3 and idleRegionID=102
idleRegionID103:monthID3	-0.04358	Applicable when monthID=3 and idleRegionID=103
idleRegionID101:monthID3	-0.0334	Applicable when monthID=3 and idleRegionID=101
idleRegionID104:monthID4	-0.02855	Applicable when monthID=4 and idleRegionID=104
idleRegionID102:monthID4	-0.01194	Applicable when monthID=4 and idleRegionID=102
idleRegionID103:monthID4	-0.04759	Applicable when monthID=4 and idleRegionID=103
idleRegionID101:monthID4	-0.03841	Applicable when monthID=4 and idleRegionID=101
idleRegionID104:monthID5	-0.04011	Applicable when monthID=5 and idleRegionID=104
idleRegionID102:monthID5	-0.01453	Applicable when monthID=5 and idleRegionID=102
idleRegionID103:monthID5	-0.05713	Applicable when monthID=5 and idleRegionID=103
idleRegionID101:monthID5	-0.0465	Applicable when monthID=5 and idleRegionID=101
idleRegionID104:monthID6	-0.04388	Applicable when monthID=6 and idleRegionID=104
idleRegionID102:monthID6	-0.01298	Applicable when monthID=6 and idleRegionID=102
idleRegionID103:monthID6	-0.05729	Applicable when monthID=6 and idleRegionID=103
idleRegionID101:monthID6	-0.05025	Applicable when monthID=6 and idleRegionID=101
idleRegionID104:monthID7	-0.04935	Applicable when monthID=7 and idleRegionID=104
idleRegionID102:monthID7	-0.0138	Applicable when monthID=7 and idleRegionID=102
idleRegionID103:monthID7	-0.06494	Applicable when monthID=7 and idleRegionID=103
idleRegionID101:monthID7	-0.05502	Applicable when monthID=7 and idleRegionID=101

Variable	Coefficients	Comments
idleRegionID104:monthID8	-0.04589	Applicable when monthID=8 and idleRegionID=104
idleRegionID102:monthID8	-0.01495	Applicable when monthID=8 and idleRegionID=102
idleRegionID103:monthID8	-0.06051	Applicable when monthID=8 and idleRegionID=103
idleRegionID101:monthID8	-0.05	Applicable when monthID=8 and idleRegionID=101
idleRegionID104:monthID9	-0.04807	Applicable when monthID=9 and idleRegionID=104
idleRegionID102:monthID9	-0.02195	Applicable when monthID=9 and idleRegionID=102
idleRegionID103:monthID9	-0.06001	Applicable when monthID=9 and idleRegionID=103
idleRegionID101:monthID9	-0.04851	Applicable when monthID=9 and idleRegionID=101
idleRegionID104:monthID10	-0.05049	Applicable when monthID=10 and idleRegionID=104
idleRegionID102:monthID10	-0.03221	Applicable when monthID=10 and idleRegionID=102
idleRegionID103:monthID10	-0.06831	Applicable when monthID=10 and idleRegionID=103
idleRegionID101:monthID10	-0.05287	Applicable when monthID=10 and idleRegionID=101
idleRegionID104:monthID11	-0.02092	Applicable when monthID=11 and idleRegionID=104
idleRegionID102:monthID11	-0.0262	Applicable when monthID=11 and idleRegionID=102
idleRegionID103:monthID11	-0.04514	Applicable when monthID=11 and idleRegionID=103
idleRegionID101:monthID11	-0.04651	Applicable when monthID=11 and idleRegionID=101
idleRegionID104:monthID12	-0.0075	Applicable when monthID=12 and idleRegionID=104
idleRegionID102:monthID12	-0.02558	Applicable when monthID=12 and idleRegionID=102
idleRegionID103:monthID12	-0.04263	Applicable when monthID=12 and idleRegionID=103
idleRegionID101:monthID12	-0.04724	Applicable when monthID=12 and idleRegionID=101

Table E-2 shows a sample calculation of MOVES default total idle fractions using the coefficients for passenger cars (sourceTypeID=21) in rural counties (countyTypeID=0) in idleRegionID=101 (represented by New Jersey). The total idle fractions for all the sourceTypeID 21 and 32 derived from the TIF regression equation is available in the MOVES totalIdleFraction table.

Table E-2 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 F Source Masses for Light-Duty Vehicles

In MOVES4, the source masses of light-duty vehicles were unchanged from MOVES3, MOVES2014 and MOVES2010b. This appendix describes the derivation of these source masses. Information on the updated source masses for heavy-duty vehicles is provided in Section 15.

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 F-1, each source type's source mass was calculated using an activity-weighted average of their associated source bins' midpoint weights:

$$M = \frac{\sum_a \left\{ f_a \cdot \left(\frac{\sum_b \alpha_b \cdot m}{\sum_b \alpha_b} \right) \right\}}{\sum_a f_a}$$

Equation F-1

where M is the source mass factor for the source type, f_a is the age fraction at age a, α_b is the source bin activity fraction for source bin b and m is the vehicle midpoint mass. Table F-1 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 F-1 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 light-duty vehicles in MOVES.

F1. 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 were 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 F-2.

Table F-2 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. 50%: 500lbs. -700lbs.
280+ cc (9)	0.792	0.792	0.908	0.928	30%: 500 lbs.-700 lbs. 70%: > 700lbs.

F2. 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 were 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.

F3. Light-Duty Trucks

Light truck weights came from VIUS1997 data, which 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.[115] data, to correlate engine size with vehicle weight distributions by model year.

For source types 31 and 32 (Passenger Trucks and Light Commercial Trucks) in regClassID 30 (Light-Duty 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.

Note that the source mass for source types 31 and 32 in regClassID 41 (class 2b trucks) was calculated as described in Section 15.

Appendix G NREL Fleet DNA Preprocessing Steps

This appendix 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 G-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.

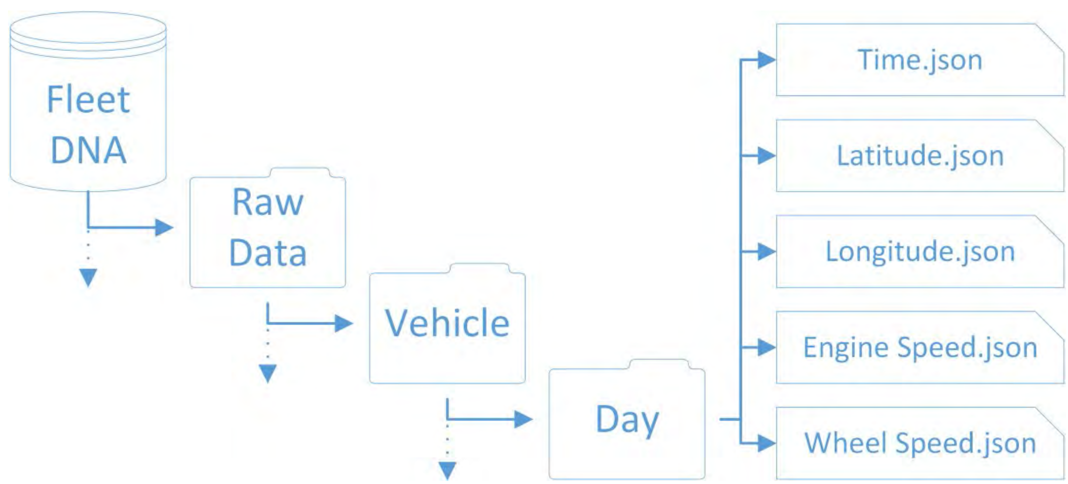


Figure G-1 Diagram of Fleet DNA database file structure

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 its 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 G-2 and Figure G-3 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 G-2 and Figure G-3 to demonstrate what effect changes in gap length might have. Figure G-2 provides the distributions for source type 62 which consists of combination long-haul trucks that have very few starts per day and Figure G-3 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.

