Greenhouse Gas and Energy Consumption Rates for Onroad Vehicles in MOVES5

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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EPA-420-R-24-018
November 2024

Contents

List of Acronyms

ABT	emissions averaging, banking and trading program
A/C	Air Conditioning
ALPHA	Advanced Light-Duty Powertrain and Hybrid Analysis
APU	auxiliary power units
BEV	battery electric vehicle
bhp	brake horsepower
BTU	British Thermal Unit
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CBD	Central Business District
CFR	Code of Federal Regulations
CH_4	methane
CNG	Compressed Natural Gas
CO	carbon monoxide
CO_2	carbon dioxide
CRC	Coordinating Research Council
DB	database
DOE	U.S. Department of Energy
DPF	Diesel Particulate Filter
EMFAC	CARB emissions factors model
EPA	U.S. Environmental Protection Agency
EER	Energy Efficiency Ratio
FCEV	Hydrogen Fuel Cell Vehicle
FHWA	Federal Highway Administration
FTP	Federal Test Procedure
g	grams
GHG	Greenhouse Gases
g/mi	Grams per mile
GVWR	Gross Vehicle Weight Rating
GWP	Global Warming Potential
THC	Total Hydrocarbons
HD	Heavy-Duty
HDIU	Heavy-Duty Diesel In-Use
HDT	Heavy-Duty Truck
HFC	Hydrofluorocarbon
HHD	Heavy-Heavy-Duty Class 8 Trucks (GVWR > 33,000 lbs)
HHDD	Heavy Heavy-Duty Diesel
HP	horsepower
HPMS	Highway Performance Monitoring System
hr	hour
HV	heating value
H_2O	water
ICE	Internal Combustion Engine
I/M	Inspection and Maintenance program

kJ	Kilojoules
kW	Kilowatt
LD	Light-Duty
LHD	Light-Heavy-Duty
LHD2b3	Light-Heavy-Duty Class 2b and 3 Truck ($8{,}500 < GVWR \leq 14{,}000$ lbs)
LHD45	Light Heavy-Duty Class 4 or 5 Truck ($14{,}000 < GVWR \leq 19{,}500$ lbs)
LHDDT	Light Heavy-Duty Diesel Truck
MC	Motorcycle
MDPV	Medium-Duty Passenger Vehicle
MHD	Medium-Heavy-Duty Class 6 and 7 Trucks ($19{,}500 < GVWR \leq 33{,}000$ lbs)
MOBILE6	EPA Highway Vehicle Emission Factor Model, Version 6
MOVES	Motor Vehicle Emission Simulator Model
MY	model year
MYG	model year group
NREL	National Renewal Energy Laboratory
N_2O	nitrous oxide
OBD	On-Board Diagnostics
OEM	Original Equipment Manufacturer
PERE	Physical Emission Rate Estimator
SCR	selective catalytic reduction
STP	scaled tractive power
UDDS	Urban Dynamometer Driving Schedule
VIN	Vehicle Identification Number
VIUS	Vehicle Inventory and Use Survey
VMT	Vehicle Miles Traveled
VSP	vehicle specific power

1 Introduction

This report describes the energy and greenhouse gas (GHG) rates in MOVES 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.

The content of this report intersects with several other MOVES technical reports, including:

- **Exhaust Emission Rates for Heavy-Duty Onroad Vehicles in MOVES5,**[1] referred to here as the HD Exhaust Report. Energy consumption rates for heavy-duty conventional vehicles are detailed in this report. It also describes the total hydrocarbon emissions used to estimate methane emissions.
- **Emission Adjustments for Onroad Vehicles in MOVES5,**[2] referred to here as the Emission Adjustments Report. This report describes adjustments to account for charging efficiency, battery deterioration, cabin temperature control and the modeling of fleet-averaging emission standards for CO_2 and energy such that electric vehicle fractions impact the effective energy consumption rates for internal combustion engine (ICE) vehicles.
- **Exhaust Emission Rates for Light-Duty Onroad Vehicles in MOVES5,**[3] referred to here as the LD Exhaust Report. This report describes the total hydrocarbon emissions used to estimate methane emissions.
- **Fuel Supply Defaults: Regional Fuels and the Fuel Wizard in MOVES5,**[4] referred to here as the Fuel Supply Report.
- **Population and Activity of Onroad Vehicles in MOVES5**,[5] referred to here as the Population and Activity Report. This report explains MOVES default vehicle activity and vehicle populations, including age distributions and fuel mix. MOVES default electric vehicle fractions are explained in this report.
- **Speciation of Total Organic Gas and Particulate Matter Emissions from Onroad Vehicles in MOVES5,**[6] referred to here as the Onroad Speciation Report. This report describes how MOVES estimates methane emissions.

All MOVES onroad technical reports can be accessed from the MOVES webpage.[7]

MOVES accounts for federal regulations on fuel consumption and GHG emissions from onroad vehicles. The most recent of these are listed below:

- Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for model years 2012 through 2016 (LD GHG Phase 1)[8]
- Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles (HD GHG Phase 1)[9]
- 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards (LD GHG Phase 2)[10]
- Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles—Phase 2 Rule (HD GHG Phase 2)[11]
- Safer Affordable Fuel Efficient (SAFE) Vehicles Rule for Model Years 2021-2026 Passenger Cars and Light Trucks[12]
- Revised 2023 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emission Standards (LD GHG 2023-2026)[13]

- Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles (LMDV2027)[14]
- Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles – Phase 3 (HD GHG Phase 3)[15]

MOVES5 is the first MOVES version to account for LMDV2027 and HD GHG Phase 3. Both rules are performance-based vehicle emissions standards covering model years 2027 and later. They do not mandate the sales of electric vehicles, but we model manufacturers will comply with them by selling a significant portion of electric vehicles.

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,[16] however, they have been significantly updated in subsequent versions of MOVES. This report documents the changes in energy rates that were made between MOVES2010 and current versions of MOVES. We point the reader to the earlier reports that document the development of the energy rates prior to MOVES2010.[16] [17] And, as noted above, energy rates for heavy-duty vehicles are described in the HD Exhaust Report.[1]

The carbon dioxide (CO_2) emission rates in MOVES are calculated based on energy consumption. The values used to convert energy consumption to CO_2 emissions are presented in this report in addition to the equation and values used to calculate carbon dioxide equivalent (CO_2) emissions. 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 *Exhaust and Crankcase Emissions Factors for Nonroad Compression-Ignition Engines* and *Exhaust Emission Factors for Nonroad Engine Modeling – Spark Ignition*.[18]

We also present the values that MOVES uses to calculate volumetric fuel consumption (gallons). MOVES currently reports fuel usage in terms of energy consumption (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. Methane emissions in MOVES are calculated as a fraction of total hydrocarbons. Methane fractions and total hydrocarbon emission rates are documented in the Onroad Speciation Report,[6] LD Exhaust Report,[3] and HD Exhaust Report.[1]

2 Energy Rates

In MOVES, energy consumption rates (energy use per time) are recorded in the emissionRate table by fuel type, regulatory class, model year group, emission process, and operating mode. For heavy-duty vehicles, further adjustments are recorded by source type, regulatory class, fuel type, and model year in the emissionRateAdjustment table. Additional adjustments to energy consumption are described in the Emission Adjustments Report.[2]

The first full suite of energy rates, released in MOVES2004, 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[16]. Since then, the energy rates in MOVES have been updated to account for several 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 vehicles include passenger cars, passenger trucks, and light commercial trucks. For details about corresponding vehicle weights and HPMS classes, refer to the Population and Activity Report.[5] For information about operating modes and vehicle-specific power (VSP) bins, see the LD Exhaust Report.[3]

2.1.1 Light-Duty GHG and CAFE Regulations

Several regulations are relevant for LD energy consumption rats in MOVES. These are discussed in the sections below.

2.1.1.1 LD GHG Rule Phase 1 and Phase 2

The Light Duty GHG Phase 1 rule covers model years 2012 through 2016, while the Phase 2 rule covers model years 2017 through 2025. Both Phase 1 and 2 rules apply to passenger cars and light trucks. A summary of source type 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]

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

LD Vehicle Group	Model Year				
	2012	2013	2014	2015	2016
Passenger Cars	263	256	247	236	225
Light Trucks	346	337	326	312	298
Combined Cars and 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

LD Vehicle Group	Model Year									
	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	**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 project fleet average emissions. Each vehicle has a projected CO_2 emission rate based on its footprint,[b] [19] represented by footprint curves. Figure 2-1 is an example of the footprint curve for passenger cars under the 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.

[a] While the LD GHG and SAFE rules apply to the Medium-Duty Passenger Vehicles portion of LHD2b3 vehicles (GVWR 8,500 to 14,000 lbs), most LHD2b3 vehicles are covered by HD GHG rules. Thus, until MY 2027, MOVES models the entire LHD2b3 class under the HD GHG rules as described in the HD section.

[b] "Footprint" refers to the size of the vehicle, specifically, the product of wheelbase times average track width (the area defined by where the centers of the tires touch the ground) as explained in the 2020 EPA Automotive Trends report.

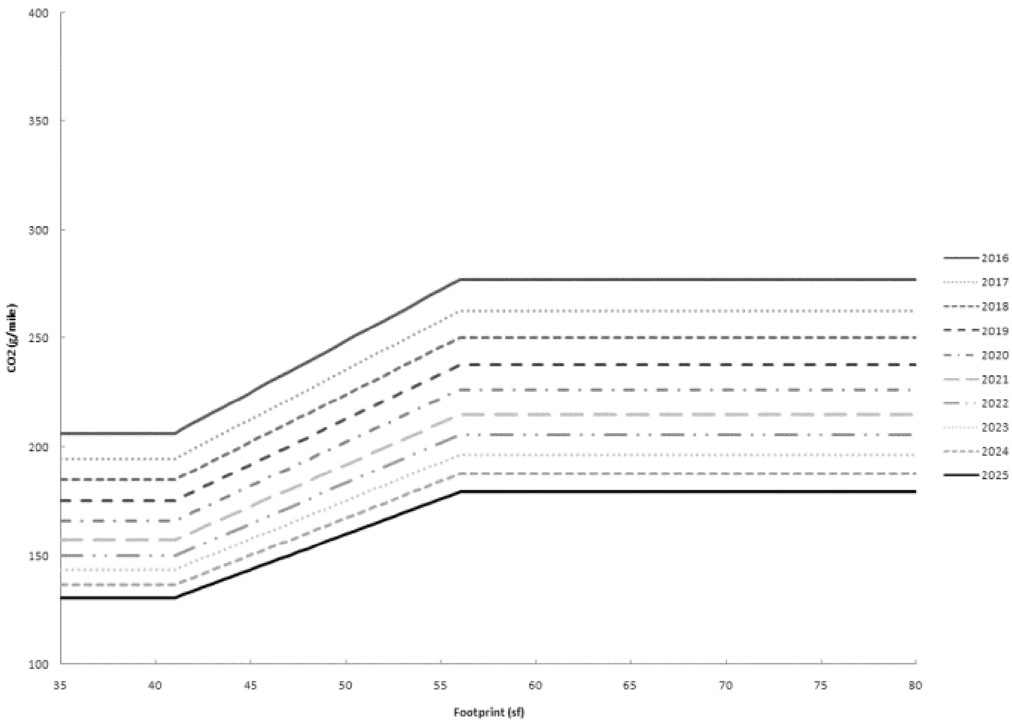

Figure 2-1. CO_2 (g/mile) footprint curves for passenger cars

Air conditioning (A/C) systems contribute 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, increasing energy consumption and tailpipe CO_2 emissions. Second, they contribute 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.

