Greenhouse Gas and Energy Consumption Rates for Onroad Vehicles in MOVES3

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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Contents

1 Introduction

This report describes the energy and greenhouse gas (GHG) rates in MOVES3 and documents the data sources and analyses we used to develop the energy and greenhouse gas emission rates. A timeline of the development of the energy and greenhouse gas emission rates in MOVES is presented in Appendix A.

This report is divided into four major sections:

1. Energy Rates
2. Nitrous Oxide (N_2O) Emission Rates
3. Carbon Dioxide (CO_2) Emission Rates
4. Fuel Consumption Calculations

The energy rates for light-duty vehicles are based on the work conducted for MOVES2004,[1] however, they have been significantly updated in subsequent versions of MOVES, including MOVES2009, MOVES2010, MOVES2014, and MOVES3. This report documents the changes in energy rates that were made between MOVES2010, MOVES2014, and MOVES3. We point the reader to the earlier reports that document the development of the energy rates prior to MOVES2010.[1,2] The energy rates were updates in MOVES3 to incorporate the Safer Affordable Fuel Efficient (SAFE) Vehicles standards[3] for light-duty passenger cars and trucks. MOVES2014 incorporated the light-duty greenhouse gas emission standards affecting model years 2017 and later cars and light trucks.[4] MOVES2014 also incorporated the Heavy-Duty GHG Phase 1 emissions standards for model years 2014 and later.[5] In this report, we briefly discuss the impact of the HD GHG Phase 1 and Phase 2 standards implemented in MOVES2014 and MOVES3 respectively, however, the details of the energy rates for heavy-duty are documented in the MOVES3 heavy-duty emissions rates report.[6]

The nitrous oxide emission rates have not been updated since MOVES2010. However, this report includes summary tables and figures to provide greater detail and clarify their original derivation.

The carbon dioxide (CO_2) emission rates in MOVES are calculated using the energy emission rates. The values used to convert energy to carbon dioxide emissions are presented here, along with the equation and values used to calculate carbon dioxide equivalent emission rates. The methods and data used to calculate nonroad fuel consumption and CO_2 emission rates for nonroad equipment are documented in the nonroad emission rate reports.[7,8]

We also present the values that MOVES uses to calculate fuel consumption in volume (gallons). MOVES currently reports fuel usage in terms of energy (e.g., KiloJoules), but calculates gallons for use in internal calculators as well. The values are presented in this report, so that users can calculate fuel volumes using MOVES output in a manner consistent with the MOVES calculators.

Lastly, although methane is considered one of the major greenhouse gases, the development of methane emission rates is not documented in this report. The methane emissions in MOVES are calculated as a fraction of the total hydrocarbon emissions. Both the methane fractions and total hydrocarbon emission rates were updated in MOVES3 and are documented in the following reports: MOVES3 speciation report[9] and MOVES3 light-duty[10] and heavy-duty[6] exhaust emission rate reports.

2 Energy Rate

A full suite of energy rates (energy use per time) were first released in MOVES2004 and were developed by binning second-by-second (1 Hz) data from test programs, including 16 EPA-sponsored test programs and multiple non-EPA test programs. Details about the data and programs are documented in MOVES2004 Energy and Emission Inputs report[1]. Since then, the energy rates in MOVES were updated to incorporate a number of GHG and Corporate Average Fuel Economy (CAFE) regulations.

In this chapter, we discuss the energy rates for both light-duty and heavy-duty vehicles. In each section, relevant regulations are briefly introduced, and the modeling approaches used to incorporate them into MOVES are explained or referenced.

2.1 Light-Duty Vehicles

In MOVES, light-duty vehicle category includes passenger cars, passenger trucks, and light commercial trucks. For details about corresponding vehicle weight and HPMS classes, please refer to section 2 of the population and activity of on-road vehicles technical report[16].

2.1.1 Light-Duty GHG and CAFE Regulations

2.1.1.1 LD GHG Rule Phase 1 and Phase 2

Light Duty GHG Phase 1 rule[11] covers model years 2012 through 2016, while the Phase 2 rule[4] covers model years 2017 through 2025. Both Phase 1 and 2 rules apply to passenger cars and light trucks. A summary of source types and regulatory class combination that are covered under LD GHG rules is in Table 2-1. Projected fleet average emission targets are shown in Table 2-2 and Table 2-3.

Table 2-1 A summary of source type and regulatory class combinations covered under LD GHG rules

Source Type (sourceTypeID)	Regulatory Class (regClassID)
passenger cars (21)	Light-duty vehicles (LDV) (20)
passenger trucks (31)	Light-duty Trucks (LDT) (30), Light Heavy-duty Class 2b and 3 Trucks (LHD2b3) (41)[a]
light commercial trucks (32)	LDT (30), LHD2b3 (41)[a]

[a] The LD GHG rules only applies to the Medium-Duty Passenger Vehicles (MDPV, GVWR 8,500 to 10,000 lbs) portion of LHD2b3 vehicles (GVWR 8,500 to 14,000 lbs). The CO_2 emission rates for MDPV were previously updated based on HD GHG rule, thus are not updated with LD GHG rules nor SAFE rules.

Table 2-2 Projected fleet-wide emissions compliance levels under the footprint-based CO_2 standards (g/mi) – LD GHG Phase 1[11]

	2012	2013	2014	2015	2016
Passenger Cars	263	256	247	236	225
Light Trucks	346	337	326	312	298
Combined Cars & Trucks	295	286	276	263	250

Table 2-3 Projected fleet-wide emissions compliance levels under the footprint-based CO_2 standards (g/mi) – LD GHG Phase 2[4]

	2016 base	2017	2018	2019	2020	2021	2022	2023	2024	2025
Passenger Cars	225	212	202	191	182	172	164	157	150	143
Light Trucks	298	295	285	277	269	249	237	225	214	203
Combined Cars and Trucks	[69] 250	243	232	222	213	199	190	180	171	163

The footprint-based methodology was used for both LD GHG Phase 1 and Phase 2 rules to generate the projected fleet average emission. Each vehicle has a projected CO_2 emission based on its footprint, and this relationship is captured by footprint curves. Figure 2-1 is an example of the footprint curve for passenger cars for passenger cars under LD GHG Phase 2 rule. The footprint-based CO_2 emission rates were then weighted by the historical and projected vehicle sales to generate the fleet average emissions shown in Table 2-2 and Table 2-3.