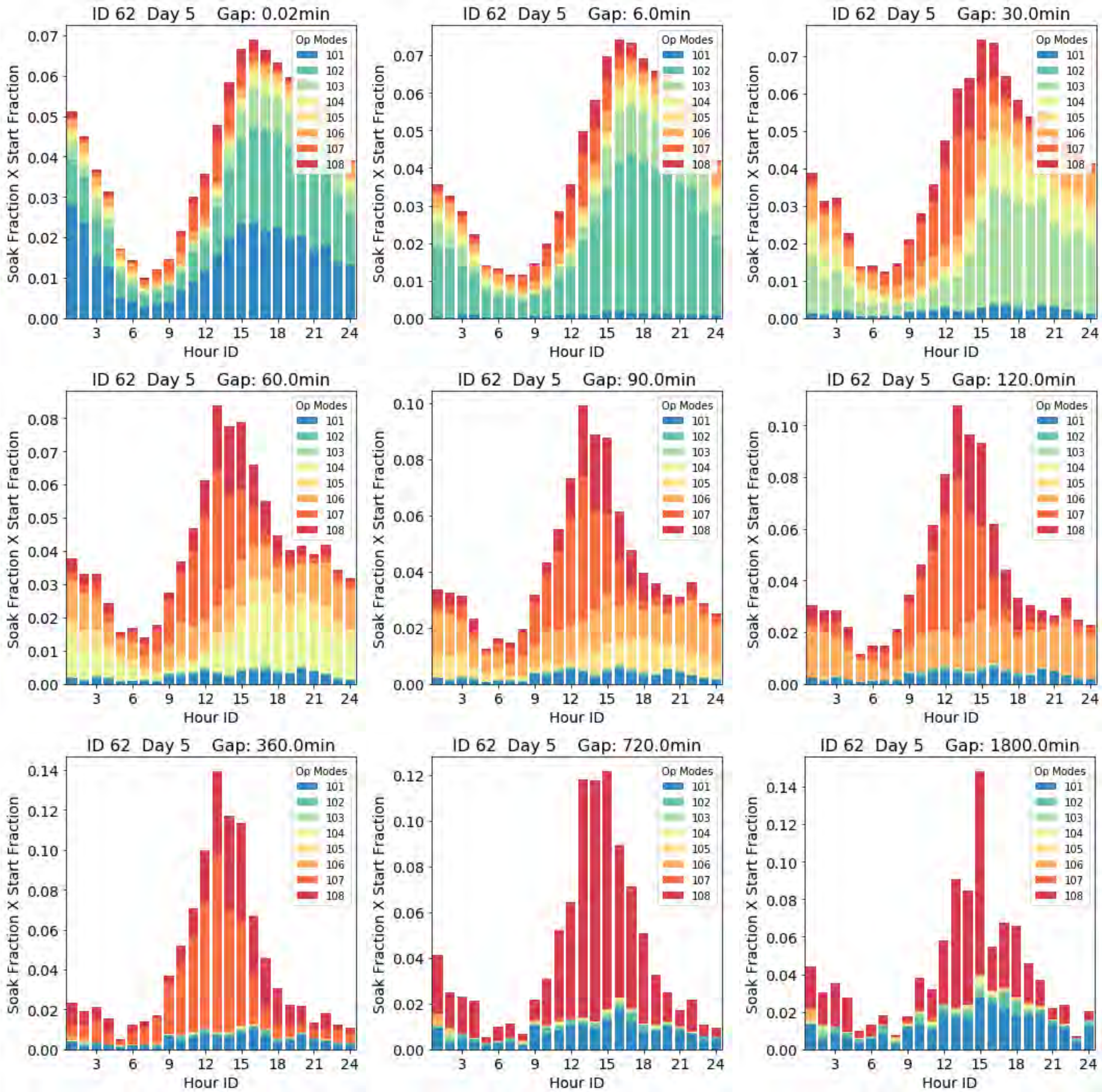


Figure G-2 Start fraction weights soak distribution weighted by gap length: source type 62

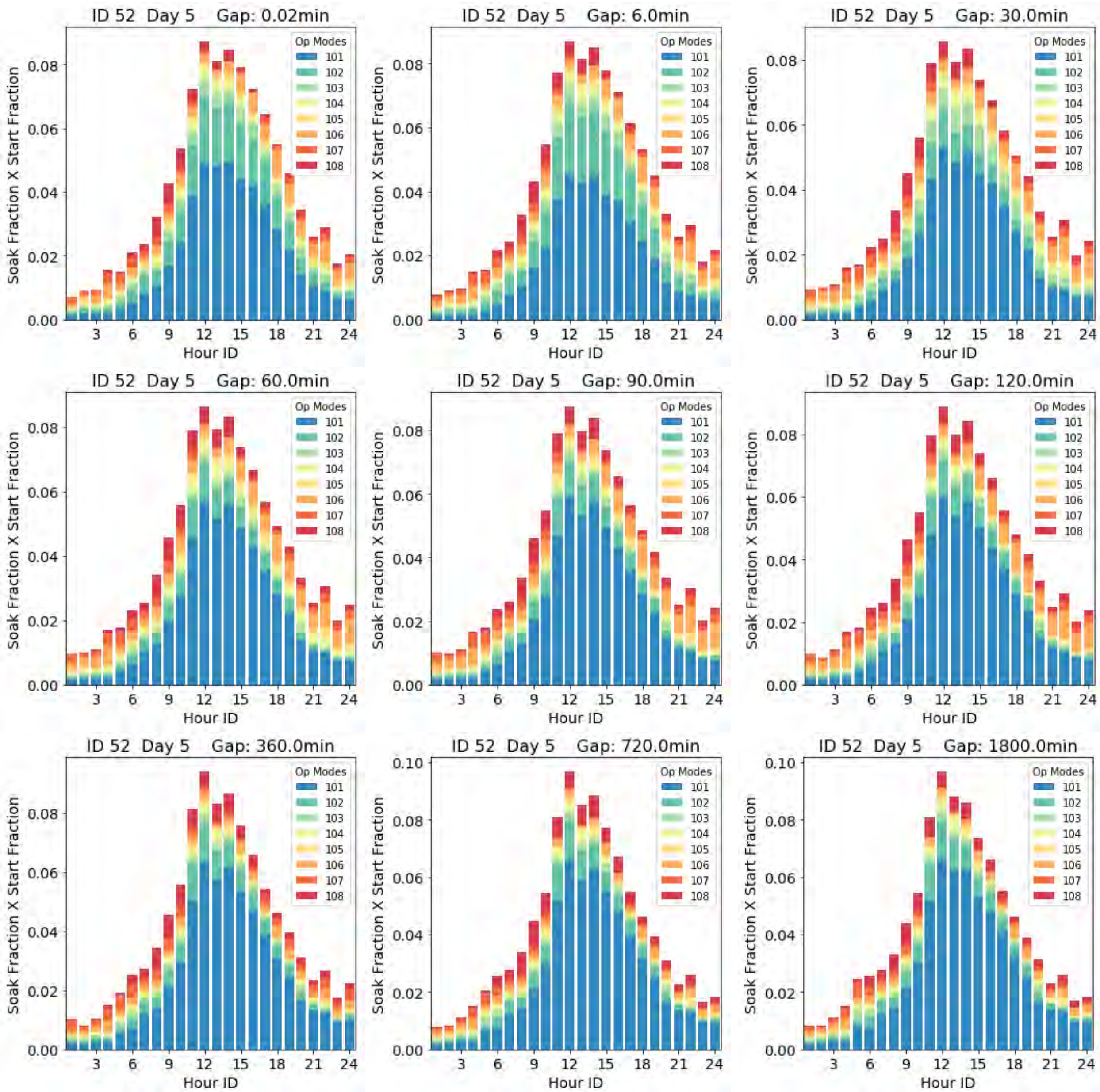


Figure G-3 Start fraction weights soak distribution weighted by gap length: source type 52

Appendix H Averaging Methods for Heavy-duty Telematics Activity Data

Telematics data provides great detail on vehicle activity, but to calculate MOVES inputs for heavy duty starts, soaks and idle fractions, we need to compute averages across the available data. Because different averaging methods lead to different results, we evaluated several different approaches to calculating these averages. The following discussion uses the calculation of the idle fraction by sourcetypeID and dayID (weekend and weekday) to illustrate the strengths and weaknesses of each of the methods.