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

Model Year	Projected CO_2 compliance target	Incentives		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	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	173	0.8	13.8	5.0	193
2022	164	0	0	164	0.9	13.8	5.0	184
2023	157	0	0	157	1.0	13.8	5.0	177
2024	150	0	0	150	1.1	13.8	5.0	170
2025	143	0	0	143	1.4	13.8	5.0	163

MOVES uses the real-world tailpipe CO_2 defined in LD GHG rule Regulatory Impact Analysis (RIA)[20] 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. The value 1.25 multiplying factor in Equation 2-1 is derived from the 20% gap between test (NHTSA's CAFE 2-Cycle test including the FTP and HWFET) and on-road MPG (EPA's 5-cycle test used for fuel economy labeling, including the FTP, HWFET, US06, SC03, and UDDS)[21] for liquid fueled vehicles. We believe that EPA's 5-cycle test is more representative of real-world driving, so we converted the 2-cycle CO_2 emission to real-world CO_2 by dividing by 0.8 (equal to multiplying by 1.25).

$$\begin{aligned} Real\ World\ Tailpipe\ CO2 \\ = (Projected\ 2\ Cycle\ CO2 - Off\ Cycle\ Credit \\ - A/C\ Efficiency\ Credit) * 1.25 \end{aligned}$$ **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)

Model Year	Real-World Tailpipe CO_2 (g/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	45.5	32.1	40.0

2.1.1.2 SAFE Rule

The SAFE rule, finalized in March 2020 and effective on June 29, 2020, amended existing CAFE and GHG standards for passenger cars and light trucks. The fleet-average targets for light-duty passenger cars and trucks in the SAFE rule are shown in Table 2-6. We updated energy rates based on the SAFE rule in MOVES3 as described in Section 2.1.2 (running energy rates) and in Section 2.1.3 (start energy rates).[c]

Table 2-6 Fleet-average fuel economy and CO_2 targets in the SAFE rule

Model Year	Average of OEM Established Requirements			
	Passenger Cars		Passenger Trucks	
	CAFE mpg	CO_2 g/mile	CAFE mpg	CO_2 g/mile
2021	44.2	183	31.6	264
2022	44.9	180	32.1	259
2023	45.6	177	32.6	255
2024	46.3	174	33.1	251
2025	47.0	171	33.6	247
2026	47.7	168	34.1	243

2.1.1.3 Revised 2023 and Later LD GHG Standards

The Revised 2023 and Later Model Year Light Duty Vehicle Greenhouse Gas Emission Standards (LD GHG 2023-2026) rule[22] tightened the CO_2 emission requirements for model years 2023 and later. These standards, shown in Table 2-7, are expected to increase the fraction of electric vehicles in the fleet as described in the Population and Activity Report[5] and to change the average energy consumption of the remaining ICE vehicles.

Table 2-7 Estimated fleet-wide CO_2 targets corresponding to the final LD GHG 2023-2026 standards

Model Year	CO_2 Emission Targets (g/mile)		
	Passenger Cars	Passenger Trucks	Fleet-Average
2023	166	234	**202**
2024	158	222	**192**
2025	149	207	**179**
2026 and beyond	132	187	**161**

2.1.1.4 LMDV2027 Standards

The Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles (LMDV2027) rule was finalized by EPA in 2024 and incorporated into MOVES5. The standards increase in stringency each year over a six-year period from model years 2027 to 2032. The proposed standards are projected to result in an industry-wide average target for the light-duty fleet of 82 g/mile of CO_2 in MY 2032. The CO_2 emission rates for

[c] The SAFE "Part 1" Final Rule (One National Program) was released in September 2019. As a result, EPA withdrew the Clean Air Act preemption waiver for LD vehicles it had granted to California. The California Clean Air Act preemption waiver was reinstated in 2023.

gasoline, diesel, and E-85 vehicles in MOVES regulatory classes 20, 30, and 41 were updated by matching MOVES output to the rates generated by the EPA Optimization Model for reducing Emissions of Greenhouse Gases from Automobiles (OMEGA) model for the final rule (FRM) central case scenario, which can be found in the docket for the rulemaking.[23]

2.1.2 Light-Duty Running Energy Rates for Internal Combustion Engines

This section focuses on running energy rates for light-duty vehicles with internal combustion engines (ICE). The main text focuses on gasoline vehicles, including hybrids. Hybrids are subject to the same CO_2 standards as conventional gasoline vehicles and are incorporated into the fleet average emissions for gasoline vehicles. Energy consumption rates for vehicles running on diesel and ethanol fuels are described in Section 2.1.2.6.

2.1.2.1 Motorcycles

Motorcycle energy consumption rates have not been updated since MOVES2014. The energy rates were developed initially for MOVES2004[16] 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). We consolidated the energy consumption rates into a single energy rate by model year for all motorcycles in MOVES2010a.[17] Due to a population shift to larger motorcycles[24], this resulted in an average increase in motorcycle energy consumption rates between MY 1991 and MY 2000. 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.

2.1.2.2 Model Years Prior to 2017

Energy consumption rates for light-duty vehicles (LDV) from before MY 2017, and light-duty trucks (LDT) from before MY 2017 are unchanged from MOVES2014. The energy rates for motorcycles, light-duty cars and light-duty trucks are distinguished by fuel type, engine technology, regulatory class, and model year.

Before MOVES2010a, MOVES stored energy rates in significantly more detail than it does now; rates varied by engine technology, engine size and more refined loaded weight classes. For MOVES2010a, the energy rates were simplified to use 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 vehicle populations in MOVES2010. Because this approach used highly detailed energy consumption data, coupled with information on engine size and vehicle weight for the vehicle fleet that varied for each model year, year-by-year variability was introduced into the pre-2000 MY aggregated energy rates used in MOVES2010a and carried into later MOVES versions.

The effects of the LD GHG Phase 1 and Phase 2 rules were modelled by adjusting the energy rates in previous MOVES versions, as documented in the MOVES2010 and MOVES2014 GHG and Energy Consumption Rates reports.[17, 25]

2.1.2.3 Model Years 2017-2026

Light-duty energy consumption rates for model years 2017 through 2022 are based sales and certification data from the 2023 Automotive Trends Report.[26]

For model years 2023-2026, MOVES estimates the effects of the LD GHG 2023-2026 rule. The basic methodology we used is the same as the one used to incorporate LD GHG rules in MOVES2014, where we used ratios of the estimated real-world CO_2 (or on-road CO_2) values developed in the rulemaking as input to update the MOVES rates in the emissionRate table. The real-world CO_2 calculation for model years 2023-2026 uses CO_2 2-cycle g/mile rates, off-cycle credits, and A/C efficiency credits, as shown in Equation 2-1.

MOVES also incorporates an adjustment to ICE energy rates that accounts for fleet averaging and the sales of electric vehicles as documented in the Emission Adjustments Report.[2] The adjustment results in an increase in the average CO_2/mile for gasoline and diesel vehicles.

2.1.2.4 Model Years 2027 and beyond

For LMDV2027, we calculated adjustment ratios from on-road CO_2 values generated by OMEGA and applied them directly to running energy rates in the emissionRate table, including for all ICE light-duty vehicles (regulatory classes 20 and 30) and all medium-duty vehicles (regulatory class 41). The new, more stringent emissions standards for criteria pollutants and greenhouse gases (GHG) for light-duty vehicles and medium-duty vehicles (LMDV) phase in over model years 2027 through 2032 and then are stable beyond model year 2032.

The LMDV2027 standards are different for Class 2b and Class 3 vehicles, which are both modeled in MOVES as regulatory class 41. In MOVES, we set the regClass 41 values in the emissionRate table to the rate appropriate for Class 3 vehicles and adjust this to reflect the Class 2b standards for source types 31 and 32 by applying adjustments via the emissionrateadjustment table.

MOVES also incorporates an adjustment to ICE energy rates that accounts for the fleet averaging provisions of LMDV2027 as documented in the Emission Adjustments Report. The fleet averaging adjustment results in higher CO_2 g/mile rates for ICE vehicles in years where we project that Inflation Reduction Act subsidies will result in higher EV sales fractions than needed to comply with the LMDV2027 rule.

2.1.2.5 LD Running Energy by Operating Mode

Figure 2-2 shows the energy consumption rates by operating mode for motorcycles, LDVs, and LDTs in model year 2025. The relative energy consumption rates by operating mode are the same for all passenger cars beginning in MY 1999 and all light-duty trucks beginning in MY 2001.

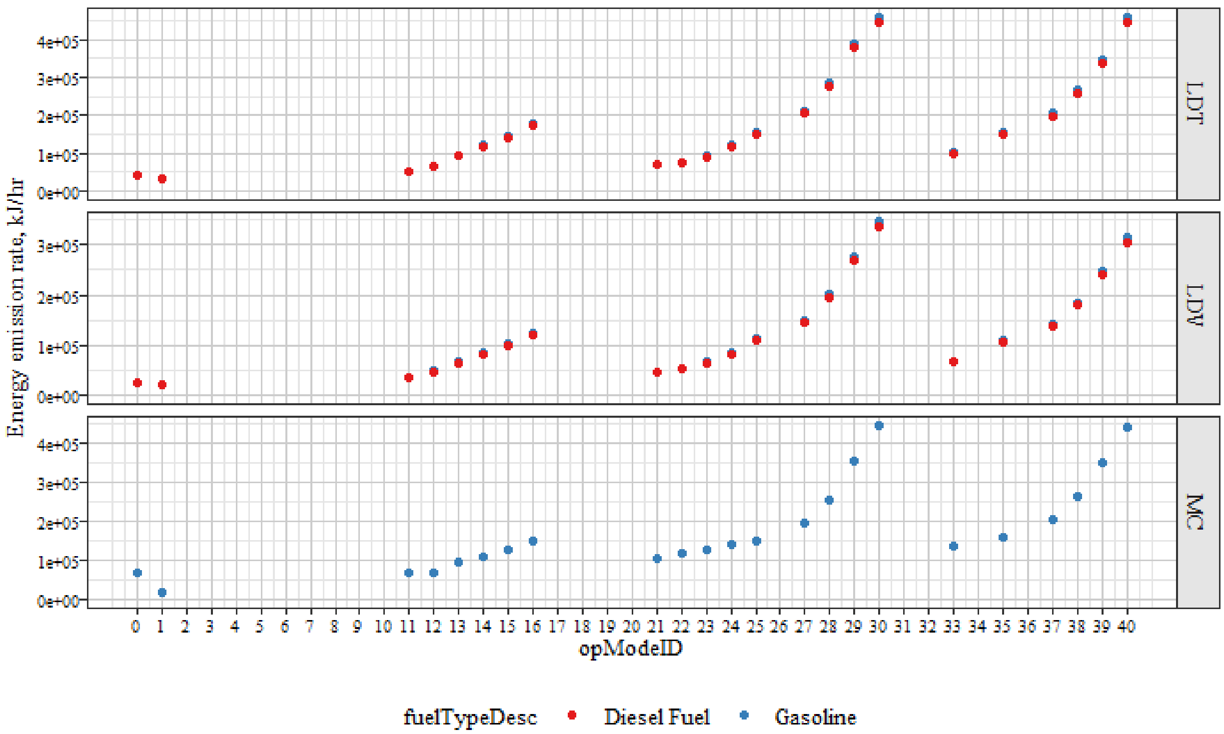

Figure 2-2. Running energy rates by operating mode (opModeID) for motorcycles (MC), light-duty vehicles (LDV) and light-duty trucks (LDT) for model year 2025

2.1.2.6 LD Running Energy Rate Summary

Beginning in MY 2021, the absolute magnitude of light-duty energy consumption rates fall, driven by EPA rules. This can be seen in Figure 2-3 and Figure 2-4, which plot the MOVES national average CO_2 emission rates for motorcycles, LDVs, and LDTs for the running process. Model years 1950-1969 have the same CO_2 emission rates as MY 1970.

These emission rates represent fleet average emissions and do not necessarily reflect GHG standards directly. Some changes in base rates may be caused by MOVES modeling of fleet averaging when EVs represent a significant portion of total light-duty sales.