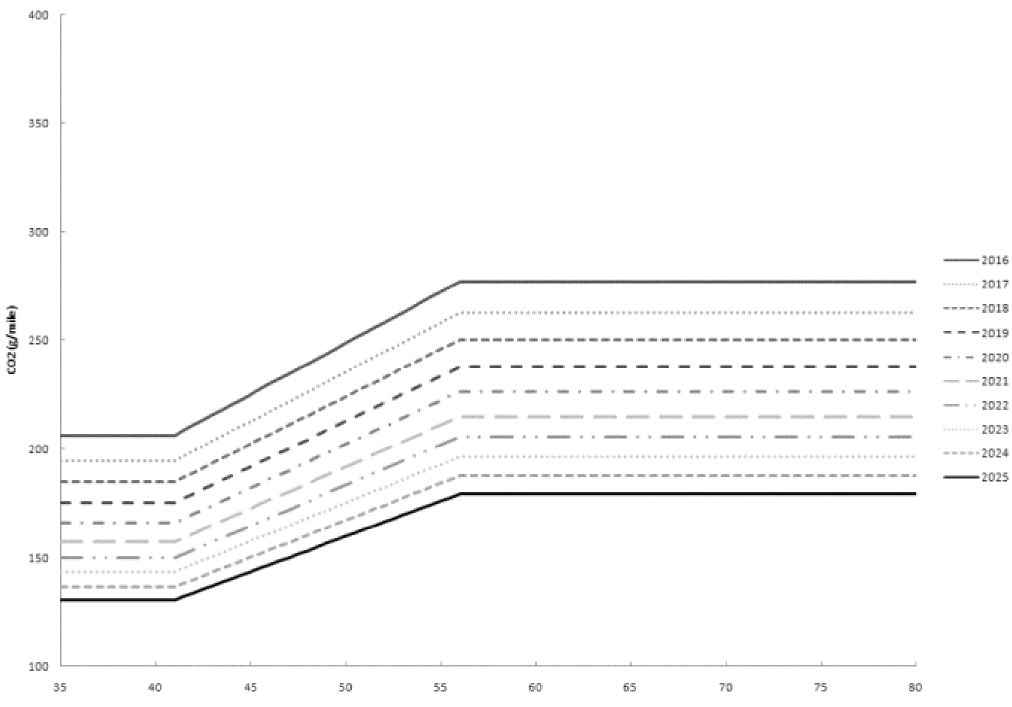

Figure 2-1. CO_2 (g/mile) passenger car standards[4]

Air conditioning (A/C) system contributes to vehicle GHG emissions in two ways. First, when the compressor pumps the refrigerant around the system loop, it adds an extra load to the powertrain, resulting in an increase in tailpipe CO_2 emissions. Second, it contributes directly to GHG emissions via refrigerant leakage (for example, hydrofluorocarbons (HFCs) leakage).

Accordingly, there are two types of A/C credits in the LD GHG rules – A/C efficiency credits and A/C refrigerant credits (aka. leakage credits). Both types of credits are used when converting projected CO_2 compliance target to projected 2-cycle CO_2. Projected CO_2 compliance targets represent the curve standard numbers, while projected 2-cycle CO_2 represent the actual standards that manufactures need to comply with. The projected 2-cycle CO_2 is the sum of projected CO_2 compliance targets, incentives, and credits, where incentives include advanced technology multipliers and intermediate volume provisions, and credits include off cycle credit, A/C refrigerant credit, and A/C efficiency credit. Table 2-4 shows the values for projected CO_2 compliance targets, incentives, credits, and projected 2-cycle CO_2 emissions for passenger cars for model years 2016 to 2025. There are similar tables for passenger trucks and the combined passenger cars and trucks fleet in the LD GHG Phase 1 and 2 rules[4,11].

Table 2-4 Projections for fleetwide tailpipe emissions compliance with CO_2 standards for passenger cars (g/mile) – LD GHG Phase 2[4]

Model year	Projected CO_2 compliance target	Incentives [402]		Projected achieved CO_2	Credits			Projected 2-cycle CO_2
		Advanced technology multiplier	Intermediate volume provisions		Off cycle credit	A/C refrigerant	A/C efficiency	
2016 (base)	225 [403]	0	0	225	0.4	5.4	4.8	235
2017	212	0.6	0.1	213	0.5	7.8	5.0	226
2018	202	1.1	0.3	203	0.6	9.3	5.0	218
2019	191	1.6	0.1	193	0.7	10.8	5.0	210
2020	182	1.5	0.1	183	0.8	12.3	5.0	201
2021	172	1.2	0.0	173	0.8	13.8	5.0	193
2022	164	0.0	0.0	164	0.9	13.8	5.0	184
2023	157	0.0	0.0	157	1.0	13.8	5.0	177
2024	150	0.0	0.0	150	1.1	13.8	5.0	170
2025	143	0.0	0.0	143	1.4	13.8	5.0	163

However, in MOVES, we used the real-world tailpipe CO_2, which is defined in LD GHG rule Regulatory Impact Analysis (RIA)[12], to represent on-road fleet average CO_2 emissions (see Table **2-5**). The real-world tailpipe CO_2 was calculated using Equation 2-1 shown below. 1.25 in Equation 2-1 is a multiplying factor derived from a 20% gap between test and on-road MPG for liquid fueled vehicles[12]. The test refers to NHTSA's CAFE 2 Cycle test (FTP and HFET), while the on-road MPG refers to EPA's 5 cycle test that is used for fuel economy label (FTP, HFET, US06, SC03, UDDS). We believe that the EPA 5 cycle test is more representative of real-world driving, and therefore, we converted the 2 cycle CO_2 emission to the real-world CO_2 by dividing by 0.8 (a factor of 1.25).

$$Real\ World\ Tailpipe\ CO2 = (Projected\ 2\ Cylce\ CO2 - Off\ Cycle\ Credit - A/C\ \text{Efficiency Credits}) * 1.25$$

Equation 2-1

Table 2-5 Projections for the average, real-world fleetwide tailpipe CO_2 emissions and fuel economy associated with the CO_2 standards (g/mile)[4]

Model year	Real world tailpipe CO_2 (grams per mile)			Real World Fuel Economy (miles per gallon)		
	Cars	Trucks	Cars + trucks	Cars	Trucks	Cars + trucks
2016 (base)	287	381	320	30.9	23.3	27.8
2017	276	378	313	32.2	23.5	28.4
2018	266	373	304	33.5	23.9	29.2
2019	255	363	294	34.8	24.5	30.2
2020	244	357	284	36.4	24.9	31.3
2021	234	334	269	38.0	26.6	33.1
2022	223	318	256	39.9	27.9	34.7
2023	215	304	244	41.3	29.3	36.4
2024	205	289	233	43.4	30.8	38.1
2025	196	277	223	45.4	32.1	40.0

2.1.1.2 SAFE Rule

The Safer Affordable Fuel Efficient (SAFE) Vehicles Proposed Rule was issued in August 2018 for model years 2021-2026 to amend existing CAFE and GHG standards for passenger cars and light trucks. The SAFE "Part 1" Final Rule (One National Program) was released in September 2019[13]. EPA withdrew the Clean Air Act preemption waiver for LD vehicles it granted to California.

The SAFE final rule[3] was released in March 2020, effective on June 29, 2020. The fleet average targets for light-duty passenger cars and trucks in the SAFE rule are shown separately in the tables below. We updated energy rates based on the SAFE rule in MOVES3, and details are in section 2.1.2. (running energy rates) and in section 2.1.3 (start energy rates).

Table 2-6 Average fleet estimate of CO_2 emission for passenger cars in SAFE[3]

Model Year	Avg. of OEMs' Est. Requirements	
	CAFE (mpg)	CO_2 (g/mi)
2017	39.0	219
2018	40.4	208
2019	41.9	197
2020	43.6	188
2021	44.2	183
2022	44.9	180
2023	45.6	177
2024	46.3	174
2025	47.0	171
2026	47.7	168

Table 2-7 Average fleet estimate of CO_2 emission for passenger trucks in SAFE[3]

Model Year	Avg. of OEMs' Est. Requirements	
	CAFE (mpg)	CO_2 (g/mi)
2017	29.4	295
2018	30.0	285
2019	30.5	278
2020	31.1	270
2021	31.6	264
2022	32.1	259
2023	32.6	255
2024	33.1	251
2025	33.6	247
2026	34.1	243

2.1.2 Light-Duty Running Energy Rates

In MOVES3, the energy rates for motorcycles (MC) and pre-2017 model year light-duty vehicles (LDV) and light-duty trucks (LDT) are unchanged from MOVES2014. In MOVES, source bins are used for groupings of parameters which distinguish differences in energy and emission rates according to physical differences in the source. The energy rates for MC, LDV and LDT are grouped by fuel types, engine technologies, regulatory classes, and model years.