H1. Evaluated Methods

Initally, we used Method 1 (**Equation H-1**) to average the idle fractions across all vehicles within the same sourcetypeID and day ID (weekday vs weekend). Method 1 could also be referred to as an average of ratios. We initially chose to use Method 1 because it is simple to implement and it equally weights each vehicle in the sample.

Method 1 – "Average of Ratios"

$$Idle\ fraction_{s,d} = \frac{\sum Idle\ fraction_i}{n}$$

i = individual vehicle ID
n = vehicles sampled within each sourcetype
s = source type ID
d = day type ID

Equation H-1

However, to estimate a representative idle fraction, the vehicle should be weighted by its contribution to real-world activity. By weighting each individual vehicle idle fraction equally, Method 1 over-represents the vehicles with little real-world activity (with possibly unrealistic idle fractions) and under-respresents the idle fractions from the vehicles with the most activity.

We then considered Method 2, shown in **Equation H-2**, which is referred to as the "Sum over Sum Method." In Method 2, the average is weighted according to vehicle activity. Vehicles that are operated for long work days will have more operating hours and idle hours than vehicles that are only operated intermittently. Multiplying the *Idle fraction* estimated from Method 2 by the the total operating hours, $\sum operating\ hours_i$, will yield the total idle hours, $\sum idle\ hours_i$, measured in our sample. This property assures that the relationship between idle hours and operating time is consistent between our model estimates and the source data.

Method 2 – "Sum over Sum"

$$Idle\ fraction_{s,d} = \frac{\sum idle\ hours_i}{\sum operating\ hours_i}$$

i = individual vehicle ID
s = source type ID
d = day type ID

Equation H-2

One disadvantage of Method 2 is that the *Idle fraction* is dependent on the instrumentation time. For example, a vehicle that is instrumented for two months will be weighted twice as much in the idle fraction calculation as a vehicle with the same duty cycle that is only measured for one month. In some cases, using more information from vehicles that are instrumented longer would be a desirable property; however, if instrumentation times are not random, this can skew the average to overrepresent certain groups of vehicles. For example, we hope in the future to develop idle, start and soak inputs from multiple datasets with different instrumentation times, such as the Fleet DNA dataset with an average instrumentation time of 35 days/vehicle and the HD SCR (CE-CERT) data with an 86-day average instrumentation time. Using Method 2 to combine data from these two datasets, the HD SCR vehicle data would be weighted twice as much as the vehicles in the Fleet DNA sample. This is undesirable, because we have no reason to assume that the HD SCR sample vehicles are more representative of the national fleet than the Fleet DNA sample vehicles.

In Method 3, we propose using a "Normalized Sum over Sum" approach as shown in Equation H-3. Method 3 is similar to Method 2, except that the sum of idle hours and the operating hours from each vehicle is divided (or normalized) by the number of days each sample vehicle was instrumented. Method 3 controls for the different lengths of time each vehicle is instrumented and the *Idle fraction* is weighted most heavily by the vehicles with the most daily average activity, rather than the most measured activity. Method 3 (Equation H-3) is the current approach we are using for developing MOVES inputs and is equivalent to

Equation 10-7 presented in Section 10.

Method 3 – "Normalized Sum over Sum"

$$Idle\ fraction_{s,d} = \frac{\sum \left({idle\ hours_i}/{days_i} \right)}{\sum \left({operating\ hours_i}/{days_i} \right)}$$

i = individual vehicle ID
days$_i$ = # of days vehicle$_i$ is instrumented
s = source type ID
d = day type ID

Equation H-3

The methods we explained above are also applicable to estimating start fractions. The start fraction determines at fraction of total daily starts occur at each hour of the day. The following table contains the equations for the start fractions for each of the three methods.

Method 1 – "Average of Ratios"

$$Start\ fraction_{h,s,d} = \frac{\sum Start\ fraction_{h,i}}{n}$$

h= hour of the day
i = individual vehicle ID
n = # of sampled vehicles
s = source type ID
d = day type ID

Equation H-4

$$Start\ fraction_{h,s,d} = \frac{\sum starts_{h,i}}{\sum starts_i}$$

Method 2 – "Sum over Sum"

h= hour of the day
i = individual vehicle ID
s = source type ID
d = day type ID

Equation H-5

$$Start\ fraction_{h.s.d} = \frac{\sum \left({starts_{h,i}}/{days_i} \right)}{\sum \left({starts_i}/{days_i} \right)}$$

Method 3 – "Normalized Sum over Sum"

h= hour of the day
i = individual vehicle ID
$days_i$ = days $vehicle_i$ is instrumented
s = source type ID
d = day type ID

Equation H-6

The three different averaging method was also applied for calculating the soak fractions in the table below. The soak fraction determines the distribution of starts occuring for the 8 different start operating modes in MOVES (or soak lengths) as defined in Table 12-3.

$$Soak\ fraction_{h,o,s,d} = \frac{\sum Soak\ fraction_{h,i,o}}{n}$$

Method 1 – "Average of Ratios"

h= hour of the day
i = Vehicle ID
n = # of sampled vehicles
s = source type ID
d = day type ID

Equation H-7

$$Soak\ fraction_{h,o,s,d} = \frac{\sum starts_{h,i,o}}{\sum starts_{h,i}}$$

Method 2 – "Sum over Sum"

h= hour of the day
i = Vehicle ID
o = operating mode (soak length)
s = source type ID
d = day type ID

Equation H-8

$$Soak\ fraction_{h,o,s,d} = \frac{\sum \left({starts_{h,i,o}}/{days_i} \right)}{\sum \left({starts_{h,i}}/{days_i} \right)}$$

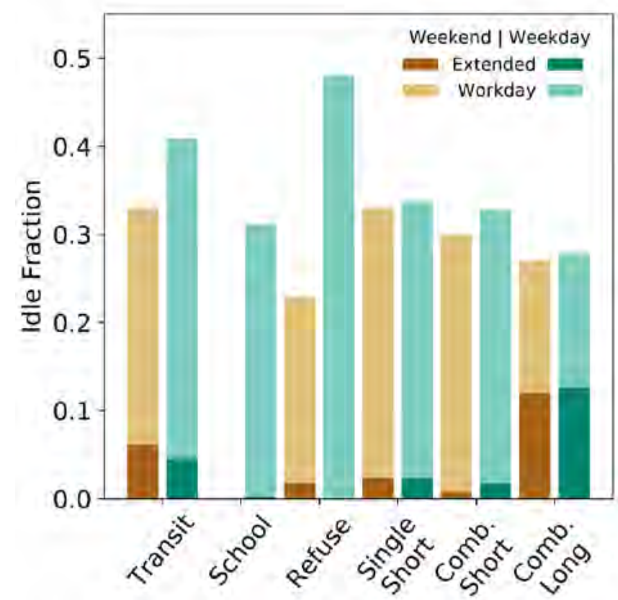
Method 3 – "Normalized Sum over Sum"

h= hour of the day
i = Vehicle ID
o = operating mode (soak length)
$days_i$ = days $vehicle_i$ is instrumented
s = source type ID
d = day type ID