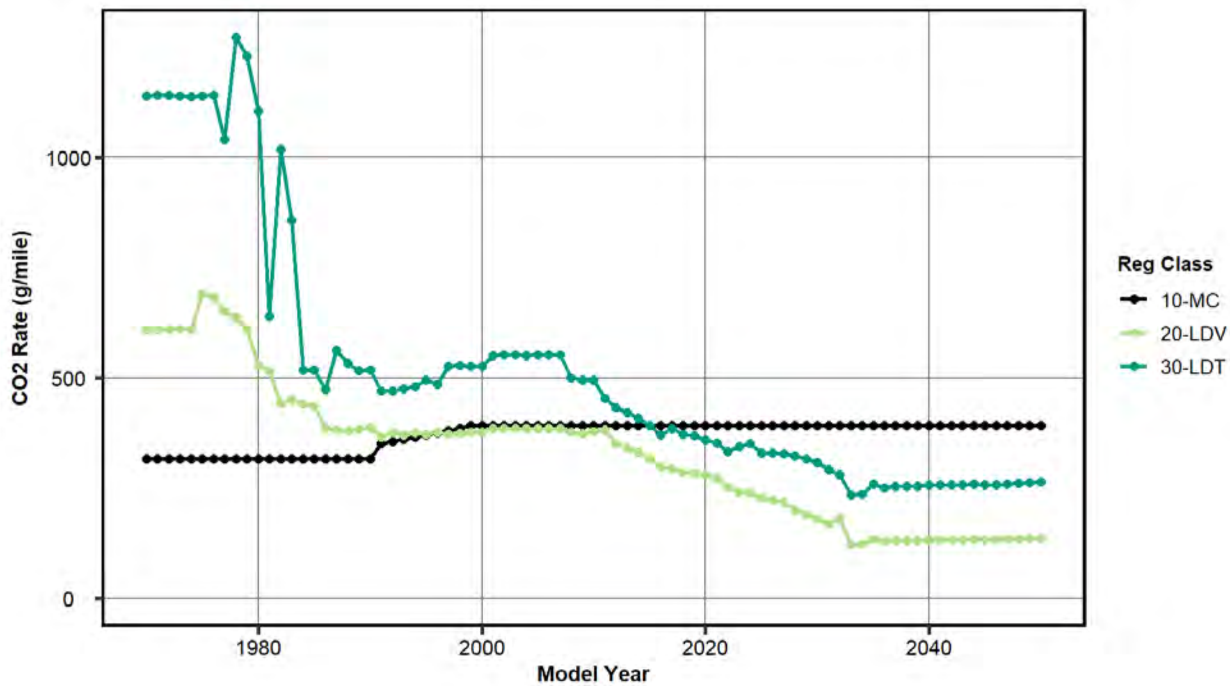

Figure 2-3. Base running rates in MOVES5 for atmospheric CO_2 from gasoline motorcycle, light-duty vehicles and light-duty trucks averaged over nationally representative operating mode distributions.

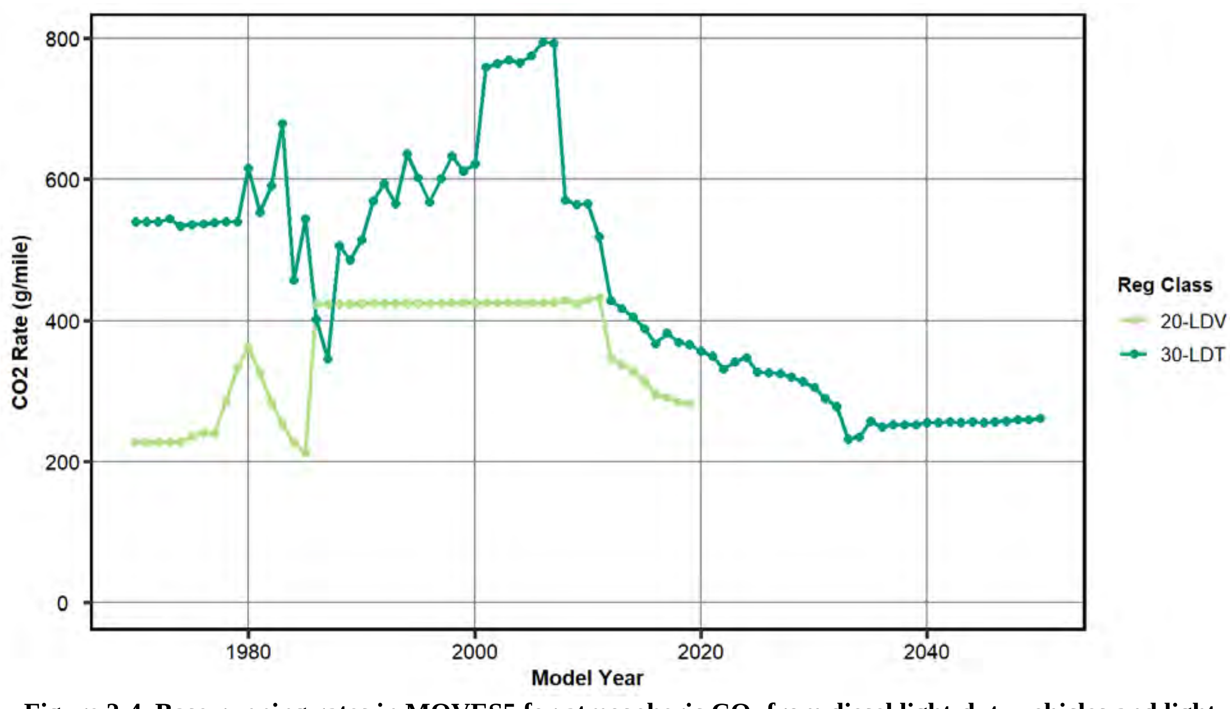

Figure 2-4. Base running rates in MOVES5 for atmospheric CO_2 from diesel light-duty vehicles and light-duty trucks averaged over nationally representative operating mode distributions. MOVES5 models no diesel passenger cars after MY 2019.

Starting in MY 2012, diesel LDVs and LDTs have the same relative energy rates (for starts and running) and operating mode trends as corresponding 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) as 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 2-4.

Ethanol (E-85) vehicles are assumed to have the same energy consumption rates as comparable gasoline vehicles. However, the differences in carbon content results in different CO_2 emission rates as discussed in Section 4.1.

2.1.3 Light-Duty Running Energy Rates for Electric Vehicles

Energy rates for battery electric vehicles (BEVs) were significantly updated in MOVES4, relative to MOVES3. There is limited experimental data available at the 1 HZ level, which is the resolution that MOVES requires. We modeled nine BEVs representative of the 2019 fleet in EPA's ALPHA (Advanced Light-Duty Powertrain and Hybrid Analysis) model.[27] The vehicles modelled include the Chevy Bolt, Tesla Model 3, Honda Clarity (BEV), Nissan Leaf, Fiat 500e, Tesla Model S, BMW i3, VW e-Golf, and Tesla Model X. Inputs for each vehicle were compiled from the EPA test car list[28], manufacturer data, press releases, and other sources. See Appendix C for a comprehensive table of the values used for these vehicles. These rates were used for all model years 2011-2060.

In ALPHA, we simulated each vehicle over three repeats of the EPA UDDS and HWFET[21] cycles, as well as two additional sets of drive cycles in order to increase the sample sizes for the high-powered operating modes. The first set included the UDDS, LA92, US06, and Worldwide harmonized Light vehicles Test Cycles (WLTC). The second set was a custom-built cycle intended to fully populate every MOVES operating mode. It consisted of 50 hard accelerations based on a standard 0-78.5 mph acceleration curve but varied slightly with a maximum speed ranging from 75 to 80 miles per hour. This enabled rate collection for a variety of speeds and vehicle-specific power bins (VSPs). Data during deceleration back to 0 mph was ignored because the cycle was intended only to sample high-power operation, not represent real-world operation.

Typically, operating mode is assigned using power at the wheels, as calculated by ALPHA based on the individual vehicle characteristics. Since MOVES uses the same road load coefficients for BEVs and ICE vehicles, that approach meant the resulting energy consumption values were biased too high. Instead, we calculated VSP and assigned operating modes using the road loads in MOVES and the values for velocity and acceleration reported by ALPHA. After making this change, the energy rates calculated by ALPHA were much more closely aligned with the data from the test car list.[28] More details about parameters and results in ALPHA modeling can be found in Appendix C.

We derived final energy rates by calculating the average rate across all of the modelled vehicles in ALPHA, weighted by 2019 sales volumes. The sales volumes can be found in Table C-1 in

Appendix C. This approach accounts for variations in BEV engineering, increases the sample size in each operating mode, and helps make the energy rates less sensitive to differences in vehicle characteristics.

In theory, a similar methodology could be applied to passenger trucks. However, at the time of our analysis for MOVES4, there was not enough information available about EV trucks on the market or in the test car list to properly represent these vehicles in ALPHA. Therefore, we scaled the rates for light-duty electric trucks and LHD2b3 trucks (regulatory classes 30 and 41) from the light-duty electric car rates, assuming that energy gained from regenerative braking and energy used during all other operation increases linearly with vehicle mass. We calculated the specific scaling factor from the fixedMassFactor column of the sourceUseTypePhysics table. The scaling factor for converting LDV rates to LDT rates is 1.2624, while the scaling factor to convert LDV rates to LHD2b3 is 3.3811.

The MOVES energy consumption rates for MY2011-2060 passenger cars and passenger trucks are shown below in Figure 2-5 and Figure 2-6**.** In both figures, the blue bars represent energy consumption rates for a BEV and the orange bars represent the rates for an ICE vehicle. Negative energy consumption values in the plots represent regenerative braking. For passenger cars and trucks, BEV energy rates for each operating mode have lower values than ICE energy rates.

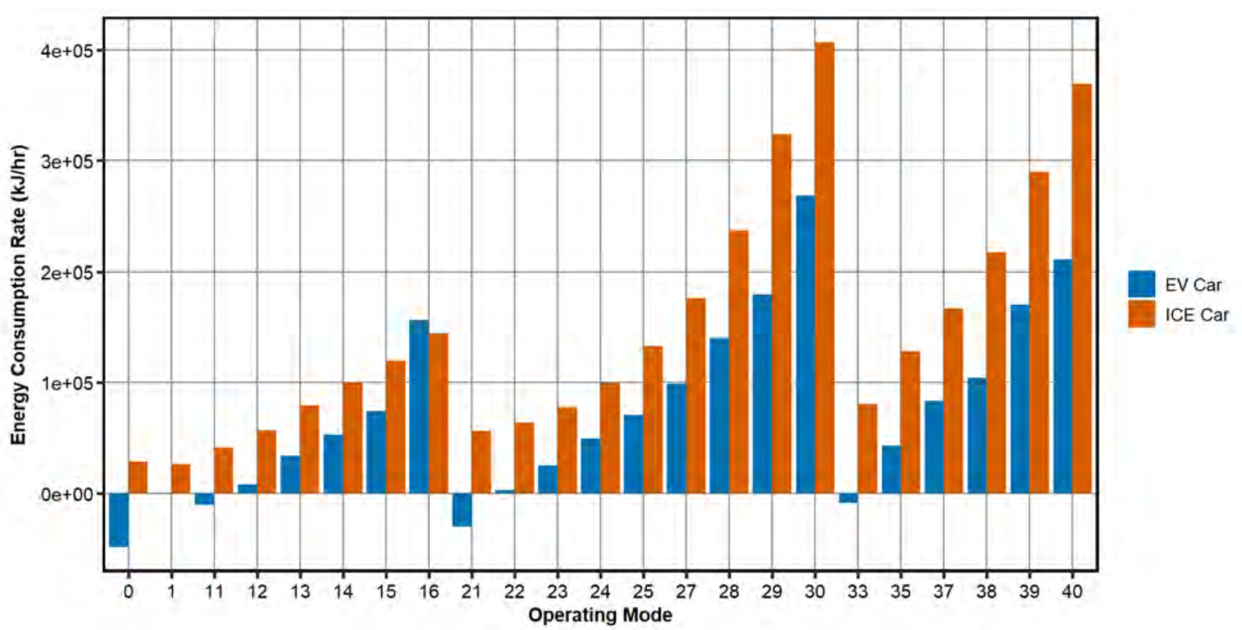

Figure 2-5. MOVES5 base energy rates for electric and ICE model year 2011-2060 passenger cars by operating mode