Earlier MOVES versions contained significantly more detail in the energy rates, which varied by engine technologies, engine size and more refined loaded weight classes. For MOVES2010a, the energy rates were simplified to be single energy rates for each regulatory class, fuel type and model year combination. This was done by removing advanced technology energy rates, and aggregating the MOVES2010 energy rates across engine size and vehicle weight classes according to the default population in the MOVES2010 sample vehicle population table. Because this approach uses highly detailed energy consumption data, coupled with information on engine size and vehicle weight for the vehicle fleet that varies for each model year, year-by-year variability was introduced into the aggregated energy rates used in MOVES2010a and now in MOVES3.

LD GHG Phase 1 and Phase 2 rules were used to update the energy rates in previous MOVES versions, as documented in MOVES2010 and MOVES2014 GHG and Energy Consumption Rates report[2,14]. In MOVES3, we made updates to energy rates based on the SAFE final rule[3]. The methodology is the same as what we used to incorporate LD GHG rules in MOVES2014, where the real-world CO_2 (or on-road CO_2) values were used as input to update MOVES3.

The real-world CO_2 calculation uses fleet target, A/C refrigerant credits, and incentives from the SAFE rule, and followed the Equation 2-2 shown below. Equation 2-2 is the same as Equation 2-1 mathematically, because the projected 2-cycle CO_2 is the sum of projected CO_2 compliance target, A/C credits, off cycle credits and incentives.

$$Real\ World\ Tailpipe\ CO2 = (Projected\ CO2\ compliance\ target + Incentives + A/C\ Refrigerant\ Credits) * 1.25$$

Equation 2-2

Adjustment ratios based on real-world CO_2 from LD GHG and SAFE rules were applied to running energy rates for all light-duty vehicles (regulatory classes 20 and 30). Adjustment ratios vary by model year from 2017 to 2025. The adjustment ratio for MY2025 were applied to model years 2026 and beyond. These adjustment ratios are stored in EmissionRateAdjustment table in the default MOVES database.

The updates to reflect the SAFE rule resulted in moderate (~15%) increases in future year LD energy consumption and CO_2 emission, which translates to about a 10% increase in total onroad (LD+HD). There are small (<1%) increases in VOC and toxic emissions due to refueling, but we expect no impact on NOx or direct PM.

Figure 2-2 and Figure 2-3 plot the MOVES3 average CO2 emission rates for motorcycles (MC), light-duty vehicles (LDV), and light-duty trucks (LDT) across all running operating modes for model year 1970 to model year 2030. 1960-1969 MY have the same CO_2 emission rates as MY 1970, and the MY 2031-2060 have the same CO_2 emission rates as MY 2030.

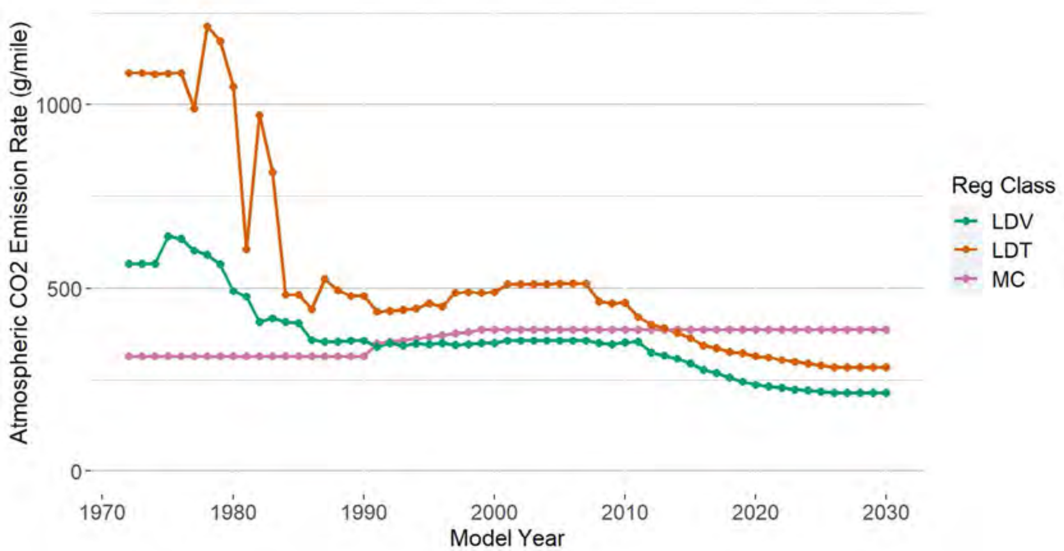

Figure 2-2. Average atmospheric CO_2 emission rates in MOVES3 for gasoline motorcycle, light-duty vehicles, and light-duty trucks across all running operating modes.

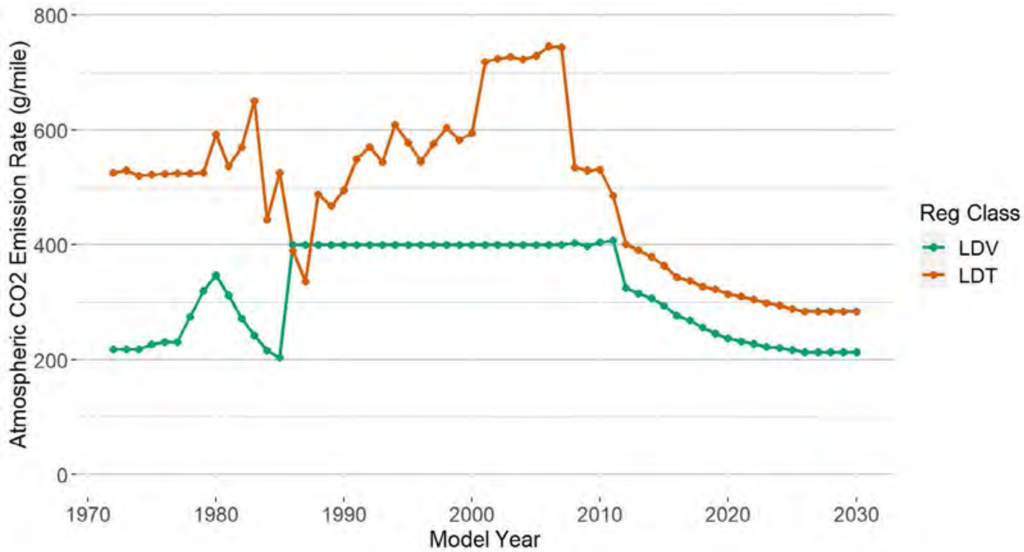

Figure 2-3. Average atmospheric CO_2 emission rates in MOVES3 for diesel light-duty vehicles and light-duty trucks across all running operating modes.

