Greenhouse Gas and Energy Consumption Rates for Onroad Vehicles in MOVES4

United States Environmental Protection Agency

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

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List of Acronyms

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 ≤ 14,000 lbs)
LHD45	Light Heavy-Duty Class 4 or 5 Truck (14,000 < GVWR ≤ 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 ≤ 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.

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]

MOVES2014 incorporated the light-duty greenhouse gas emission standards affecting model years 2017 and later cars and light trucks.[3] MOVES2014 also incorporated the Heavy-Duty GHG Phase 1 emissions standards for model years 2014 and later.[4] 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 MOVES heavy-duty emissions rates report.[5]

As explained below, energy rates were updated in MOVES3 to incorporate the 2020 Safer Affordable Fuel Efficient (SAFE) Vehicles standards[6] for light-duty passenger cars and trucks and to incorporate the Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles—Phase 2 Rule ("HD GHG2") published in 2016.[7] .

In MOVES4, we updated energy consumption rates for light-duty internal combustion engines to account for the Revised 2023 and Later Model Year Light Duty Vehicle Greenhouse Gas Emission Standards (LD GHG 2023-2026) rule.[8] We also updated running process energy consumption for light-duty electric vehicles (Section 2.1.3), and added energy consumption for heavy-duty electric and fuel-cell vehicles (Section 2.2). Additional updates relevant to GHGs and energy are described in the MOVES4 emission adjustment report.[23] 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.

In MOVES4, we also updated the heavy-duty diesel emission rates 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; they have not been updated since MOVES2010.

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.[9,10]

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 in MOVES4 stay the same as in MOVES3 and are documented in the following reports: MOVES onroad speciation report[11] and MOVES light-duty[12] and heavy-duty[5] exhaust emission rate reports.

2 Energy Rates

In MOVES, energy consumption rates (energy use per time) are recorded in the emissionRate table by fueltype, regulatory class, model year group, process, and operating mode. And for heavy-duty regulatory classes, adjustments by sourcetype, regulatory class, fueltype and model year are recorded in the emissionRateAdjustment table. Additional adjustments to energy consumption are described in the MOVES4 emission adjustment report.[23]

A full suite of energy rates 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 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 vehicle category includes passenger cars, passenger trucks, and light commercial trucks. For details about corresponding vehicle weight and HPMS classes, refer to the MOVES Population and Activity Report.[13] For information about operating modes and vehicle-specific power (VSP) bins, see the MOVES Light Duty Report.[12]

2.1.1 Light-Duty GHG and CAFE Regulations

A number of 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

Light Duty GHG Phase 1 rule[14] covers model years 2012 through 2016, while the Phase 2 rule[3] 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]

Table 2-2 Projected fleet-wide emissions compliance levels under the footprint-based CO_2 standards (g/mi) – LD GHG Phase 1[14]

	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[3]

	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 rate based on its footprint[b], and this relationship is captured by footprint curves. Figure 2-1 is an example of the footprint curve for passenger cars under the LD GHG Phase 2 rule. The

[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.

[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: https://www.epa.gov/sites/default/files/2021-01/documents/420r21003.pdf

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.

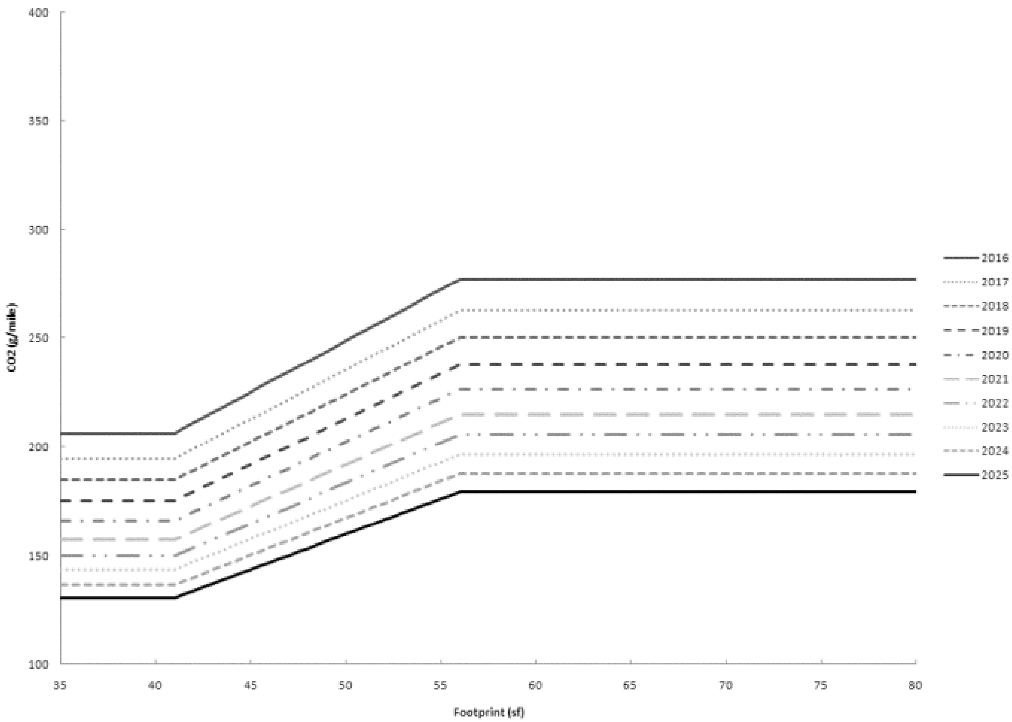

Figure 2-1. CO_2 (g/mile) passenger car standards[3]

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, resulting in an increase in 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[3,14].

Table 2-4 Projections for fleetwide tailpipe emissions compliance with CO_2 standards for passenger cars (g/mile) – LD GHG Phase 2[3]

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)[15], 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 value1.25 in Equation 2-1is a multiplying factor derived from a 20% gap between test and on-road MPG for liquid fueled vehicles[15]. The test refers to NHTSA's CAFE 2-Cycle test (i.e. FTP and HWFET), while the on-road MPG refers to EPA's 5-cycle test that is used for fuel economy label (FTP, HWFET, US06, SC03, UDDS)[c]. 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). This conversion factor is stored in the "adjustment" column of the EVPopICEAdjustLD table.

$$Real\ World\ Tailpipe\ CO2 = (\,Projected\ 2\ Cycle\ CO2 - \ Off\ Cycle\ Credit - \ A/C\ Efficiency\ Credit)\ *1.25 \qquad \textbf{Equation 2-1}$$

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)[3]

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

[c] More information on EPA dynamometer drive cycles is available at https://www.epa.gov/vehicle-and-fuel-emissions-testing/dynamometer-drive-schedules

light trucks. The SAFE "Part 1" Final Rule (One National Program) was released in September 2019.[16]Per which, EPA withdrew the Clean Air Act preemption waiver[d] for LD vehicles it granted to California.

The SAFE rule[6] was finalized 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[6]

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[6]

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

2.1.1.3 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[17] tightened the CO_2 emission requirements for model years 2023 and later. These standards are expected to increase the fraction of electric vehicles in the

[d] California Clean Air Act preemption waiver was reinstated in 2023.

fleet as described in the MOVES4 vehicle population and activity report,[13] and to change the average energy consumption of the remaining ICE vehicles.

Table 2-8 Estimated fleet-wide CO2 target levels corresponding to the final standards[17]

Model year	Cars CO_2 (g/mile)	Trucks CO_2 (g/mile)	Fleet CO_2 (g/mile)
2023	166	234	202
2024	158	222	192
2025	149	207	179
2026 and later	132	187	161

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). This includes vehicles running on gasoline, diesel and ethanol fuels, including hybrids.

In MOVES4, the energy rates for motorcycles (MC) and pre-2017 model year light-duty vehicles (LDV) and light-duty trucks (LDT) are unchanged from MOVES2014. The energy rates for MC, LDV and LDT are distinguished by fuel types, engine technologies, regulatory classes, and model years.

Before MOVES2010a, MOVES modelled 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 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 population in the MOVES2010 sample vehicle population table. Because this approach used 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 pre-2000 MY aggregated energy rates used in MOVES2010a and carried into later MOVES versions.

In MOVES4, we updated running energy rates in the emissionRate table for all light-duty vehicles based on the 2021 EPA automotive trends report[18] for MY2017 to 2019.

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[2,19]. In MOVES3, we updated energy rates based on the SAFE final rule[6]. And in MOVES4, we updated the rates to account for the LD GHG 2023-2026 rule. The main methodology is the same as the one used to incorporate LD GHG rules in MOVES2014, where the estimated real-world CO_2 (or on-road CO_2) values developed in the rulemaking were used as input to update the MOVES rates.

In MOVES4, the real-world CO_2 calculation uses CO_2 2-cycle g/mile rates, off-cycle credits, and A/C efficiency credits, as shown in Equation 2-1. Adjustment ratios based on real-world CO_2 values estimated in the LD GHG 2023-2026 rule were applied directly to running energy rates in the emissionRate table for all light-duty vehicles (regulatory classes 20 and 30). Those adjustment ratios vary by model year for model year 2020 to 2050. The adjustment ratios for MY2050 were applied to model years 2051 and beyond.

MOVES4 also incorporates an adjustment to ICE energy rates that accounts for averaging, banking, and trading (ABT) with the penetration of electric vehicles (see Section 7 in Emission Adjustments for Onroad Vehicles in MOVES4 report[23]). The ABT adjustment results in an increase in the average CO_2/mile for gasoline and diesel vehicles in years when the Inflation Reduction Act implies higher EV sales fractions, as detailed in the Population and Activity of Onroad Vehicles in MOVES4 report[13]

Figure 2-2 and Figure 2-3 plot the MOVES4 average CO_2 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 2040. 1960-1969 MY have the same CO_2 emission rates as MY 1970.

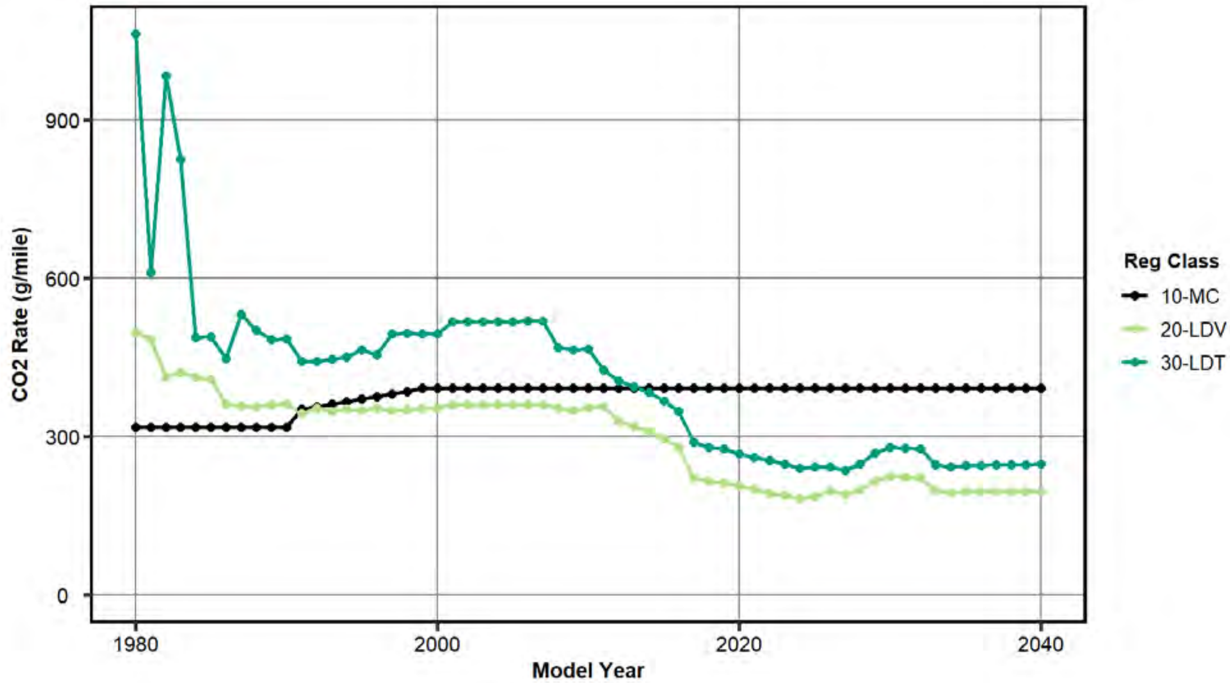

Figure 2-2. Base running rates in MOVES4 for atmospheric CO_2 from gasoline motorcycle, light-duty vehicles and light-duty trucks averaged over nationally representative operating mode distributions.