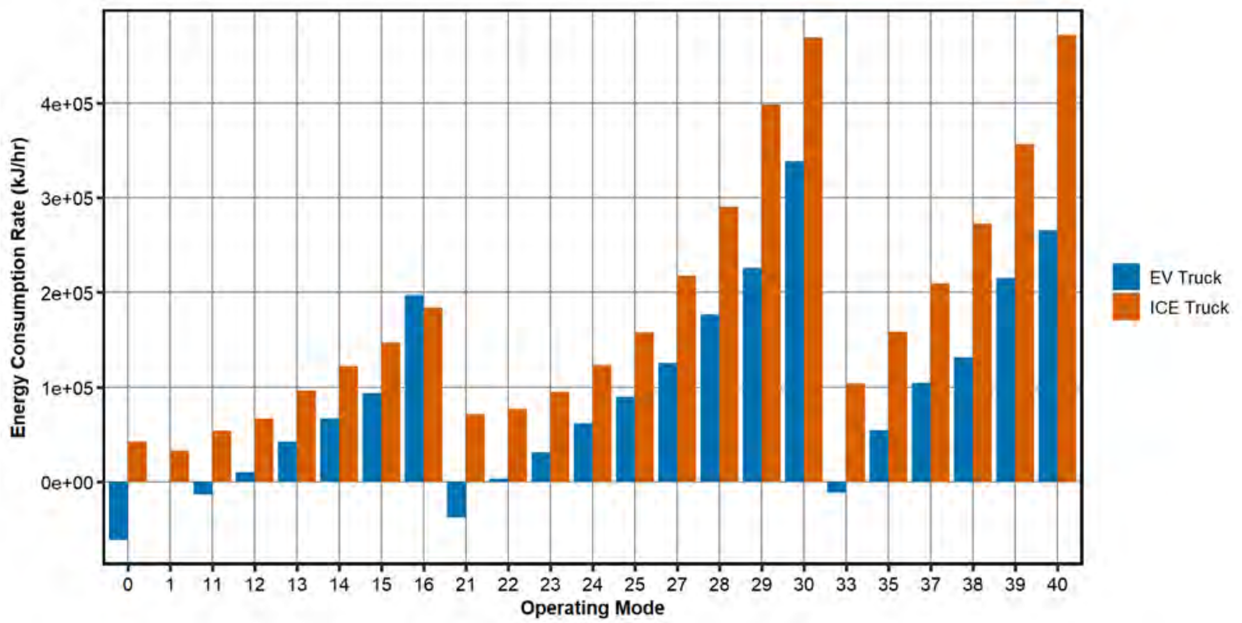

Figure 2-6. MOVES5 base energy rates for electric and ICE model year 2011-2060 passenger trucks by operating mode

Further adjustments to BEV energy consumption rates are documented in the Emission Adjustments Report,[2] including adjustments for ambient temperature, air conditioning, and for charging and battery efficiency. MOVES does not model light-duty fuel cell electric vehicles.

2.1.4 Light-Duty Start Energy Rates

LD BEVs are modelled with zero energy consumption for starts. ICE vehicles, on the other hand, require energy to start the internal combustion engine, especially when the engine has been sitting ("soaking") for a long time or in low ambient temperatures.

Figure 2-7 displays the start energy rates for gasoline motorcycles (MC), light-duty vehicles (LDV), and light-duty trucks (LDT) by operating mode for model year 2020. Start energy rates increase for operating modes with longer soak times as defined in Table 2-8. The operating mode fractions are used for all model years and fuel types of light-duty vehicles and motorcycles. MOVES also adjusts the start rates for the increased fuel consumption required to start a vehicle at cold ambient temperatures. The temperature effects on start energy consumption are documented in the Emission Adjustments Report[2] and the 2004 Energy Report.[16]

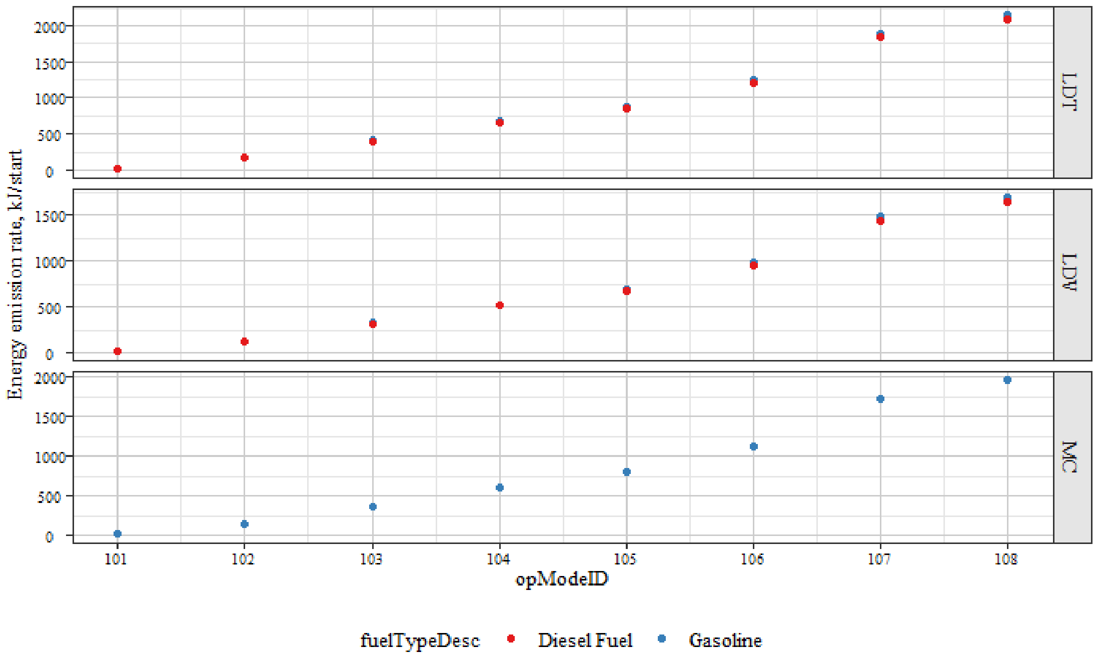

Figure 2-7. Start energy rates by operating mode (opModeID) for motorcycles (MC), light-duty vehicles (LDV) and light-duty trucks (LDT) for model year 2025

Table 2-8. Proportion 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	Proportion 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

To account for the LD GHG 2023-2026 rule, we reduced start energy rates (based on the rule's estimated real-world CO_2) for all ICE light-duty vehicles by the same ratios as used for running energy consumption rates. This was discussed in Section 2.1.1.3. We similarly applied the same adjustment factors for model years 2027 and beyond as we did for running emissions to capture the impact of the LMDV2027 rule. This was discussed in Section 2.1.1.4. The adjustment ratios vary by model year from 2020 to 2050. The adjustment ratio for MY 2050 was applied to model years 2051 and beyond.

Figure 2-8 and Figure 2-9 plot the start CO_2 emission rates for cold starts (opMode108) across model years for gasoline and diesel light-duty vehicles, respectively. Motorcycles have a sharp decrease in CO_2 emission starts in 1991 because MOVES assumes ‘controlled’ energy starts beginning in MY 1991 as documented in the MOVES2004 energy report.[16] The start rates for LDV and LDT have a large decrease starting in MY 2012 that follows the same general trends as the running rates.

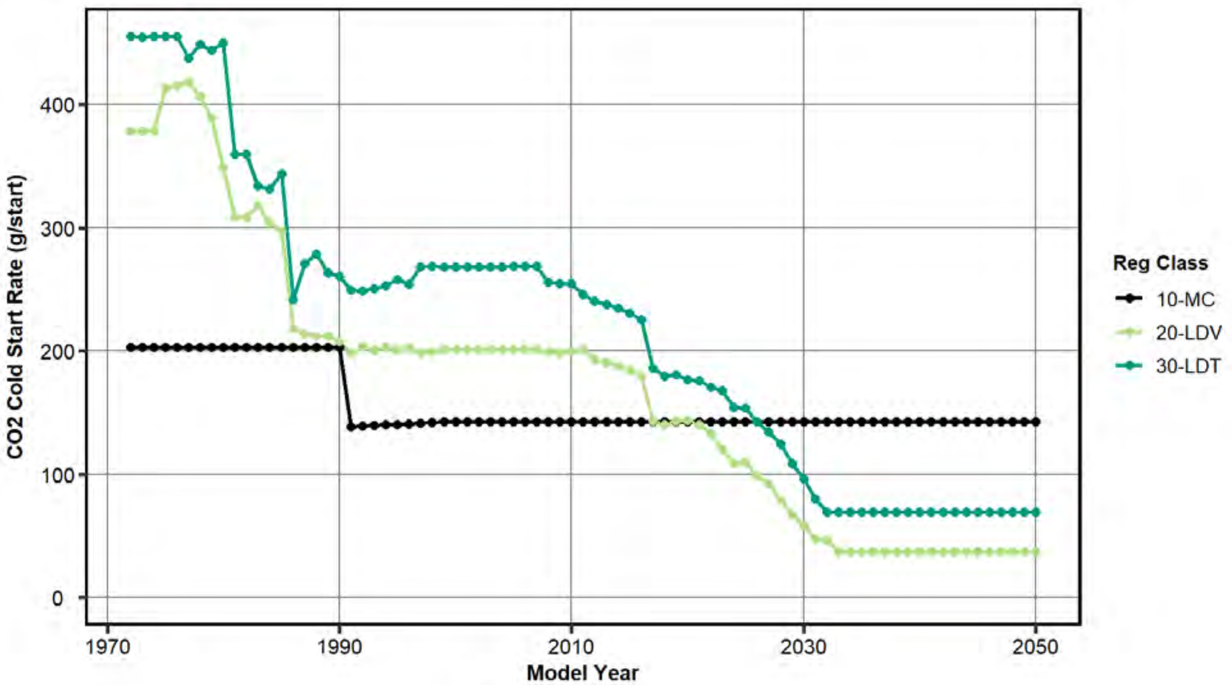

Figure 2-8. Cold start CO_2 emission rates (opMode 108) for gasoline motorcycle, light-duty vehicles, and light-duty trucks