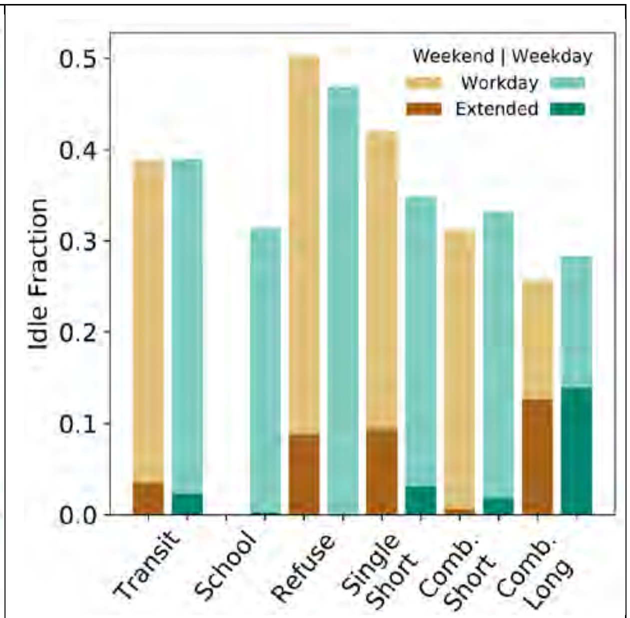
Equation H-9

H2. Comparison of Evaluated Methods

Figure H-1 graphically compares the idle fractions calculated using Method 1 and Method 3, using the data for single-unit short-haul trucks. In the graph, the darker colors represent idling that is over 1 hour in duration, classified as extended idle. The height of the bars represents the total idle fraction. For refuse trucks and single-unit short haul trucks there is a significantly higher idle fraction on the weekends, when using method 3. This implies that the refuse and single unit truck vehicles that operate most on the weekend, also have higher idle fractions. Method 3 appropriately weights the idle fractions from each vehicle according to its average daily activity.



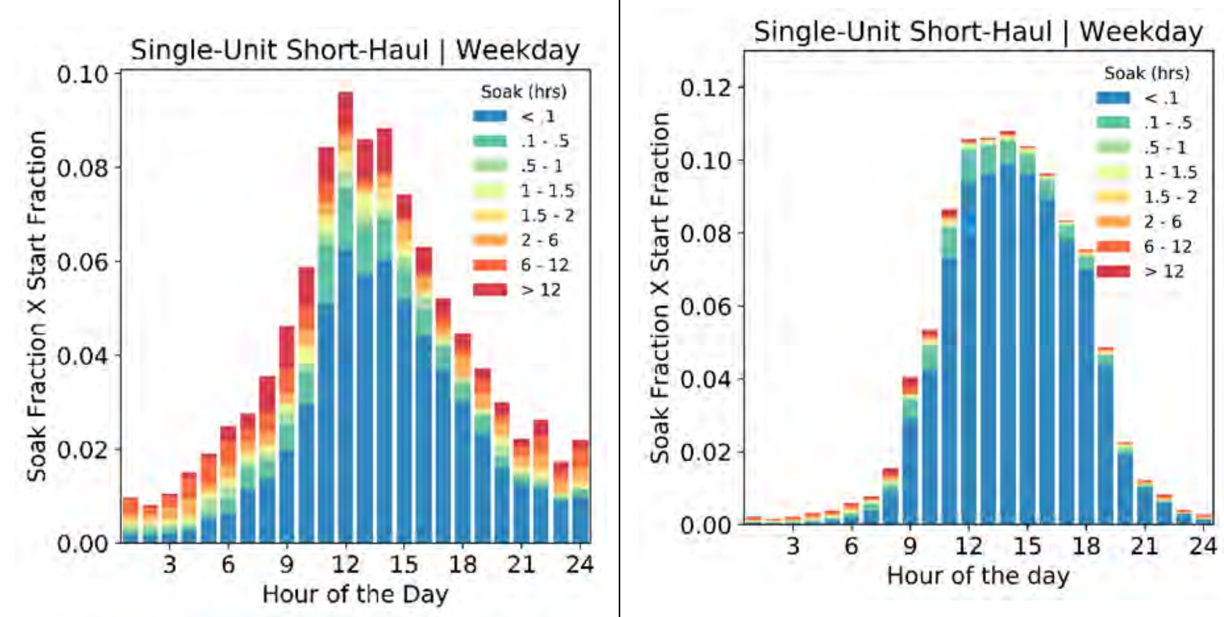
Method 1 "Average of Ratios"



Method 3 "Normalized Sum over Sum"

Figure H-1. Idle fraction calculated using Method 1 and Method 3.

Figure H-2 graphically compares the start fractions and soak fractions calculated using Method 1 and Method 3, using the data for single-unit short-haul trucks on weekdays. The start distribution calculated with Method 1 weights all vehicles the same and thus overrepresents the start times and soak times of vehicles which have few starts (and long soak periods). With Method 3 the start and soak distribution more accurately characterize all the starts. The start distribution with Method 3 is dominated by vehicles that have many starts per day. The starts occur more evenly across the work-day and have shorter soak periods. Because emission rates increase with longer soak periods, the differences in averaging methods can have significant impacts on the total emissions, as well as the temporal allocation of the emissions.



Method 1 "Average of Ratios"	Method 3 "Normalized Sum over Sum"

Figure H-2 Start fraction and Soak fraction calculated using Method 1 and Method 3.

H3. Future Work

The previous methods are all based on the assumption that the sample of vehicles are representative of the entire vehicle population. However, as presented in Section 12.12.2.2, there is significant variation in idle fractions and starts per day by truck vocation within the MOVES sourcetypes. For example, parcel delivery trucks and concrete mixers are are both single unit short haul trucks, but parcel delivery trucks have many more starts per day in the Fleet DNA database.

The truck samples we are currently using (FleetDNA) and which we intend to use in the future (CE-CERT), made efforts to collect data from a variety of important vocational classes. However, the truck samples in these programs were not systematically chosen to be representative of U.S. truck vocations. To address this deficiency, we would like to use a method that weights each vehicle according to its average activity as well as the population of each vocation. The proposed Method 4 "Vocation and Activity Weighted fraction" would use a weighting factor to weight the vehicles within each vocation according to how many vehicles were sampled, compared to how many exist in the national population.

Method 4 – "Vocation and Activity Weighted fraction"

$$Idle\ fraction_{s,d} = \frac{\sum\left({}^{idle\ hours_i}/_{days_i} \times w_v\right)}{\sum\left({}^{operating\ hours_i}/_{days_i} \times w_v\right)}$$

Equation H-10

i = individual vehicle ID
$days_i$ = # of days $vehicle_i$ is instrumented
v = vehicle vocation
w_v= (population/sample size of each vocation, v)
s = source type ID
d = day type ID

In practice, we are not yet able to implement Method 4, because we are unable to accurately map instrumented truck vocations to national truck populations because we lack information on both parts of the equation.

1) We lack information on the total number of vehicles in each vocation. The IHS vehicle registration data provides sufficient information to classify trucks by the MOVES sourcetype, but not by vocation or specific firm. Some are characterized by the industry sector of the firm that owns the truck, but, with large populations of trucks classified in sectors such as: individual, general freight, government/miscellaneous, lease/rental, wholesale/retail, manufacturing and services, these sector distinctions are insufficient to determine the vocation of the truck. For example, should a "service truck" be classified as a utility truck or a single unit box delivery truck?

2) The trucks in the Fleet DNA database only represent a subset of truck vocations classified by these industrial sectors. For example, we do not have instrumented truck data from many of the industry sectors in the registration data including: agriculture/farm, petroleum, landscaping, mining, logging and emergency vehicles,

Additional work is needed to have confidence that the additional data needs and complexity of Method 4 would yield meaningful improvements in emissions accuracy.

Appendix I Road Load Coeffiecient for Combination Trucks in HD GHG Rule

In the HD GHG rules, 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. While trailers were ultimately not regulated in Phase 2, new test procedures were developed for trailers 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 modeled 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 analysis, the drag value is represented by the aerodynamic drag area, C_dA. In the trailer analysis, the drag value is represented as a reduction in drag area, ΔC_dA, relative to a commonly available baseline trailer that is not equipped with aerodynamic devices.