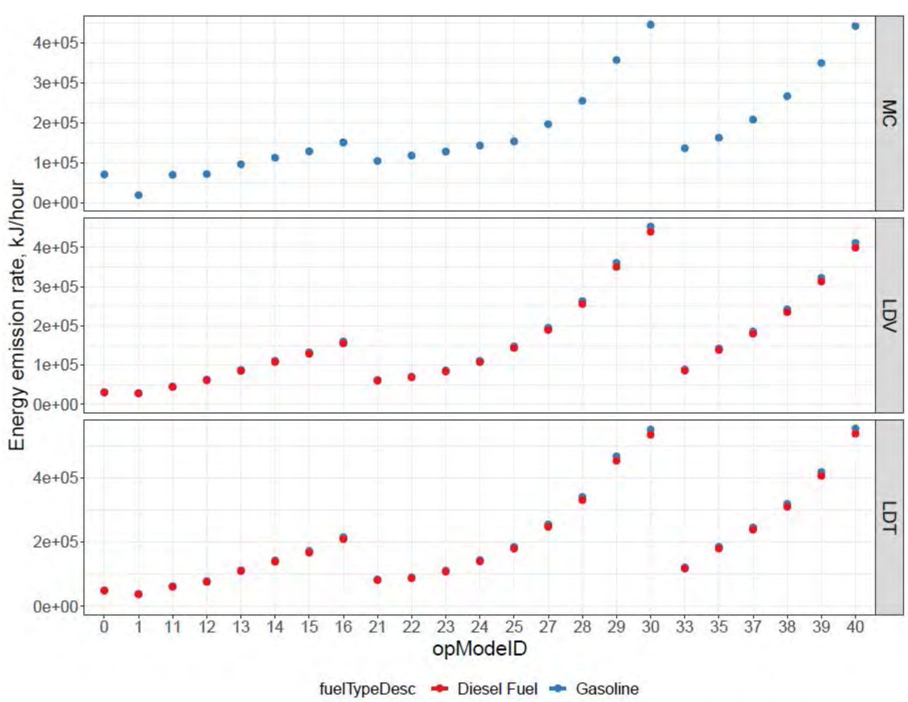

Figure 2-4. Running energy rates by operating mode (opModeID) for motorcycles (MC), light-duty vehicles (LDV) and light-duty trucks (LDT) for model year 2020.

Figure 2-4 plots the MOVES3 running energy rates by operating mode for motorcycles (MC), light-duty vehicles (LDV), and light-duty trucks (LDT) for model year 2020. In MOVES3, running energy rates for both gasoline and diesel LDV and LDT vehicles are adjusted based on SAFE rule for model year 2017 and forward.

For gasoline LDV, MOVES uses the same relative trend between energy rates and operating modes shown in Figure 2-4 starting in 1999 model year going forward. For gasoline LDT, the relative trend between energy rates and operating modes is constant starting in MY 2001 going forward to MY 2060. However, as shown in Figure 2-2, the absolute magnitude of gasoline LDV and LDT CO_2 emission rates across all operating modes decreases sharply beginning in MY 2012.

Diesel LDV and LDT vehicles, starting in model year 2012, have the same relative energy rate (for start and running) and operating mode trend as the corresponding MY gasoline vehicles. The diesel energy rates are 2.9% lower than the gasoline running energy rates. The 2.9% difference accounts for the higher carbon content in diesel fuel (Table 4-1.) compared to gasoline fuel, such that the CO_2 emission rates are equivalent for 2012 MY+ gasoline and diesel vehicles. The model year trends for diesel LDV and LDT CO_2 emission rates are similar to gasoline vehicles beginning in MY 2012 (as shown in Figure 2-3).

The energy rates for ethanol (E-85) and electricity continue to have equivalent energy consumption as gasoline vehicles. Although the energy rates are the same for these alternative fuels, the carbon content is different, resulting in different CO_2 emission rates as discussed in Section 4.1.

The motorcycle running energy rates stay the same as in MOVES2014. The energy rates were developed initially for MOVES2004[1] for three weight categories (<500 lbs, 500-700 lbs, and >700 lbs), and three engine size categories (<170 cc, 170-280 cc, and > 280 cc). When the energy rates were consolidated to a single energy rate by model year for all motorcycles in MOVES2010a[2], this resulted in an average increase in energy motorcycle rates between MY 1991 and MY 2000 due to an accompanying shift to larger motorcycles[15]. We assumed the same distributions of motorcycles starting in MY 2000 going forward to MY 2060 (2.9% <170cc, 4.3% 170-280cc, and 92.8%>280 cc, with 30% between 500-700 lbs, and 70% > 700 lbs), thus the motorcycle energy running rates for MY 2000 through MY 2060 remain constant.

2.1.3 Light-Duty Start Energy Rates

Figure 2-5 displays the energy rates of motorcycles (MC), light-duty vehicles (LDV), and light-duty trucks (LDT) for starts by operating mode for model year 2020 in MOVES3. As shown, start energy rates increase for operating modes with longer soak times as defined in Table 2-8. These fractions are used for all model years and fuel types of light-duty vehicles and motorcycles. Additionally, the start energy rates were adjusted in MOVES for increased fuel consumption required to start a vehicle at cold ambient temperatures. The temperature effects are documented in the 2004 Energy Report.[1]

Adjustment ratios based on real-world CO_2 from LD GHG and SAFE rules were also applied to start energy rates for all light-duty vehicles (regclasses 20 and 30). Adjustment ratios vary by model year from 2017 to 2025. The adjustment ratio for MY2025 were applied to model years 2026 and beyond. These adjustment ratios for start energy rates are the same as for running energy rates for each model year, and are stored in EmissionRateAdjustment table in the default MOVES database.

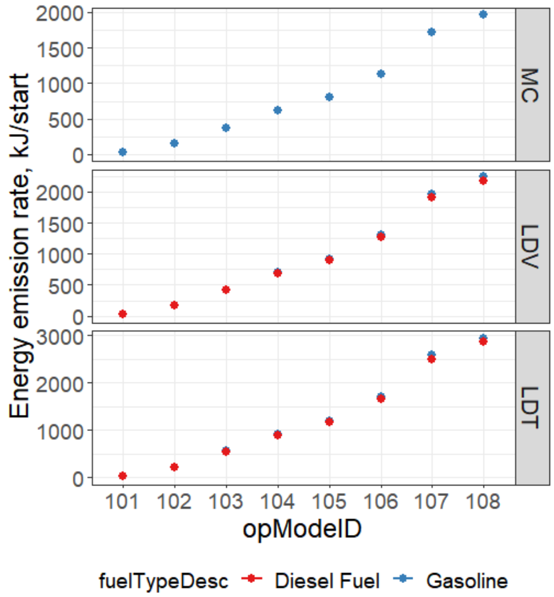

Figure 2-5. Start energy rates by operating mode (opModeID) for motorcycles (MC), light-duty vehicles (LDV) and light-duty trucks (LDT) for model year 2020.

Table 2-8. Fraction of energy consumed at start of varying soak lengths compared to the energy consumed at a full cold start (operating mode 108).

Operating Mode	Description	Fraction of energy consumption compared to cold start
101	Soak Time < 6 minutes	0.013
102	6 minutes <= Soak Time < 30 minutes	0.0773
103	30 minutes <= Soak Time < 60 minutes	0.1903
104	60 minutes <= Soak Time < 90 minutes	0.3118
105	90 minutes <= Soak Time < 120 minutes	0.4078
106	120 minutes <= Soak Time < 360 minutes	0.5786
107	360 minutes <= Soak Time < 720 minutes	0.8751
108	720 minutes <= Soak Time	1

Figure 2-6 and Figure 2-7 depict the start CO_2 emission rates for a cold start (opMode108) across model years for light-duty vehicles. Motorcycles have a sharp decrease in CO_2 emission starts in 1991 because MOVES assumes 'controlled' energy starts starting with MY 1991 as documented in the MOVES2004 energy report[1]. The start rates for LDV and LDT have a large decrease starting in MY 2012 that follows the same trend as the running rates.