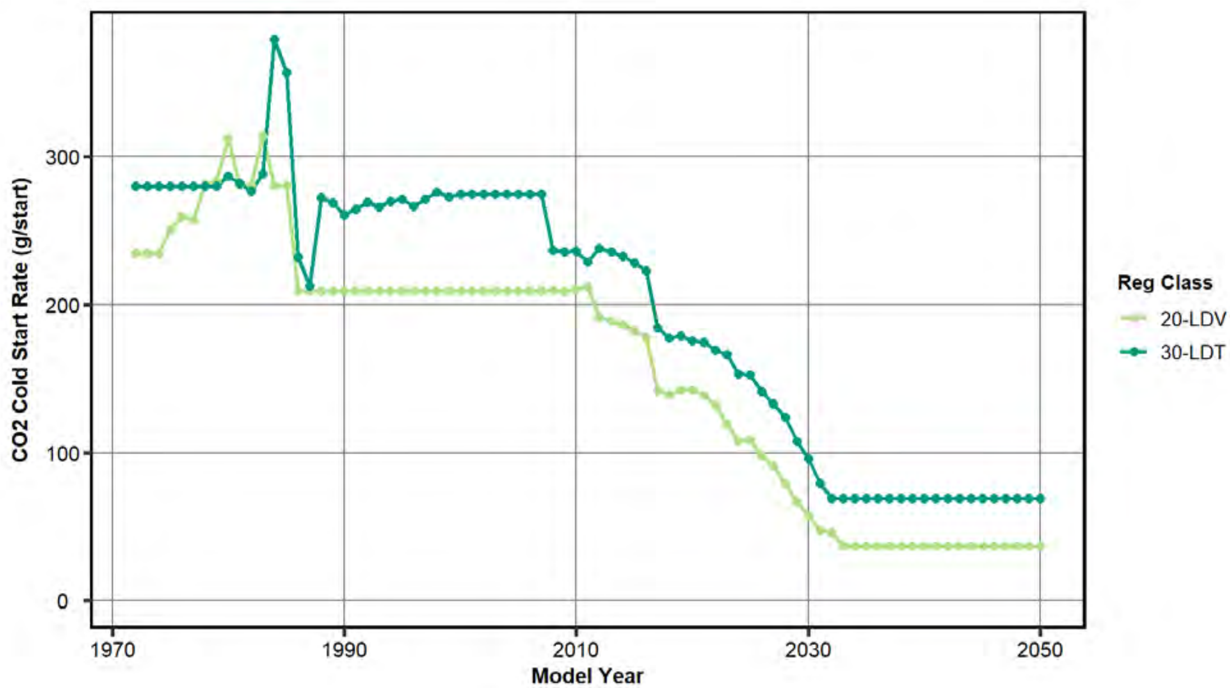

Figure 2-9. Cold start CO_2 emission rates (opMode 108) for diesel light-duty vehicles, and light-duty trucks

2.2 Heavy-Duty Vehicles

MOVES has heavy-duty running energy consumption rates for five fuel types: diesel, gasoline, compressed natural gas (CNG), battery electric (BEV) and hydrogen fuel cell (FCEV). Note that the output for BEVs and FCEVs is combined as the electricity fuel type.

The development of the heavy-duty energy rates by regulatory class, fuel type, and model year for ICE technologies are documented in the HD Exhaust Report.[1] These rates include the reductions from the HD GHG Phase 1, Phase 2 and Phase 3 standards which are only summarized here. Energy consumption rates for heavy-duty electric vehicles are documented in Section 2.2.1 of this report.

The HD GHG Phase 1 standards began in MY 2014 and increase in stringency through MY 2018. The standards were set to continue indefinitely after 2018. The program divides the diverse truck sector into three 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.[d]

The HD GHG Phase 1 rule was incorporated into MOVES through three key elements. These include (a) revised running emission rates for energy consumption, (b) new aerodynamic

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

coefficients and weights, (c) auxiliary power units (APUs), which largely replace extended idle in long-haul trucks and were added as a new process in MOVES. The Phase 1 reductions vary by fuel type, regulatory class, and model year. CNG and diesel vehicles have the same reductions because they have the same standards. The effect of the HD GHG Phase 1 rule on running energy consumption rates, APU energy consumption rates, and criteria emission rates is documented in the HD Exhaust Report.[1] The revised aerodynamic coefficients for MY 2014 and later heavy-duty trucks are documented in the Population and Activity Report.[5]

MOVES also accounts for the HD GHG Phase 2 rule. 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. For details regarding these updates, please refer to HD Exhaust Report.[1]

In MOVES5, we updated heavy-duty vehicle energy rates to incorporate the HD GHG Phase 3 rule. As with Phase 1 and Phase 2, the Phase 3 reductions in energy rates vary by vehicle type and are documented in the HD Exhaust Report.[1]

2.2.1 Heavy-Duty Battery Electric and Fuel Cell Energy Rates

In MOVES, heavy-duty EVs can have either battery electric or fuel cell powertrains, referred to as battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs), respectively.

Light-duty EV energy consumption was estimated using EPA's ALPHA model, based on the average energy consumption of real BEV passenger cars and SUVs (see Section 2.1.3). Unfortunately, there is not enough data for heavy-duty BEVs or FCEVs to implement a similar approach to developing energy consumption rates.

Therefore, we used a more general approach based on an Energy Efficiency Ratio (EER) of electric vehicles to diesel vehicles. The EER allows MOVES to calculate EV energy consumption relative to diesel energy consumption, which is much better understood. CARB has used the EER to express EV energy consumption as well.[29] The energy consumption of an HD EV can be calculated using Equation 2-2:

$$Energy_{EV} = \frac{Energy_{diesel}}{EER} \quad \textbf{Equation 2-2}$$

BEV EERs are generally greater than 1, indicating EVs are generally more efficient than comparable diesel vehicles. An EER of 2 means an electric vehicle is twice as efficient as its diesel counterpart and therefore consumes half the energy. While an EER can be formulated relative to any ICE vehicle, we use diesel as the reference because it is the dominant fuel type in the heavy-duty sector. For BEVs, we implemented this approach by first duplicating diesel energy consumption rates for all electric vehicles in the EmissionRate table, then applying the EERs using the EmissionRateAdjustment table.

Heavy-duty FCEVs have a lower efficiency ratio than comparable BEVs. However, MOVES aggregates BEVs and FCEVs together into the electricity fuel type by the time the EERs are applied. The result is that the same EER is applied to both engine technologies. To account for this, the energy consumption rates for FCEVs in the EmissionRate table are scaled up by a FCEV:BEV scaling factor. This scaling factor incorporates all operational differences between the two vehicle types, including differences in energy conversion efficiency and other MOVES effects such as the temperature effect and charging efficiency adjustments for BEVs.[2]

In MOVES4, we calculated BEV EERs and the FCEV:BEV ratio based on a literature review of sources available at the time. For MOVES5, we updated the EERs to be based entirely on heavy-duty vehicle modeling in EPA's Heavy-Duty Technology Resource Use Case Scenario Tool (HD TRUCS). HD TRUCS was developed for the HD GHG Phase 3 rule and was EPA's technology assessment tool to support the development of technology packages for the final HD Phase 3 standards. It was peer reviewed in 2023[30] and is more fully discussed in the HD Phase 3 Regulatory Impact Analysis Chapter 2.[31] For our analysis, we used the FRM version of HD TRUCS available in the HD Phase 3 docket.[32]

HD TRUCS evaluates the energy and power demands of 101 representative HD vehicle types. The representative vehicles cover many aspects of work performed by vehicles in the heavy-duty sector. This work was translated into total energy and power demands by vehicle type based on everyday use of HD vehicles. HD TRUCS then identifies the technical properties required for electric vehicles (BEV, FCEV, or plug-in hybrids) to meet the operational needs of a comparable diesel vehicle. In other words, HD TRUCS estimates the energy consumption rates of BEVs and directly comparable diesel using component-level vehicle modeling and data.

We used the HD TRUCS output to calculate sales-weighted average diesel and BEV energy consumption by MOVES source type and regulatory class.[e] This, then, allows for the calculation of BEV EERs, which appear in Table 2-9. Similarly, we used HD TRUCS output to calculate a single FCEV:BEV scaling factor of 1.211 that includes all the operational differences between BEVs and FCEVs.

[e] The sales volumes used to calculate the sales-weighted averages are included in HD TRUCS.

Table 2-9 BEV Energy Efficiency Ratios (EER) calculated from HD TRUCS

Source Type	LHD45 regClassID 42	MHD67 regClassID 46	HHD8 regClassID 47	Urban Bus regClassID 48
Other Buses sourceTypeID 41	4.23	3.84	2.70	
Transit Buses sourceTypeID 42	3.59	3.44	3.65	3.65
School Buses sourceTypeID 43	3.89	4.05	3.15	
Refuse Trucks sourceTypeID 51	3.53	3.53	3.70	
Single Unit Short-Haul Trucks sourceTypeID 52	3.78	3.45	3.03	
Single Unit Long-Haul Trucks sourceTypeID 53	3.47	2.92	2.39	
Motor Homes sourceTypeID 54	3.33	3.08	3.04	
Combination Short-Haul Trucks sourceTypeID 61		2.34	2.28	
Combination Long-Haul Trucks sourceTypeID 62		2.15	2.15	

This approach has its limitations; the most important being the implicit assumption that relative power demand across operating modes is the same between ICE and EV vehicles. While regenerative braking is included in HD TRUCS and thus is included in the estimation of EERs, MOVES cannot explicitly model regenerative braking (a negative energy consumption for the braking operating modes) for heavy-duty EVs like it can for light-duty.

This approach is used only for running energy consumption. Heavy-duty EV energy consumption is assumed to be zero for starts, consistent with the approach for light-duty. For hotelling, we assume EV combination long-haul trucks will use shore power from the facility at which they hotel, or otherwise keep the main battery off. Energy consumption for shore power is discussed in the following section.

2.2.2 Hotelling Shore Power Energy Consumption

"Hotelling" refers to rest periods by long-haul trucking operators where the truck is used as a residence. Energy consumption and emission rates during hotelling from conventional vehicles is described in the HD Exhaust Report.[1] To fully estimate energy demand on the grid for electric and other vehicles, MOVES estimates energy consumption for combination trucks which hotel overnight plugged into the AC power at the facility – known in the industry as using shore power.

Shore power is represented by processID 93 and its energy consumption rates are stored in the operating mode 203. In MOVES3, operating mode 203 covered both shore power and battery usage for hotelling. In newer versions of MOVES, battery activity is classified as operating mode 204. Details are available in the Population and Activity Report.[5]

Combination trucks of any fuel type can use shore power if they have the correct equipment. Because the shore power is used to run accessories in the cabin, we assume that the energy consumption for all fuel types using shore power is the same. Likewise, because the energy consumption is related to accessory use, we use the same energy consumption rate for all model years.

There is little data on shore power energy consumption, in large part because shore power usage is still relatively rare – operators typically opt for auxiliary power units. Frey and Kuo (2009)[33] collected energy consumption data from hotelling trucks from late 2006 through early 2008, including engine-on idling, APU usage, and shore power for MY 2006 combination trucks. Using their published energy consumption values, we derived a shore power EER, consistent with our approach to modeling running energy consumption for heavy-duty EVs described in Section 2.2.1. Frey and Kuo report data for both a mid-temperature and high-temperature scenario, with EERs (relative to diesel engine-on energy consumption) that evaluate to 12.05 and 3.75, respectively.

We assume that the representative real-world average EER for shore power is 8, roughly averaging the EER values reported by Frey and Kuo. Therefore, the shore power energy consumption rate in MOVES is 1/8th the energy consumption for a 2006 model year Class 8 tractor extended idling. We apply this rate (12,135.6 kilojoules per hour) to combination trucks of all fuel types and model years.

3 Nitrous Oxide (N_2O) Emission Rates

Nitrous oxide (N_2O) is a powerful, long-lived greenhouse gas and is formed as a byproduct in virtually all combustion processes[34] and in catalytic exhaust emission aftertreatment systems. MOVES estimates N_2O emission rates for start and running exhaust. In general, the nitrous oxide (N_2O) emission rates in MOVES are estimated more coarsely than other pollutants. In MOVES2014 and earlier versions, running (N_2O) emission rates were estimated for one single operating mode (opModeID 300 = all running). In MOVES3, we updated the N_2O emission rates to use the 23 operating modes that we use for most other pollutants (opModeIDs 0 through 40), however, for most regulatory classes, model years, and fuel types, the average running emission rate is simply copied into the more detailed running exhaust operating modes. Start emissions continue to use a single operating mode (“Starting,” opModeID = 100). The N_2O start and running exhaust emission rates do not vary by vehicle age and are stored in the EmissionRate table.