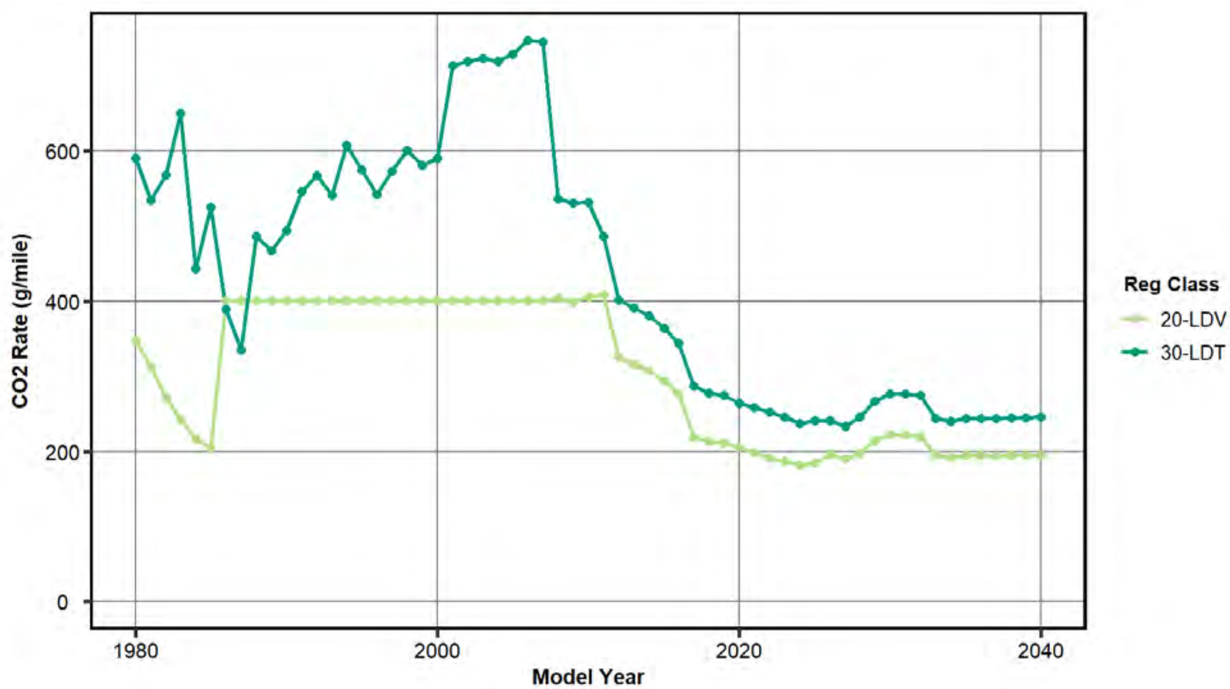

Figure 2-3. Base running rates in MOVES4 for atmospheric CO_2 from diesel light-duty vehicles and light-duty trucks averaged over nationally representative operating mode distributions.

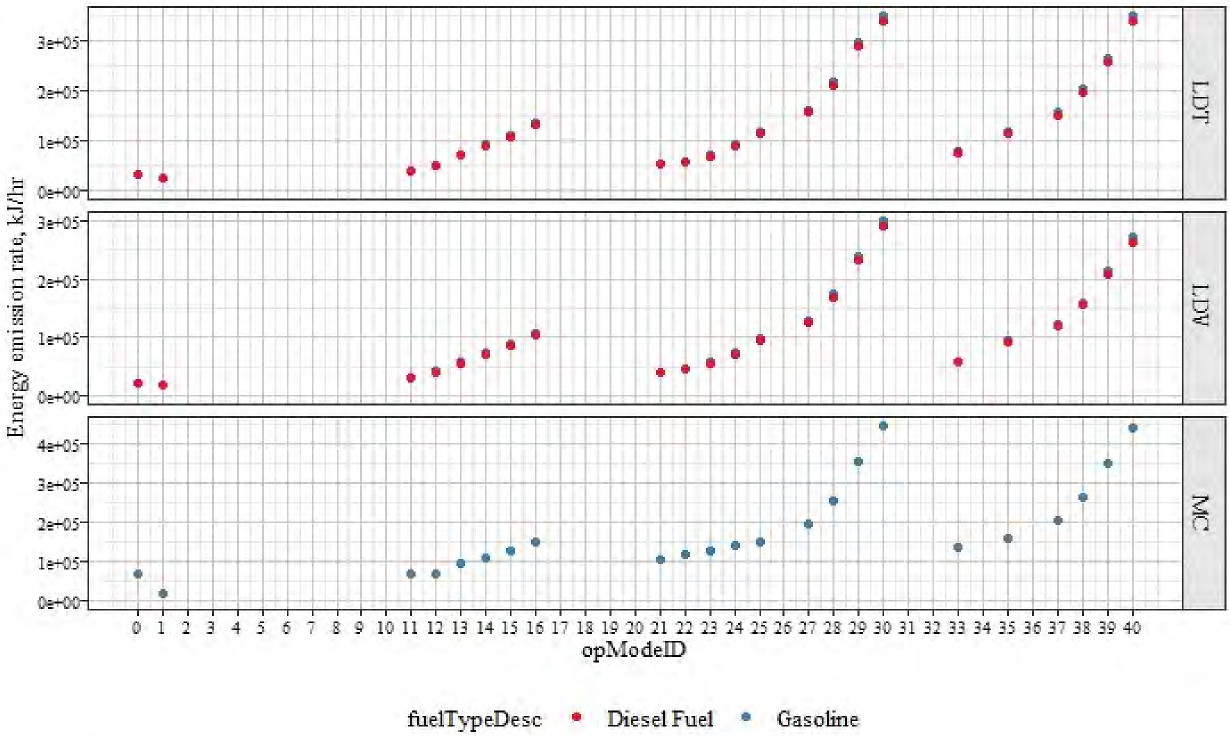

Figure 2-4. Running energy rates by operating mode (opModeID) for motorcycles (MC), light-duty vehicles (LDV) and light-duty trucks (LDT) for model year 2025 in MOVES4.

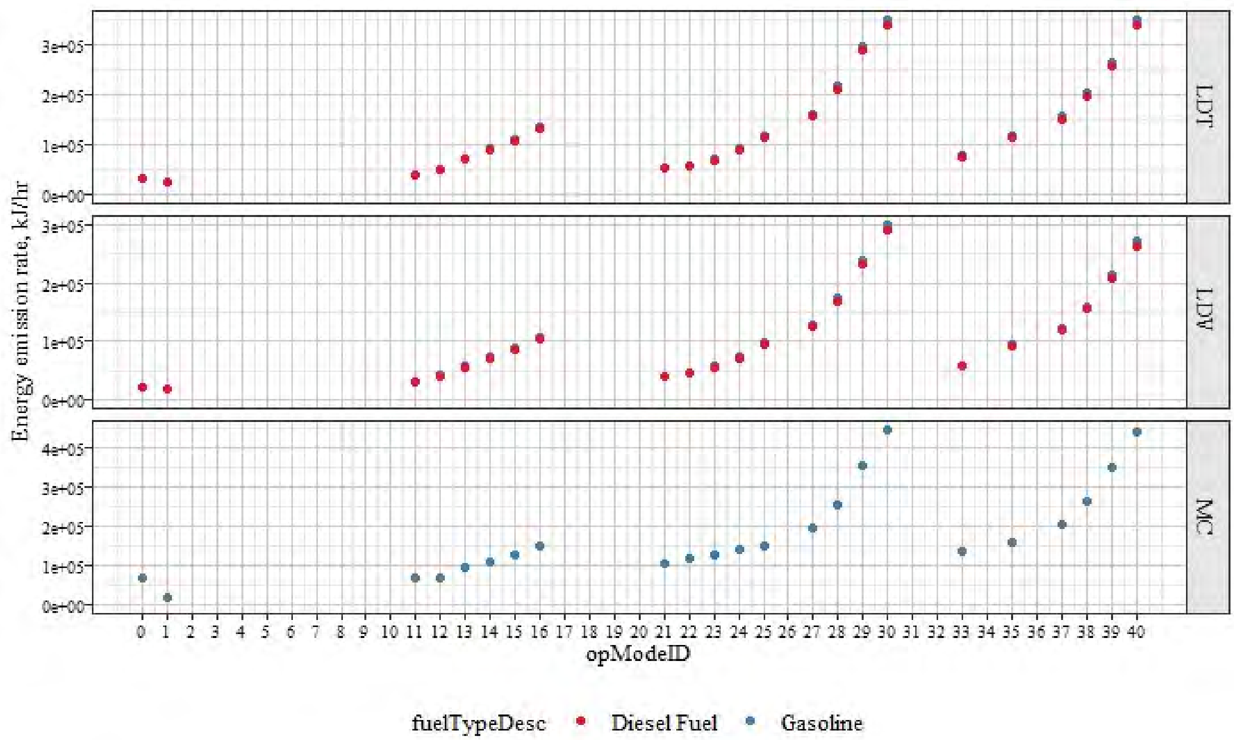

Figure 2-4 plots the MOVES4 running energy rates by operating mode for motorcycles (MC), light-duty vehicles (LDV), and light-duty trucks (LDT) for model year 2025.