The GHG rules also create bins for aerodynamic certification, so that a precise drag value is not needed to certify every tractor. 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 analysis 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 ΔC_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 respectively below in Table I-1 and Table I-2[116] [117] The trailer bin structure is common to all box van trailer types.

Table I-1 Phase 2 GHG Aerodynamic Drag Area Bin Structure for Tractors [m²]

	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 I-2 Phase 2 GHG Aerodynamic Drag Area Bin Structure for Box Van Trailers [m^2]

Trailer ΔC_dA Bin	ΔC_dA range	ΔC_dA input for GEM	Midpoint of ΔC_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. Mid-roof tractors are matched with tank trailers and low-roof tractors are matched with flatbed trailers.

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 J-1) 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 I-3.

Table I-3 Tractor aerodynamic technology adoption rates by model year groups

	Tractor Bin	Tractor Bin C_dA 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 C_dA (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 C_dA (w/o skirt) [m^2]		**7.22**	**6.45**	**6.23**	**6.07**	**5.81**

	Tractor Bin	Tractor Bin C_dA 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 day cabs	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 C_dA (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 C_dA (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 C_dA [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 C_dA [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 C_dA [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 C_dA [m^2]		**6.00**	**5.41**	**5.24**	**5.16**	**5.12**

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.[118] Therefore, 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 2014-2017 reflect voluntary improvements to trailer aerodynamics. Since trailers were not regulated in the Phase 2 HDGHG rulemaking and lacking data on further voluntary improvements, trailer aerodynamics for model years 2018 and beyond are modeled as MY2017.

Table I-4 shows the trailer technology adoption rates were used to determine the average $\Delta C_d A$ by model year group for for several trailer categories. Long box vans represent 53-ft box van trailers. 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 I-4 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%	55%	55%	55%	55%
	II	0%	0%	0%	0%	0%	0%	0%
	III	0%	35%	40%	40%	40%	40%	40%
	IV	0%	0%	5%	5%	5%	5%	5%
	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 ΔC_dA [m^2]	**0**	**0.1925**	**0.2625**	**0.2625**	**0.2625**	**0.2625**	**0.2625**
Short box vans	I	100%	100%	100%	100%	100%	100%	100%
	II	0%	0%	0%	0%	0%	0%	0%
	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 ΔC_dA [m^2]	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Partial-aero long box vans	I	100%	100%	100%	100%	100%	100%	100%
	II	0%	0%	0%	0%	0%	0%	0%
	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 ΔC_dA [m^2]	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Partial-aero short box vans	I	100%	100%	100%	100%	100%	100%	100%
	II	0%	0%	0%	0%	0%	0%	0%
	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 ΔC_dA [m^2]	**0**	**0**	**0**	**0**	**0**	**0**	**0**

The average ΔC_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 I-5 was used. Trailers in the non-aero category are incompatible with aerodynamic improvements and 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 I-5 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 ΔC_dA values by model year group and tractor category are listed in Table I-6. Trailer aerodynamic improvements are calculated using the trailer distribution shown in Table I-5 and the adoption rates of Table I-4. The average C_dA for a tractor-trailer combination by model year can be calculated by subtracting the average trailer ΔC_dA values from the average tractor C_dA values in Table I-3.

Table I-6 Average trailer ΔC_dA values by tractor category and model year group [m^2]

Category \ Model years	Pre-2008	2008-2013	2014-2017	2018-2020	2021-2023	2024-2026	2027+
High-roof sleeper cab	0	0.140	0.192	0.192	0.192	0.192	0.192
High-roof day cab	0	0	0	0	0	0	0

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

Table I-7 Drag area, C_dA [m^2], by tractor-trailer subcategory and model year group

Category \ Model years	Pre-2008	2008-2013	2014-2017	2018-2020	2021-2023	2024-2026	2027+
High-roof sleeper cab	7.2200	7.0798	6.2584	6.2584	6.0384	5.8784	5.6184
High-roof day cab	7.5200	7.5200	6.9250	6.9250	6.5550	6.3700	6.2150
Mid-roof sleeper cab	7.0000	7.0000	6.4225	6.4225	6.3250	6.2500	6.2100
Mid-roof day cab	7.0000	7.0000	6.4800	6.4800	6.3250	6.2500	6.2100
Low-roof sleeper cab	6.0000	6.0000	5.3450	5.3450	5.2400	5.1600	5.1200
Low-roof day cab	6.0000	6.0000	5.4100	5.4100	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 I-9 was calculated using the distribution from Table I-8 and the drag areas from Table I-7.

Table I-8 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 I-9 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	7.0136	6.2373	6.2373	6.0415	5.8982	5.6822
Day cab (sourceType 61)	6.6840	6.6840	6.1390	6.1390	5.8926	5.7717	5.6832

To convert from C_dA to the C coefficient, Equation 15-11 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 shown in Table I-10.

Table I-10 C coefficients [kW-s^3/m^3] of source types 61 and 62 by model year group

			2014-2017	2018-2020	2021-2023	2024-2026	2027+
Sleeper cab (sourceType 62)			0.00380	0.00380	0.00369	0.00360	0.00347
Day cab (sourceType 61)			0.00374	0.00374	0.00359	0.00352	0.00347

The Phase 1 and Phase 2 GHG emission standards also project improvements to the tire rolling resistance. MOVES3 reflected 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 where *g* is the gravitational acceleration:

$$A = C_{RR} M g \qquad \textbf{Equation I-1}$$

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 and drive tires for all model years.[119] [120] The overall rolling resistance of the vehicle is a weighted average of rolling resistance over axle based on axle loading.

$$C_{RR} = C_{RR,steer}\frac{M_{steer}}{M} + C_{RR,drive}\frac{M_{drive}}{M} + C_{RR,trailer}\frac{M_{trailer}}{M} \qquad \textbf{Equation I-2}$$

Tire rolling resistance for tractor-trailers was updated using the same tractor type distributions described in Table I-8. Rolling resistance distributions, based on tire rolling resistance levels from the GHG rules are shown in Table I-11.

Table I-11 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	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%	100%	100%	100%	100%
		3	5.1	0%	0%	0%	0%	0%	0%
		4	4.7	0%	0%	0%	0%	0%	0%
		Avg Crr [kg/metric ton]		**6.0**	**6.0**	**6.0**	**6.0**	**6.0**	**6.0**
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%	100%	100%	100%
		2	6.0	0%	0%	0%	0%	0%	0%
		3	5.1	0%	0%	0%	0%	0%	0%
		4	4.7	0%	0%	0%	0%	0%	0%
		Avg Crr [kg/metric ton]		**6.5**	**6.5**	**6.5**	**6.5**	**6.5**	**6.5**

Table I-11 (Continued) 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	2018-2020	Phase 2 GHG 2021-2023	Phase 2 GHG 2024-2026	Phase 2 GHG 2027+
High-roof day cabs	Steer tire	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%	0%	0%	0%	0%
		2	6.0	100%	100%	100%	100%	100%	100%
		3	5.1	0%	0%	0%	0%	0%	0%
		4	4.7	0%	0%	0%	0%	0%	0%
		Avg Crr [kg/metric ton]		**6.0**	**6.0**	**6.0**	**6.0**	**6.0**	**6.0**
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%	100%	100%	100%
		2	6.0	0%	0%	0%	0%	0%	0%
		3	5.1	0%	0%	0%	0%	0%	0%
		4	4.7	0%	0%	0%	0%	0%	0%
		Avg Crr [kg/metric ton]		**6.5**	**6.5**	**6.5**	**6.5**	**6.5**	**6.5**
Vocational tractors	Steer tire	Base	7.8	100%	40%	40%	15%	10%	5%
		1	6.6	0%	50%	50%	35%	20%	10%
		2	5.7	0%	10%	10%	50%	50%	50%
		3	4.9	0%	0%	0%	0%	20%	35%
		Avg Crr [kg/metric ton]		**7.8**	**6.99**	**6.99**	**6.33**	**5.93**	**5.615**
	Drive tire	Base	8.1	100%	40%	40%	15%	10%	5%
		1	6.9	0%	50%	50%	35%	20%	10%
		2	6.0	0%	10%	10%	50%	50%	55%
		3	5.0	0%	0%	0%	0%	20%	30%
		Avg Crr [kg/metric ton]		**8.1**	**7.29**	**7.29**	**6.63**	**6.19**	**5.895**
	Trailer tire	1	6.5	100%	100%	100%	100%	100%	100%
		2	6.0	0%	0%	0%	0%	0%	0%
		3	5.1	0%	0%	0%	0%	0%	0%
		4	4.7	0%	0%	0%	0%	0%	0%
		Avg Crr [kg/metric ton]		**6.5**	**6.5**	**6.5**	**6.5**	**6.5**	**6.5**

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.[aa] The result is shown in Table I-12.