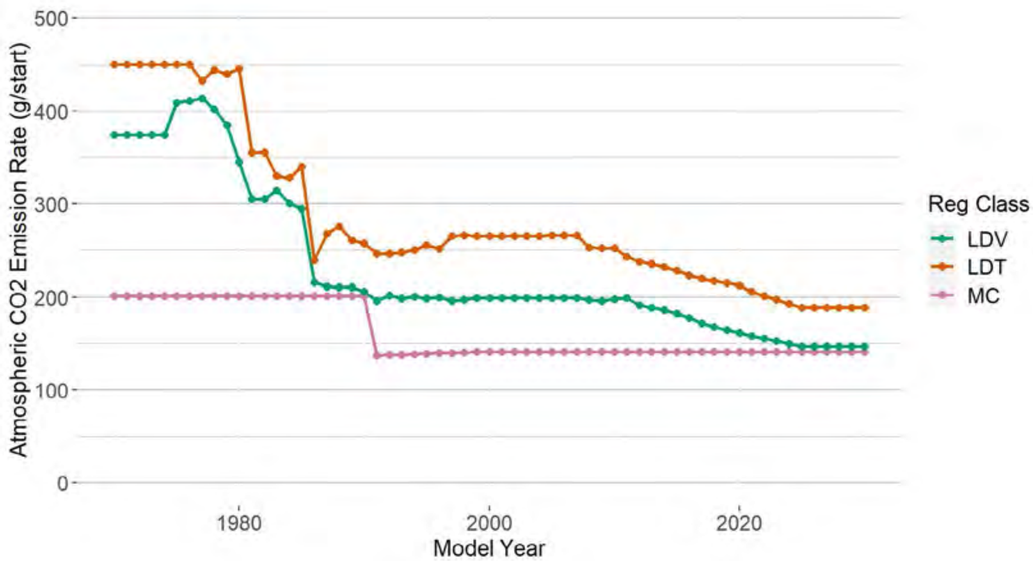

Figure 2-6. Cold start CO_2 emission rates (opMode 108) for gasoline motorcycle, light-duty vehicles, and light-duty trucks

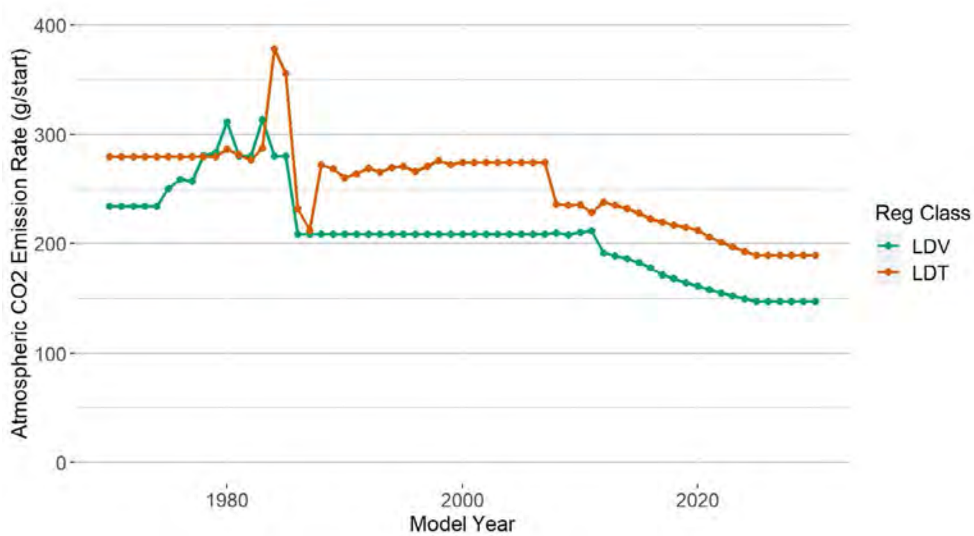

Figure 2-7. Cold start CO_2 emission rates (opMode 108) for diesel motorcycle, light-duty vehicles, and light-duty trucks

2.2 Heavy-Duty Vehicles

MOVES has heavy-duty energy rates for three fuel types in MOVES: diesel, gasoline, and compressed natural gas (CNG). In MOVES3, we expanded the use of CNG to all heavy heavy-duty (HHD) regulatory class instead of limiting it just to the Urban Bus regulatory class, allowing the users to model CNG vehicles in other source types in MOVES (including refuse trucks).The development of the heavy-duty energy rates by regulatory class, fuel type, and model year are documented in the heavy-duty exhaust emision rate report.[6] These rates include the reductions from the HD GHG Phase 1 and Phase 2 standards which are summarized here, and discussed in more detail in the heavy-duty exhaust emission rate report.

The HD GHG Phase 1 standards[5] began with the 2014 model year and increase in stringency through 2018. The standards were set to continue indefinitely after 2018. The program divides the diverse truck sector into 3 distinct categories:

- Line haul tractors (largest heavy-duty tractors used to pull trailers, i.e., semi-trucks)
- Heavy-duty pickups and vans (3/4 and 1 ton trucks and vans)
- Vocational trucks (buses, refuse trucks, concrete mixers, etc)

The program set separate standards for engines and vehicles, and set separate standards for fuel consumption, CO_2, N_2O, CH_4 and HFCs.[b]

The HD GHG Phase 1 rule was incorporated into MOVES through three key elements. These include (a) revised running emission rates for total energy, (b) new aerodynamic coefficients and weights, (c) auxiliary Power Units (APUs) largely replace extended idle in long haul trucks and are added as a new process. The Phase 1 reductions vary by fuel type, regulatory class, and model year. The same reductions are applied to CNG vehicles as diesel vehicles because they have the same standards. The effect of the HD GHG Phase 1 rule on running emissions rates for total energy and auxiliary energy and criteria emission rates are documented in the MOVES3 heavy-duty emissions rates report.[6] The revised aerodynamic coefficients for MY 2014 and later heavy-duty trucks are documented in the MOVES Population and Activity Report.[16]

In MOVES3, we updated the heavy-duty vehicle energy rates to incorporate the HD GHG Phase 2 rule.[17] The Phase 2 reductions in energy rates vary by fuel type, regulatory class, and model year like the Phase 1 rule, but also by source type. Because energy rates are stored by regulatory class in the EmissionRate table, the energy reductions by source type and regulatory class are implemented using the EmissionRateAdjustment table. We also updated the 2010-2060 baseline energy rates for diesel and CNG vehicles from the manufacturer-run heavy-duty in-use testing (HDIUT) program. Baseline heavy-duty gasoline energy rates for 2010-2060 were updated from an EPA conducted in-use measurement program. For details regarding these updates, please refer to MOVES3 heavy-duty exhaust emission rate report.[6]

[b] HFCs are not modeled in MOVES, and the N_2O and CH_4 standards are not considered forcing on emissions.

3 Nitrous Oxide (N_2O) Emission Rates

3.1 Gasoline and Diesel-Fueled Vehicles

As detailed in the MOVES2010a energy and greenhouse gas emission rate report[2], the nitrous oxide (N_2O) emission rates are derived from emission tests measured on the Federal Test Procedure (FTP)[18] and supplemented with N_2O emission rates from the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006 report[23].

In MOVES3, we duplicated the N_2O emission rates from one single operating mode (opModeID 300 = all running) into all the normal running operating modes (0-40).[c] The N_2O emission rates are stored in the EmissionRate table, and, unlike most pollutants, the emission rates do not vary by vehicle age.

The running and start emissions are derived from the composite FTP emission rates by using bag 2 of the FTP to estimate the average running emission rates (in grams per hour), and then estimating the start emissions as the remainder of the composite emissions. Table 3-1 and Table 3-2 list the FTP composite N_2O emission rates, the calculated running rates (in grams per hour), and start rates (in grams per start).