For gasoline LDV, MOVES uses the same relative trend between energy rates and operating modes shown in

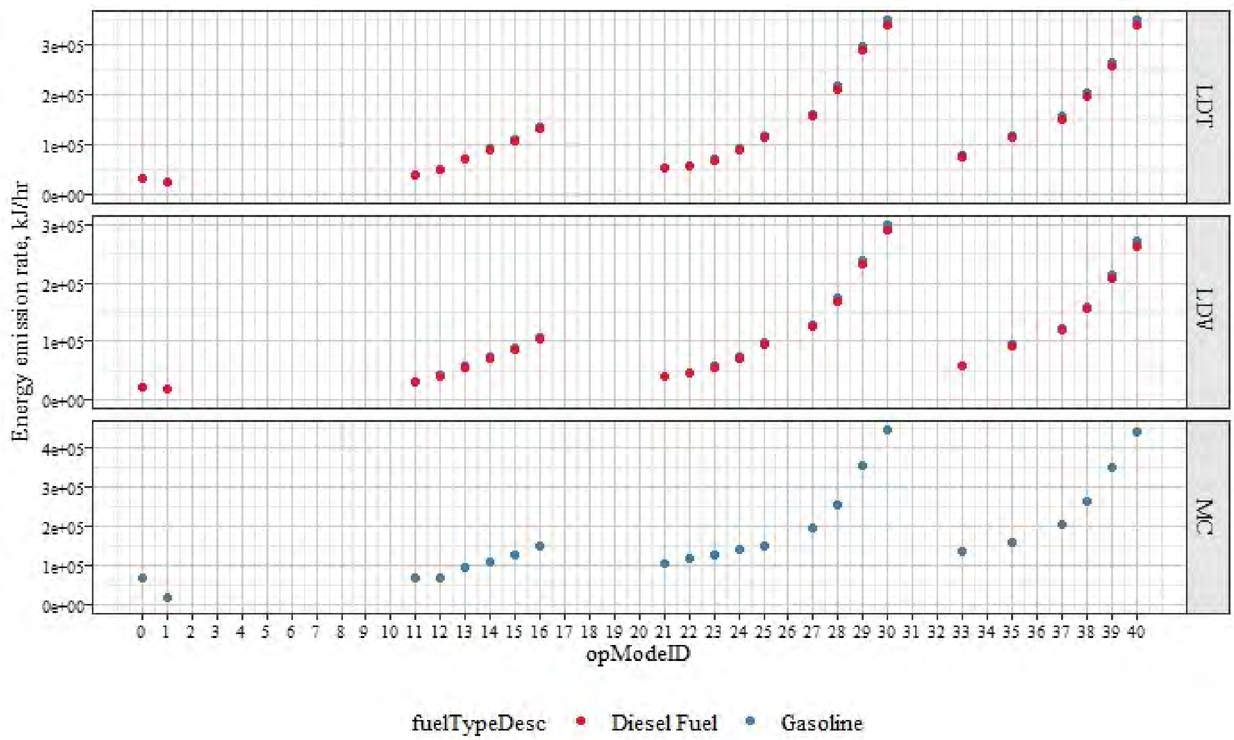

Figure 2-4 starting with the 1999 model year. For gasoline LDT, the relative trend between energy rates and operating modes is constant from MY 2001 to MY 2060. However, as shown in Figure 2-2, the absolute magnitude of gasoline LDV and LDT CO_2 emission rates across all operating modes decreases sharply beginning in MY 2012 due to the 2012-2016 LD GHG rule[14]

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) 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 2-3).

The energy rates for ethanol (E-85) are assumed to have equivalent energy consumption as gasoline vehicles. However, the differences in carbon content result in different CO_2 emission rates as discussed in Section 4.1.

The motorcycle running energy rates have not been updated since 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 into a single energy rate by model year for all motorcycles in MOVES2010a[2], this resulted in an average increase in motorcycle energy rates between MY 1991 and MY 2000 due to a population shift to larger motorcycles[20]. 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 Running Energy Rates for Electric Vehicles

Energy rates for battery electric vehicles (BEVs) in MOVES4 have been significantly updated from MOVES3. There is limited experimental data available at the 1 HZ level, which is the resolution that MOVES requires. Therefore, to develop these rates, nine BEVs representative of the 2019 fleet, based on 2019 sales estimates, were modelled in EPA's ALPHA (Advanced Light-Duty Powertrain and Hybrid Analysis) tool.[21] 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[22], manufacturer data, press releases, and other internet sources. See Appendix C for a comprehensive table of the values used for these vehicles.

Each vehicle was simulated in ALPHA over three repeats of the EPA UDDS and HWFET[28] cycles, as well as two additional sets of drive cycles in order to increase the sample sizes for the high 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 the MOVES operating mode bins. 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 75mph to 80mph to enable 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, the operating mode would be assigned using power at the wheels as calculated by ALPHA based on the individual vehicle characteristics. However, since MOVES assigns same road load coefficients to BEVs as ICE vehicles, that approach meant the resulting energy consumption values were biased too high. To address this issue, VSP was calculated using the road loads in MOVES and the values for velocity and acceleration reported by ALPHA, in assigning the operating mode. Once these adjustments had been made and the methodology updated, the energy rates calculated by ALPHA were much more closely aligned with the data from the test car list.[22] More details about parameters and results in ALPHA modeling can be found in Appendix C.

Energy rates in MOVES4 were derived by calculating the sales-weighted rate across all of the modelled vehicles in ALPHA. The sale numbers 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, there is not enough information available about EV trucks on the market or in the test car list to properly represent these vehicles in ALPHA. Therefore, the rates for light-duty electric trucks and LHD2b3 trucks (regulatory classes 30 and 41) were scaled from the light-duty electric car rates assuming that energy gained from regenerative braking and energy used during all other operation scale linearly with vehicle mass. The specific scaling factor comes from the fixedMassFactor column of the MOVES sourceUseTypePhysics table.[13] 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 energy rates for MY2019 passenger cars and passenger trucks are shown below in Figure 2-5 and Figure 2-6, the blue bars represent the energy rates for BEV passenger cars in MOVES4, and the orange bars represent the energy rates for ICE passenger cars in MOVES4. Similarly, in Figure 2-6, the blue bars represent the energy rates for BEV passenger trucks in MOVES4, and the orange bars represent the energy rates for ICE passenger trucks in MOVES4. The negative values shown in the plots are regenerative braking energy rates. For passenger cars and trucks, BEV energy rates for each operating mode have lower values than ICE energy rates.

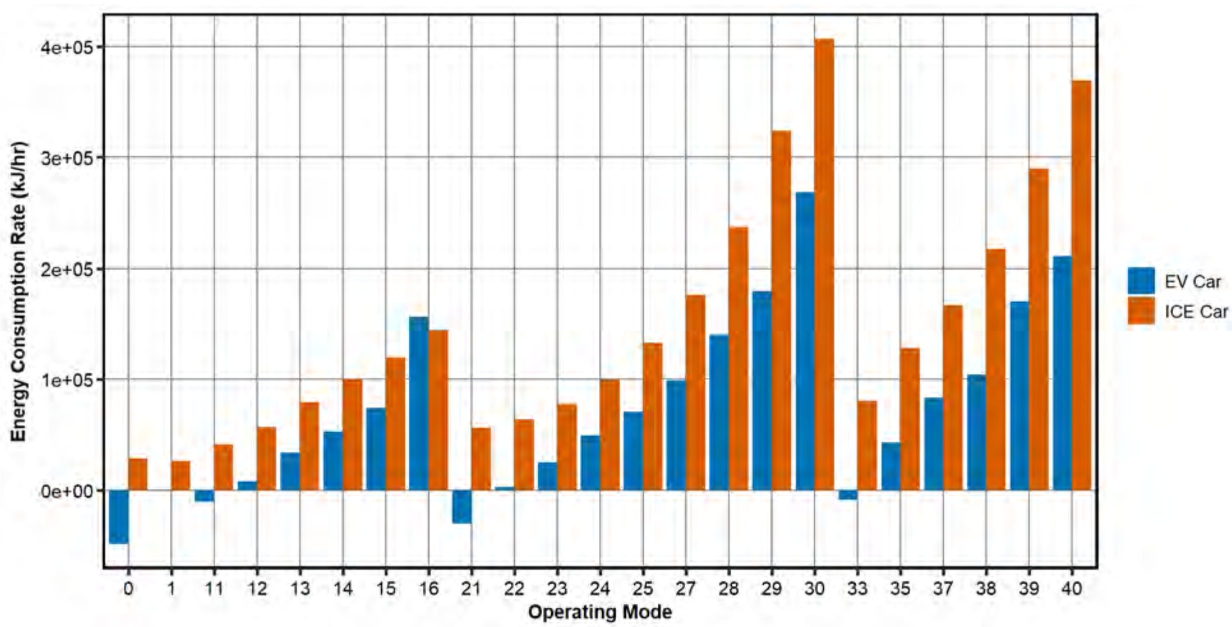

Figure 2-5. MOVES4 base energy rates for electric and ICE model year 2019 passenger cars by operating mode

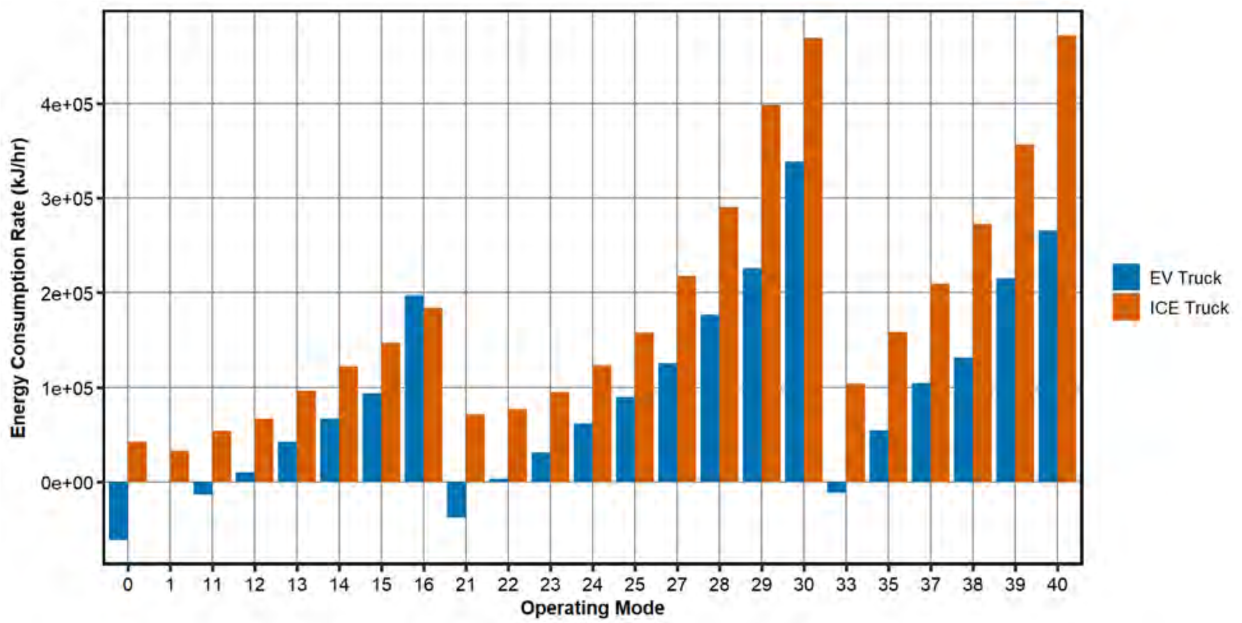

Figure 2-6. MOVES4 base energy rates for electric and ICE model year 2019 passenger trucks by operating mode

The adjustments to the light-duty BEV running energy rates are documented in the MOVES Emission Adjustments report,[23] including adjustments for ambient temperature, air conditioning, and for charging and battery efficiency. MOVES4 does not model light-duty fuel cell vehicles.

2.1.4 Light-Duty Start Energy Rates

LD BEVs are modelled with zero start energy consumption. 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 energy rates of gasoline motorcycles (MC), light-duty vehicles (LDV), and light-duty trucks (LDT) for starts by operating mode for model year 2020 in MOVES4. As shown, start energy rates increase for operating modes with longer soak times as defined in Table 2-9. 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 on start energy consumption are documented in the MOVES Emission Adjustments report[23] and the 2004 Energy Report[1] .