Table I-12 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	6.438	6.142	5.984	5.876
High-roof day cab	7.163	6.628	6.628	6.142	5.984	5.876
Low and Mid-roof sleeper cab	7.375	6.840	6.840	6.486	6.384	6.263
Low-roof day cab	7.375	6.909	6.909	6.486	6.384	6.263
Vocational tractor	7.375	6.909	6.909	6.530	6.283	6.110

Using the roof height distributions in Table I-8, the resulting Crr values are:

Table I-13 C_{rr} [kg/metric ton] values by model year group

	Pre-2014	2014-2017	2018-2020	2021-2023	2024-2026	2027+
Sleeper cab (sourceType 62)	7.2050	6.5185	6.5185	6.2109	6.0640	5.9537
Day cab (sourceType 61)	7.2794	6.2298	6.2298	5.8124	5.6932	5.5880

To calculate the A coefficient, **Equation I-1** was used in combination with the source mass values and Crr values from Table I-13. Resulting A coefficients by model year group are shown in Table I-14.

Table I-14 A coefficient values [kW-s/m] by model year group

		2014-2017	2018-2020	2021-2023	2024-2026	2027+
Sleeper cab (sourceType 62)		1.576	1.576	1.502	1.466	1.440
Day cab (sourceType 61)		1.509	1.509	1.407	1.379	1.353

[aa] 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).

Appendix J MOVES4 SourceUseTypePhysics Table

Table J-1 MOVES4 SourceUseTypePhysics Table

Source Type ID	Reg Class ID	Begin Model Year	End Model Year	Rolling Term A (kW-s/m)	Rotating Term B (kW-s2/m2)	Drag Term C (kW-s3/m3)	Source Mass (metric tons)	Fixed Mass Factor (metric tons)
11	10	1960	2060	0.0251	0	0.000315	0.285	0.285
21	20	1960	2060	0.156461	0.002002	0.000493	1.4788	1.4788
31	30	1960	2060	0.22112	0.002838	0.000698	1.86686	1.86686
31	41	1960	2009	0.22112	0.002838	0.000698	3.40194	2.05979
32	30	1960	2060	0.235008	0.003039	0.000748	2.05979	2.05979
32	41	1960	2009	0.235008	0.003039	0.000748	3.40194	2.05979
41	41	1960	2009	1.29515	0	0.003715	5.68398	2.05979
41	41	2014	2060	1.23039	0	0.003715	5.68398	5
41	42	1960	2009	1.29515	0	0.003715	7.78184	2.05979
41	42	2014	2020	1.23039	0	0.003715	7.78184	5
41	42	2021	2023	1.00646	0	0.003715	7.78184	5
41	42	2024	2026	0.974469	0	0.003715	7.78184	5
41	42	2027	2060	0.926484	0	0.003715	7.78184	5
41	46	1960	2009	1.29515	0	0.003715	11.3666	17.1
41	46	2014	2020	1.23039	0	0.003715	11.3666	7
41	46	2021	2023	1.00646	0	0.003715	11.3666	7
41	46	2024	2026	0.974469	0	0.003715	11.3666	7
41	46	2027	2060	0.926484	0	0.003715	11.3666	7
41	47	1960	2009	1.29515	0	0.003715	15.6028	17.1
41	47	2014	2020	1.23039	0	0.003715	15.6028	10
41	47	2021	2023	1.00646	0	0.003715	15.6028	10
41	47	2024	2026	0.974469	0	0.003715	15.6028	10
41	47	2027	2060	0.926484	0	0.003715	15.6028	10
42	42	1960	2009	1.0944	0	0.003587	7.78184	2.05979
42	42	2014	2020	1.03968	0	0.003587	7.78184	5
42	42	2021	2023	1.03968	0	0.003587	7.78184	5
42	42	2024	2026	1.03968	0	0.003587	7.78184	5
42	42	2027	2060	0.913879	0	0.003587	7.78184	5
42	46	1960	2009	1.0944	0	0.003587	11.3666	17.1
42	46	2014	2020	1.03968	0	0.003587	11.3666	7
42	46	2021	2023	1.03968	0	0.003587	11.3666	7
42	46	2024	2026	1.03968	0	0.003587	11.3666	7
42	46	2027	2060	0.913879	0	0.003587	11.3666	7
42	47	1960	2009	1.0944	0	0.003587	15.6028	17.1
42	47	2014	2020	1.03968	0	0.003587	15.6028	10
42	47	2021	2023	1.03968	0	0.003587	15.6028	10

Source Type ID	Reg Class ID	Begin Model Year	End Model Year	Rolling Term A (kW-s/m)	Rotating Term B (kW-s2/m2)	Drag Term C (kW-s3/m3)	Source Mass (metric tons)	Fixed Mass Factor (metric tons)
42	47	2024	2026	1.03968	0	0.003587	15.6028	10
42	47	2027	2060	0.913879	0	0.003587	15.6028	10
42	48	1960	2009	1.0944	0	0.003587	15.6028	17.1
42	48	2014	2020	1.03968	0	0.003587	15.6028	10
42	48	2021	2023	1.03968	0	0.003587	15.6028	10
42	48	2024	2026	1.03968	0	0.003587	15.6028	10
42	48	2027	2060	0.913879	0	0.003587	15.6028	10
43	41	1960	2009	0.746718	0	0.002176	5.68398	2.05979
43	41	2014	2060	0.709382	0	0.002176	5.68398	5
43	42	1960	2009	0.746718	0	0.002176	7.78184	2.05979
43	42	2014	2020	0.709382	0	0.002176	7.78184	5
43	42	2021	2023	0.637734	0	0.002176	7.78184	5
43	42	2024	2026	0.603684	0	0.002176	7.78184	5
43	42	2027	2060	0.569634	0	0.002176	7.78184	5
43	46	1960	2009	0.746718	0	0.002176	11.3666	17.1
43	46	2014	2020	0.709382	0	0.002176	11.3666	7
43	46	2021	2023	0.637734	0	0.002176	11.3666	7
43	46	2024	2026	0.603684	0	0.002176	11.3666	7
43	46	2027	2060	0.569634	0	0.002176	11.3666	7
43	47	1960	2009	0.746718	0	0.002176	15.6028	17.1
43	47	2014	2020	0.709382	0	0.002176	15.6028	10
43	47	2021	2023	0.637734	0	0.002176	15.6028	10
43	47	2024	2026	0.603684	0	0.002176	15.6028	10
43	47	2027	2060	0.569634	0	0.002176	15.6028	10
51	41	1960	2009	1.58346	0	0.003572	3.57431	2.05979
51	41	2014	2060	1.50429	0	0.003572	3.57431	5
51	42	1960	2009	1.58346	0	0.003572	5.76818	2.05979
51	42	2014	2020	1.50429	0	0.003572	5.76818	5
51	42	2021	2023	1.50429	0	0.003572	5.76818	5
51	42	2024	2026	1.50429	0	0.003572	5.76818	5
51	42	2027	2060	1.32227	0	0.003572	5.76818	5
51	46	1960	2009	1.58346	0	0.003572	13.8001	17.1
51	46	2014	2020	1.50429	0	0.003572	13.8001	7
51	46	2021	2023	1.50429	0	0.003572	13.8001	7
51	46	2024	2026	1.50429	0	0.003572	13.8001	7
51	46	2027	2060	1.32227	0	0.003572	13.8001	7
51	47	1960	2009	1.58346	0	0.003572	20.7044	17.1
51	47	2014	2020	1.50429	0	0.003572	20.7044	10
51	47	2021	2023	1.50429	0	0.003572	20.7044	10