[c] This is done to enable MOVES to output all running N_2O emissions from the code design perspective.

Table 3-1 Composite FTP N_2O emissions, running and start for gasoline vehicles

Vehicle Type / Control Technology	FTP Comp (g / mile)	Running (g / hour)	Start (g / start)
Motorcycles			
Non-Catalyst Control	0.0069	0.0854	0.0189
Uncontrolled	0.0087	0.1076	0.0238
Gasoline Passenger Cars			
EPA Tier 2	0.0050	0.0399	0.0221
LEVs	0.0101	0.0148	0.0697
EPA Tier 1	0.0283	0.2316	0.1228
EPA Tier 0	0.0538	0.6650	0.1470
Oxidation Catalyst	0.0504	0.6235	0.1379
Non-Catalyst Control	0.0197	0.2437	0.0539
Uncontrolled	0.0197	0.2437	0.0539
Gasoline Light-Duty Trucks			
EPA Tier 2	0.0066	0.0436	0.0325
LEVs	0.0148	0.0975	0.0728
EPA Tier 1	0.0674	0.6500	0.2546
EPA Tier 0	0.0370	0.2323	0.1869
Oxidation Catalyst	0.0906	0.8492	0.3513
Non-Catalyst Control	0.0218	0.2044	0.0845
Uncontrolled	0.0220	0.2062	0.0853
Gasoline Heavy-Duty Vehicles			
EPA Tier 2	0.0134	0.1345	0.0486
LEVs	0.0320	0.3213	0.1160
EPA Tier 1	0.1750	1.7569	0.6342
EPA Tier 0	0.0814	0.8172	0.2950
Oxidation Catalyst	0.1317	1.3222	0.4773
Non-Catalyst Control	0.0473	0.4749	0.1714
Uncontrolled	0.0497	0.4990	0.1801

Table 3-2 Composite FTP N_2O emissions, composite, running and start for diesel vehicles

Vehicle Type / Control Technology[a]	FTP Comp (g / mile)	Running (g / hour)	Start (g / start)
Diesel Passenger Cars			
Advanced	0.0010	0.0168	0.0010
Moderate	0.0010	0.0168	0.0010
Uncontrolled	0.0012	0.0202	0.0012
Diesel Light-Duty Trucks			
Advanced	0.0015	0.0253	0.0015
Moderate	0.0014	0.0236	0.0014
Uncontrolled	0.0017	0.0286	0.0018
Diesel Heavy-Duty Vehicles			
Advanced	0.0049	0.0828	0.0051
Moderate	0.0048	0.0809	0.0049
Uncontrolled	0.0048	0.0809	0.0049

[a] Table B-5 defines the model year group definitions of the diesel control technologies groups

The N_2O emission rates are applied in MOVES using model year group ranges that map to technology distinctions. Table B-1 through Table B-5 in Appendix B provide the distribution of vehicles types/technology types by model year. The running and start emission rates in Table 3-1 and Table 3-2 are multiplied by the model-year specific technology penetrations to provide model year specific emission rates in MOVES. The values in Table B-1 through Table B-5 are taken directly from the Inventory of the US GHG emissions and sinks, Annex Tables A-84 through A-87[23], except for the few instances as noted in the footnotes of the tables.

Figure 3-1 displays the model year-specific N_2O emission rates used in MOVES3 for gasoline and diesel-fueled vehicles that are calculated as the product of the technology-specific rates provided in Table 3-1 and Table 3-2 and the model-year/technology penetrations provided in the Appendix. In general, MOVES uses the model-year specific rates. The spike in N_2O observed in Figure 3-1 for heavy-duty gasoline for model years 1996-1999 model years is because the EPA Tier 1 values shown in Table 3-1 are elevated over the other technology groups, and the model years 1996-1999 have over 65% technology penetration of the Tier 1 emission rates (Table B-4). However, For model years 2001-2010, MOVES has a single N_2O emission rate to represent the range of model year groups, and the emission rate for these model year groups in MOVES is the average of the model-year specific rates. MOVES3 uses the same N_2O emission rate within vehicle class and fuel type for 2011 through 2060 model year vehicles.

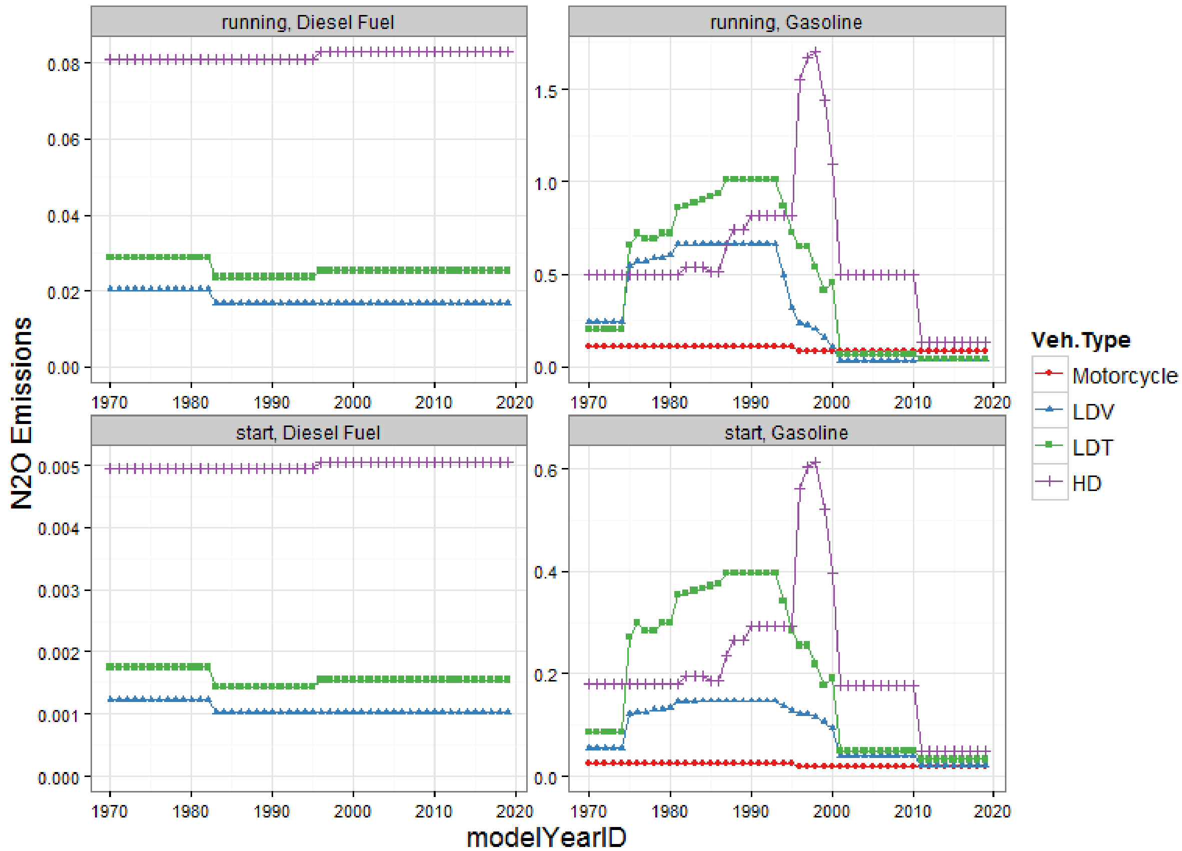

Figure 3-1. N_2O emission rates for running and start processes for gasoline and diesel vehicles in MOVES3. The N_2O emission rates are constant from 1960-1970 model year and are constant from 2011-2060 model years

3.2 Alternative-Fueled Vehicles

MOVES includes N_2O emission rates for alternative fuels, including E85 and compressed-natural gas fueled vehicles. The N_2O emission rates were based on limited data from the Sources and Sinks report[23]. In MOVES, the N_2O emission rates for E85-fueled vehicles are assumed to be the same as gasoline vehicles. We will revisit the N_2O E85 rates as more data becomes available.