To account for the Revised 2023 and Later Model Year Light Duty Vehicle Greenhouse Gas Emission Standards (LD GHG 2023-2026) rule,[17] adjustment ratios based on the rule's estimated real-world CO_2 were also applied to start energy rates for all light-duty vehicles (regclasses 20 and 30). Adjustment ratios vary by model year from 2020 to 2050. The adjustment ratio for MY2050 were applied to model years 2051 and beyond. These adjustment ratios for start energy rates are the same as for running energy rates for each model year and are directly applied in EmissionRate table in the default MOVES database.

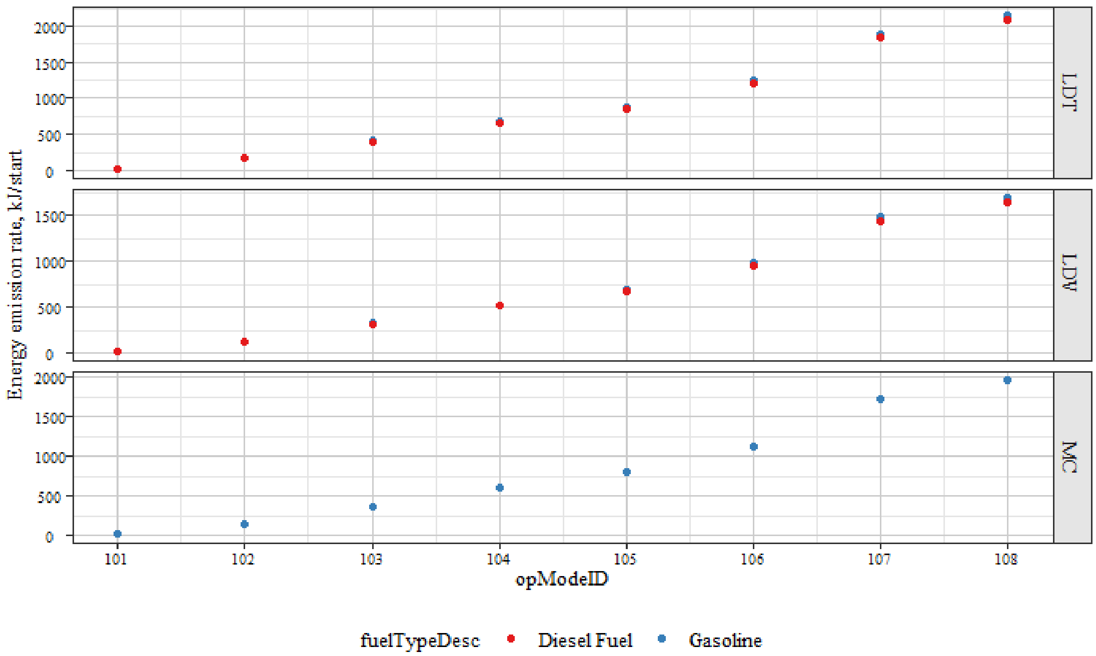

Figure 2-7. Start energy rates by operating mode (opModeID) for motorcycles (MC), light-duty vehicles (LDV) and light-duty trucks (LDT) for model year 2025.

Table 2-9. 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 2-8 and Figure 2-9 depict the start CO_2 emission rates for a cold start (opMode108) across model years for gasoline and diesel 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.

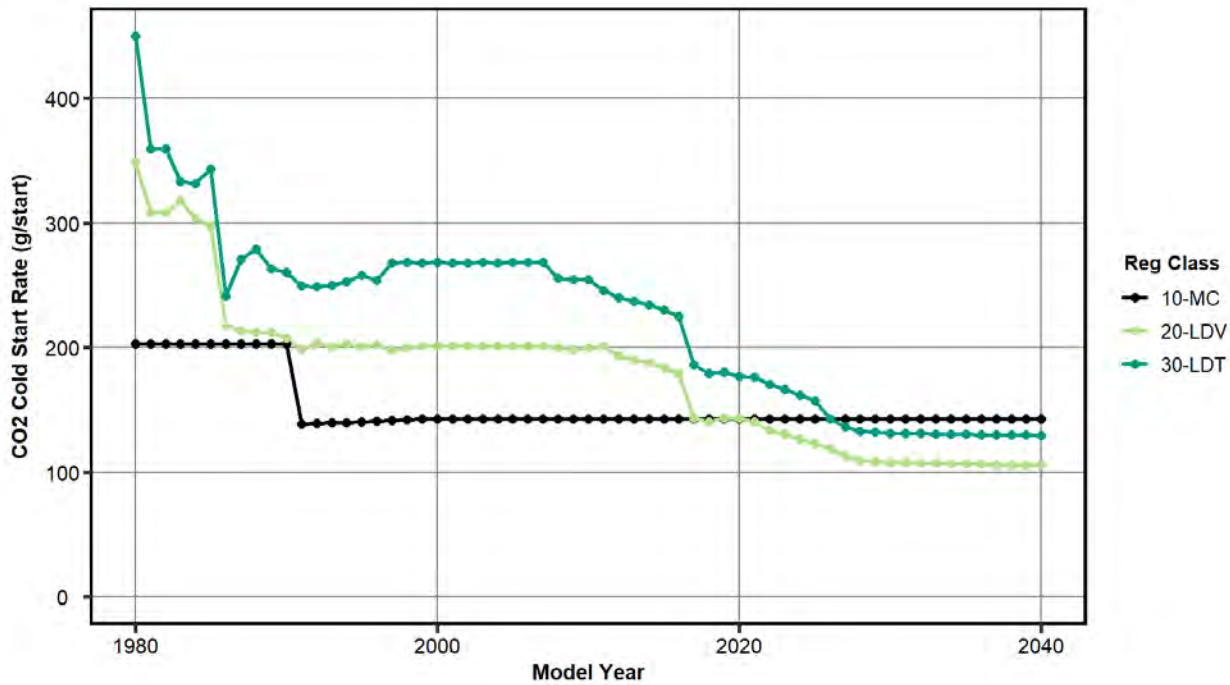

Figure 2-8. Cold start CO_2 emission rates (opMode 108) for gasoline motorcycle, light-duty vehicles, and light-duty trucks

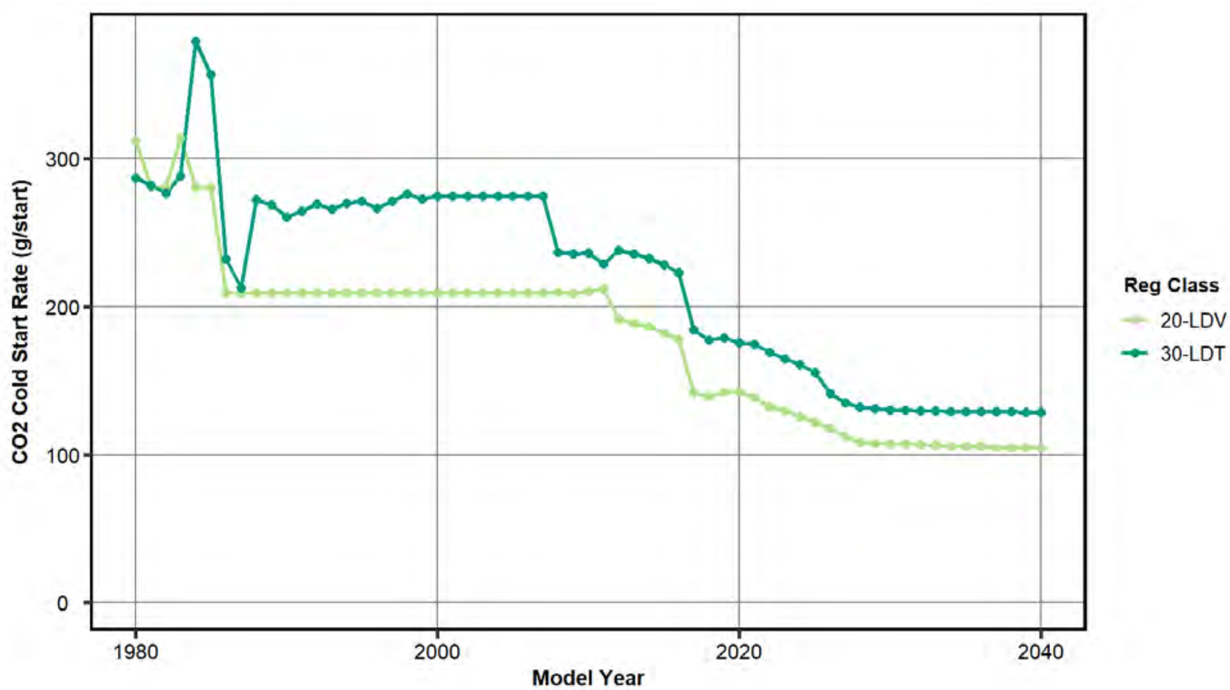

Figure 2-9. Cold start CO_2 emission rates (opMode 108) for diesel light-duty vehicles, and light-duty trucks

2.2 Heavy-Duty Vehicles

MOVES has heavy-duty running energy rates for five fuel types: diesel, gasoline, compressed natural gas (CNG), battery electric (BEV) and hydrogen fuel cell (FCEV). In MOVES3, we expanded the use of CNG to most vehicles in heavy heavy-duty (HHD) regulatory class instead of limiting it just to the Urban Bus regulatory class. In MOVES4, we added the ability to model heavy-duty BEV and FCEV vehicles and CNG long-haul combination trucks. Note that the output for BEV and FCEV is combined as the electricity fueltype in MOVES4.

The development of the heavy-duty energy rates by regulatory class, fuel type, and model year for internal combustion engine technologies are documented in the Heavy-duty Exhaust Emision Rates Report.[5] 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 Emision Rates Report. Energy consumption values for heavy-duty electric vehicles are documented in Section 2.2.1 of this report.

The HD GHG Phase 1 standards[4] 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 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.[e]

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), 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. 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 MOVES Heavy-duty Exhaust Emision Rates Report.[5] The revised aerodynamic coefficients for MY 2014 and later heavy-duty trucks are documented in the MOVES Population and Activity Report.[13]

In MOVES3, we updated the heavy-duty vehicle energy rates to incorporate the HD GHG Phase 2 rule.[24] 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 MOVES Heavy-duty Exhaust Emision Rates Report.[5]

In MOVES4, we added the ability to model heavy-duty BEV and FCEV vehicles as described below.

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

2.2.1 Heavy-Duty Battery Electric and Fuel Cell Energy Rates

MOVES4 includes the addition of heavy-duty electric vehicles. In the heavy-duty sector, 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 a number 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 in MOVES.

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. While this approach may be new in a modeling context, CARB has used the EER to express EV energy consumption as well.[25] The energy consumption of an HD EV can be calculated based on the following Equation 2-2:

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

The EER for an electric vehicle would generally be greater than 1, indicating EVs are more efficient than their diesel counterparts. 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.

Table 2-10 lists the EERs used for each heavy-duty source type. Appendix D provides a more detailed description of the data sources and derivation of these EER values.

Table 2-10. Heavy-Duty EV Energy Efficiency Ratios

sourceTypeID	Source Type Name	EER
41	Other Buses	2.0
42	Transit Buses	3.3
43	School Buses	3.5
51	Refuse Trucks	2.9
52	Single Unit Short-Haul Trucks	3.5
53	Single Unit Long-Haul Trucks	2.0
54	Motor Homes	2.0
61	Combination Short-Haul Trucks	2.6
62	Combination Long-Haul Trucks	2.0

For BEVs, this approach is implemented by first duplicating diesel energy consumption rates for all electric vehicles in the EmissionRate table. The EER is applied in the EmissionRateAdjustment table.