Source Type ID	Reg Class ID	Begin Model Year	End Model Year	Rolling Term A (kW-s/m)	Rotating Term B (kW-s2/m2)	Drag Term C (kW-s3/m3)	Source Mass (metric tons)	Fixed Mass Factor (metric tons)
51	47	2024	2026	1.50429	0	0.003572	20.7044	10
51	47	2027	2060	1.32227	0	0.003572	20.7044	10
52	41	1960	2009	0.627922	0	0.001603	3.57431	2.05979
52	41	2014	2060	0.596526	0	0.001603	3.57431	5
52	42	1960	2009	0.627922	0	0.001603	5.76818	2.05979
52	42	2014	2020	0.596526	0	0.001603	5.76818	5
52	42	2021	2023	0.558348	0	0.001603	5.76619	5
52	42	2024	2026	0.558348	0	0.001603	5.76344	5
52	42	2027	2060	0.53568	0	0.001603	5.76069	5
52	46	1960	2009	0.627922	0	0.001603	13.8001	17.1
52	46	2014	2020	0.596526	0	0.001603	13.8001	7
52	46	2021	2023	0.558348	0	0.001603	13.7981	7
52	46	2024	2026	0.558348	0	0.001603	13.7953	7
52	46	2027	2060	0.53568	0	0.001603	13.7926	7
52	47	1960	2009	0.627922	0	0.001603	25.0484	17.1
52	47	2014	2020	0.596526	0	0.001603	25.0484	10
52	47	2021	2023	0.558348	0	0.001603	25.0464	10
52	47	2024	2026	0.558348	0	0.001603	25.0437	10
52	47	2027	2060	0.53568	0	0.001603	25.0409	10
53	41	1960	2009	0.557262	0	0.001474	3.57431	2.05979
53	41	2014	2060	0.529399	0	0.001474	3.57431	5
53	42	1960	2009	0.557262	0	0.001474	5.76818	2.05979
53	42	2014	2020	0.529399	0	0.001474	5.76818	5
53	42	2021	2023	0.484929	0	0.001474	5.76461	5
53	42	2024	2026	0.458989	0	0.001474	5.75747	5
53	42	2027	2060	0.458989	0	0.001474	5.75033	5
53	46	1960	2009	0.557262	0	0.001474	13.8001	17.1
53	46	2014	2020	0.529399	0	0.001474	13.8001	7
53	46	2021	2023	0.484929	0	0.001474	13.7965	7
53	46	2024	2026	0.458989	0	0.001474	13.7894	7
53	46	2027	2060	0.458989	0	0.001474	13.7822	7
53	47	1960	2009	0.557262	0	0.001474	25.0484	17.1
53	47	2014	2020	0.529399	0	0.001474	25.0484	10
53	47	2021	2023	0.484929	0	0.001474	25.0449	10
53	47	2024	2026	0.458989	0	0.001474	25.0377	10
53	47	2027	2060	0.458989	0	0.001474	25.0306	10
54	41	1960	2009	0.68987	0	0.002105	3.57431	2.05979
54	41	2014	2060	0.655376	0	0.002105	3.57431	5
54	42	1960	2009	0.68987	0	0.002105	5.76818	2.05979

Source Type ID	Reg Class ID	Begin Model Year	End Model Year	Rolling Term A (kW-s/m)	Rotating Term B (kW-s2/m2)	Drag Term C (kW-s3/m3)	Source Mass (metric tons)	Fixed Mass Factor (metric tons)
54	42	2014	2020	0.655376	0	0.002105	5.76818	5
54	42	2021	2023	0.519058	0	0.002105	5.76818	5
54	42	2024	2026	0.519058	0	0.002105	5.76818	5
54	42	2027	2060	0.493498	0	0.002105	5.76818	5
54	46	1960	2009	0.68987	0	0.002105	13.8001	17.1
54	46	2014	2020	0.655376	0	0.002105	13.8001	7
54	46	2021	2023	0.519058	0	0.002105	13.8001	7
54	46	2024	2026	0.519058	0	0.002105	13.8001	7
54	46	2027	2060	0.493498	0	0.002105	13.8001	7
54	47	1960	2009	0.68987	0	0.002105	25.0484	17.1
54	47	2014	2020	0.655376	0	0.002105	25.0484	10
54	47	2021	2023	0.519058	0	0.002105	25.0484	10
54	47	2024	2026	0.519058	0	0.002105	25.0484	10
54	47	2027	2060	0.493498	0	0.002105	25.0484	10
61	46	1960	2007	1.64062	0	0.004077	14.0122	17.1
61	46	2008	2009	1.64062	0	0.004077	14.0122	17.1
61	46	2014	2017	1.509	0	0.003745	13.8666	7
61	46	2018	2020	1.509	0	0.003745	13.8666	7
61	46	2021	2023	1.407	0	0.003594	13.8666	7
61	46	2024	2026	1.379	0	0.003521	13.8666	7
61	46	2027	2060	1.353	0	0.003467	13.8666	7
61	47	1960	2007	1.64062	0	0.004077	24.8298	17.1
61	47	2008	2009	1.64062	0	0.004077	24.8298	17.1
61	47	2014	2017	1.509	0	0.003745	24.6842	10
61	47	2018	2020	1.509	0	0.003745	24.6842	10
61	47	2021	2023	1.407	0	0.003594	24.6842	10
61	47	2024	2026	1.379	0	0.003521	24.6842	10
61	47	2027	2060	1.353	0	0.003467	24.6842	10
62	46	1960	2007	1.73882	0	0.004347	14.0122	17.1
62	46	2008	2009	1.73882	0	0.004278	14.0122	17.1
62	46	2014	2017	1.576	0	0.003805	13.8308	7
62	46	2018	2020	1.576	0	0.003805	13.8308	7
62	46	2021	2023	1.502	0	0.003685	13.8308	7
62	46	2024	2026	1.466	0	0.003598	13.8308	7
62	46	2027	2060	1.44	0	0.003466	13.8308	7
62	47	1960	2007	1.73882	0	0.004347	24.8298	17.1
62	47	2008	2009	1.73882	0	0.004278	24.8298	17.1
62	47	2014	2017	1.576	0	0.003805	24.6484	10
62	47	2018	2020	1.576	0	0.003805	24.6484	10