Compressed natural gas (CNG) transit buses use the emission rates reported in Table 3-3. These rates remain unchanged from the numbers reported for MOVES2010a[2]. The composite emission rate was obtained from the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2006[23], and disaggregated into running and starts using the same relative running and start splits as heavy-gasoline vehicles.

Table 3-3: Nitrous oxide emission Rates for CNG-fueled transit buses

FTP Comp (g / mile)	Running (g / hour)	Starts (g / start)
0.175	1.6797	0.6636

4 Carbon Dioxide (CO_2) Emission Rates

4.1 Carbon Dioxide Calculations

MOVES does not store carbon dioxide emission rates in the emission rate tables (e.g., CO_2/mile or CO_2/hour operation), but calculates carbon dioxide emissions from total energy consumption as shown in Equation 4-1.

$$CO_2 = Total\ Energy\ Consumed\ \times Carbon\ Content \times Oxidation\ Fraction \times \left(\frac{44}{12}\right) \qquad \textbf{Equation 4-1}$$

Carbon content is expressed in units grams of carbon/KJ of energy consumed. Oxidation fraction is the fraction of carbon that is oxidized to form CO_2 in the atmosphere. A small mass percentage of fuel is emitted as carbon monoxide, organic gases and organic carbon. Currently, MOVES assumes an oxidation fraction of 1 for all the hydrocarbon-based fuels. The value (44/12) is the molecular mass of CO_2 divided by the atomic mass of carbon.

The carbon content and oxidation fractions used to calculate CO_2 emissions are provided in Table 4-1.. The carbon content values used in MOVES were developed for MOVES2004[1] based on values derived from the life-cycle model GREET.

Table 4-1. Carbon content, oxidation fraction and energy content by fuel subtype

fuelSubtypeID	fuelTypeID	Fuel Subtype	Carbon Content (g/KJ)	Oxidation Fraction
10	1	Conventional Gasoline	0.0196	1
11	1	Reformulated Gasoline (RFG)	0.0196	1
12	1	Gasohol (E10)	0.0196	1
13	1	Gasohol (E8)	0.0196	1
14	1	Gasohol (E5)	0.0196	1
15	1	Gasohol (E15)	0.0196	1
20	2	Conventional Diesel Fuel	0.0202	1
21	2	Biodiesel	0.0201	1
22	2	Fischer-Tropsch Diesel (FTD100)	0.0207	1
30	3	Compressed Natural Gas (CNG)	0.0161	1
40	4	Liquefied Petroleum Gas (LPG)	0.0161	1
50	5	Ethanol	0.0194	1
51	5	Ethanol (E85)	0.0194	1
52	5	Ethanol (E70)	0.0194	1
90	9	Electricity	0	0

4.2 Carbon Dioxide Equivalent Emissions

CO_2 equivalent is a combined measure of greenhouse gas emissions weighted according to the global warming potential of each gas, relative to CO_2. Although the mass emissions of CH_4 and N_2O are much smaller than CO_2, the global warming potential is higher, which increases the contribution of these gases to the overall greenhouse effect. CO_2 equivalent is calculated from CO_2, N_2O and CH_4 mass emissions according to Equation 4-2.

$$CO_2\ equivalent = CO_2 \times GWP_{CO_2} + CH_4 \times GWP_{CH_4} + N_2O \times GWP_{N_2O} \qquad \textbf{Equation 4-2}$$

MOVES uses 100-year Global Warming Potentials (GWP) for a 100-year timescale, listed in Table 4-2. and stored in the pollutant table of the MOVES default database. The GWP values for methane and nitrous oxide were updated in MOVES2014 with the values used in the 2007 IPCC Fourth Assessment Report (AR4)[19], which is consistent with values used in the LD GHG Phase 2 rule[4] and the HD GHG Phase 2 rule[17].

Table 4-2. 100-year Global Warming Potentials used in MOVES

Pollutant	Global Warming Potential (GWP)
Methane (CH_4)	25
Nitrous Oxide (N_2O)	298
Atmospheric CO_2	1

5 Fuel Consumption Calculations

MOVES reports fuel consumption in terms of energy use, but not in terms of volume or mass in the output run results. However, MOVES calculates fuel usage in terms of volume and mass within the refueling[20] and sulfur dioxide emission calculators, respectively.[9]

MOVES uses energy content and the density of the fuel to calculate fuel volume, as presented in Equation 5-1 and the values in Table 5-1.

$$Fuel\ (gallons) = Energy\ (KJ)\ \times \left(\frac{1}{energyContent}\right)\left(\frac{g}{KJ}\right) \times \left(\frac{1}{fuelDensity}\right)\left(\frac{gallons}{g}\right) \qquad \textbf{Equation 5-1}$$

The fuel density and the energy content values are stored in the fuelType and fuelSubType tables, respectively. Fuel density is classified according to the more general fuel types, and energy content varies according to fuel subtype. Because MOVES reports energy content by fueltype, rather than fuelsubtype, the average of the energy content can be calculated for each fueltype using the energy content of each fuel subtype using the respective fuel subtype market share stored in the fuelSupply table. The derivation of the fuelSupply table is documented in the MOVES technical report on fuel supply defaults[21].

Table 5-1. Fuel density and energy content by fuel type in MOVES3

fuelTypeID	fuelSubtypeID	fuelSubtypeDesc	Fuel Density (g/gallons)	Energy Content (KJ/g)
1	10	Conventional Gasoline	2839	43.488
1	11	Reformulated Gasoline (RFG)	2839	42.358
1	12	Gasohol (E10)	2839	41.762
1	13	Gasohol (E8)	2839	42.1
1	14	Gasohol (E5)	2839	42.605
1	15	Gasohol (E15)	2839	40.92
2	20	Conventional Diesel Fuel	3167	43.717
2	21	Biodiesel	3167	43.061
2	22	Fischer-Tropsch Diesel (FTD100)	3167	43.247
3	30	Compressed Natural Gas (CNG)	NULL	48.632
4	40	Liquefied Petroleum Gas (LPG)	1923	46.607
5	50	Ethanol	2944	26.592
5	51	Ethanol (E85)	2944	29.12
5	52	Ethanol (E70)	2944	31.649
9	90	Electricity	NULL	NULL