The energy efficiency of BEVs is based on energy consumed by the vehicle and does not account for losses from charging. EER based on energy from the electrical grid would be lower based on charging efficiency, but this is accounted for elsewhere in MOVES as described in the MOVES Emission Adjustments Report. Adjustments to account for energy used in heating and cooling the cabin and passenger compartment are documented in that same report.[23]

In addition, heavy-duty fuel cell vehicles (FCEVs) have a lower efficiency ratio than their BEV counterparts. However, an identical EER is implicitly applied to both BEVs and FCEVs in MOVES, since BEV and FCEV vehicles are aggregated as the electricity fuel type by the time the EERs are applied. To account for this, the energy consumption rates for FCEVs in the EmissionRate table are scaled up by a ratio of 1.6, based on values in GREET 2021[63] as explained in Appendix D, to ensure the final energy consumption rates for FCEVs are representative of their real operation.

The EmissionRateAdjustment table can support EER data by source type, regulatory class, model year. Due to a lack of available data from our research and literature study, we define EER only by source type and apply the same ratio for all heavy-duty regulatory classes and model years. The only exception is regulatory class 41 (Class 2b3), which is modelled based on the ALPHA runs done for light-duty. Their EmissionRateAdjustment is one, which means mathematically there is no adjustment applied.

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 the estimation of EERs, MOVES4 cannot explicitly model regenerative braking (a negative energy consumption for the braking operating modes) for heavy-duty EVs like it can for light-duty.

Heavy-duty EV energy consumption is assumed to be zero for starts, consistent with the approach for light-duty.

This approach is used for running energy consumption, but not for hotelling energy consumption for combination long-haul trucks. 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

MOVES4 introduced the capability to model combination long-haul trucks of non-diesel fuel types, including fuel cells. Because MOVES estimates energy demand on the grid for all electric vehicles, MOVES4 also introduces energy consumption for combination trucks which hotel overnight plugged into the AC power at the facility – known in the industry as using shore power.

In MOVES4, shore power is represented by a new process assigned to processID 93 and is represented by energy consumption rates for the operating mode 203. In MOVES3, operating mode 203 covered both shore power and battery usage for hotelling. However, in MOVES4, battery activity is moved to operating mode 204. Details are available in the Population and Activity Report.[13]

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)[26] collected energy consumption data from hotelling trucks from late 2006 through early 2008, including engine-on idling, APU usage, and shore power for model year 2006 combination trucks.

Using their published energy consumption values, we derived an EER of shore power relative to diesel engine-on energy consumption, consistent with our approach to modeling running energy consumption for EVs. Frey and Kuo report data for both a mid-temperature and high-temperature scenario, with EERs 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 MOVES4 is 1/8th the energy consumption for a 2006 model year Class 8 tractor extended idling. This works out to 12,135.6 kilojoules per hour, applied to 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[27] 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[2], the gasoline N_2O emission rates are derived from emission measurements on the Federal Test Procedure (FTP)[28] and supplemented with N_2O emission rates from the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006 report[42].

The running and start emissions 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).

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[42], except for a few revisions noted in the footnotes of the tables. The resulting N_2O base rates for gasoline vehicles are shown in Figure 3-2 and Figure 3-2.

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

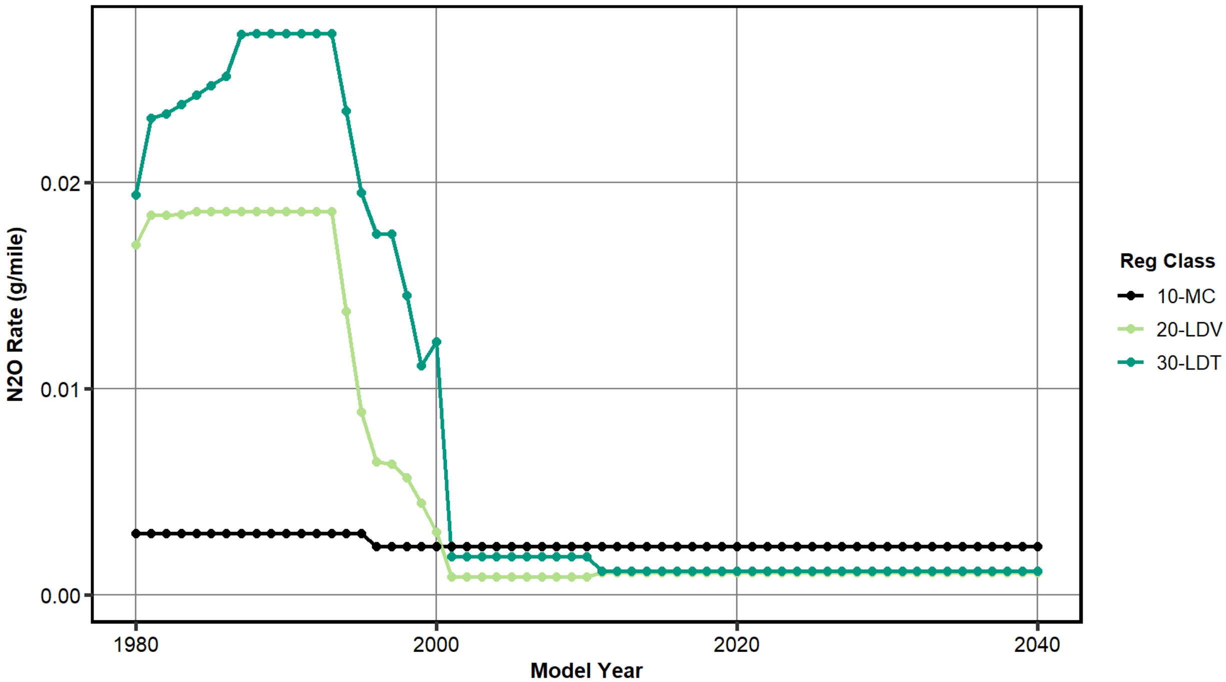

Figure 3-1. Base running rates in MOVES4 for N_2O from gasoline motorcycle, light-duty vehicles and light-duty trucks averaged over nationally representative operating mode distributions.

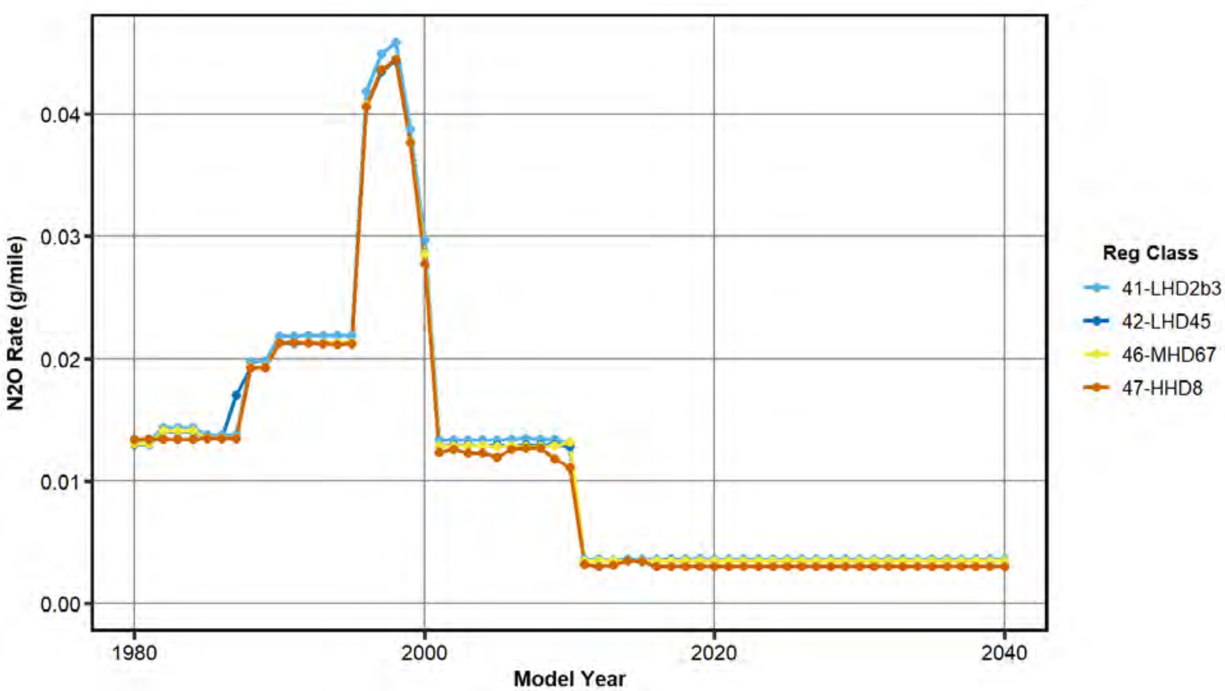

Figure 3-2. Base running rates in MOVES4 for N_2O from gasoline heavy-duty vehicles averaged over nationally representative operating mode distributions.

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[42], 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. 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.

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

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

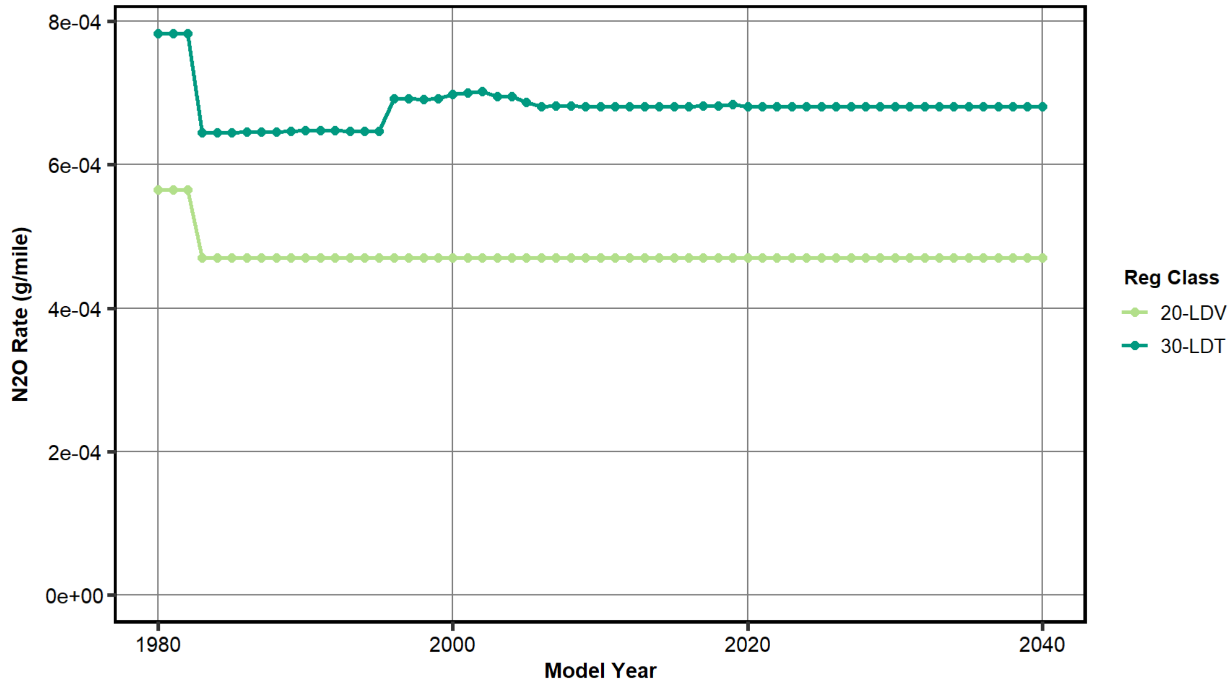

Figure 3-3. Base running rates in MOVES4 for N_2O from diesel passenger cars and passenger trucks averaged over nationally representative operating mode distributions.