3.1 Gasoline Vehicles

As detailed in the MOVES2010a energy and greenhouse gas emission rate report[17], the gasoline N_2O emission rates are derived from emission measurements on the Federal Test Procedure (FTP)[21] and supplemented with N_2O emission rates from the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006 report[46].

The running and start emission rates are derived from 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 lists the FTP composite N_2O emission rates, calculated running rates (in grams per hour) and start rates (in grams per start). The heavy-duty gasoline vehicle emission rates are used for all heavy-duty regulatory classes (LHD2b3, LHD45, MHD, and HHD).

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

Vehicle Type / Control Technology	FTP Composite (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

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-4 in Appendix B provide the distribution of gasoline emission control technologies by model year. The running and start emission rates in Table 3-1 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-4 are taken directly from the Inventory of the US GHG Emissions and Sinks, Annex Tables A-84 through A-87[46], except for a few revisions noted in the footnotes of the tables. Nationally representative N_2O base rates for gasoline vehicles are shown in Figure 3-1 and Figure 3-2.

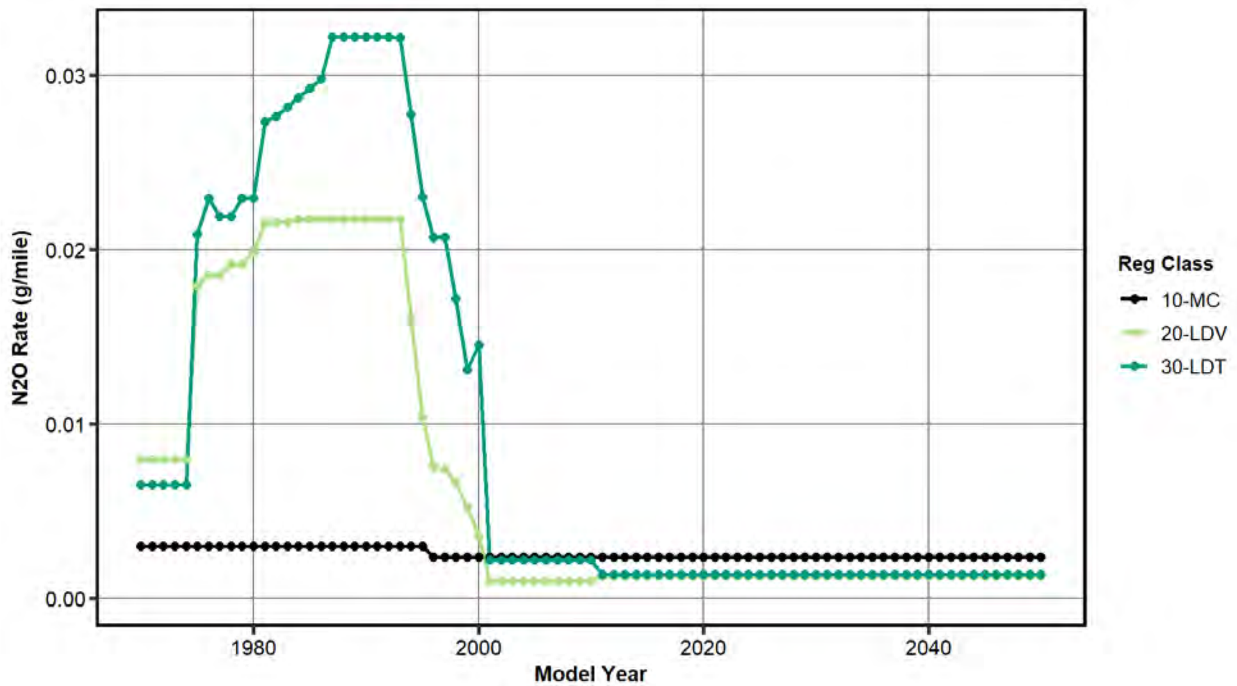

Figure 3-1. Base running rates in MOVES5 for N_2O from gasoline motorcycle, light-duty vehicles and light-duty trucks averaged over nationally representative operating mode distributions.

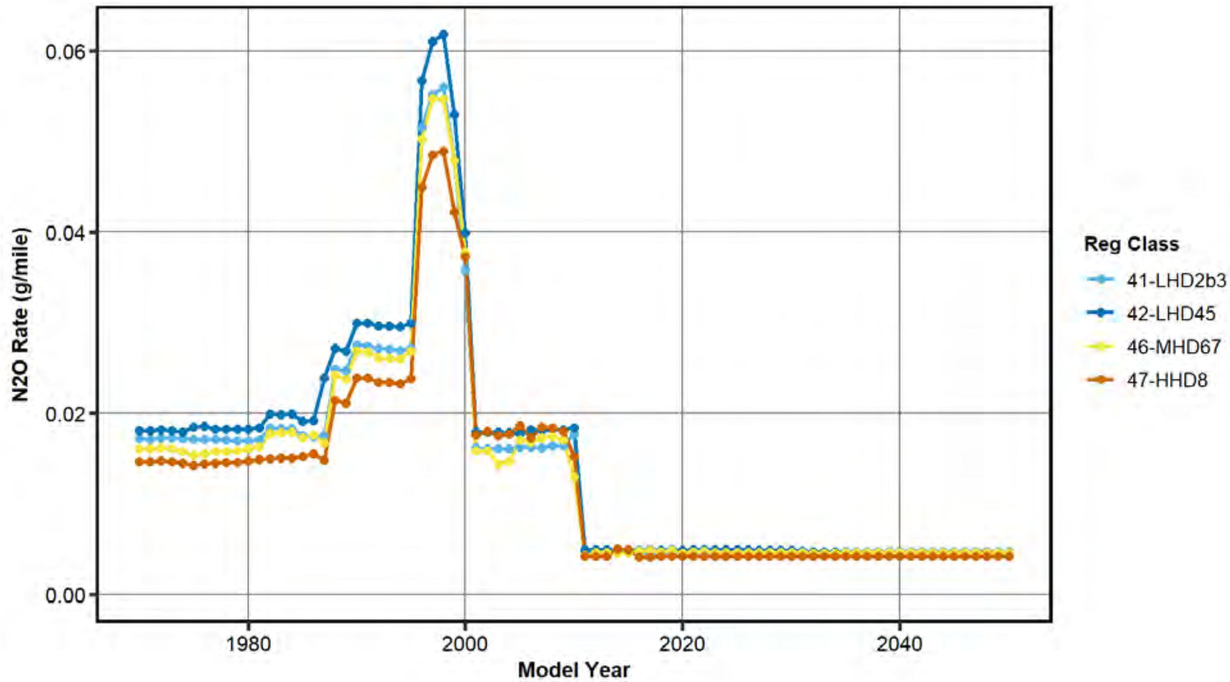

Figure 3-2. Base running rates in MOVES5 for N_2O from gasoline heavy-duty vehicles averaged over nationally representative operating mode distributions.

3.2 Diesel Vehicles

3.2.1 Light-Duty Diesel

For light-duty diesel vehicles, we estimated N_2O emission rates using the FTP composite emission rates reported in the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006 report[46], and the algorithm described above for gasoline vehicles. The emission rates by control technology used for light-duty diesel vehicles and light-duty trucks are shown in Table 3-2.

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

Vehicle Type / Control Technology[a]	FTP Composite (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

[a] Table B-4 defines the model year group definitions of the diesel control technologies groups

We used the distribution of light-duty diesel technology types by model year in Table B-4 to estimate model year specific N_2O emission rates in MOVES. The model year specific N_2O rates are shown in Figure 3-3.

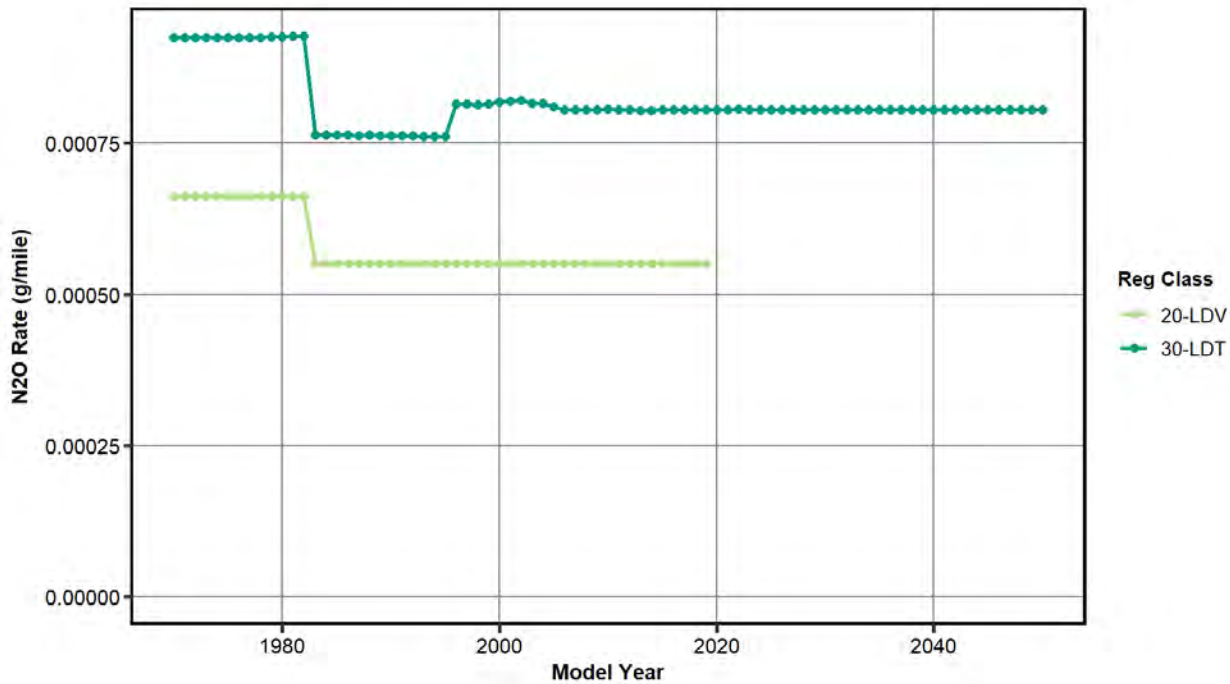

Figure 3-3. Base running rates in MOVES5 for N_2O from diesel passenger cars and passenger trucks averaged over nationally representative operating mode distributions. MOVES5 models no diesel passenger cars after MY 2019.

3.2.2 Heavy-Duty Diesel

3.2.2.1 MY 1950-2003 Heavy-Duty Diesel

For heavy-duty diesel vehicles, the N_2O emission rates by technology for MY 1950-2003 were taken from the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006 report[46] shown in Table 3-3. These emission rates are used in conjunction with the technology to model year mapping in Table B-4 to estimate model-year-specific N_2O emission rates in MOVES. The heavy-duty diesel emission rates are used for all heavy-duty diesel regulatory classes including: LHD2b3, LHD45, MHD, HHD, and Urban Bus. In addition, glider vehicles (regClassID 49) use the "Advanced" emission rate in Table 3-5 for model years 1996-2060.

Table 3-3 Composite FTP, running, and start N_2O emissions for model year 1950-2003 heavy-duty diesel vehicles

Vehicle Type / Control Technology[a]	FTP Composite (g / mile)	Running (g / hour)	Start (g / start)
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-4 defines the model year group definitions of the diesel control technologies groups

3.2.2.2 MY 2004-2060 Heavy-Duty Diesel

Diesel exhaust aftertreatment technologies are known to increase N_2O from diesel trucks. For MOVES4, we updated heavy-duty diesel N_2O emission rates based on information reported in recent emission studies, as summarized in Table 3-4. The heavy-duty diesel emission rates are classified according to engine model year and aftertreatment technology, including diesel particulate filters (DPF) and selective catalytic reduction (SCR) systems. Since net emissions for gasoline and light-duty diesel vehicles are expected to remain relatively low (see Figure 3-1, Figure 3-2, and Figure 3-3), we did not update those rates and they continue to be based on the older data and methodology described in the sections above.