Appendix A. Timeline of Energy and GHG emissions in MOVES

- **MOVES2004**[1]
  - Released with a full suite of energy, methane, rates to allow estimation of fuel consumption and GHG emissions.
  - Energy rates developed at a fine level of detail by vehicle attributes including classes for engine technologies, engine sizes, and loaded weight classes. The emission rates were created by analyzing second by second (1 Hz) resolution data from 16 EPA test programs covering approximately 500 vehicles and 26 non-EPA test programs covering approximately 10,760 vehicles.
  - “Holes” in the data were filled using either the Physical Emission Rate Estimator (PERE)[22] or interpolation.
  - Energy consumption at starts increases at temperatures < 75F
- **MOVES2009**
  - Updates of Nitrous Oxide (N_2O) and methane (CH_4) emission rates
    - Based on an enlarged database of Federal Test Procedure (FTP) emission tests and the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006[23]
  - Energy start rates adjusted for soak time
- **MOVES2010**
  - Heavy-duty energy rates replaced based on new data and analysis using scaled tractive power (STP) methodology[6]
  - Light-duty rates updated to include 2008-2011 model year Corporate Average Fuel Economy (CAFE) Standards for light trucks
- **MOVES2010a**[2]
  - Updates to the MOVES database to reflect new data and projections for 2008 and newer light-duty energy rates
    - Model year 2008-2010 vehicle data
    - Model year 2011 Fuel Economy (FE) final rule projections
    - Model year 2012-2016 LD GHG Phase 1 rule[11]
    - Corrections to model year 2000+ light-duty diesel energy start rates
  - Modifications to the organization of energy rates in MOVES database (DB)
    - Improved consistency between energy rates and other MOVES emission rates.
    - Redefined energy rate structure
    - Removed engine size classes, and consolidated the loaded weight classes to a single weight class for each regulatory class
    - Removed unused engine technologies and emission rates from the MOVES DB
  - Updates to the methane algorithm such that methane is calculated as a fraction of total hydrocarbons (THC)
    - MOVES2010 methane and THC emission rates used to derive methane/THC ratios
- **MOVES2014**
  - Medium- and heavy-duty energy rates for model year 2014 and later updated to account for the Phase 1 of the Greenhouse Gas Emissions Standards and

    - Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles[5]
    - Light-duty energy rates for model year 2017 and later updated to account for the Light-duty EPA and NHTSA greenhouse gas and fuel economy standards (LD GHG Phase 2 FRM)[4]

- **MOVES3**
    - The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021-2026 Passenger Cars and Light Trucks[3] was incorporated for MY 2017-2026 and forward
    - Updates to heavy-duty vehicle energy rates to account for the HD GHG Phase2 rule
    - Updated the 2010-2060 HD baseline energy rates
        - HD diesel and CNG vehicles rates were updated based on the manufacturer-run heavy-duty in-use testing (HDIUT) program
        - Baseline heavy-duty gasoline energy rates for 2010-2060 were updated from an EPA conducted in-use measurement program[6]

Appendix B. Emission Control Technology Phase-In used for N_2O Emission Rate Calculations.

Table B-1 Control Technology Assignments for Gasoline Passenger Cars (Percent of VMT). Reproduced with exceptions from Table A-84 from Inventory of US GHG Emissions and Sinks: 1990-2006.

Model Years	Non-Catalyst Control	Oxidation Catalyst	EPA Tier 0	EPA Tier 1	LEVs	EPA Tier 2
1973-1974	100%					
1975	20%	80%				
1976-1977	15%	85%				
1978-1979	10%	90%				
1980	5%	88%	7%			
1981		15%	85%			
1982		14%	86%			
1983		12%	88%			
1984-1993			100%			
1994			60%	40%		
1995			20%	80%		
1996			1%	97%	2%	
1997			1%	97%	3%	
1998			0%	87%	13%	
1999			0%	67%	33%	
2000				44%	56%	
2001				3%	97%	
2002				1%	99%	
2003				0%	87%	13%
2004				0%	41%	59%
2005					38%	62%
2006+					0%	100%[a]

[a] We assume 100% EPA Tier 2 emission rates for model years 2006 and forward which differs from the US GHG Emissions and Sinks.

Table B-2 Control Technology Assignments for Gasoline Light-Duty Trucks (Percent of VMT) Reproduced with exceptions from Table A-85 from Inventory of US GHG Emissions and Sinks: 1990-2006.

Model Years	Not Controlled	Non-Catalyst Control	Oxidation Catalyst	EPA Tier 0	EPA Tier 1	LEVs	EPA Tier 2
1973-1974	0%	100%					
1975		30%	70%				
1976		20%	80%				
1977-1978		25%	75%				
1979-1980		20%	80%				
1981			95%	5%			
1982			90%	10%			
1983			80%	20%			
1984			70%	30%			
1985			60%	40%			
1986			50%	50%			
1987-1993			5%	95%			
1994				60%	40%		
1995				20%	80%		
1996					100%		
1997					100%		
1998					80%	20%	
1999					57%	43%	
2000					65%	35%	
2001					1%	99%	
2002					10%	90%	
2003					<1%	53%	47%
2004						72%	28%
2005						38%	62%
2006+							100%[a]

[a] We assume 100% EPA Tier 2 emission rates for model years 2006+, which differs from the US GHG Emissions and Sinks.

Table B-3 Control Technology Assignments for Gasoline Light-Duty Trucks (Percent of VMT) Reproduced with exceptions from Table A-85 from Inventory of US GHG Emissions and Sinks: 1990-2006.

Model Years	Not Controlled	Non-Catalyst Control	Oxidation Catalyst	EPA Tier 0	EPA Tier 1	LEVs	EPA Tier 2
1973-1974	0%	100%					
1975		30%	70%				
1976		20%	80%				
1977-1978		25%	75%				
1979-1980		20%	80%				
1981			95%	5%			
1982			90%	10%			
1983			80%	20%			
1984			70%	30%			
1985			60%	40%			
1986			50%	50%			
1987-1993			5%	95%			
1994				60%	40%		
1995				20%	80%		
1996					100%		
1997					100%		
1998					80%	20%	
1999					57%	43%	
2000					65%	35%	
2001					1%	99%	
2002					10%	90%	
2003					<1%	53%	47%
2004						72%	28%
2005						38%	62%
2006+							100%[a]

[a] We assume 100% EPA Tier 2 emission rates for model years 2006+, which differs from the US GHG Emissions and Sinks.

Table B-4 Control Technology Assignments for Gasoline Heavy-Duty Vehicles (Percent of VMT) Reproduced with exceptions from Table A-86 from Inventory of US GHG Emissions and Sinks: 1990-2006.

Model Years	Not Controlled	Non-Catalyst Control	Oxidation Catalyst	EPA Tier 0	EPA Tier 1	LEVs	EPA Tier 2
Pre-1982	100%						
1982-1984	95%		5%				
1985-1986		95%	5%				
1987		70%	15%	15%			
1988-1989		60%	25%	15%			
1990-1995		45%	30%	25%			
1996			25%	10%	65%		
1997			10%	5%	85%		
1998					96%	4%	-
1999					78%	22%	-
2000					54%	46%	-
2001					64%	36%	-
2002					69%	31%	-
2003					65%	30%	5%
2004					5%	37%	59%
2005						23%	77%
2006+							100%[a]

[a]We assume 100% EPA Tier 2 emission rates for model years 2006+ , which differs from the US GHG Emissions and Sinks.

Table B-5 Control Technology Assignments for Diesel Highway Vehicles and Motorcycles. Reproduced with exceptions from Table A-87 from Inventory of US GHG Emissions and Sinks: 1990-2006.

Vehicle Type/Control Technology	Model Years
Diesel Passenger Cars and Light-Duty Trucks	
Uncontrolled	1960-1982
Moderate control	1983-1995
Advanced control	1996-2006+[a]
Diesel Medium- and Heavy-Duty Trucks and Buses	
Uncontrolled	1960-1982
Moderate control	1983-1995
Advanced control	1996-2006+
Motorcycles	
Uncontrolled	1960-1995
Non-catalyst controls	1996-2006+

[a] In MOVES we continue using the 1996-2006 rates for all model years beyond 2006. The 2013 US GHG Emissions and Sinks updates the Advanced Control to up to 2011 model year vehicles, and adds a new category of diesel (aftertreatment diesel). However, the N2O emission rates of aftertreatment diesel are unchanged from advanced control.[24]

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