3.2.2 Heavy-Duty Diesel

3.2.2.1 MY 1960-2003 Heavy-Duty Diesel

For heavy-duty diesel vehicles, the N_2O emission rates by technology for MY 1960-2003 were taken from the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006 report[42] 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 1960-2003 heavy-duty diesel vehicles

Vehicle Type / Control Technology[a]	FTP Comp (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, Figure 3-3, and Figure 3-5), 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)[29] 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 MOVES Heavy-duty Exhaust Emission Rates Report.[30] Quiros et al. (2016)[31] 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)[32,33] 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.[34,35,31] To assure 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,[36]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[37] in Table 3-4, which shows that the average FTP cycle average N_2O emission rates is two times below 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 Model Year	N_2O emission rate (g/kg)
Preble et al. (2019)[29]	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)[29]	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)[31]	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)[33]	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)[32]		4	DPF	2007	0.05 ± 0.03 (16-hour cycle)
					0.07 ± 0.07 (FTP)
EPA Certification Data (2020)[37]	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)[29] 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.

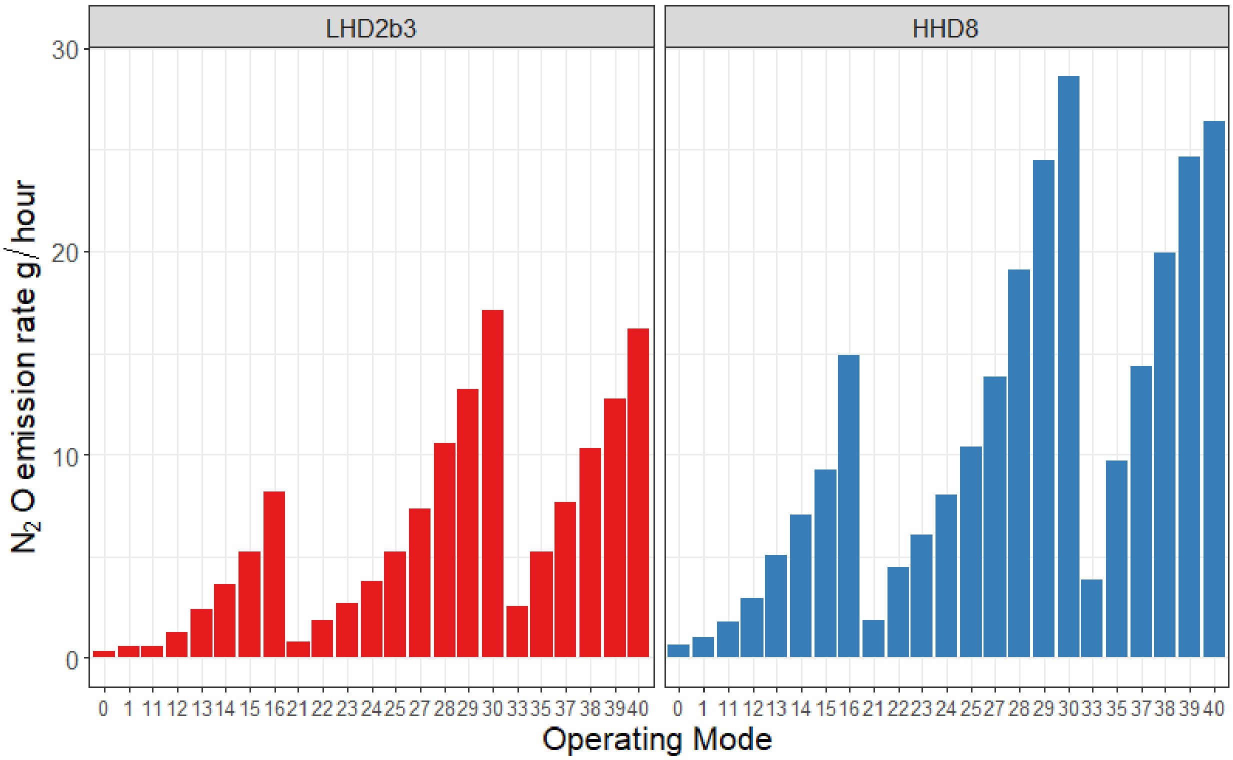

Figure 3-4. N_2O running emission rates (g/hour) by operating mode for model year 2017 LHD2b3 and HHD

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

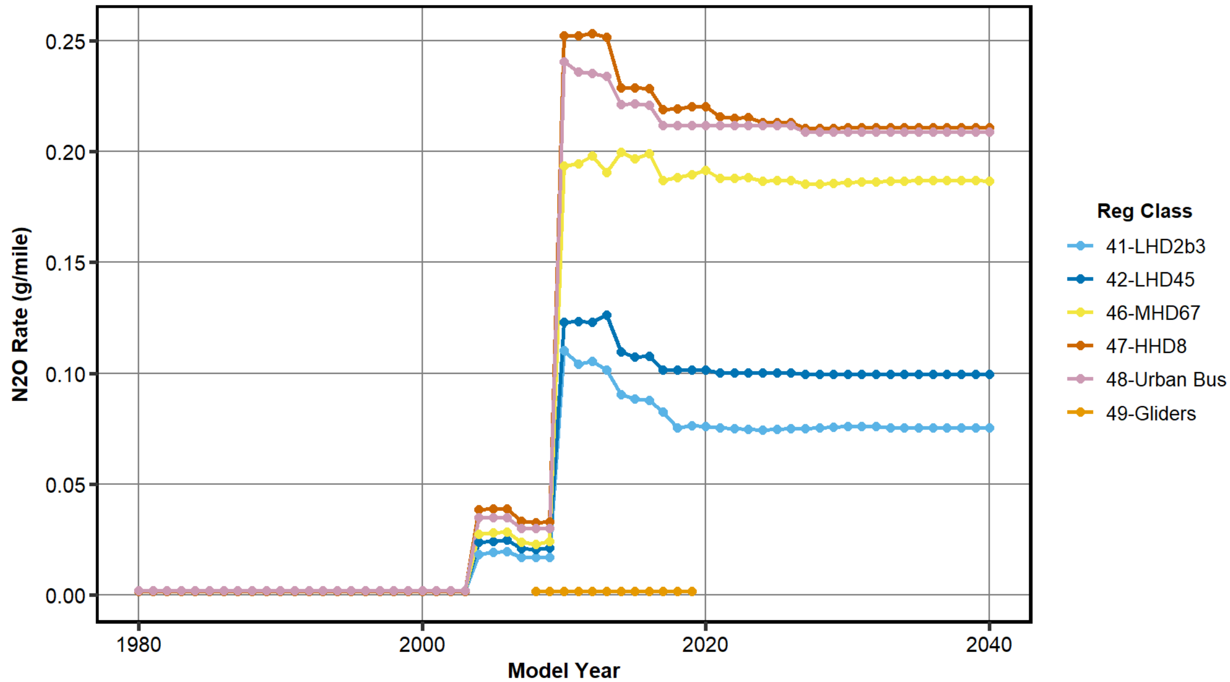

Figure 3-5. Base running rates in MOVES4 for N_2O from diesel heavy-duty vehicles averaged over nationally representative operating mode distributions.

We evaluated for 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).[28] 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 extended idle and auxiliary power unit exhaust processes. Overall, we anticipate the N_2O from these processes to be 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 compressed-natural gas fueled vehicles. The N_2O emission rates were based on limited data from the Sources and Sinks report.[42] In MOVES, the N_2O emission rates for E85-fueled vehicles are set to be the same as gasoline vehicles.

Heavy-duty vehicles fueled by compressed natural gas (CNG) use the emission rates reported in Table 3-5. 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[42], 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 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.

$$CO_2 = Total\ Energy\ Consumed\ \times Carbon\ Content \times Oxidation\ Fraction \times \left(\frac{44}{12}\right)$$ **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[1] based on values derived from the life-cycle model GREET. MOVES does not model upstream emissions, thus, the carbon content for electricity (whether from BEVs or FCEVs) is zero.

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 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)[38], which is consistent with values used in the LD GHG Phase 2 rule[3] and the HD GHG Phase 2 rule[24].

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[39] and sulfur dioxide emission calculators, respectively.[11]

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[40].

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

fuelTypeID	fuelSubtypeID	fuelSubtypeDesc	Fuel Density (g/gallons)	Energy Content (KJ/g)
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**[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)[41] 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[42]
  - 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[5]
  - 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[14]
    - 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[4]
  - 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)[3]

- **MOVES3**
  - The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021-2026 Passenger Cars and Light Trucks[6] 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[5]

- **MOVES4**
  - The Revised 2023 and Later Model Year Light Duty Vehicle Greenhouse Gas Emission Standards (LD GHG 2023-2026) rule[17] was incorporated, updating rates for light-duty ICE vehicles for MY2020 -2060
  - Light-duty and heavy-duty BEV penetrations were updated as documented in the MOVES Population and Activity Report[13]
  - 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.[23] 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

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	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	1996-2004
Motorcycles	
Uncontrolled	1960-1995
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.[43]

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 the tables below.

Table C-1: Vehicle Parameters for ALPHA Modeling

Vehicle	2019 Sales [44]	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 [45]	16,313	60	350[46]	3	96	288	360	J	8810	150	kW	17	7.05	3875	28.4	0.2018	0.0195
Tesla Model 3 [47]	154,840	53.6	360[47]	3	86	256	389[48]	lb-ft	9000	282	Hp	18	9.04	3875	36.01	-0.1289	0.0167
Honda Clarity BEV [49]	742	25.5	323[50]	3	88	264	222	lb-ft	9500	161	Hp	18	9.333	4250	25.41	0.2338	0.0176
Nissan Leaf [51]	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 [52]	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 [53]	15,090	85	320	6	74	444	440	J	13700	400	kW	19	9.34	4500	40.218	0.0604	0.0171
BMW i3 [54]	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 [55]	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 [56]	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

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 below.

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%

Appendix D. Derivation of Heavy-Duty EV and FCEV Energy Efficiency Ratios

As explained in Section 2.2.1, heavy duty energy consumption rates for BEVs in MOVES were calculated using ratios to the energy consumption of similar diesel vehicles. EER data is available in the literature from both simulations and empirical measurements for a variety of source types across common uses for those source types. The available EER data describes energy efficiency at the scale of trips or days of operation rather than individual operating modes (e.g., cruising in a specified speed band). Because it is based on real-world data collection, this data implicitly includes differences in operational behavior across source types, such as differing driving and idling behaviors that may impact the observed efficiency ratios.

The energy efficiency of BEVs is based on energy consumed by the vehicle and does not account for losses from charging. EER based on energy from the electrical grid would be lower based on charging efficiency, but this is accounted for elsewhere in MOVES as described in the MOVES emission adjustment report. Similarly, energy used in heating and cooling the cabin and passenger compartment is accounted for with later adjustments.[23]

EER data is shown in Table D-1, Table D-2, and Table D-3. Each table contains a different set of source types, grouped by HPMS class.