Source Type ID	Reg Class ID	Begin Model Year	End Model Year	Rolling Term A (kW-s/m)	Rotating Term B (kW-s2/m2)	Drag Term C (kW-s3/m3)	Source Mass (metric tons)	Fixed Mass Factor (metric tons)
62	47	2021	2023	1.502	0	0.003685	24.6484	10
62	47	2024	2026	1.466	0	0.003598	24.6484	10
62	47	2027	2060	1.44	0	0.003466	24.6484	10
31	41	2010	2060	0.22112	0.002838	0.000698	3.40194	5
32	41	2010	2060	0.235008	0.003039	0.000748	3.40194	5
41	41	2010	2013	1.29515	0	0.003715	5.68398	5
41	42	2010	2013	1.29515	0	0.003715	7.78184	5
41	46	2010	2013	1.29515	0	0.003715	11.3666	7
41	47	2010	2013	1.29515	0	0.003715	15.6028	10
42	42	2010	2013	1.0944	0	0.003587	7.78184	5
42	46	2010	2013	1.0944	0	0.003587	11.3666	7
42	47	2010	2013	1.0944	0	0.003587	15.6028	10
42	48	2010	2013	1.0944	0	0.003587	15.6028	10
43	41	2010	2013	0.746718	0	0.002176	5.68398	5
43	42	2010	2013	0.746718	0	0.002176	7.78184	5
43	46	2010	2013	0.746718	0	0.002176	11.3666	7
43	47	2010	2013	0.746718	0	0.002176	15.6028	10
51	41	2010	2013	1.58346	0	0.003572	3.57431	5
51	42	2010	2013	1.58346	0	0.003572	5.76818	5
51	46	2010	2013	1.58346	0	0.003572	13.8001	7
51	47	2010	2013	1.58346	0	0.003572	20.7044	10
52	41	2010	2013	0.627922	0	0.001603	3.57431	5
52	42	2010	2013	0.627922	0	0.001603	5.76818	5
52	46	2010	2013	0.627922	0	0.001603	13.8001	7
52	47	2010	2013	0.627922	0	0.001603	25.0484	10
53	41	2010	2013	0.557262	0	0.001474	3.57431	5
53	42	2010	2013	0.557262	0	0.001474	5.76818	5
53	46	2010	2013	0.557262	0	0.001474	13.8001	7
53	47	2010	2013	0.557262	0	0.001474	25.0484	10
54	41	2010	2013	0.68987	0	0.002105	3.57431	5
54	42	2010	2013	0.68987	0	0.002105	5.76818	5
54	46	2010	2013	0.68987	0	0.002105	13.8001	7
54	47	2010	2013	0.68987	0	0.002105	25.0484	10
61	46	2010	2013	1.64062	0	0.004077	14.0122	7
61	47	2010	2013	1.64062	0	0.004077	24.8298	10
62	46	2010	2013	1.73882	0	0.004278	14.0122	7
62	47	2010	2013	1.73882	0	0.004278	24.8298	10
61	49	1960	2007	1.64062	0	0.004077	24.8298	17.1
61	49	2008	2009	1.64062	0	0.004077	24.8298	17.1

Source Type ID	Reg Class ID	Begin Model Year	End Model Year	Rolling Term A (kW-s/m)	Rotating Term B (kW-s2/m2)	Drag Term C (kW-s3/m3)	Source Mass (metric tons)	Fixed Mass Factor (metric tons)
61	49	2010	2013	1.64062	0	0.004077	24.8298	17.1
61	49	2014	2017	1.509	0	0.003745	24.6842	17.1
61	49	2018	2020	1.509	0	0.003745	24.6842	17.1
61	49	2021	2023	1.407	0	0.003594	24.6842	17.1
61	49	2024	2026	1.379	0	0.003521	24.6842	17.1
61	49	2027	2060	1.353	0	0.003467	24.6842	17.1
62	49	1960	2007	1.73882	0	0.004347	24.8298	17.1
62	49	2008	2009	1.73882	0	0.004278	24.8298	17.1
62	49	2010	2013	1.73882	0	0.004278	24.8298	17.1
62	49	2014	2017	1.576	0	0.003805	24.6484	17.1
62	49	2018	2020	1.576	0	0.003805	24.6484	17.1
62	49	2021	2023	1.502	0	0.003685	24.6484	17.1
62	49	2024	2026	1.466	0	0.003598	24.6484	17.1
62	49	2027	2060	1.44	0	0.003466	24.6484	17.1

Appendix K AVFT Tool

The AVFT Tool is a user tool available in the MOVES GUI that can be used to develop the AVFT (Alternate Vehicle Fuel and Technology) table, which allows users to modify the fraction of vehicles capable of using different fuels and technologies. The purpose of this tool is to project future fuel type distributions based on the combination of local historic data and projected national trends. The projections are applied to model years beyond the user-specified last complete model year in the input data to the user-specified analysis year. The last complete model year is needed, as partial model years are common in vehicle registration data. For simplicity, the last complete model year will be referred to as the “base model year” throughout this appendix.

The tool contains the following methods to project future fuel type distributions: proportional, national average, known fractions, and constant.

The proportional, national average, and known fraction projection methods are dependent on knowing the national default fuel type distributions. These are calculated from the default SampleVehiclePopulation table by summing the stmyFraction values associated with each source type, model year, fuel type, and engine technology combination (see Section 5.2 for information on how the default SampleVehiclePopulation table was calculated). In effect, this calculation is aggregating over the regClassID column in the SampleVehiclePopulation table to calculate a nationally representative AVFT table. In keeping with the naming convention of the AVFT columns, the resulting sum of the stmyFraction column will be referred to as the fuelEngFraction throughout this appendix.

The following subsections describe each projection method. Note that these projection methods are selected by source type, so different source types can use different methods. As such, the algorithm descriptions below assume the algorithm is operating on a single source type for clarity.

K1. Proportional

This method projects future fuel type distributions based on proportional differences between the local and the national distributions in the base model year. The intention with this method is to preserve differences between local conditions and the national average, while still accounting for expected changes in national fuel type distribution trends.

To implement this method, the ratio between the input AVFT fuelEngFraction and the national default fuelEngFraction is calculated for the base model year for each fuel type and engine technology. This ratio is subject to the boundary limits of 0.5 and 2.0, which effectively limits the proportional projection to stay between 50% lower and 200% higher than the national default fraction for any given fuel type and engine technology combination. These limits were chosen because there is considerable uncertainty as to the future geographic distribution of EVs, and we did not want extreme differences between the national averages and local conditions in the base model year to inappropriately bias the projected data. For example, if an area has no EVs in the base model year, a proportional projection without a lower boundary limit would result in no EVs in the future. Given the projected future EV sales fractions incorporated into MOVES (see

Section 5.2), this does not seem reasonable. Conversely, if an area is an early adopter of EVs in the base model year, a proportional projection without an upper boundary limit could result in an unrealistic projection of 100% EVs. We chose boundary limits of 50% and 200% (instead of looser limits, like 33% and 300% or 25% and 400%) because the ratio is based on a single model year and we wanted to prevent the single model year from introducing too much bias in the results.

After calculating the ratio and applying the boundary limits, the projected fuelEngFraction is calculated by multiplying the base model year ratio with the national default fuelEngFraction for all model years between the base model year and the analysis year. Since the base model year ratio is calculated independently for each fuel type, the resulting projected fuelEngFraction values are normalized so that the sum of the fuelEngFraction values by model year sum to 1.0.

K2. National Average

This method applies the national default fuel type distributions for all model years beyond the base model year in the input data. The intention of this method is to allow users to provide AVFT inputs for source types where local data do not reflect local vehicle activity (for example, long haul source types), or where local data are not available for a particular source type.

To implement this method, the national default fuelEngFraction for each model year, fuel type, and engine technology is used as-is for the projected fuelEngFraction.

K3. Known Fractions

This method allows the user to provide known fuel fractions for specific fuel types. The intention with this method is to allow users to input values mandated by local programs (such as a ZEV program), and the tool will handle fuel types not explicitly covered by the local program. Essentially, this method applies the proportional method for all model years, fuel types, and engine technologies not included in the user provided fractions.

To implement this method, the known fractions are used directly for the projected fuelEngFraction values. Then, like the proportional method, the ratio between the input AVFT's fuelEngFraction and the national default fuelEngFraction is calculated for the base model year for each fuel type and engine technology. This ratio is subject to the same boundary limits of 50% and 200%.

For all model years, fuel types, and engine technologies not included in the input known fractions, the projected fuelEngFraction is calculated by multiplying the base model year ratio with the national default fuelEngFraction. Finally, the projected fuelEngFraction values are normalized so that the sum of the fuelEngFraction by model year sums to 1.0, without changing the input known fractions.

K4. Constant

This method uses the fuelEngFraction for the base model year for each fuel type and engine technology as-is for the projected fuelEngFraction values for all projected model years.

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