Preble et al. (2019)[35] sampled individual heavy-duty vehicle exhaust plumes at the entrance to the Caldecott Tunnel near Oakland, California and at the Port of Oakland for multiple years. At the entrance of the Caldecott Tunnel, heavy-duty trucks were traveling up a 4% grade between 30 and 75 mph. At the Port of Oakland, the trucks were traveling on a level roadway at around 30 mph. The data from Preble et al. (2019) is also used to update the NH_3 and NO/NO_2 fractions as discussed in the HD Exhaust Report.[1] Quiros et al. (2016)[36] sampled six heavy-duty diesel tractors hauling a mobile emissions laboratory trailer. They sampled the vehicles along six routes intended to represent goods movement in Southern California. The confidence intervals reported for Quiros et al. (2016) in Table 3-4 were calculated from the average N_2O emission rate associated with each of the six routes, which ranged between 0.27 (near-port route) to 0.97 (urban route) g/kg-fuel. The Advanced Collaborative Emissions Study (ACES)[37,38] tested four model year 2007 and three model year 2010 heavy-duty diesel engines using an engine dynamometer.

Each of the studies demonstrate that model year 2010 and later diesel vehicles have significantly higher N_2O emission rates than earlier models of heavy-duty vehicles. N_2O is an unintended byproduct formed within the selective catalytic reduction and ammonia oxidation catalysts aftertreatment systems used to control NO_x and NH_3.[39,40,36] To ensure that these systems do not produce excessive N_2O emissions, the Phase 1 Heavy-Duty Greenhouse Gas Rule implemented an N_2O emission standard on the FTP cycle of 0.1 g/hp-hr for 2014 and newer engines, which is roughly equivalent to 0.6 g/kg-fuel. We summarized manufacturer submitted certification data for heavy-duty engines between model year 2016 and 2020[41] in Table 3-4, which shows that the average FTP cycle average N_2O emission rates are roughly half the fuel-specific equivalent Phase 1 standard.

For the SCR-equipped vehicles, there is significant variability in the N_2O emission rates among the different studies, likely due to different operating conditions. The fuel-based rate reported in Quiros et al. (2016) varied significantly across different road types, and Preble et al. (2019) measured significantly higher SCR-equipped N_2O emission rates at the high load conditions of the Caldecott Tunnel compared to the more moderate conditions of the Port of Oakland.

Table 3-4. Fuel-based N_2O emission rates (± 95% Confidence Intervals, if available) from heavy-duty diesel vehicles by aftertreatment system and engine model year reported from recent studies

Study	Description	Sample Size	Aftertreatment	Engine MY	N_2O emission rate (g/kg)
Preble et al. (2019)[35]	Caldecott Tunnel near Oakland California, Plume-Capture, Sample Years: 2014, 2015, 2018	1447	DPF + SCR	2010-2018	0.93 ± 0.13
		744	DPF	2007-2009	0.01 ± 0.01
		346	DPF Retrofit	1994-2006	0.01 ± 0.02
		183	No DPF	2004-2006	0.00 ± 0.03
		433	No DPF	1965-2003	0.00 ± 0.09
Preble et al. (2019)[35]	Port of Oakland, Sample Year: 2015	300	DPF + SCR	2010-2016	0.44 ± 0.11
		866	DPF	2007-2009	0.06 ± 0.01
		11	No DPF	2004-2006	0.07 ± 0.06
Quiros et al. (2016)[36]	Six good movements routes in Southern California sampled using mobile laboratory	4	DPF + SCR	2013-2014	0.51 ± 0.28 (0.27 to 0.97)
		1	DPF (Hybrid Diesel)	2011	0.03 ± 0.01
		1	DPF	2007	0.06 ± 0.06
Khalek et al. (2013)[38]	Advanced Collaborative Emissions Control Study, engine dynamometer	3	DPF + SCR	2011	0.26 ± 0.48 (16-hour cycle)
					0.38 ± 0.59 (FTP[A])
Khalek et al. (2009)[37]		4	DPF	2007	0.05 ± 0.03 (16-hour cycle)
					0.07 ± 0.07 (FTP)
EPA Certification Data (2020)[41]	Heavy-duty FTP Transient Certification Test	60	DPF + SCR	2016-2020	0.34 (FTP Transient)
					0.34 (SET[B] Steady-State)

[A] Federal Test Procedure (FTP)
[B] Supplemental Emission Test (SET)

For developing N_2O emission rates, we chose to use the fuel-based rates from the Port of Oakland collected by Preble et al. (2019)[35] because the DPF+SCR rates fell within the range of the other DPF+SCR fuel-based rates, and the DPF-only rates were similar to the other reported studies.

To develop MOVES heavy-duty diesel N_2O emission rates by regulatory class, model year, and operating mode, we multiplied the MOVES3 heavy-duty diesel vehicle fuel-consumption rates by regulatory class, model year, operating mode $\left(Fuel\ Rates_{Reg,MY,op}\right)$ by the Preble et al. (2019) fuel-based N_2O emission rates $\left(\overline{FER}_{Model\ Year\ Group}\right)$ listed in Table 3-4, as shown below in Equation 3-1.

$$\overline{ER}_{Reg,MY,age,op} = Fuel\ Rates_{Reg,MY,op} \times \overline{FER}_{Model\ Year\ Group} \qquad \textbf{Equation 3-1}$$

Figure 3-4 shows example N_2O emission rates for the LHD2b3 and HHD regulatory classes for model year 2017. Even though the fuel-based emission rate is the same, the N_2O gram/hour rate is higher for the HHD regulatory class due to the higher fuel consumption rates. The N_2O emission rates for model years 2018 and later were set equal to the rates for 2017.

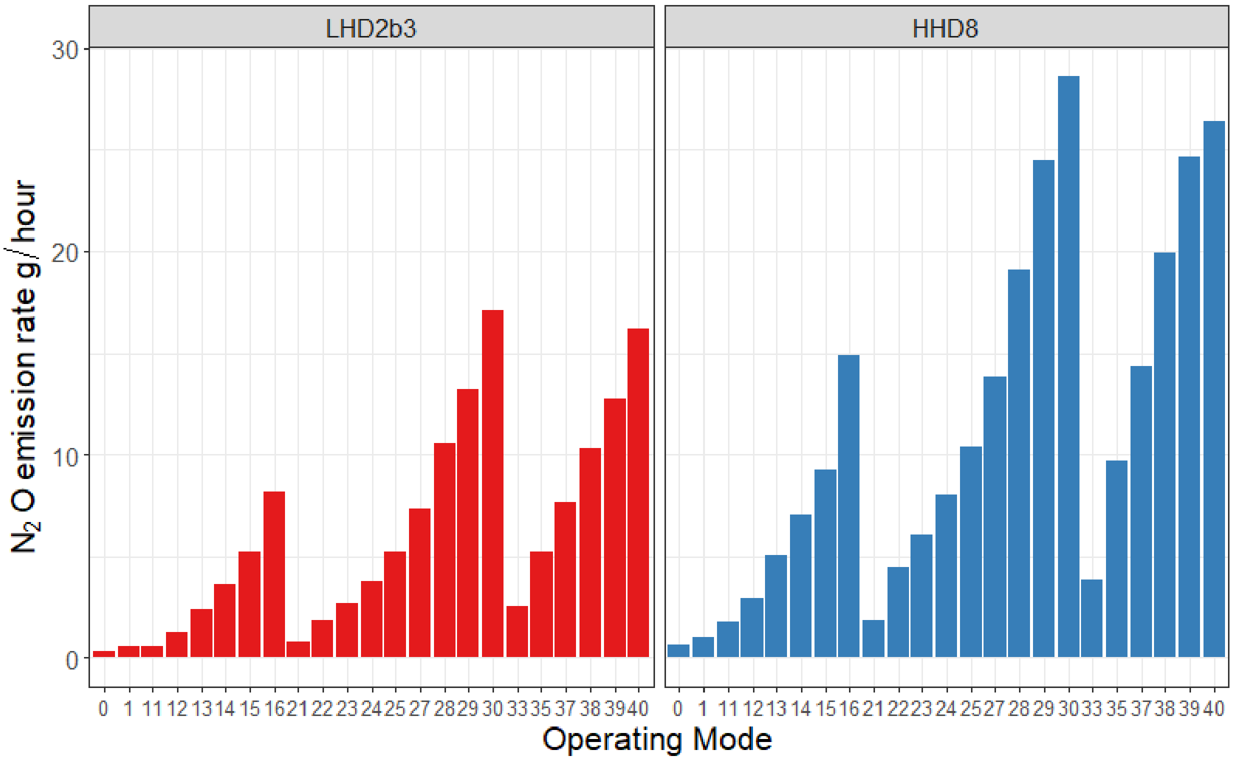

Figure 3-4. N_2O running emission rates (g/hour) by operating mode for model year 2017 LHD2b3 and HHD

Figure 3-5 shows heavy-duty diesel N_2O rates by regulatory class, averaged over nationally representative operating mode distributions, in grams per mile.

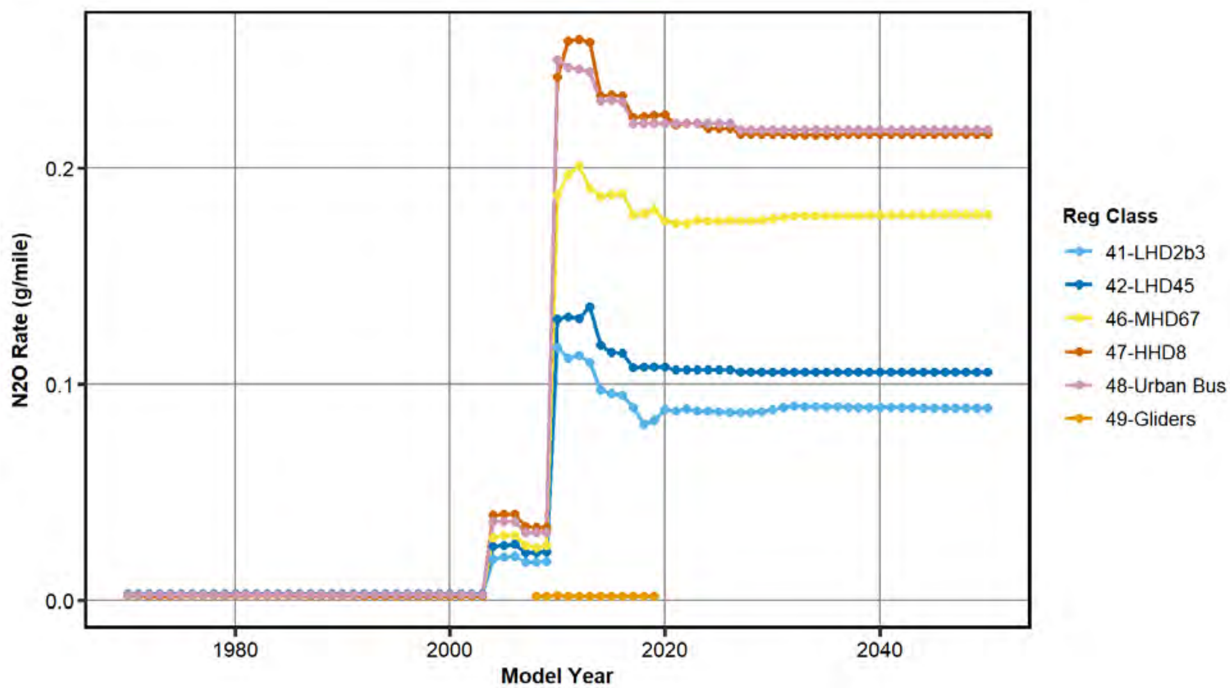

Figure 3-5. Base running rates in MOVES5 for N_2O from diesel heavy-duty vehicles averaged over nationally representative operating mode distributions.