Table D-1:Bus EER values from the literature by source type.

sourceTypeID	Source Type Name	EER	Data source	Other notes
42	Transit Buses	3.5	ADVISOR simulations[57]	Average of transit and inter-city bus from Table 7, transit bus from Table 15. Year used: 2030.
42	Transit Buses	4.6	Altoona[58], CARB[59], NREL[60]	Fuel efficiency was calculated from "Average" cycles when available, otherwise the average of Manhattan, Orange County, and UDDS cycles. EER was calculated by dividing average fuel efficiency of all selected EVs by average fuel efficiency of all selected ICEVs.
42	Transit Buses	3.7	FASTSim modeling with in-use GPS speed traces[61]	Transit buses (9.1 m to 12.1 m long) from Figure 5.
42	Transit Buses	1.6	Equations for tractive power demand, etc. informed by NREL Fleet DNA database[62]	Class 7 city bus from Figure 4c
42	Transit Buses	3.0	Autonomie (from GREET 2021)[63]	Model year 2020
43	School Buses	1.8	Equations for tractive power demand, etc. informed by NREL Fleet DNA database[62]	Class 6 school bus from Figure 4c.
43	School Buses	3.8	Autonomie (from GREET 2021)[63]	Model year 2020

Table D-2: Heavy-duty EERs from the literature by source type

sourceTypeID	Source Type Name	EER	Data source	Other notes
51	Refuse Trucks	4.2	Autonomie (from GREET 2021)[63]	Model year 2020
51	Refuse Trucks	1.5	Equations for tractive power demand, etc. informed by NREL Fleet DNA database[62]	Class 8 refuse truck from Figure 4c
52	Single Unit Short-Haul Trucks	4.8	Autonomie (from GREET 2021)[63]	Average of Classes 8, 6, and 4 vocational trucks model year 2020
52	Single Unit Short-Haul Trucks	3.8	ADVISOR simulations[57]	Average of MD delivery truck (city) and HD short-haul truck (city) from Table 7, delivery truck from Table 15. Year used: 2030.
52	Single Unit Short-Haul Trucks	4.9	Measurements reported in CARB ACT Rule AppG[64]	Average of two CalHEAT Class 5 Step Vans, one CalHEAT Class 3 Sprinter Van, and two SD Class 3 Shuttle Vans.
52	Single Unit Short-Haul Trucks	3.5	Measurements reported in ORNL/NREL Frito Lay study[65]	Original data from Figure 16 from nine ICEVs and 10 Class 6 BEVs. EER calculated from the linear fits, averaged across daily distances every 5 mi from 10-65 mi.
52	Single Unit Short-Haul Trucks	2.8	FASTSim[66]	Class 4 parcel delivery current fuel efficiencies from Figure 25.
52	Single Unit Short-Haul Trucks	1.6	Equations for tractive power demand, etc. informed by NREL Fleet DNA database[62]	Average of Class 5 linen delivery van, Class 5 food delivery truck, Class 4 parcel delivery van, Class 3 food delivery truck, Class 3 bucket truck from Figure 4c.
52	Single Unit Short-Haul Trucks	2.9	VECTO simulation in Scania LCA report[67]	Class 8 regional and urban delivery truck from “Fuel and energy consumption” subsection of “Use phase” section.
53	Single Unit Long-Haul Trucks	2.0	Calculation of traction power at 65 mph and assumption about diesel engine efficiency of 49%[68].	Class 8 long-haul truck, single unit or combination not specified. BEV traction energy from Table 2, ICEV fuel efficiency from page 4.

Table D-3: Combination truck EER values in the literature by source type.

sourceTypeID	Source Type Name	EER	Data source	Other notes
61	Combination Short-Haul Trucks	2.4	FASTSim[66]	Class 8 short haul truck current fuel efficiencies from Figure 25.
61	Combination Short-Haul Trucks	3.8	Autonomie (from GREET 2021)[63]	Model year 2020
61	Combination Short-Haul Trucks	1.5	Equations for tractive power demand, etc. informed by NREL Fleet DNA database[62]	Class 7 food delivery truck and Class 8 port drayage tractor (both run <200 mi/day on average, which is short-haul in MOVES) from Figure 4c.
62	Combination Long-Haul Trucks	2.0	Calculation of traction power at 65 mph and assumption about diesel engine efficiency of 49%[68].	Class 8 long-haul truck, single unit or combination not specified. BEV traction energy from Table 2, ICEV fuel efficiency from page 4.
62	Combination Long-Haul Trucks	2.0	FASTSim[66]	Average of Class 8 long haul (750 mi), long haul (500 mi), and short haul (which has a range of >200 mi/day and thus could be long haul in MOVES) current fuel efficiencies from Figure 25.
62	Combination Long-Haul Trucks	2.1	Autonomie (from GREET 2021)[63]	Model year 2020
62	Combination Long-Haul Trucks	1.8	ADVISOR simulations[57]	Average of HD long-haul truck (highway) from Table 7 and long-haul truck from Table 15. Year used: 2030.

Table D-4 shows EERs averaged for each available source type with equal weighting given to each reference. References were not available for other buses and motor homes, so their EERs were copied from single unit long-haul trucks due to similar expected driving behavior – mostly long trips on highways. Only two references were available for school buses, which were two of the five references used for transit buses. Given the similar operational behavior of these two source types, the school buses' average EER was calculated from the same EERs used for transit buses, swapping the EERs from their common references.

Table D-4: Average EER values from the literature by source type.

sourceTypeID	Source Type Name	Average EER
41	Other Buses	2.0
42	Transit Buses	3.3
43	School Buses	3.5
51	Refuse Trucks	2.9
52	Single Unit Short-Haul Trucks	3.5
53	Single Unit Long-Haul Trucks	2.0
54	Motor Homes	2.0
61	Combination Short-Haul Trucks	2.6
62	Combination Long-Haul Trucks	2.0

In addition, heavy-duty fuel cell vehicles (FCEV) have a lower efficiency ratio than their BEV counterparts. However, in MOVES, by the time the EERs are applied, BEV and FCEV vehicles have been aggregated within the electricity fuel type, which means an identical EER is implicitly applied to both powertrain types. To account for this, the energy consumption rates for FCEVs in EmissionRate are scaled up for FCEVs by a ratio of 1.25 to ensure the final energy consumption rates for FCEVs are representative of their real operation.

The multiplier for the FCEV emission rates was derived from the relative energy consumption for heavy-duty fuel cell and battery electric vehicles as published by Islam, et al. in 2022.[69] The authors used Autonomie to estimate the fuel savings of various alternative fuels for heavy-duty vehicles and show that FCEVs consume, on average, 1.6 times more energy than comparable BEVs. This is consistent with values estimated in GREET 2022.[70]

We adjusted this value down to account for the fact that MOVES calculates an energy consumption for charging and battery losses and for HVAC usage as documented in the MOVES adjustment report. FCEVs do not have batteries chargeable by grid energy, so we removed that effect by a typical charging and battery efficiency value of 15%. We found two sources regarding the relationship between FCEV energy consumption and temperature. The first, an ICCT study on FCEV tractor-trailer fuel economy,[71] showed that FCEV energy consumption does not change with ambient temperature, while the second, a real-world study of BEV and FCEV bus energy demand,[72] showed that FCEV energy demand changes with temperature but to a lesser extent than BEVs. Therefore, we also applied an 8% correction to the FCEV multiplier to remove the national average temperature adjustment applied in MOVES. The final result is an FCEV energy demand multiplier of 1.25.

6 References

[1] USEPA (2005). *Energy and Emissions Inputs*. EPA-420-P-05-003. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. March, 2005.

[2] USEPA (2012). *Updates to the Greenhouse Gas and Energy Consumption Rates in MOVES2010a*. EPA-420-R-12-025. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. August, 2012.

[3] USEPA (2012). 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards (77 FR No. 199, October 15, 2012)

[4] USEPA (2011). Greenhouse Gas Emission Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles (76 FR 57106, September 15, 2011)

[5] USEPA (2023). *Exhaust Emission Rates of Heavy-Duty Onroad Vehicles in MOVES4*. EPA-420-R-23-027 . Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. August, 2023. https://www.epa.gov/moves/moves-onroad-technical-reports

[6] USEPA (2020). The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021-2026 Passenger Cars and Light Trucks (85 FR No.84, April 30, 2020)

[7] USEPA (2016). *Final Rulemaking to Establish Greenhouse Gas Emission Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles – Phase 2: Regulatory Impact Analysis*. EPA-420-R-16-900, August 2016.

[8] USEPA (2021). Revised 2023 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions Standards (86 FR 74434, December 30, 2021)

[9] USEPA (2021). *Exhaust and Crankcase Emission Factors for Nonroad Compression-Ignition Engines in MOVES3.0.2*. EPA-420-R-21-021 Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. September 2021. https://www.epa.gov/moves/moves-onroad-technical-reports

[10] USEPA (2010). *Exhaust Emission Factors for Nonroad Engine Modeling -- Spark-Ignition*. NR-010f. EPA-420-R-10-019. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. July 2010. https://www.epa.gov/moves/nonroad-technical-reports

[11] USEPA (2023). *Speciation of Total Organic Gas and Particulate Matter Emissions from Onroad Vehicles in MOVES4*. EPA-420-R-23-006 . Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. August 2023 . https://www.epa.gov/moves/moves-onroad-technical-reports

[12] USEPA (2023). *Exhaust Emission Rates for Light-Duty Onroad Vehicles in MOVES4*. EPA-420-R-23-028 . Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. November 2020. https://www.epa.gov/moves/moves-onroad-technical-reports

[13] USEPA (2023). *Population and Activity of Onroad Vehicles in MOVES4*. EPA-420-R-23-005 Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. August 2023.

[14] USEPA (2010). Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule (75 FR No. 88, May 7, 2010)

[15] USEPA (2012). Regulatory Impact Analysis: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards. EPA-420-R-12-016. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI.August,2012.

[16] USEPA (2019). The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule Part One: One National Program (84 FR No.188, September 27, 2019)

[17] USEPA (2021). Revised 2023 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions Standards (86 FR 74434, December 30, 2021)

[18] US Environmental Protection Agency. *2021 EPA Automotive Trends Report*. Data available at www.epa.gov/automotive-trends/explore-automotive-trends-data Accessed *June 15, 2022*.

[19] USEPA (2015*). Greenhouse Gas and Energy Consumption Rates for On-road Vehicles: Updates for MOVES2014*. EPA-420-R-15-003. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. October 2015.

[20] USEPA (2009). *Draft MOVES2009 Highway Vehicle Population and Activity Data*. EPA-420-P-09-001. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. August, 2009.

[21] USEPA (2020). *Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) Tool.* Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. December, 2020. https://www.epa.gov/regulations-emissions-vehicles-and-engines/advanced-light-duty-powertrain-and-hybrid-analysis-alpha#overview

[22] USEPA (2021). *Data on Cars used for Testing Fuel Economy*. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. 2021. https://www.epa.gov/compliance-and-fuel-economy-data/data-cars-used-testing-fuel-economy

[23] USEPA (2023). *Emission Adjustments for MOVES4*. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. August 2023.

[24] USEPA (2016). *Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles—Phase 2*. (81 FR No.206, October 25,2016)

[25] California Air Resources Board. (2018). "Battery Electric Truck and Bus Energy Efficiency Compared to Conventional Diesel Vehicles." Available online: https://ww2.arb.ca.gov/sites/default/files/2018-11/180124hdbevefficiency.pdf.

[26] H. Christopher Frey & Po-Yao Kuo (2009) Real-World Energy Use and Emission Rates for Idling Long-Haul Trucks and Selected Idle Reduction Technologies, Journal of the Air & Waste Management Association, 59:7, 857-864.

[27] Wallington, T. J. and P. Wiesen (2014). N2O emissions from global transportation. *Atmospheric Environment,* 94, 258-263.

[28] USEPA (2020). Vehicle and Fuel Emissions Testing. Dynamometer Drive Schedules.

https://www.epa.gov/vehicle-and-fuel-emissions-testing/dynamometer-drive-schedules#vehicleDDS

[29] Preble, C. V., R. A. Harley and T. W. Kirchstetter (2019). Control Technology-Driven Changes to In-Use Heavy-Duty Diesel Truck Emissions of Nitrogenous Species and Related Environmental Impacts. *Environ Sci Technol,* 53 (24), 14568-14576.

[30] USEPA (2023). Exhaust Emissions from Heavy-Duty Vehicles in MOVES4. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. August 2023.

[31] Quiros, D. C., J. Smith, A. Thiruvengadam, T. Huai and S. Hu (2017). Greenhouse gas emissions from heavy-duty natural gas, hybrid, and conventional diesel on-road trucks during freight transport. *Atmospheric Environment,* 168 (Supplement C), 36-45.

[32] Khalek, I., T. Bougher and P. Merrit (2009). *Phase 1 of the Advanced Collaborative Emissions Study*. CRC Report: ACES Phase 1.

[33] Khalek, I. A., M. G. Blanks and P. M. Merritt (2013). *Phase 2 of the Advanced Collaborative Emissions Study*. CRC Report: ACES Phase 2. Coordinating Research Council, Inc. & Health Effects Institute. November 2013.

[34] Majewski, W. A. (2005). Selective catalytic reduction. *Ecopoint Inc. Revision*.

[35] Khalek, I. A., M. G. Blanks, P. M. Merritt and B. Zielinska (2015). Regulated and unregulated emissions from modern 2010 emissions-compliant heavy-duty on-highway diesel engines. *Journal of the Air & Waste Management Association,* 65 (8), 987-1001.

[36] USEPA (2011). Greenhouse Gas Emission Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles (76 FR 57106, September 15, 2011)

[37] USEPA (2020). Annual Certification Data for Vehicles, Engines, and Equipment. Heavy-Duty Highway Gasoline and Diesel Certification Data Retrieved November, 25, 2020.

https://www.epa.gov/compliance-and-fuel-economy-data/annual-certification-data-vehicles-engines-and-equipment

[38] The Intergovernmental Panel on Climate Change*, Climate Change 2007: Impacts, Adaptation and Vulnerability*.

https://www.ipcc.ch/site/assets/uploads/2018/03/ar4_wg2_full_report.pdf

[39] USEPA (2023). *Evaporative Emissions from Onroad Vehicles in MOVES4*. EPA-420-R-23-023 Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. August 2023. https://www.epa.gov/moves/moves-technical-reports.

[40] USEPA (2023). *Fuel Supply Defaults: Regional Fuels and the Fuel Wizard in MOVES4*. EPA-420-R-23-025. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI.August 2023. https://www.epa.gov/moves/moves-technical-reports.

[41] USEPA (2005). *Fuel Consumption Modeling of Conventional and Advanced Technology Vehicles in the Physical Emission Rate Estimator (PERE)*. EPA420-P-05-001. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. February, 2005.

[42] USEPA (2008). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2006*. U.S. Environmental Protection Agency. 1200 Pennsylvania Avenue, N.W. Washington, DC 20460. April 15, 2008.

[43] USEPA (2013). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2013*. U.S. Environmental Protection Agency. 1200 Pennsylvania Avenue, N.W. Washington, DC 20460. April 15, 2015.

[44] Energy, U. D. (2020, January). *Maps and Data - U.S. Plug-in Electric Vehicle Sales by Model*. Retrieved from

Alternative Fuels Data Center: https://afdc.energy.gov/data/10567

[45] *Chevrolet Bolt EV - 2019*. (n.d.). Retrieved from Chevrolet:

https://media.chevrolet.com/media/us/en/chevrolet/vehicles/bolt-ev/2019.tab1.html

[46] *2019 Chevrolet Bolt EV - Specifications and Price*. (n.d.). Retrieved from EV Specifications:

https://www.evspecifications.com/en/model/18a190

[47] *2019 Tesla Model 3 Standard Range RWD - Specifications*. Retrieved from EV Specifications:

https://www.evspecifications.com/en/model/bc5896

[48] Halvorson, B. (2019, March 2). *2019 Tesla Model 3*. Retrieved from The Car Connection:

https://www.thecarconnection.com/overview/tesla_model-3_2019

[49] *2019 Honda Clarity Electric*. (n.d.). Retrieved from Honda:

https://mygarage.honda.com/s/find-honda#mid^ZC6F3KGNW

[50] *2019 Honda Clarity Fuel Cell Specifications & Features*. (2019, April 10). Retrieved from Honda Auto News:

https://hondanews.com/en-US/honda-automobiles/releases/release-0748feefcc68437a94892c160e085aa7-2019-clarity-fuel-cell-specifications-features

[51] *2019 Leaf*. (n.d.). Retrieved from Nissan: https://www.nissanusa.com/content/dam/Nissan/us/vehicle-brochures/2019/2019-nissan-nissan-leaf-brochure-en.pdf

[52] *2019 Fiat 500e Specifications.* (n.d.). Retrieved from Fiat: https://media.fcanorthamerica.com/download.do?id=20137

[53] *2019 Tesla Model S Standard Range - Specifications and Price*. (n.d.). Retrieved from EV Specifications: https://www.evspecifications.com/en/model/d14199

[54] *The new 2019 BMW i3120 Ah and i3s 120 Ah*. (2018, September 28). Retrieved from BMW Group:

https://www.press.bmwgroup.com/usa/article/detail/T0285420EN_US/the-new-2019-bmw-i3-120ah-and-i3s-120ah?language=en_US

[55] *2019 e-Golf Technical Specifications*. (n.d.). Retrieved from Volkswagen:

https://media.vw.com/assets/documents/original/9221-2019eGolfTechnicalSpecifications.pdf

[56] *2019 Tesla Model X Performance (SR) - Specifications and Price*. (n.d.). Retrieved from EV Specifications:

https://www.evspecifications.com/en/model/befbc2

[57] Burke, A., & Sinha, A. (2020). Technology, Sustainability, and Marketing of Battery Electric and Hydrogen Fuel Cell Medium-Duty and Heavy-Duty Trucks and Buses in 2020-2040. UC Davis: National Center for Sustainable Transportation. http://dx.doi.org/10.7922/G2H993FJ Retrieved from https://escholarship.org/uc/item/7s25d8bc.

[58] LTI Bus Research and Testing Center (2012-2020). Bus Testing Report. https://www.altoonabustest.psu.edu/bus-list.aspx

[59] California Air Resources Board. (2018). Battery Electric Truck and Bus Energy Efficiency Compared to Conventional Diesel Vehicles. http://ww2.arb.ca.gov/sites/default/files/barcu/regact/2019/act2019/appg.pdf

[60] Johnson, C., Nobler, E., Eudy, L., and Jeffers, M. (2020). "Financial Analysis of Battery Electric Transit Buses". *National Renewable Energy Laboratory.* https://afdc.energy.gov/files/u/publication/financial_analysis_be_transit_buses.pdf

[61] Kotz, A.J., Miller, E., Watson, A., Kelly, K.J., "Transit Bus Electrification Evaluation from GPS Speed Traces."

[62] Gao, Z., Lin, Z., Davis, S. C., & Birky, A. K. (2018). Quantitative Evaluation of MD/HD Vehicle Electrification using Statistical Data. Transportation Research Record, Vol. 2672(24) 109-121.

[63] GREET 2021, Argonne National Laboratory, https://greet.es.anl.gov/ Accessed 10/12/2021

[64] CARB ACT Rule Appendix G for CalHEAT data. http://ww2.arb.ca.gov/sites/default/files/barcu/regact/2019/act2019/appg.pdf

[65] Robert Prohaska, Mike Simpson, Adam Ragatz, Kenneth Kelly, Kandler Smith and Kevin Walkowicz, Field Evaluation of Medium-Duty Plug-in Electric Delivery Trucks, Technical Report NREL/TP-5400-66382, December 2016. https://afdc.energy.gov/files/u/publication/field_evaluation_md_elec_delivery_trucks.pdf.

[66] Chad Hunter, Michael Penev, Evan Reznicek, Jason Lustbader, Alicia Birky, and Chen Zhang, Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks, Technical Report NREL/TP-5400-71796, September 2021. https://www.nrel.gov/docs/fy21osti/71796.pdf

[67] Burul, D., Algesten, D., Life cycle assessment of distribution vehicles - Battery electric vs diesel driven, Scania report, 2021.

[68] Zhao, H., Wang, Q., Fulton, L., Jaller, M., & Burke, A. (2018). A Comparison of Zero-Emission Highway Trucking Technologies. UC Office of the President: University of California Institute of Transportation Studies. http://dx.doi.org/10.7922/G2FQ9TS7 Retrieved from https://escholarship.org/uc/item/1584b5z9.

[69] Ehsan Sabri Islam, Ram Vijayagopal, Aymeric Rousseau. "A Comprehensive Simulation Study to Evaluate Future Vehicle Energy and Cost Reduction Potential", Report to the US Department of Energy, Contract ANL/ESD-22/6, October 2022.

[70] Wang, Michael, Elgowainy, Amgad, Lu, Zifeng, Baek, Kwang H., Bafana, Adarsh, Benavides, Pahola T., Burnham, Andrew, Cai, Hao, Cappello, Vincenzo, Chen, Peter, Gan, Yu, Gracida-Alvarez, Ulises R., Hawkins, Troy R., Iyer, Rakesh K., Kelly, Jarod C., Kim, Taemin, Kumar, Shishir, Kwon, Hoyoung, Lee, Kyuha, Lee, Uisung, Liu, Xinyu, Masum, Farhad, Ng, Clarence, Ou, Longwen, Reddi, Krishna, Siddique, Nazib, Sun, Pingping, Vyawahare, Pradeep, Xu, Hui, and Zaimes, George. Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model ® (2022 .Net). Computer Software. USDOE Office of Energy Efficiency and Renewable Energy (EERE). 10 Oct. 2022. Web. doi:10.11578/GREET-Net-2022/dc.20220908.2

[71] Basma, Hussein and Rodriguez, Felipe. "Fuel cell tractor-trailers: Technology overview and fuel economy". International Council on Clean Transportation. July 2022. Available online: https://theicct.org/wp-content/uploads/2022/07/fuel-cell-tractor-trailer-tech-fuel-1-jul22.pdf

[72] Henning, Mark; Thomas, Andrew R.; and Smyth, Alison, "An Analysis of the Association between Changes in Ambient Temperature, Fuel Economy, and Vehicle Range for Battery Electric and Fuel Cell Electric Buses" (2019). Urban Publications. 0 1 2 3 1630. https://engagedscholarship.csuohio.edu/urban_facpub/1630