We evaluated N_2O start emissions from the data collected in the ACES engine dynamometer study by comparing the FTP cycle (40 minute cycle with one cold start and one hot start) and the 16-hour cycle (one cold and one hot-start over a 16-hour cycle). The N_2O emissions from both the 2011 and 2007 engines were higher in the FTP than the 16-hour cycle (Table 3-4), but a paired-test showed that the difference was not statistically significant (p-value of 0.08 and 0.12, respectively). Because the start emissions appear to make a negligible contribution to the total tailpipe N_2O emissions, we estimate zero N_2O start emission rates for model year 2004-2060 heavy-duty diesel vehicles.

MOVES does not include estimates of N_2O from the extended idle and auxiliary power unit exhaust processes. Overall, we anticipate the N_2O from these processes to be very low, in part because auxiliary power units are not anticipated to be equipped with SCR systems. Future versions of MOVES could consider incorporating N_2O emission from extended idling and auxiliary power unit exhaust as more data become available.

3.3 Alternative-Fueled Vehicles

MOVES includes N_2O emission rates for alternative fuels, including E85 and CNG fueled vehicles. The N_2O emission rates were based on limited data from the Sources and Sinks report.[46] In MOVES, the N_2O emission rates for E85-fueled vehicles are set to be the same as gasoline vehicles.

Heavy-duty CNG vehicles use the emission rates reported in Table 3-5. These rates remain unchanged from the numbers reported for MOVES2010a[17]. The composite emission rate was obtained from the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2006[46], and disaggregated into running and starts using the same relative running and start splits as heavy-gasoline vehicles.

Table 3-5. N_2O emission rates for CNG-fueled heavy-duty vehicles in MOVES

FTP Composite (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 grams of carbon per 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[16] based on values derived from the life-cycle model GREET. In MOVES4, we updated the values for subtypes 12-21 to reflect measured properties of certification test fuels (subtypes 12 and 20) with mathematical adjustments for other blend levels using biofuel properties published by DOE's Alternative Fuel Data Center.[42] [43] Because MOVES doesn't model upstream emissions, the carbon content for electricity (whether from BEVs or FCEVs) is zero. Energy content refers to lower heating values.

Table 4-1. Carbon content and oxidation fraction 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)	0.01982	1
13	1	Gasohol (E8)	0.01982	1
14	1	Gasohol (E5)	0.01984	1
15	1	Gasohol (E15)	0.01980	1
20	2	Conventional Diesel Fuel	0.02022	1
21	2	Biodiesel Blend	0.02022	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 (CO_2e) is a combined measure of greenhouse gas emissions weighted according to the global warming potential (GWP) 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. MOVES calculates CO_2e from CO_2, N_2O, and CH_4 mass emissions according to Equation 4-2.

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

By definition, the GWP of CO_2 is 1. For CH_4 and N_2O, MOVES uses the 100-year GWPs listed in Table 4-2 and stored in the pollutant table of the MOVES default database. MOVES uses the 100-year GWP values from the 2014 International Panel on Climate Change (IPCC) Fifth Assessment Report (AR5).[44]

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

Pollutant	Global Warming Potential (GWP)
Methane (CH_4)	28
Nitrous Oxide (N_2O)	265
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. However, MOVES calculates fuel usage in terms of volume and mass within the refueling and sulfur dioxide emission calculators,[1] respectively. To do so, it 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 outputs energy consumption by fueltype but not fuelsubtype, the average energy content by fuel type can be calculated using the energy content of each fuel subtype and its market share, stored in the fuelSupply table. The derivation of the fuelSupply table is documented in the Fuel Supply Report.[4]

The fuel properties shown here were originally derived from GREET and other published references, as described in Section 6 of the MOVES2004 Energy and Emissions Inputs draft report.[16] For MOVES4, we updated the values for subtypes 12-21 to reflect measured properties of certification test fuels (subtypes 12 and 20) with mathematical adjustments for other blend levels using biofuel properties published by DOE's Alternative Fuel Data Center.[42 43] Energy content figures are lower heating values.

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

fuelTypeID	fuelSubtypeID	fuelSubtypeDesc	Fuel Density (g/gallon)	Energy Content (kJ/g, LHV)
1	10	Conventional Gasoline	2829	43.488
1	11	Reformulated Gasoline (RFG)	2829	42.358
1	12	Gasohol (E10)	2829	41.696
1	13	Gasohol (E8)	2829	42.027
1	14	Gasohol (E5)	2829	42.523
1	15	Gasohol (E15)	2829	40.877
2	20	Conventional Diesel Fuel	3203	42.869
2	21	Biodiesel Blend	3203	42.700
2	22	Fischer-Tropsch Diesel (FTD100)	3203	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

Appendices

Appendix A. Timeline of Energy and GHG emissions in MOVES

- **MOVES2004**
  - 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)[45] 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[46]
  - 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
  - Light-duty rates updated to include 2008-2011 model year Corporate Average Fuel Economy (CAFE) Standards for light trucks
- **MOVES2010a**
  - 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
    - 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
  - 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)

- **MOVES3**
  - The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021-2026 Passenger Cars and Light Trucks 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 based on the HDIUT program

- **MOVES4**
  - The Revised 2023 and Later Model Year Light Duty Vehicle Greenhouse Gas Emission Standards (LD GHG 2023-2026) rule[22] was incorporated, updating rates for light-duty ICE vehicles for MY2020 -2060
  - Updated light-duty and heavy-duty BEV adoption rates were updated
  - Energy rates for Light duty BEVs were updated based on BEV modeling instead of using the same rates as gasoline vehicles
  - Energy rates for heavy-duty BEVs were added using EER approach based on diesel rates
  - Additional updates relevant to GHGs and energy such are described in the MOVES4 Emission Adjustments report. These include adjustments to account for charging efficiency, battery deterioration, cabin temperature control and the impact of electric vehicle fractions on the effective standards for internal combustion engine (ICE) vehicles.
  - Heavy-duty diesel emission rates were updated to account for newer studies which show the significant impacts that selective catalytic reduction (SCR) systems have on N_2O emissions (Section 3.2.2.2). The nitrous oxide (N_2O) emission rates for light-duty diesel and all gasoline and CNG vehicles remain the same. Carbon content and energy content updates
  - HD fuel cell EV EER updates
  - Kept constant the HD GHG Phase 2 energy reductions for regulatory class 41 stored in the EmissionRateAdjustment table for MY2025 and later at the MY2024 level

- **MOVES5**

- Updated light-duty energy consumption rates for MY 2017-2022 based on the 2023 Automotive Trends Report
- The LMDV2027 rule was incorporated to update light-duty and medium-duty CO_2 fleet average rates
- HD GHG Phase 3 rule was incorporated to update heavy-duty CO_2 fleet average rates
- HD EV EERs were updated based on the Phase 3 technology assessment in HD TRUCS
- Additional updates relevant to GHGs and energy as described in the MOVES5 Emission Adjustments report. These include the new fleet averaging algorithm update and new EV multipliers.
- Updated GWP values for methane and nitrous oxide consistent with the IPCC AR5 report

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 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-4 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	1950-1982
Moderate control	1983-1995
Advanced control	1996-2006+[a]
Diesel Medium- and Heavy-Duty Trucks and Buses	
Uncontrolled	1950-1982
Moderate control	1983-1995
Advanced control	1996-2004
Motorcycles	
Uncontrolled	1950-1995
Non-catalyst controls	1996-2006+

[a] In MOVES, we continue using the 1996-2006 rates for all light-duty 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 N_2O emission rates of aftertreatment diesel are unchanged from advanced control.[47]

Appendix C. EV ALPHA Parameters and Results

To develop energy rates for light-duty battery electric vehicles, BEVs representative of the 2019 fleet, based on 2019 sales figures, were modelled in EPA's ALPHA (Advanced Light-Duty Powertrain and Hybrid Analysis) tool using values from the EPA test car list, manufacturer data, press releases, and other internet sources. These values are listed in Table C-1.

Overall range, highway mileage, and city mileage were calculated for all selected vehicles in ALPHA, and the output was then compared to published values to determine how well each vehicle was being modeled. This is represented via the percent difference between the two values. These percentages were then averaged by sales within each category to observe how well ALPHA modeled the 2019 fleet as a whole. Those values are listed in the Table C-2.

Table C-1: Vehicle Parameters for ALPHA Modeling

Vehicle	2019 Sales [48]	Battery Size (kWh)	Battery Voltage	Parallel	Series	Total Cells	Max Torque	Max Torque Units	Max RPM	Max Power	Max Power Units	Wheel Diameter (in)	Final Drive Gear Ratio	Vehicle Mass	A Coeff	B Coeff	C Coeff
Chevy Bolt [49]	16,313	60	350[50]	3	96	288	360	J	8810	150	kW	17	7.05	3875	28.4	0.2018	0.0195
Tesla Model 3 [51]	154,840	53.6	360[51]	3	86	256	389[52]	lb-ft	9000	282	Hp	18	9.04	3875	36.01	-0.1289	0.0167
Honda Clarity BEV [53]	742	25.5	323[54]	3	88	264	222	lb-ft	9500	161	Hp	18	9.333	4250	25.41	0.2338	0.0176
Nissan Leaf [55]	12,365	40	350	2	96	192	236	lb-ft	10390	147	Hp	16	8.19	3500	25.89	0.3449	0.0195
Fiat 500E [56]	632	24	364	1	100	100	147	lb-ft	9500	110	Hp	15	9.59	3250	24.91	0.2365	0.0182
Tesla Model S [57]	15,090	85	320	6	74	444	440	J	13700	400	kW	19	9.34	4500	40.218	0.0604	0.0171
BMW i3 [58]	4,854	42.2	350	3	67	201	184	lb-ft	10000	181	Hp	19	9.67	3375	29	0.297	0.0178
VW e-Golf [59]	4,863	35.8	323	3	88	264	214	lb-ft	12000	134	Hp	16	9.747	3750	32.8	0.3849	0.0156
Tesla Model X [60]	19,425	100	350	5	96	480	660	J	12300	400	kW	20	9.34	5250	40.32	0.099	0.0214
Jaguar i-Pace	2,594	90.2	389	4	108	432	696	J	13000	294	kW	20	9.04	5000	35.706	0.6402	0.0177
MOVES Values															35.174	0.2012	0.0221

Table C-2: Comparison of Published and Modelled Range

Vehicle	Published Range	Test Car UDDS	Test Car HWY	ALPHA Range	ALPHA UDDS	ALPHA HWY	RangeDiff	UDDSDiff	HWYDiff
Chevy Bolt	238	182.2	157.4	193.89	207.62	142.17	-18.53%	13.95%	-9.68%
Tesla Model 3	220	197.3	176.6	225.28	204.77	167.73	2.40%	3.79%	-5.02%
Honda Clarity BEV	89	179.6	146.5	94.79	211.74	153.29	6.51%	17.90%	4.63%
Nissan Leaf	150	174	141.1	121.52	209.08	133.98	-18.99%	20.16%	-5.05%
Fiat 500E	84	172.9	147.8	108.9	221.86	176.28	29.64%	28.32%	19.27%
Tesla Model S	271	151.7	140.1	241.54	165.7	140.13	-10.87%	9.23%	0.02%
BMW i3	153	177.7	145.5	144.75	211	143.47	-5.39%	18.74%	-1.40%
VW e-Golf	125	174.4	154	113.55	191.9	135.09	-9.16%	10.03%	-12.28%
Tesla Model X	305	140	130.5	238.89	151.37	119.09	-21.68%	8.12%	-8.74%
Jaguar i-Pace	246	114.1	102.9	198.2	150.5	107.9	-19.44%	31.88%	4.84%
Fleet Sale-Weighted Avg Diffs							9.51%	10.81%	4.73%

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